CRANFIELD UNIVERSITY

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AN APPLICATION OF HIGH RELIABILITY THEORY IN THE WATER UTILITY SECTOR

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Abstract

In the literature, a need was identified to consider the provision of drinking water to be a 'high reliability' societal service. This thesis reports on an investigation into the technical and organisational reliability of a defined section in the water utility sector and a Regional Water Utility. Here, the organisational reliability in operations and incident management, and, secondly, the management of technical reliability of water supply systems arising from risk-based asset management were the emphasis of this project.

In order to substantiate this investigation, three main research components were designed and conducted: firstly, a characterisation of the nature of incidents and their impact on customers; secondly, an investigation into organisational capabilities to manage incidents and its role in maintaining a resilient water supply system that minimises the impact of incidents on customers, and thirdly, an investigation into risk-based asset management strategies that provide and maintain the technical reliability of the water supply system. In the latter perspective, the opportunity to learn from previous incidents to enhance asset risk assessments was investigated.

In this study, it was found that many HRO principles are readily observable in the water utilities that participated in this research. Following the characterisation of incidents, it is demonstrated that the observation of HRO principles during incident management has a positive effect on the overall reduction of incident impacts on customers. Beyond the immediate effect of HRO principles in incident management, it could be demonstrated that 'learning from failure' provides a mechanism to understand and manage future risks. The concept of incident meta-analysis is introduced that compares series of past incidents with documented perceived, future risks. The statistical analysis of incident time series facilitated the monitoring of incident trends, the validation of the risk model used in the Regional Water Utility and the verification of risk data, in particular for the risk components 'probability, cause, effect and impact'.

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Glossary

Asset	Plant, maschinery, property, buildings, vehicles and other items and related systems that have a distinct and quantifiable business function or service (British Standard Institution, 2003)
Asset management	Systematic and coordinated activities and practices through which and organisation optimally manages its assets, and their associated performance, risks and expenditures over their lifecycle for the purpose of achieving its statutory and/or regulatory obligations and economic levels of service (British Standard Institution, 2003)
Asset inventory	A standardised dataset covering the asset base of a water company. It divides assets into classifications and records physical attributes for each (Office of Water Services, 2007)
Asset register	A record of asset information including historical, financial, condition, construction, technical and financial information (NAMS Group, 2006).
Business objectives	A goal that a company has set itself or is set by a regulator.
Capital expenditure	Expenditure used to create new assets or to increase the capability of existing assets beyond their original design capacity, capability or service potential (NAMS Group, 2006)
Capital maintenance	Planned work to replace, repair or refurbish waterassets to provide continuing services to customers (Office of Water Services, 2007).
Cause	An effect or event producing entity.
Consequence	The direct or indirect impact that [an event] has on the provision by the overall system of service to customers and the environment, and/or on [company] cost. (UK Water Industry Research Limited, 2002)
Control measures	Activities and processes applied to prevent or lessen risk events or risk consequences that might occur.
Discounting	A technique for converting cashflows that occur over time to an equivalent amount at a common point in time (NAMS Group, 2006).
Frequency	The number of occurrences within a specified period.
Hazard	An entity that has potential to cause harm.

Impact	The measurable result of an incident (or risk event) and its effects.
Incident	An adverse impact on customers, the environment or normal operation of a water utility.
Infrastructure	Assets such as water mains, water treatment works, pumping stations and service reservoirs
Life cycle (Asset)	Time interval of an assets that commences with the identification of the need for an asset and terminates with the decommissioning of the asset or any liabilities thereafter (British Standard Institution, 2003)
Net Present Value	The present value of an asset derived from its future use in return for future cash flows
Operating expenditures	Expenditure for the daily running of assets and services.
Probability or likelihood	The chance of a defined outcome to eventuate which is based on sufficient information and knowledge.
Risk	The probability or frequency of adverse effects and impacts measured as a consequence.
Risk assessment	Qualitative or quantitative evaluation of risk.
Risk management	The process of risk assessment and decision making that considers measures to reduce, contain or accept identified risks.
Risk mitigation	Options to control or reduce risk. They may be applied to any identified risk causes or to control or reduce the impact.
Root cause	The underlying reasons that triggers an event or incident.
Service	Services to customers (*e.g.* the safe and reliable provision of drinking water), the environment (*e.g.* pollution control) and employees (*e.g.* health and safety at work) (UK Water Industry Research Limited, 2002)
Serviceability	The capability of an asset to provide service (UK Water Industry Research Limited, 2002).
Uncertainty	Insufficient information and knowledge to confidently determine probabilities or frequencies.

Notation

AWWARF	American Water Works Association Research Foundation
Av	Average
CBA	Cost Benefit Analysis
CI 95%	Confidence interval at 95%
CAPEX	Capital Expenditure
D	Duration
DOMS	Distribution Operations & Maintenance Strategy
DMA	Distribution Management Area
DWI	Drinking Water Inspectorate
ETA	Event tree analysis
F	Frequency of incidents
FTA	Failure tree analysis
H	Hazard
H0	Null hypothesis
HACCP	Hazard Analysis, Critical Control Points
HAZOP	Hazards and Operability study
HRO	High Reliability Organisation
HRT	High Reliability Theory
IT	Information Technology
MTBF	Mean time between failures
NAT	Normal Accident Theory
NPV	Net Present Value
OFWAT	Office of Water Services
OPEX	Operational Expenditure
P	Population
RCM	Reliability Centred Maintenance
RWU	Regional Water Utility
SCADA	Supervisory control and Data acquisition
SD	Standard Deviation
SE	Standard error

SL	Significance level
SRE	Service reservoir for drinking water
SN	National standard
WACC	Weighted Average Cost of Capital
WHO	World Health Organisation
WPS	Water pumping station
WSP	Water Safety Plan
WT	Water tower
WTW	Water treatment works

1 Introduction

This thesis reports on the investigation into the technical and organisational reliability of a defined section of the water utility sector and a Regional Water Utility in particular. Chapter 1 introduces the background, literature review, aims, objectives, and outline methodology for this research project. Recent academic publications have focussed on major failures in water supply organisations to provide safe drinking water to customers (Hrudey and Hrudey, 2004) and risk management systems are increasingly promoted as a means to control failure (World Health Organisation, 2004). Others have argued that the provision of drinking water should be a 'high reliability' societal service, subject to the sectoral rigours inherent to the nuclear, offshore and aerospace industries (Pollard *et al.*, 2005).

Based on the literature review, it was decided to investigate high reliability theory in the water utility context. Firstly, a need was identified to investigate how water utilities cope under trying conditions. Secondly, a need was identified to understand how water utilities learn from trying conditions, in particular to enhance assessments of perceived, future risks. This thesis places a particular emphasis on learning from failure to enhance risk assessments that are used in asset investment and maintenance decision making. The relationship of these themes is conceptualised in Figure 1.

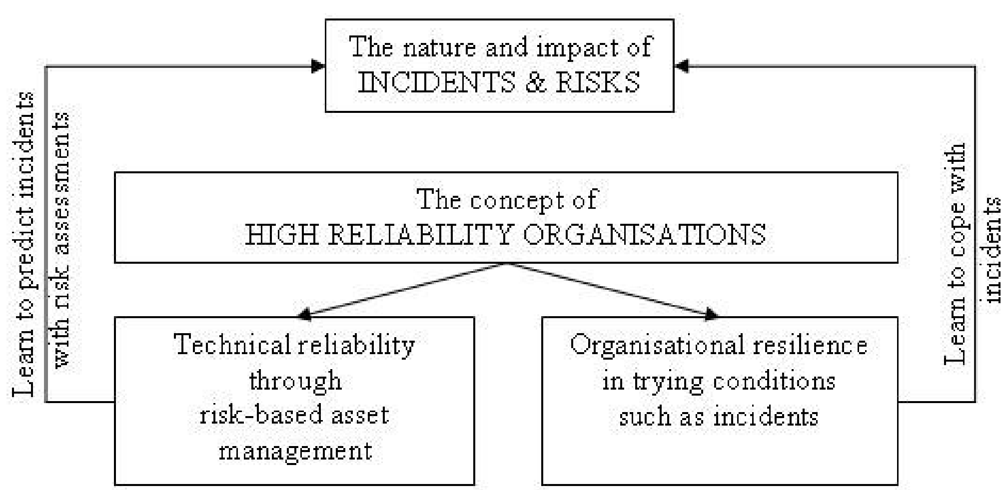

Figure 1 A high reliability organisations' perspective on technical reliability and organisational resilience

Chapter 2 investigates the causes, effects and impacts on customers of incidents in England and Wales and a Regional Water Utility. With a view to subsequent chapter, a methodology was adopted that enables a comparative assessment of incident impacts on customers. This methodology is used throughout this thesis to compare incidents but also to evaluate the consequential impact of perceived, future risks. The findings of this chapter are subsequently used to validate the risk model and verify the risk data used in the Regional Water Utility.

Based on the findings in the previous chapter, chapter 3 investigates the familiarity of the water sector with the principles identified in the HRO literature. A HRO framework was developed as an organisational assessment tool that was used to survey a number of water utilities but also to structure observations, interviews and document reviews. This chapter emphasises the organisational ability to remain resilient under trying conditions, *i.e.* during incident management. The previously introduced assessment of incident impacts is used as a metric to correlate observations and assessments of HRO in the Regional Water Utility.

Chapter 4 investigates the organisational ability to learn from incidents with a particular emphasis on enhancing risk assessments for subsequent risk-based asset management decision making. The use of risk data in the asset investment and maintenance decision-making process is further illustrated and findings from the second chapter are used to validate the risk model and verify the risk data acquired in the Regional Water Utility.

Chapter 5 investigates the financial and customer evaluation of risk in the water sector. In addition to *prior art* of risk-based decision making in the literature, the previous chapter further established and verified a distinct relationship between the price of risk and the cost of risk reduction. In this chapter, the influence of the price of risk or the benefit of risk reduction in asset management decision making is investigated and it is sought to explain why incidents occur despite the availability of risk assessments that predicted failure.

The subsequent chapters discuss the research findings, present the conclusions and suggest further work.

1.1 Background

A water utility's prime objective is to provide *"good safe drinking water that has the trust of consumers."* Water must be safe, reliable, of good aesthetic quality and maintain the trust and confidence of customers (International Water Association, 2004). The probability of an event or incident with an adverse impact on this objective is a public health risk and their management is the primary function of the water utility sector (Ministry of Health, 2005b).

Dramatic incidents in recent years, such as the *E. coli* and *Campylobacter jejuni* related outbreak in Walkerton in 2000 (O'Connor, 2002), the outbreak of cryptosporidiosis in north Battleford (Laing, 2002), various *Cryptosporidium* outbreaks in the UK (Badenoch, 1995; Bouchier, 1998) and in Milwaukee (MacKenzie *et al.*, 1994), led to an increased emphasis in the water sector to explicitly assess and mange risks. *E.g.*, the Water Supply (Water Quality) (Amendment) Regulation 1999 (Department of Environment, 1999) introduced the legal and regulatory framework to assess and manage *Cryptosporidium* risk in drinking water supplies (Colbourne, 2004; Drinking Water Inspectorate, 1999). Increasing use of explicit assessment and management of public health risk is also the subject in the Bonn Charter (International Water Association, 2004) and the World Health Organisation's Guidelines for Drinking Water Quality (World Health Organisation, 2004; Deere *et al.*, 2001) which introduce the concept of Drinking Water Safety Plans that are strongly supported by regulatory authorities (Drinking Water Inspectorate, 2005a), implemented by water utilities (Lake, 2004) and operationalised in IT-based models (Breach, 2004) for catchment to tap risk assessments.

According to MacGillivray *et al.* (2006), the water sector has sufficient risk management tools and techniques at hand to assess and manage public health, technical and business risks. Descriptions and examples of risk strategies to provide safe and reliable drinking water are found in (Pollard *et al.*, 2007; MacGillivray *et al.*, 2007; Pollard *et al.*, 2004; Pollard *et al.*, 2005; Ministry of Health, 2005a; International Water Association, 2004; World Health Organisation, 2004; Deere *et al.*, 2001).

According to Pollard *et al.* (2005), the water sector has embarked on explicit risk management strategies and is making good progress in formulating risk management strategies to face practical implementation issues (Pollard *et al.*, 2005). As part of an

Awwa Research Foundation (AWWARF) project, a capability maturity model has been developed for water companies to assess their risk management capabilities (Pollard *et al.*, 2007; MacGillivray *et al.*, 2007; Pollard *et al.*, 2004). However, since the collapse of Enron, risk management systems, too, came under critical scrutiny. In 2000, Deloach (2000) praised Enron for its "*leading edge in enterprise wide risk management*". Rather astonishingly, this enterprise wide risk management system failed to forecast Enron's rapid escalation into catastrophic, economic failure which casts some doubts on the effectiveness of risk management systems in isolation of the organisational culture (Gebler, 2005). Cultural issues have also been identified in Hrudey *et al*. (2002) who investigated a series of incidents to conclude that "*complacency*" is "*an endemic problem underlying water borne disease outbreaks*".

The role of organisational culture in the management of incidents and risks was further researched in a recent project for the Awwa Research Foundation (Pollard *et al.*, 2008). Culture in this context denotes *"the way we do things here"* (Johnson, 1992; Content, 2005) and various case studies were compiled to illuminate processes, organisational and control structures, power structures, rituals and routines but also stories that circulate in the organisation and the symbols that identify how the organisation manages incidents and risks. This project had two emphases: firstly, on how water utilities manage incidents and, secondly, how water utilities manage risk, *i.e.* the probability of incidents. As a means to describe the context of management culture, a Regional Water Utility was benchmarked against the principles of high reliability organisations (Pollard *et al.*, 2008) that were previously identified in the literature and communicated in Bradshaw *et al.* (2006).

This thesis further focuses on the investigation of HRO principles in the water utility sector, in particular their effective contribution to incident impact reduction on customers and 'learning from failure' to enhance risk assessments. The latter aspect aims to identify a novel approach to learning from failure by using historical incident data to validate the structure of risk models and to verify risk data. It further seeks to find evidence for the influence of cultural settings as well as psychological and sociological factors that shape the understanding and perception of risk.

1.2 Literature review

1.2.1 Literature review methodology

The literature review comprised of a systematic review based on a rigorous, transparent and replicable methodology for locating, selecting and appraising relevant existing research studies (Bradshaw *et al.*, 2006). Tranfield and Denyer *et al.* (2003) state that in order to ensure that reviews in the management field are rigorous, scientific investigations that limit bias and random error, they need to include:

- the development of clear and precise aims and objectives;
- pre-planned methods;
- a comprehensive search of all potentially relevant articles;
- the use of explicit reproducible criteria in the selection of articles for the review;
- an appraisal of the quality of the research and the strength of the findings;
- a synthesis of individual studies using an explicit analytical framework; and
- a balanced, impartial and comprehensible presentation of the results.

In this thesis, it was aimed to adhere to all these principles in undertaking the literature review on the principles of HROs, risk-based asset management and incident management and analysis.

1.2.2 Water safety and reliability objectives

In the UK, the water utility's prime objective to provide "*good safe drinking water that has the trust of consumers*" (International Water Association, 2004) is reflected in the *"level of service"* and serviceability criteria (Office of Water Services, 1998; Drinking Water Inspectorate and Office of Water Services, 2001) that are used to regulate privatised water utilities. Serviceability is the ability of assets to maintain a standard of service that customers directly receive from a water utility and is a measure of exceedance or non-compliance against standards. This relates to asset performance and operational performance in four principal areas (Drinking Water Inspectorate and Office of Water Services, 2001; WRc and BHR, 2001):

- Water quality from the assets.

- Capacity of assets and networks available to meet demand (Availability).
- Reliability of assets and networks to supply services.
- Customer satisfaction.

In the regulated UK water industry, the regulatory objective of strategic maintenance planning is to maintain and enhance serviceability benefits to customers (UK Water Industry Research Limited, 2002). Water companies in England and Wales are required to appraise their capital maintenance planning in light of past and future maintenance to provide a view on long term trends on investment and financial requirements, whilst considering "*the trade off between cost and risk*" (Office of Water Services, 2000; Drinking Water Inspectorate and Office of Water Services, 2001; Day, 2006; Parsons, 2005). The key elements of maintenance planning is the identification of failure modes with impact on customer service, the environment or cost to the water company if no proactive capital maintenance is undertaken and the development of an estimation method for probability of failure, consequence of failure and cost of failure (UK Water Industry Research Limited, 2002). This approach emphasises the importance of assessing risks in relation to serviceability criteria (Drinking Water Inspectorate and Office of Water Services, 2001) and emphasises explicit cost benefit (risk reduction) analysis as previously introduced by Haimes (1980a; 1980b) for water resource economics.

1.2.3 Risk and decision making theory

In his investigation into the North Battleford outbreak, Justice Laing (2002) found "*…the end result was that the quality drinking water program was sacrificed as a matter of choice, not necessity. The choice was made knowing the result would be a reduction in the overall quality of drinking water in the province.*" In Justice Laing's view, the decision making processes that led to the outbreak implicitly assumed that the decision maker used judgment and choice in full awareness of the risks and consequences of pursued action to derive desirable (or undesirable) outcomes (Hogarth, 1980). According to Hogarth (1980), choice between alternatives is a process of conflict resolution based on numerous paths or options that could be followed. The "*accuracy of judgement depends on the extent to which the mind mirrors the environment it attempts* *to predict*" (Hogarth, 1980). Predictions and evaluations are based on a combination of information from different sources. Information is weighted and combined to form judgement. Yet, according to Hogarth (1980), the literature on judgement present two findings: firstly, people are generally overconfident in judgements made and the degree of confidence is not matched by subjective reality; secondly, the problem of "*illusory correlations*" phenomena in seeing a relationship between variables that do not exist. According to Hogarth (1980), this is a disturbing fact if we are to believe that people learn from experience. Hogarth (1980) offers two explanations for the above two findings: firstly, they are motivational using selective memory for making judgements and secondly, the assumption of illusory correlation – a persistence in instances of poor feedback and where others share illusions (Hogarth, 1980).

From an economic perspective, utility theory assumes rationality and describes all decision outcomes in terms of utility. Here, decisions are to be understood by the level of utility attached to different outcomes. The decision making process to derive greatest utility defines the problem, identifies the decision criteria, weights those criteria, generates weighted alternatives and computes the optimal decision (Bazerman, 1998). Similarly, micro-economic theory uses the economic-rational approach to derive a customer demand function and a firm's product supply function for production of goods and services. Here, the overwhelming driver for decision making is the market price to achieve effective and efficient allocation of products and resources (Bonart and Peters, 1997). From an environmental economics viewpoint, the market price also contains 'social cost' for adverse effects (Endres, 1994). More sophisticated versions of the decision making process use the calculation of probabilities for different possible outcomes that are associated to each alternative (Wisniewski, 2000).

De Bondt (1998), however, found evidence that individuals do not form rational decisions: "*for at least forty years psychologists have amassed evidence that economic man is very unlike a real man and that reason – for now, defined by the principles that underlie utility theory, Bayesian learning and rational expectations – is not an adequate basis for a descriptive theory of decision making.*" Decisions are bounded in their rationality by limitations of intelligence and perception of decision makers (Bazerman, 1998).

According to Kahneman and Tversky, decision makers use a number of simplifying strategies, or rules of thumb, to make decisions that they called 'heuristics' (Kahneman and Tversky, 1972; Kahneman and Tversky, 1973; Kahneman and Tversky, 1979; Tversky and Kahneman, 1971; Tversky and Kahneman, 1973; Tversky and Kahneman, 1974; Tversky and Kahneman, 1981). Gigerenzer *et al.* (1999) explained heuristics as a range of simplifying and confidence-sustaining mental short-cuts that enable quick decisions in circumstances when pausing to undertake a full analysis would be unwise. From birth, people start to learn to filter information to cope with the excess information that the human brain cannot process. Filtering information comes at a cost and introduces significant biases. These filters enable (over-)confidence in decision making because sources of uncertainty are filtered out. Availability heuristic describes that people pay more attention to information that is easily available; retrieveability heuristics overweight memories that are more easily retrievable either because they are emotionally vivid or have personal relevance. A further heuristic relates to representativeness and denotes an assessment of *"likelihoods of an event's occurrence by the similarity of that occurrence to their stereotypes of similar occurrences"* (Bazerman, 1998).

As soon as new information becomes available, decisions need revisiting and updating. According to Rutledge (1993), insufficient anchoring adjustment, *i.e.* failing to update one's targets as the knowledge of the environment changes, describes how initial decisions or judgments provide a mental anchor which acts as a source of resistance to reach significantly different conclusions once new information becomes available (Rutledge, 1993).

From a sociological perspective, the pursuit of legitimacy shapes the cognitive schema in decision-making; social pressures like coercive, mimetic and normative pressures influence the decision maker. Coercive pressures arise from social sanctions that are applied if action is pursued in socially illegitimate ways. Mimetic pressures drive people and organisations to copy strategies of others despite different circumstances and little regard for the different contexts and challenges. Normative pressures are concerned with what we think we should do (DiMaggio and Powell, 1983; Abrahamson, 1996; Ashworth *et al.*, 2005).

The perception, definition and assessment of risk, too, relates to the economic-rational, psychological and sociological perspectives introduced above. From a rational-economic perspective in utility theory, risk represents a combination of the expected magnitude of a loss and is combined with probability distributions of anticipated outcomes (Bazerman, 1998). In Appendix 1, the general mathematical model to derive optimal supply functions for production of goods and services of a firm (Bonart and Peters, 1997) was adapted to internalise risk in asset decision making. From a theoretical perspective, it was found that the rate of technical substitution between assets and risk equates to the negative ratio of the production input factor prices (Bonart and Peters, 1997), *i.e.* the price of risk and the price of assets. It theoretically demonstrates that the optimal rate of substitution for production input factors, *i.e.* assets and risks, are directly dependant on their factor prices (Bonart and Peters, 1997). Such rational-economic asset risk trade-off models are increasingly used in the water sector to internalise risks in decision making (Abell, 2005; Lifton and Smeaton, 2003; Lifton, 2005; Bradshaw, 2005), yet, the assessment of risk has to consider the psychological and sociological perspectives that risk assessors use in their heuristic models of perceiving and expressing risks *e.g.* in explicit risk assessments.

From a psychological perspective, the literature introduces the concept of risk neutrality, risk adversity and risk seeking that is governed by the fear factor, *i.e.*, the dread of potential outcomes, and the control factor, *i.e.* the extent to which we are in control of adverse events. Prospect theory describes the combination of risk and loss aversion (Kahneman and Tversky, 1979; Rowe, 1980). "*An individual who has a certainty equivalent (e.g. £1,000) for an uncertain event that is <u>equal</u> to the expected value of the uncertain pay-off (e.g. £10,000 at a probability of 10%) is risk neutral"*. "*An individual with a certainty equivalent (e.g. <£1,000) for an uncertain event that is less than the expected value of that uncertain pay-off (e.g. £10,000 at a probability of 10%) is risk averse"* An exceeding certainty equivalent over the expected value of that uncertain pay-off denotes risk seeking (Bazerman, 1998). From a psychological perspective, it was also found that decision maker discount risks on the basis that they felt they could control them: illusory control beliefs lead to under-estimation of risk (Fenton-O'Creevy *et al.*, 2003).

From a sociological perspective, a shared cognitive schema defines risk, the dread or fear factors that people attribute to them and the perceived likelihood of their occurrence. Risk perceptions dictate behaviour and some sociologists have suggested that our approach to risk depends on fundamental assumptions about the way the world operates. Schwartz, Thompson, and Adams characterised these assumptions as the four myths of nature; they are the myth of nature as capricious, *i.e.* the world is entirely unpredictable and small actions can have unpredictable consequences of unknown scale, the myth of nature as benign that denotes an everlasting equilibrium. A strong disturbance to the world is subsequently is restored to the status quo. The perverse/tolerant myth believes that the world in predictable and tolerant to shocks within defined boundaries. The ephemeral myth regards even small disturbances to have profound and potentially catastrophic changes (Schwarz and Thompson, 1990; Adams, 1995).

One aspect of this thesis is to investigate whether the psychological and sociological perspectives on risk influence the quality and consistency of risk data used for decision-making. The rational-economic, psychological and sociological perspectives on risk may also explain why the term ‘risk’ is very widely used without an accurate and precise definition of its real meaning (Douglas and Wildavsky, 1982). It is often used interchangeably with hazard, probability and danger (Jones *et al.*, 2001). The Society of Risk Analysis aimed to provide a holistic and clear definition of risk and recommended that each author and researcher define their own meaning of risk (Kaplan, 1997). What seems simplistic turned out to be a contentious debate leading up to the definition of risk (Dombrowsky, 1995). Eventually, a definition was derived stating that “*risk is the potential for realisation of unwanted, adverse consequences to human life, health, property, or the environment; estimation of risk is usually based on the expected value of the conditional probability of the event occurring times the consequence of the event given that it has occurred*” (Society for Risk Analysis, 2004).

Risk as a likelihood and potential effect of impact are both measurable characteristics (Jones *et al.*, 2001), however ‘probability’ can have three distinct meanings: firstly, what can be called ‘frequency’ referring to repeated action forming a rate of reoccurrence for an event (Rowntree, 1991); secondly, the degree of confidence (in evidentiary-based probability) about a given circumstance as a subjective concept for individual assessors (Bernardo and Adrian, 1994); and, thirdly, the mathematicians' meaning of probability as a curve of data points without any regard for real-world interpretation (Rice, 1995). Risk as a mathematical function is an absolute figure that can be measured and compared to other risks (Moore, 1983). Others contend that risk exists primarily as a social phenomenon (Douglas, 1992; Douglas and Wildavsky, 1982) that is evaluated as an elusive volume of space between a population and a hazard (Hayes, 1992). From a social perspective, risk is "*a social process of examination; the discovery of the relationship between hazards and a population*" (Adams, 1995) and risk management is the method of controlling that relationship by preventing or lessening the impact of a hazard on a population. Risk as a social phenomenon also enables the definition of safety as the "*immediate and individual level of potential risk*" (Reider, 1974). Unfortunately, Reider (1974), again, introduces confusion when speaking of potential risk, *i.e.* the potential probability of adverse consequences.

The Australian and New Zealand risk management standard (AZ/NZ 4360) (Australian/New Zealand Standard, 1999) is regarded as an authoritative source for principles and guidelines for risk and risk management (Business Continuity Institute (BCI), 2002) as a preventionist approach whilst regarding risk as a social construct and seeking to develop responses to hazards in order to reduce or control their effect (Australian/New Zealand Standard, 1999). Here, the phases of risk management are to 'establish the context', 'identify the risk', 'analyse the risk', 'evaluate the risk', 'treat the risk' and 'monitor' and 'review risks'.

In practice, a number of different uses of the term 'risk' can be found: Kaplin and Garrick (1981) define risk by a multi-dimensional entity comprising the answer to three questions (Hrudey, 2005): 'What can go wrong?', 'How likely is it?' and 'What are the consequences?'. Hrudey (2000) also offers the risk definition as 'a hazard', the 'uncertainty of occurrence and outcomes (expressed by the probability or chance of occurrence)' and the 'adverse consequences'(Hrudey, 2005). It is interesting to note the change in language: In the first example, the author referred to 'likelihood' whereas in the second example the term 'uncertainty' is used. There is a marked difference between the two: The former is based an accurate knowledge, whereas the latter is best described as a degree of knowledge about probability (Vose, 2000).

The WHO defines risk as the likelihood of identified hazards causing harm in exposed populations including the assessment of the severity of the consequences in a specified time frame (World Health Organisation, 2004). Risk can be defined as a threat to strategic and business objectives (Fraser, 2005) or as likelihood (% chance per year) times business impact (supply interruption + reputational + financial) expressed in monetary terms (Lifton, 2005). Risk can be defined as the probability times impact on regulatory objectives (Abell, 2005) or as a probability of an adverse consequence measured for hazard type, affected population and duration of hazard exposure (Deere *et al.*, 2001). Risk can be evaluated as a probability to incur consequential costs (including moral, economic and social costs) (Hughes and Ferrett, 2003) or the probability of an incident with incident defined as impact on regulatory objectives. In analogy to Deere *et al.* (2001), risk can also be defined as the probability of an incident with incident defined as a combination of hazard types, affected population and duration of hazard exposure. Considering the cause effect relationships during an incident, risk can be defined as 'probability of an event (*e.g.* chlorine equipment failure) that has a probability to have an adverse impact'. Another perspective is offered by assessing the risk per affected person, risk per population and risk per asset.

In this thesis, the definition of public health risk advanced by Deere *et al*. (2001) is used that proposes a probability assessment and evaluation of impact in terms of the hazard type, the size of the affected population and the duration of hazard exposure. The severity of a hazard is defined by the dose-response of biological and chemical hazards to human health. Here, a number of concepts can be used to compare different hazard types and Havelaar *et al.* (2003) introduce the concepts of 'disability-adjusted life years', 'quality adjusted life years' and 'willingness to pay' as common denominators for comparative hazard assessments. The two former concepts are further discussed in Fewtell and Bartram (2001). In engineered systems risk can be assessed as a failure event that leads to a deviation from the normal operational function, changes to the physical, chemical and biological status, a transmission pathway and the effect of exposure to the receiving population, object or environment (Crossland *et al.*, 1992).

1.2.4 Managing public health risk with assets

The provision of safe and reliable drinking water requires competencies to design, operate and maintain assets in line with the strategic objectives. Asset management is defined as *"systematic and co-ordinated activities and practices through which an organisation optimally manages its physical assets, and their associated performance, risks and expenditures over their lifecycle for the purpose of achieving its organizational strategic plan"* (British Standard Institution, 2003). The aim of asset management is to optimise returns on investments (Woodhouse, 2000) and, in the public utility context, to improve the accountability and performance of public works (Lee and Fisher, 2004).

Asset management aligns the organisational strategy and the level of service with capital investment planning for asset creation, maintenance and financial planning (United States General Accounting Office, 2004). It requires the optimisation of total cost of ownership and operation with the objective of delivering service levels to customer expectation at defined levels of risk. Managing risk in the face of limited resources has long been an implicit component of asset management in the water sector. Increasing pressures from financial self-sufficiency and price control have created a climate in which utilities have to negotiate spending on capital investment and maintenance schemes in light of acceptable levels of public health risk. Over- or under-engineering facilities with the presumption of screening out all risk or tolerating excessive levels of risk is no longer acceptable for stakeholders. Instead, asset management is becoming an increasingly explicit trade off between cost and risk (Booth and Rogers, 2001; Abell, 2005; Lifton and Smeaton, 2003; Muto, 2002) and water sector specific models were developed for asset decision making (Barnes *et al.*, 2008; Oakes and Skipworth, 2006; Hall, 2006).

Risk management is pursued, in part, through investments in physical, human, information and intangible assets so as to eliminate, reduce, isolate or control risk (Bradshaw *et al.*, 2006). When optimally designed and operated, these assets are active barriers against chronic exposure to hazards and sufficiently reduce the probability of hazard exposure during incidents (Bradshaw, 2006; Bradshaw, 2007; Bradshaw, 2008).

The management of assets requires evidence-based decisions on the correct course of action to take in time and by reference to cost and risk and builds on strategic planning and organisational development (Brueck *et al.*, 2004). Monitoring, evaluation and optimisation in asset management activities are supported by formal systematic processes. Tools and processes at strategic, policy and tactical level form an integrated framework (Organ *et al.*, 1997a) to proactively and consistently identify risk, assess risks and select appropriate controls (Faber and Stewart, 2003). Here, risk-based asset management considers the probability of events and the consequences from physical failure, operational risks, human factor and activities which affect performance, condition and safety (British Standard Institution, 2003). This places risk identification, assessment and control (together, risk management) at the centre of asset management (Bradshaw *et al.*, 2006) and the availability and quality of risk data at the centre of asset decision making.

1.2.5 Asset risk data

Risk-based asset management requires systematic collection of data. Managing risk at a programme level, *i.e.* the entire asset base consisting of all assets from catchment to tap across a region (Drinking Water Inspectorate, 2005a; UK Water Industry Research Limited, 2003; UK Water Industry Research Limited, 2005), requires consistent and comparable risk data to facilitate the risk-ranking procedures that evaluate and prioritise risks to achieve best value in the context of performance, service provision, cost and risk (Pollard *et al.*, 2004). Unfortunately, data management strategies that are supposed to identify and assess risks are very often initiated from a need for regulatory compliance (Burns, 2002). Adding purpose transforms data into asset information; asset information in conjunction with professional judgement creates asset knowledge; asset wisdom is supposed to align additional information which considers community, social and environmental aspects. Very often data do not progress to ‘asset wisdom’ and Burns (2002) suggests to define asset wisdom before identifying knowledge, information and data requirements. Asset wisdom is then derived from the strategic objective that, in turn, provides a definition for risks.

Processes are required to facilitate effective and consistent risk data acquisition that is of sufficient quality to provide for effective risk-based decision making for asset investments and asset maintenance. A risk-orientated systems approach from catchment to tap (Bannister *et al.*, 2000; Hrudey, 2001) is increasingly used for hazard identification, reliability and failure analysis and estimation of consequences (Crossland *et al.*, 1992). Here, reliability is the probability of a system to perform within the boundaries of specified functionality (Crossland *et al.*, 1992).

The World Health Organisation (2004) promotes Water Safety Plans to facilitate 'Hazard Analysis' and the evaluation of 'Critical Control Points' (HACCP) (Codex Alimentarius Commission, 1997) as a principle model to consistently assess public health risk. HACCP, introduced to the water sector by Havelaar (1994), identifies hazards at the point of source and facilitates the assessment of risk (Deere and Davidson, 1998; Deere and Davidson, 1999a; Deere and Davidson, 1999b; Aertgeerts, 2006). The Critical Control Points are the barriers that significantly contribute to risk elimination, reduction or control. Their critical limits to act as an effective barrier determine the performance requirements under event condition and Deere *at al.* (2001) identify the critical concept of the multiple barrier approach to reduce public health risks to a tolerable level. Multiple barriers are promoted for practical reasons: firstly, barriers reduce rather than eliminate risk. Secondly, failure or poor performance of one barrier is safeguarded by other simultaneously operating barriers to maintain reduced levels of risk preventing worst-case consequences. Individual barriers require independence from the overall system to reduce the probability of simultaneous barrier failure during an event or incident.

Risk management tools can apply quantitative and qualitative techniques (Hood *et al.*, 1992). Techniques to assess hazards and risks in engineered systems and 'Critical Control Points' require the definition of a system, failure and hazards identification with HACCP, HAZOP or FMECA and reliability modelling with FTA (Tung, 2004), ETA and reliability block diagrams (Strutt, 2004; Mays, 2004). Failure modes, effects and criticality analysis (FMECA) identify failure modes of equipment and their effects and criticality on the system. The failure mode is a functional failure of the system, *e.g.* an open valve when expected to be closed. The effect of the failure mode and the criticality determines the consequence of failure on the system (American Institute of Chemical Engineers, 1992). Practical applications in the water sector are found in Demotier *et al.* (2002) who use FTA / FMEA to determine the risk of non-compliance in drinking water production. Their study considers a range of water quality parameters, removal

efficiencies and reliability of the treatment processes. Similar studies are found in Eisenberg *et al*. (2001) and Haas and Trussell (1998).
Scottish Water also use catchment-to-tap FMECA studies to identify and prioritise risks. Scottish Water employs an asset risk and criticality scoring system that is designed to assess the 'total business impact' of asset failures. For this comparison, a 'common currency of risk' in which one point equates to £1000 of business impact is introduced. The scoring system informs the asset management strategy that guides prioritisation of reliability studies and scenario modelling. Critical risk assets are further subjected to maintenance optimisation based on cost, risk and performance (Lifton and Smeaton, 2003). Using the monetary evaluation of public health risk as a common denominator is also found in Hall (2006).
Examples for quantitative risk assessment are found in (Kent *et al.*, 2003) and (Sadiq *et al.*, 2004). Kent *at al.* (2003) describe a strategy to identify the probability of water trunk main failures using historical data. The consequences of failure are assessed with a network analysis computer package. However, they conclude that vast, complex factors have to be considered for which relevant data is limited. Sadiq *et al.* (2004) used probabilistic risk analysis to corrosion associated failures in grey cast iron water mains using Monte Carlo simulations to compute the reduction in the factor of safety over time. Further risk assessment techniques for large-diameter transmission mains using fuzzy logic are introduced by Kleiner *et al.* (2005). Regression analysis of failure frequency with material age of distribution mains is introduced by Herz (2005) and the technical and cost optimisation of distribution networks is introduced by Richter (2006) and Grimshaw (2006) for leakage-driven water mains renewal.

Systematic capture of data requires the organisation to build suitable information systems (*e.g.* asset register) (Office of Water Services, 2000; Marlow *et al.*, 2005; Marlow and Kowalski, 2005; Hoffman and Lambert, 1990). Houlihan (1995) describes early initiatives of improving the decision making process in infrastructure maintenance with a computer-based system. This system integrated data analyses on asset condition, risk of failure, economic consequences of failure and renewal cost. The system linked into a feasibility study with other construction and rehabilitation projects whilst minimising cost and disruption.

According to the U.S. General Accounting Office (2004), key challenges to implementation of an asset management approach remain the lacking availability, completeness and accuracy of existing data to support the asset management process (United States General Accounting Office, 2004). Chadwick and Rees (2003) recognise the importance of data requirements. They conclude that data weaknesses have to be mitigated in planning future data requirements to reduce uncertainty in medium term programmes and Skipworth (2006) proposes a bottom-up and top-down approach to asset data acquisition.

One top down strategy to understand future risks is to learn from past failures and incidents (Health and Safety Executive, 2000). This may enable the enhancement of risk assessments and, hence, improves the quality of risk data.

1.2.6 Learning from incidents and emergencies

Learning from incidents and emergencies requires suitable learning strategies. The literature suggest the most suitable strategies to be "*reflection*" and "*asking questions*" (Morgan and Saxton, 1991; Van Ments, 1990; Moon, 1999). Reflection is the re-examination and re-interpretation of experience that could be defined "*in two senses, first as a process by which experience is brought into consideration and secondly, deriving from the first, the creation of meaning and conceptualisation from experience and the capacity to look at things as potentially other than they appear, the latter part embodying the ideas of critical reflection". When experience is brought into consideration it will include thought, feeling and action*" (Brockbank and McGill, 1998).

Asking questions facilitates the process of reflection and Smyth (1987) offers a set of learning questions to facilitate critical reflection. They are:

- Where do the ideas I embody in my practice come from historically?
- Why did I appropriate them and continue to endorse them in my work?
- Whose interests do they serve and what power relationships are involved?
- How do these ideas influence my interaction and relationships with others?

Good questions can be subjective and often contain tacit assumptions and intuition to be aware of when commencing an inquiry (Carr, 1985). Often questions can summarise what the researcher already knows as well as what they wish to discover (Carr, 1985).

For the purpose of learning from failure, Johnson (2003) developed a thorough methodology to investigate accidents and incident reporting that considers the sources of failure and causal analysis, detection and notification of incidents, primary responses, incident investigation and the anatomy of incident reporting. These are commonly used in the nuclear sector that has a series of tools and techniques to investigate safety incidents at nuclear power plants (International Atomic Energy Agency, 2002). They emphasise the identification and analysis of root causes and encompass people factors, technology, organisational factors and the environment in which the incident unfolded. In analogy, the following section reviews learning models and learning outcomes from water contamination incidents in recent years.
Hrudey *et al.* (2002) investigated failed water supply systems using a five barriers model (Figure 2) (Hrudey and Hrudey, 2004) to identify the causes of incidents and, subsequently, to understand risks. Hrudey *et al*. (2002) proposed a framework with the 'barriers' to incidents consisting of "*catchment, treatment, distribution, monitoring and response*". In all 16 outbreak cases reviewed, Hrudey *et al.* (2002) identified a failure of at least one barrier which ought to have operated simultaneously and subsequently led to microbiological outbreaks. Later on, Hrudey and Hrudey (2004) and Hrudey and Rizak (2006) aimed to learn lessons from a significantly larger review of incidents using the above model to explain incidents.

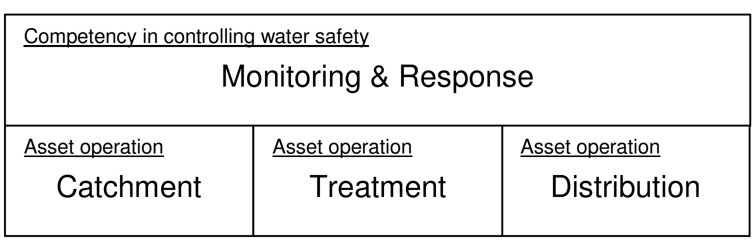

Figure 2 Catchment to tap model for drinking water safety

Learning valuable lessons from incidents can be challenging: it assumes that the future risks are a reflection of past incidents. However, the adoption of new technologies is increasingly concerning decision makers in the water industry, because of the inherent and unknown risks (Clark *et al.*, 2000). Decision-making processes in systems design are usually based on a deterministic approach, because they incorporate the judgements on the acceptable standard of practice and therefore risk. The deterministic approach does not apply to evolving technologies since previous experience does not exist (Crossland *et al.*, 1992). Technology problems arise from new processes, materials or subsystems with limited experience on parameters controlling cost and failure modes as well as extending technology applications beyond previously experienced design envelopes from unexpected interactions between subsystems (Hartmann and Lakatos, 1998).

A further challenge to learn from previously experienced failure relates to complexity theory. According to Perrow (1999), complexity and tight coupling of systems increases the probability of failure. System accidents constitute a sequence of unanticipated, in hindsight obvious, interaction of multiple failures from system components. These complex interactions occur in unfamiliar, unplanned and unexpected sequences (Perrow, 1999). Complex systems are characteristic for common mode connections with interconnected subsystems and integrated, multiple and interacting controls (Perrow, 1999). Pool (1997) identified an ever increasing trend of designed complexity of our technologically built environment and Woo and Kim (2003) observed this trends with respect to continuous improvement in performance and quality. It might be difficult to argue that water supply systems technologies are complex technologies, yet, water supply system assets have substantial interfaces with the environment that affect their processes, performance and asset condition. Asset design decisions that extend technologies beyond experience, increasing interconnectivity between supply systems, operational interfaces and challenging maintenance decision-making processes also contribute to an increasingly complex management and operation of assets.

It is believed that lessons can be learnt from experience in the water sector. Fine (1998) introduces the concept of industry 'clock speeds' to characterise the speed in which industries change over time. Here, the water industry would be considered to have a slow clock speed when considering the long-term investment in physical water supply assets that are used to provide service over a few decades; hence, previous experience may provide valuable learning opportunities to enhance risk assessments since the fabric of the physical assets will not have dramatically changed. One example was previously introduced by Kent *et al.* (2003) who use historical water mains failure data to derive probabilities for future asset failures.

Learning from failure does not only relate to technical learning, despite the physical asset centric nature of the water sector. Learning can also relate to the cultural settings of a water utility, its concern for water safety and staff attitudes. For example, in May 2000, Walkerton, Ontario experienced its worst failure in public health obligation when the water distribution system became contaminated with predominantly *E.coli* O157:H7 and *Campylobacter jejuni* bacteria. In the town of 4800 residents seven inhabitants died and *ca*. 2300 contracted illness related to the bacteria (O'Connor, 2002). According to O'Connor (2002), the most significant failure arose from lack of professional knowledge, training and competence from operators, managers, regulators and public health authorities. A few months later North Battleford saw an outbreak of cryptosporidiosis infecting 5800 to 7100 persons (Laing, 2002). Budget cuts had been imposed at a time where public health objectives already were not achieved. The question remains why these budget cuts had been executed which had such a significant, adverse impact on technical and organisational reliability to provide safe drinking water and what specific learning outcomes have been gained from this outbreak. Prudham (2004) investigated the Walkerton outbreak in order to identify the reason for this accident: According to his analysis, this outbreak came as a result of irresponsible environmental regulatory reforms that resulted in poor governance. The regulatory reform of the water sector increased the risk to the public to a point where an incident inevitably had to occur. The analysis of Prudham (2004) captures a systemic view of the socio-technical interaction of a utility with its environment. Despite the 'regularity of complacent behaviour' (Hrudey *et al.*, 2002) across different involved organisations, the majority of criticism was directed at the Manager of the Walkerton Public Utility Commission who played a key role in the failings before and during the outbreak. However, as Howard and Richardson (Howard and Richardson, 2002) put it: "*Stan Koebel likely could have prevented Walkerton, but the Ontario government could have prevented Stan Koebel*". The government had a public health duty of "*enacting* *and enforcing strong regulations, supported by fiscal and staffing resources*" (Howard and Richardson, 2002).

Considering the public policy changes in the Ontario water sector, Woo and Vicente (2003) applied the Rasmussen framework for complex socio-technical systems to compare the Walkerton and Battleford outbreaks based on the investigations by O'Connor (2002) and Laing (2002). The Walkerton incident has previously been investigated using this methodology (Vicente and Christoffersen, 2002) that has been developed to identify possible causes of safety incidents (Rasmussen, 1997). It is a structural hierarchy of individuals and organizations within a complex socio-technical system. The framework aims to uncover contributing factors that are causes to accidents and threats to public safety. In this model, threats to public safety result from a loss of control over organisational reliability caused by a lack of integration, *i.e.* lack of transparency, communication, and feedback and system response, at the different levels of a complex socio-technical system, rather than shortcomings or misconduct at one level in the hierarchy (Woo and Vicente, 2003). Dynamic forces modified the structure and behaviour of complex socio-technical system over time. Financial, functional, social and psychological pressures required the socio-technical system to work in a more fiscally responsible and mentally/physically in a more efficient manner that changed work practices over time. The uncoordinated adaptation to financial, psychological and environmental pressures gradually eroded a safe system and the catastrophe resulted in combination with a key critical event at which the degradation in safety was revealed (Woo and Vicente, 2003).

Figure 3 is an adaptation of the socio-technical model from Woo and Vicente (2003). The model shows different levels of interdependencies and pressures on a water utility that can have an adverse impact on the organisational and technical reliability of service provision to the customer. Stakeholder pressures and key influences on organisational reliability and the decision-making processes of a water utility are represented as arrows.

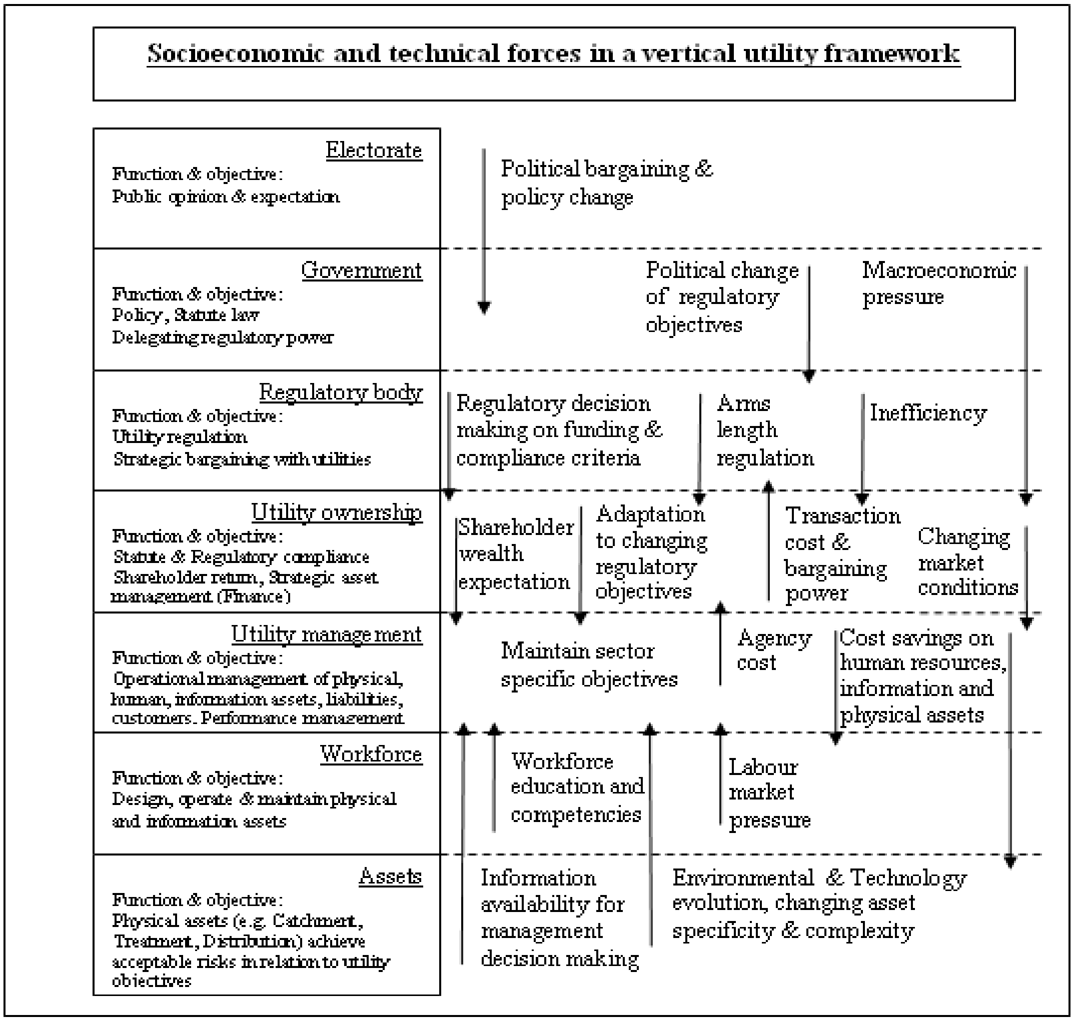

Figure 3 A socio-technical framework for a water utility

It could be argued that the model from Hrudey *et al.* (2002) (Figure 2) and the socio-technical framework in Figure 3 are complementary learning models for the assessment of system risk. The design of an 'operational and socio-technical integrated' framework system should be robust to safeguard public health objectives and introduces a theoretical framework for risk management. Identifying root causes with such a framework shapes risk management into a multi-faceted phenomenon (Woo and Vicente, 2003).

Leveson (2004) introduced a further adaptation of the Rasmussen framework. The 'System-Theoretic Accident Model and Processes (STAMP)' (Leveson *et al.*, 2003) demonstrated how systems theory provides important information about accident causation in the Walkerton outbreak. The STAMP model considers four factors as core principles of system theory:

- Emergence as a characterisation of a system property,
- Hierarchy of levels of organisation,
- control and communication.

Leveson *et al*. summarised the circumstances leading to the outbreak as "*inadequate control or enforcement of safety-related constraints on the design, development, and operation of the system*" (Leveson *et al.*, 2004). Furthermore, Leveson *et al.* recommend, "*when designing safer systems is the goal rather than identifying who to punish, the emphasis needs to shift from cause (in terms of events or errors), which has a limiting, blame orientation, to understanding accidents in terms of reasons, i.e., why the events and errors occurred*" (Leveson *et al.*, 2004).

In hindsight, many disasters can be interpreted as 'waiting to happen' where minor errors, omissions and slips accumulate and trigger a major accident. Risk management should identify the chains of causation, shortcomings and conflicting requirements and improve the system accordingly. Vulnerability of a system can stem from the complex interaction of organisations and their environment (Hood *et al.*, 1992) and Walkerton and North Battleford have highlighted some gross organisational failures that suggest a systemic failure in the organisations involved. The application of a socio-technical framework maps out all structural pressures on organisational reliability that can ultimately impact on public health objectives.

Learning from failure may not only consider physical asset failures but also the information assets, personnel, decision making processes and the prevailing organisational culture that contributed to an incident. Reason (1997) explained the root causes of many organisational accidents with latent flaws in the fabric of an organisation that act as precursors for failures. These latent precursors eventually align under "*favourable*" circumstances leading to the unfolding of accidents. Aiming to identify latent precursors to failure is a scientific challenge. Often neither their existence nor their role in a performance failure is known in advance, regardless how very obvious the contributing factors are in hindsight (Hrudey and Hrudey, 2004).

In this section, an important finding was identified: Various approaches and models have been identified in the literature to explain why incidents happen. The application of these models to specific incidents, such as the Walkerton outbreak, demonstrate that different models provide different results. The models used for incident and accident investigation represent heuristic frames used for reducing the complex circumstances of incidents into simplistic means of understanding (Bazerman, 1998). The use of heuristic models with a background of complex environments and bounded rationality are useful strategies to explain accidents but can sometimes lead to systematic biases and possibly severe errors. In analogy to a diamond, each simplifying model represents a true facet to understand one aspect of incidents; yet, all the facets provide a more 'objective', valid as well as trustworthy and authentic representation of the causes and reasons for failure.

Learning from incidents requires asking the right questions and the use of appropriate models. The water sector is fast adopting the paradigm of risk-based asset and operations management to consider public health risk in the context of costs (UK Water Industry Research Limited, 2002). Proponents argue that risk based approaches to public health are designed to reduce risk to acceptable levels as the only approach to provide safe systems. Others are more critical. Nichols (2004) inquired whether outbreaks of waterborne diseases are actually the consequences of implementing risk-based approaches to water safety rather than the cure. Similarly, the German Association for Gas and Water does not endorse the risk-based water safety plan approach for its members. It praises the technical superiority of the German water sector and, instead, recommends a non-risk-based approach to technical and organisational water systems reliability that builds on a precautionary principle-driven best practice guide and technical specifications for the design, operation and maintenance of water supply systems (Castell-Exner, 2005; Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003).

Others argued that the provision of drinking water should be a 'high reliability' societal service, subject to the sectoral rigours inherent to the nuclear, offshore and aerospace industries (Pollard *et al.*, 2005), echoing Roberts (1990b) who identified the need for high reliability characteristics to manage risks in metropolitan water supplies. Considering the multi-faceted dimension of incident propagation, the principles of HROs may enhance the technical and organisational reliability of water supply provision for customers.

In the following section, the principles of HROs are reviewed.

1.2.7 High Reliability Organisations

High reliability organisations (HROs) operate under trying conditions and yet have outstanding safety records (Weick, 1987). They have been described for nuclear power plants, aircraft carrier flight decks and air traffic control operations (LaPorte and Consolini, 1991; LaPorte and Consolini, 1998; Weick *et al.*, 1999), for offshore oil platforms (Rosness *et al.*, 2005), nuclear powered aircraft carriers (Roberts, 1990a) and certain parts of the energy sector (Schulman *et al.*, 2004) but not for the water sector. So far, the organisational attributes of an HRO are partially tested in that they have not been challenged under conditions of major failure to evidence that their absence contributed to failure.

Based on the literature research, HROs possess (Bradshaw *et al.*, 2006):

- a strong organisational culture of reliability;
- continuous learning and intensive training;
- effective and varied patterns of communication;
- adaptable decision making dynamics and flexible organisational structures;
- system and human redundancy (retained margins of safety);
- precise procedures for managing technology; and
- human resource management practices that support reliability.

Each component is characterised in turn.

1.2.7.1 Organisational culture of reliability

A strong organisational culture of reliability is required as a bulwark against failure resulting in catastrophic consequences. Staff need to have a strong sense of the primary mission of the organisation and share a common system of beliefs and perceptions (Grabowski and Roberts, 1996). With the development of such a 'mindful (vigilant) culture' the formal system can be monitored, understood and failure events foreseen (Roberts *et al.*, 1994a). Members of staff require a highly developed understanding of their contribution and role in the system, acting in a collaborative and collegiate manner to deliver ‘collective intelligent’ interaction (Weick and Roberts, 1993).

Constant vigilance and concern for reliability dictate behaviour (Roberts and Bea, 2001), and alertness, attentiveness and care (Weick and Roberts, 1993) can prevent cascading errors and their escalation into system failure. Employees are encouraged to take responsibility, in particular, where problems are identified and immediate corrective action programmes are required (Bierly and Spender, 1995). Errors are regarded as system faults and employees are encouraged to report their mistakes without fear of punishment. On the other hand, individual behaviours that deliberately jeopardise the primary mission of reliability are labelled as disgrace.

The commitment of senior management to the reliability of the organisation is communicated to all levels in the organisation and demonstrated with investments in technology, processes and personnel (Laporte, 1996). There is a strong sense of collective needs and goals. Individuals *“monitor, advise, criticize and support”* another, in particular in situations where mistakes are more likely to occur (Bierly and Spender, 1995).

1.2.7.2 Continuous learning and intensive training

In order to facilitate continuous learning and intensive training, HROs constantly review their processes and standard operating procedures (SOPs). Staff training is extensive and focuses on the requirements for maintaining a safe system which is embedded in formal rules, generalised guidelines and standardised frameworks (Rochlin *et al.*, 1987). The emphasis is not only on adherence to SOPs but also on identifying potential sources of failure and actions to stop faults from escalating. Staff maintains a commitment to continuous learning and seeks the acquisition and improvement of skills.

HROs also learn by studying the failures, near misses and mistakes by others. They use these as a means to study the failure susceptibility of their own organisation (Weick *et al.*, 1999). Even minor errors and incidents provide a source for learning (Weick *et al.*, 1999), which might be assessed using root cause analysis (Bierly and Spender, 1995). This way, the organisation develops a collective memory for failures, incidents and their root causes that help the organisation anticipate future problems (Bierly and Spender, 1995). Much research on HROs has been undertaken in ‘high hazard’ environments where, because of the high consequence of failure, trial and error is not a realistic learning method. Offline methods of learning are required, consisting of realistic drills, simulations and exercises to replicate potential scenarios (Weick, 1987).

1.2.7.3 Effective and varied patterns of communication

Effective communication facilitates a complex system to become more understandable, predictable and controllable (Grabowski and Roberts, 1996). HROs create information rich environments. Processes are measured and understood, with data made transparent and available to all.

Communication not only considers inter-personnel communication but also human-machine interfaces and data flow between machines. Here, technical system performance and control are often not observable directly and intervention is based on systematic reasoning and process assumptions (Perrow, 1999). Control logics are the operational interfaces with linear and complex systems. They are based on control parameters and process specifications and accommodate known, anticipated and foreseeable linear system failures. The design of control logics does not integrate every eventuality of system failure which usually becomes apparent after an incident occurred. The uncertainty of failure probability is further increased with the level of indirect parameters for process control (Perrow, 1999).

Within an HRO information is a public good and staff are encouraged to share their experiences relating to the reliability of the system. Communication is designed as both bottom up and top down to ensure rapid flow of information through the hierarchy of the system. Rapid dissemination of information helps the organisation respond to mistakes, with corrective action aiming to prevent the escalation of error into failure (Bierly and Spender, 1995).

Communicating information allows staff to shape and share the 'big picture' of the HROs vision, mission and responsibility of individuals towards reliability (Roberts and Bea, 2001). HROs use multiple channels to transmit different types of information – direct and complementary. Indirect information enhances information reliability and provides a form of redundancy (Roberts, 1990a). Multiple signals from a variety of sources provide information density that allows individual signals to be scrutinised for fitting into the whole information pattern. Abnormal signals are treated as an indication of latent errors about to unfold into failures (LaPorte and Consolini, 1991; Roberts, 1990a). Where possible, communications are formalised in a brief, precise, unambiguous, impersonal and efficient manner. This does not allow individuals to complicate or distort the message and ensures clarity of information (Bierly and Spender, 1995).

The enabling environment for open and honest communication is also central to the learning organisation. Reason (2000a) describes the culture of communication and learning with an emphasis on

- a reporting culture, where people are prepared to report incidents and near misses;
- a just culture, which encourages the reporting of safety-related information without jeopardising clear understanding of acceptable and unacceptable behaviour;
- a flexible culture where, in particular under trying conditions, control passes from the formal hierarchical structure to the task expert; and
- a learning culture, which is characteristic for "*the willingness and the competence to draw the right conclusions from its safety information system and the will to implement major reforms when their need is indicated*".

1.2.7.4 Adaptable decision making dynamics and flexible organisational structures

Perrow (1999) argues that complex and tightly coupled systems can only prevent accidents with a high level of centralisation because low level decision makers have insufficient understanding of the inter-relationship between their actions and consequences on other elements of the system (Rochlin *et al.*, 1987). HRO research has demonstrated that decentralisation is required to respond rapidly to unfolding failures. Yet, centralisation is essential in tightly coupled technical systems where interdependency is high. Where systems can be de-coupled, decentralisation provides for action at the point of need (Bierly and Spender, 1995; Roberts, 1990b; Rochlin *et al.*, 1987; Weick *et al.*, 1999).

HROs therefore can be described as 'holistic' or 'decomposable'. In emergency conditions, a holistic HRO needs to be centrally managed in order to maintain an overview of the entire system. In a decomposable organisation, emergencies can be confined to one sub-unit which is then isolated from the entire system. Control over such an emergency is decentralised to this sub-unit until the problem is cleared.

Holistic HROs enforce stringent adherence to SOPs aiming for a repeatability of actions and routines. Such formal rules and procedures identify and mitigate risk (Roberts and Libuser, 1993). Activities based on decisions that are not defined in SOPs are taken at the most senior levels, for these individuals should have the best overall knowledge of the system (Bigley and Roberts, 2001).

Effective HROs build slack into the decision making process (Schulman, 1993; Weick, 1987) in order to assess and challenge decisions so as to avoid faulty decisions to escalate into failure.

1.2.7.5 System and human redundancy

HROs maintain reserve capacity in their system that includes back-up functions, overlapping tasks and responsibilities (Rochlin *et al.*, 1987; Roberts, 1990b). It is important to recognise that designing redundancy for a system can be counterproductive, as back-up functions can increase technical complexity, conceal errors and lead individuals into not performing their required tasks under the assumptions that someone else takes care of it (Sagan, 1994). This 'diffusion of responsibility' (Latane and Darley, 1970) can be a significant cause of system error.

1.2.7.6 Precise procedures in managing technology

An HRO does not necessarily require 'state of the art' equipment, since such technology can add unnecessary complexity (Bierly and Spender, 1995). HROs usually aim to simplify complex technical systems and avoid unnecessary automation (Bierly and Spender, 1995). New technology acquisition is only justified if existing equipment does not perform to required specification (Rochlin *et al.*, 1987). On the other hand, existing technology is maintained to exceptionally high standards and there is zero tolerance of defective, substandard or malfunctioning equipment (Roberts, 1990b). Maintenance activity and protocols as well as performance data are used to monitor the healthy operation of the system (Laporte, 1996).

1.2.7.7 Human resource management practices that support reliability

According to Weick (1987), "*humans who operate and manage complex systems are themselves not sufficiently complex to sense and anticipate the problems generated by those systems*". In recruitment and selection, HROs try to recruit and select suitable and skilled candidates aiming to match as closely as possible the complexity of the environment with appropriate people skills and competences. Having recruited, it is vital to align reward and control systems, remunerating reliability with incentives, recognition and career opportunities. Job rotation can increase networking between teams and help the organisation to transfer and diffuse knowledge and lessons learnt (Rochlin *et al.*, 1987).

In order to nurture a culture promoting the absence of failure, a human resource strategy has to consider four components of total reward (Zingheim and Schuster, 2000). These are individual growth opportunities, total pay, a compelling future in the organisation and a positive workplace (Zingheim and Schuster, 2000). Employee participation and autonomy, as well as more formalised work activities are regarded to increase staff retention and being appreciated as a valued team member underpins commitment (Cappelli, 2000). Operator training (Truss, 2000) and certification (DeNileon, 2000) also play a pivotal role in achieving high reliability.

Practical steps to implement HRO strategies have been described by Burke *et al.* (2005). They describe how to unfreeze the existing organisation, create resilience, develop a pre-occupation with failure and creating a learning organisation before re-freezing the organisation. These implemented skills are adaptability to new information on the environment, close loop communication, competencies in decision making based on information and building of inter-personal relations, leadership and team management, performance monitoring and feedback and heightened awareness for situations in the environment (Figure 4). In a water sector context, this was presented in Bradshaw *et al.* (2006).

<table>
<tr><th>Process steps</th><th>Activity</th><th>Skills & competencies</th></tr>
<tr><td>Unfreeze the organisation</td><td>- Identify regulatory constraints
- Identify cognitive-cultural frame of behaviour
- Identify normative behaviour</td><td rowspan="3">Adaptability to new situations
- based on information
- reallocate resources
Closed-loop communication
- accurate information exchange
- acknowledge receipt of information
Co-ordination of activities
Decision making
- knowledge based
- best option
Inter-personal relations
- motivational techniques
- co-operative behaviour
Leadership/team management
- -co-ordinate, guide, plan activities
- motivate teams
- positive atmosphere
Performance monitoring
- constructive feedback
Shared situational awareness
- common mental models of the environment
Shared mental models
- roles in the team
- collective requirements for team interaction</td></tr>
<tr><td>Change the organisation</td><td>- Create resilience
- Combat human error & catch out system errors
- Monitoring behaviour & feedback
- Learning from failure & incidents in double loop learning
- Systematic, multi level training evaluation
- Embrace complexity rather than simplify
- -Promote importance of information gathering,
- Closed loop communication
- Promote situational assessment to create awareness</td></tr>
<tr><td>Freeze the organisation</td><td>- Institutionalise new processes</td></tr>
</table>

Figure 4 Evolving towards a High Reliability Organisation

Taken together, all of these HRO dimensions can be seen as contributing to a design template for HROs. Individually, each dimension is important, but it is when acting together as a coherent configuration that failure susceptibility might be expected to be reduced.

High reliability theory and 'normal accident theory (NAT)' (Perrow, 1999) are inherently conflicting theories. Whereas the former claims the ability to control major accidents by emphasising organisational competencies, the latter discounts such efforts due to the unpredictability of (technical) accident precursors that seem obvious in hindsight. Furthermore, HRT emphasises the detection and management of abnormal operating conditions which, according to NAT, may cascade into unpreventable system meltdown.

During the literature review, a number of issues were identified that have an impact on the findings relating to HRT. A number of HRO studies were conducted for systems that were nowhere near a "*trying condition*" (Weick, 1987). An aircraft carrier and a nuclear submarine were studied that was not performing in its primary function of warfare but rather in a state of cold war preparedness. Hence, a clear definition of 'trying conditions' is required that relate to the primary objective of an organisation. In the water sector this is the provision of safe and reliable drinking water and 'trying conditions' are the exposure of customers to public health hazards *e.g.* during incidents.

HRT does not explicitly consider risk, *i.e.* the probability and impact of 'trying conditions', or risk reductions from implementing HRO principles. A significant proportion of journal articles primarily focus on reducing the impact during 'trying conditions', *e.g.* by using systems redundancy, but neglect the management of incident probabilities. The latter is only implicitly stated for the management of technology that is - in the author's interpretation - regarded as a means to manage the probability of failure.

It was found that HRO studies hardly considered the absence of individual HRO principles that led to catastrophic failure of an HRO. Similarly, there is limited evidence that the cause effect relationships that inadvertently avoided catastrophic failure of systems can be attributed to HRO principles. As a result, past studies do not attribute a value to individual HRO parameters that may be critical to safety whereas other may seem beneficial but not critical. The value of HRO principles arises in their ability to reduce risk, *i.e.* their contribution to reduce the probability and impact of adversity. The value of their risk reduction capability also needs to be considered in the context of the cost of implementing those HRO principles in order to provide maximum utility as stipulated by Bazerman (1998).

Finally, the term 'high reliability' denotes absence or minimal failure rates. The theory states that "*minor errors and incidents provide a source for learning"* (Weick *et al.*, 1999), "*which might be assessed using root cause analysis"* (Bierly and Spender, 1995). With increasing 'high reliability', *i.e.* minimal failure rates, an organisation does not have the opportunity to learn from failures. This is a paradox that underlies the academic concept of HROs and again suggests that previous studies were a) not based on truly High Reliability Organisations or b) assumed a causal relationship between HRO principles and system safety. Furthermore, limited evidence was found on the nature and methodologies that underpin the 'learning from failure'.

1.2.8 Application of HRO in the water sector

In (Bradshaw *et al.*, 2006), Reason's 'Swiss Cheese' model (Reason, 1997) for incident propagation was adapted and instead presented as a series of organisational requirements for delivering water safety (Figure 5). Here, continuous changes in the natural and built environment, in labour markets, in competition for financial resources and in the evolution of data available to underpin management decisions must be actively managed to deliver water safety.

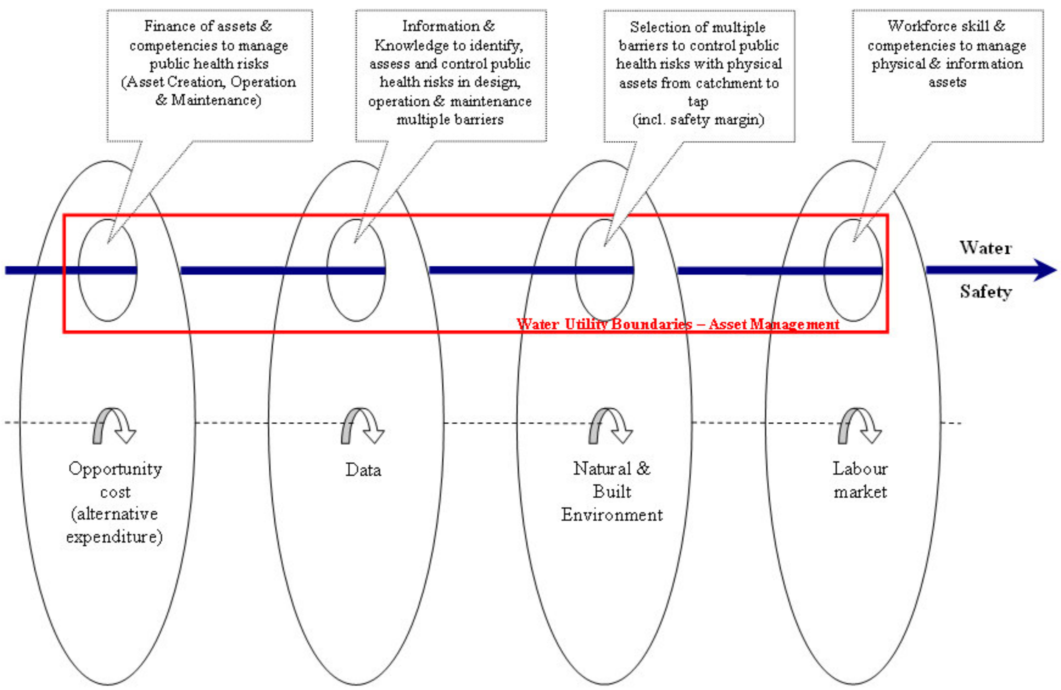

Figure 5 Organisational requirements for the delivery of safe drinking water

This can only be delivered if there is the optimal design, construction, operation and maintenance of a physical water supply infrastructure. Operators, asset managers, public health specialists and engineers make decisions using relevant information to design, operate and maintain physical assets so that water safety is ensured. The HRO principles described above are thought to contribute to this aim. Hence, asset and operations management are a clear candidate for an exploration of high reliability organisational principles within the water utility sector and, in tandem, offers the opportunity to explore risk management practice since risk analysis and the use of risk assessments is paradigmatically seen as an essential aspect for managing the water supply asset base (Pollard *et al.*, 2008).

1.2.8.1 Organisational asset management process

For water supply assets, the asset management decision process involves a periodic (public health) risk assessment to determine operational and maintenance requirements and the design of new physical assets (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003; Ministry of Health, 2005b; Ministry of Health, 2005a; World Health Organisation, 2004; British Standard Institution, 2003; Haimes, 1998). This decision process includes:

- setting operational objectives for assets (British Standard Institution, 2003);
- managing data from asset performance and statistical reliability data (British Standard Institution, 2003);
- deriving acceptability criteria for risk and reliability that define 'system safety' (World Health Organisation, 2004; British Standard Institution, 2003; Ministry of Health, 2005b; Ministry of Health, 2005a; Hughes *et al.*, 2000);
- risk assessment and prioritisation (Ministry of Health, 2005b; Ministry of Health, 2005a) for assets from catchment to tap (Ministry of Health, 2002c; Ministry of Health, 2002b; Ministry of Health, 2001f; Ministry of Health, 2001l; Ministry of Health, 2001m; Ministry of Health, 2001n; Ministry of Health, 2001o; Ministry of Health, 2001h; Ministry of Health, 2001p; Ministry of Health , 2001q; Ministry of Health, 2002d; Ministry of Health, 2001j; Ministry of Health, 2001r; Ministry of Health, 2001s; Ministry of Health, 2001t; Ministry of Health, 2002a; Ministry of Health, 2001w; Ministry of Health, 2001k; Ministry of Health, 2001x; Ministry of Health, 2002e; Ministry of Health, 2001g; Ministry of Health, 2001u; Ministry of Health, 2001v; Ministry of Health, 2001i; Ministry of Health, 2001c; Hughes *et al.*, 2000)
- specification of water safety criteria based on public health risk assessment (World Health Organisation, 2004);
- engineering specification, *e.g.* technical reliability, materials (British Standard Institution, 2003);

- the design specification for data flow, monitoring and control for human-machine interfaces and machine-machine interfaces (World Health Organisation, 2004);
- the design of operational processes and procedures;
- the design of incident detection and response procedures (World Health Organisation, 2004; Taylor, 1995; Sander, 1991; Ministry of Health, 2001b; Ministry of Health, 2001e; International Standards Organisation, 2007); and
- the definition of normal and abnormal operating procedures (World Health Organisation, 2004; Ministry of Health, 2001b; Ministry of Health, 2001e; Ministry of Health, 2001a; Ministry of Health, 2001d; Ministry of Health, 2001e; Hughes *et al.*, 2000);.

The assessment concludes with a recommendation how and when to:

- operate the existing physical asset better to control risk;
- design new assets to eliminate, reduce or isolate the risk; and
- maintain the existing assets to upkeep the ability to eliminate reduce and/or isolate public health risks.

Periodic assessment of assets provides a basis for prioritising the risks of non-compliance and allows a ranking of investment requirements. This, in turn, allows recommendations to be formulated on how to alter the operating regime, maintenance requirements and propositions for new asset designs. This holistic asset management model was further developed in Appendix 2.
Below then, the asset life cycle is considered and aspects of organisational reliability, *i.e.* the reliability of the corporate body, discussed as they impact on the management of the asset base. In turn, the **design**, systems **integration**, **operation** and **maintenance** phases of the asset life cycle are introduced and considered. How the principles of HROs might apply to these phases of asset and operations management are here further introduced. The discussion sets the scene for the research scope within this project – generating an evidence base for large utilities on whether these HRO principles see application in practice and, where they do, understanding their value in the provision of safe and reliable drinking water.

1.2.8.2 Organisational reliability in asset design

The design process of physical assets is concerned with the definition of the:

- scope of works;
- responsibilities during design, construction, commissioning and operation;
- design parameters;
- operating and maintenance philosophy;
- testing, commissioning and completion requirements;
- operational, design, construction and commissioning constraints;
- engineering and operational specifications; and
- contractual arrangements (Kawamura, 2000; Smith, 2002).

These amalgamate into contract specifications and design drawings for construction and commissioning. These documents reflect the designed degree of physical asset reliability anticipated for asset operation. Designing physical assets requires a detailed knowledge of the future operational and maintenance regime. This information should directly reflect the objective of safe and reliable operation and defines the role human resources (operators) occupy within operations.

The process of designing physical assets brings together project managers, operators, operations management, public health specialists, civil, geotechnical, mechanical and electrical engineers, contractors, consultants and commissioning staff, etc. (Smith, 2002). The involvement of operators in the design team reduces designer-user mismatch (Reason, 1990). The skills set of the individuals should match his/her task in the team (Reason, 1990) and the design programme should allow sufficient time for completing the design (Reason, 1990).

The workings of the team are critical. Although most likely line managed within a hierarchical system, decentralised decision making (Weick, 1987) for such a complex task is important. The project team and the peer reviewers (O'Hara, 2005) need to provide adequate checking which represents deliberate slack in the decision making process and offers the opportunity to cross-examine complex project interactions (Schulman, 1993). Human relations and communication are also known to be vital in the design phase. HROs have distinct characteristics for employee relations. Roberts (1993) summarised these as situations where:

- people are helpful and supportive to another;
- people are trustful to another;
- people nurture friendly and open relationships that emphasise credibility and attentiveness;
- the working environment allows creativity and goal achievement; and
- informal networks can be accessed in unexpected situations (Roberts *et al.*, 1994b).

In HROs, communication channels convey information to project sub-units in order to enhance the understanding of roles and responsibilities of employees and sub-units (Tranfield *et al.*, 2002). Communication design is structured in closed loops (Weick, 1987) and needs to avoid the loss of information during transmission. An enabling environment for open and honest communication is central to HROs.

The setting of operational objectives for assets should reflect the aim to zero accidents and incidents (O'Hara, 2005) and the creation of resilience for the physical asset (Pidgeon, 1997). These objectives are clearly communicated to the design team (Weick, 1987).

The definition of a physical asset design project requires the definition of risks, in particular public health risk, health and safety for operatives, commercial risks, as well as a process of risk identification. As a principal HRO philosophy, the whole organisation should participate in problem identification and devising corrective action programmes (O'Hara, 2005). The emphasis rests on learning from previous failures and incidents/accidents (Burke *et al.*, 2005) and aims to combat human error and catch out system error (Burke *et al.*, 2005). The whole organisation contributes to these aims by having behavioural monitoring systems for risks in place that feed back into the project team (Burke *et al.*, 2005).

In the risk assessment process, the project team should embrace the complexity of risks rather than simplifying them (Burke *et al.*, 2005) in order to establish acceptability criteria, *e.g.* for design parameters and performance specifications.

The project team can use dedicated risk assessment tools and reliability techniques. These have been described in the literature elsewhere (MacGillivray *et al.*, 2006; Puglionesi and McGee, 1998; Strutt, 2004; Mays, 2004; Tung, 2004).

Throughout the design phase, the current state of the design should be regularly challenged in dedicated value analysis, HAZOP workshops and in design review meetings to identify failure susceptibility of plant and equipment, maintainability as well as access and lifting arrangements. These workshops also involve other stakeholders, *e.g.* electrical field service engineers, who are not directly involved in the design, but have a peripheral role in asset operations.

The engineering and performance specifications (as well as the design parameters) should formulate the level of acceptable risk from physical assets in relation to operational performance and other identified risks, *e.g.* Health and Safety. In a HRO, specifications reflect the aim for zero incidents and accidents (O'Hara, 2005) and relate to (Kawamura, 2000):

- the technical reliability of the physical asset;
- the operator interface with the physical asset, in particular avoiding human error in operations;
- process monitoring and control;
- the design of standard operating procedures;
- emergency detection and response plans;
- health, safety and welfare;
- maintainability, accessibility and lifting arrangements; and
- skills and training requirements.

The specifications for the physical asset could include:

- reliability, including equipment and component redundancy (Rijpma, 1997; Rochlin *et al.*, 1987);
- operational availability;
- detection and indication of abnormal operating conditions (Reason, 1990);
- design of clear indication for component and equipment failure, even if standby (redundancy) operates in healthy state (Turner, 1978);
- warning systems to signal the presence and nature of hazards to all those likely to be exposed (Reason, 1990);
- containment of hazard to spread (Reason, 1990);

- multiple channels to transmit warnings for abnormal operating conditions (Reason, 1990);
- provisions for contingencies in case of failure (American Water Works Association, 2001; Taylor, 1995; Hughes *et al.*, 2000; O'Hara, 2005); and
- minimisation of data loss (Rochlin *et al.*, 1987).

The specifications to avoid human error in operations could aim for:

- avoiding irreversibility of errors (Reason, 1990);
- designing out information load (Reason, 1990); and
- designing good instructions and procedures (Reason, 1990).

When considering new technologies, the aim is to avoid blind spots in the application of technology and production processes so to minimise the potential for accidents (Rijpma, 1997). The impact assessment for new technologies considers the risks of unnecessary complexity (Perrow, 1999). These blind spots directly affect the operator interface: scope for hasty actions in the operator interface should be reduced and the organisation has to learn to comprehend the complexity of the technology applied (Rijpma, 1997). The design of Standard Operating Procedures (SOP) for bureaucratic, high tempo and emergency conditions requires both instructions and procedures (Reason, 1990).
Overall, asset design is a vital concern as it defines the boundary conditions for operational reliability for physical assets. In the next section asset construction and integration into the existing water supply system are further considered.

1.2.8.3 Organisational reliability during the integration of new assets

During construction activities (*e.g.* of new assets or maintenance of existing assets) management needs to understand the impact on the reliability of existing asset operations. The construction industry is a high risk industry in terms of health and safety (Hughes and Ferrett, 2003) presenting a risk not only to staff and the environment but also to existing assets. During the construction phase, the emphasis for a water utility operation rests on the continuation of its services provided to the customer.

The project team manages the construction progress, the assignment of responsibilities, control over construction areas and construction hazards but also contractual issues such as construction cost, the work programme and quality. In addition, all construction interfaces must be managed within existing operations. In particular, this is relevant for construction in close proximity to existing water supply assets.

The construction process should have procedures in place to negotiate work activities to be carried out on existing assets, *e.g.* work permits and safe systems of work (Hughes and Ferrett, 2003). From a water supply operations perspective, the control over existing assets and responsibilities should be clearly communicated to all stakeholders in the construction process and the transfer of existing assets to the construction organisation has to be negotiated in advance of any construction activities. Emphasis on the control of foreign material and activities, good housekeeping practices and the development of staff ownership for work areas (O'Hara, 2005) can be vital.

The construction activities undergo a risk assessment process that informs a detailed method statement for construction (Lawson *et al.*, 1999; Hughes and Ferrett, 2003). The project team identifies hazards in construction and commissioning with a view to isolate, reduce or control any risk to the existing water supply operation and health and safety (Hughes and Ferrett, 2003).

The risk assessment and method statement should be communicated to all stakeholders, in particular to water supply operations. The risk assessment and method statement can also envisage contingency planning based on failure modes in construction and their critical effects on operations (Hughes and Ferrett, 2003).

The method statement provides a detailed description of the construction activity and forms the basis for information, training, instruction and supervision of construction activities (Hughes and Ferrett, 2003). The emphasis is to provide good instructions and procedures (Reason, 1990). The workforce is committed to continual training and organisational development (O'Hara, 2005) and the organisation provides systematic, multi level training evaluation (Burke *et al.*, 2005). The construction management ensures the familiarity of its operators with the task, avoids operators inexperience and the misperception of risks and provides adequate checking and supervision (Reason, 1990).

The quality of the construction work should be monitored against the contractual description in the scope of works, design parameters and engineering specifications. With the philosophy of 'concurrent design' commonly adopted in the construction industry, the design and construction processes are no longer 'clear cut'. The design process carries forward into the construction process and all stakeholders in design and construction should be involved in change management (O'Hara, 2005).

The quality assurance system provides an auditable "trail" of compliance with the design, construction and commissioning procedures (International Standards Organisation, 2000).

Failure in construction and integration of physical assets is a concern to the continuation of services from existing assets. These concerns could be managed with the array of HRO principles described earlier.

Cost control in construction and the compliance with asset reliability criteria ensure the safe and economic operation of the new assets. In the next section, the organisational reliability in the operation of water supply systems and more importantly during incident management is further considered.

1.2.8.4 Organisational reliability in operations and incident management

The human element plays a significant role in preventing accidents (Reason, 2000a). In the process industry, it is recognised that 70-90% of industrial accidents have been attributed to human error (American Institute of Chemical Engineers, 1994a).

Work process definitions, or Standard Operating Procedures (SOP), aim to codify routine tasks in business processes and operations in order to control risk. Park *et al.* (2005) suggest that good standard operational procedures reduce the opportunity for human errors based on the provision of instructions to operators. This also appears useful for infrequent tasks and complicated or stressful situations. In adhering to standard operating procedures, the water supply operator controls public health risks at grass root level in the organisation.

However, procedures may also contribute to human error. Errors can arise from using inaccurate procedures that contain false instructions, incomplete procedure or obsolete instructions. Even procedures with accurate and complete instructions may have the potential for human error depending on the level of complexity that hinders the operator to understand instructions themselves or the technical system. The level of complexity in procedures becomes a critical factor in the design of instructions (Park *et al.*, 2005). Although the organisation aims for accurate and complete operating procedures (Reason, 1990), operators should be encouraged to question the procedures when in doubt about their appropriateness (Rijpma, 1997). This requires staff to engage with the organisational reliability and safety culture of a water utility.

Organisations should establish a safety culture that builds "*on an understanding of the cause of unsafe acts*" (Ruchlin *et al.*, 2004). Reliability is a dynamic, ongoing condition of a system where the reliable outcomes are an invisible, constant achievement (Weick, 1987). Reason describes this as a paradoxon: safety is defined and measured by the absence of "*failures*" rather than its presence (Reason, 2000b).

Viewing reliability from a dynamic perspective requires the mindset of a chronic suspicion that minor deviations can unfold into a bigger incident (Weick, 1987). A good safety culture requires (Pidgeon, 1997; Pidgeon and O'Leary, 2000):

- senior management commitment to safety;
- a shared concern for risk and their impact on people;
- realistic and flexible norms and procedure to manage risk; and
- continuous learning through monitoring, analysis and information/communication systems to provide feedback

Hence, the safety culture of an organisation is a contingent and dynamic process built on argument and rhetoric (Turner, 1995).

A HRO would decentralise decision making whilst centralising the design of decision premises (Weick, 1987). Although its operations are hierarchically structured (Yorkshire Water Services Limited, 1994), decision making, in particular during trying conditions is allocated to the most appropriate person to take effective action (Roberts, 1993) - in a water utility - the operator or operations duty manager. Different layers in the organisation act as checks and balances in the decision making process (Ruchlin *et al.*, 2004; Roberts, 1993).

HROs use redundancy and slack (Weick, 1987) to provide back-up in decision making, personnel, equipment and components to cope with unexpected circumstances and to promote the safe operation of systems (American Water Works Association, 2001).

Slack allows a decision-making unit to consider options and their outcomes that is driven by a culture of collective responsibility and accountability. Reserve capacity can consist of technical back-up functions and overlap in employee duties. Technical and human redundancy is commonly adopted in water supply systems design, where technical equipment is designed with 'duty/standby' and more than one operator is trained and licensed to operate systems.

In operational decision-making, *e.g.* the production planning or outage planning for maintenance, the organisation should understand and measures its processes.

The organisation promotes a continuous learning approach (Roberts, 1993) where trial and error may not be available as a learning vehicle "*because errors cannot be contained*" (Weick, 1987) without the risk of incurring excessive, consequential cost. "*Trial without error*" uses symbolic representation of technologies and their effects, simulations (Weick, 1987), critical incident examinations and scenario planning methods.

Employee relations are characteristic for mutual support and helpfulness in trusting, friendly and open relationships that emphasise credibility and attentiveness. The working environment is characteristic for creativity and goal achievement (Roberts, 1993).

Communication plays a central role in operations. Communication channels convey information to sub-units in order to enhance the understanding of roles and responsibilities of employees and sub-units (Tranfield *et al.*, 2002).

Communication design is structured in closed loops, similar to an aircraft captain who is required to repeat an instruction received from an air traffic controller (Weick, 1987). Closed loop communication or three-point communication avoids the loss of information during 'transmission'.

The enabling environment for open and honest communication is central to the learning organisation. Reason (2000a) describes the culture of communication and learning with an emphasis on:

- a reporting culture, where people are prepared to report incidents and near misses;

- a just culture, which encourages the reporting of safety-related information without jeopardising clear understanding of acceptable and unacceptable behaviour;
- a flexible culture where, in particular under trying conditions, control passes from the formal hierarchical structure to the task expert; and
- a learning culture, which is characteristic for "*the willingness and the competence to draw the right conclusions from its safety information system and the will to implement major reforms when their need is indicated*".

Political barriers can cause problems insofar as they can inhibit learning as a result of conflicting interests (Macgillivray, 2008). The reporting of incidents, the normalisation of errors in light of external accountability and a revisionist interpretation of failures as a success (Pidgeon, 1997; Sagan, 1993; Rijpma, 1997) inhibit open and honest communication. 'Blame cultures' inhibit learning from incidents but arguably may also enforce individual accountabilities (Pidgeon, 1997).

The American Water Works Association (2001) describe how water utilities can plan for, respond to and recover from incidents and emergencies. Building on vulnerability assessments, emergency preparedness plans are developed and staff trained to use system redundancy to re-instate normal operations. Further planning for disasters can be found in Grigg (2002).

Riordan (1995) describes how an incident command system has been created to oversee command, operations, planning/intelligence, logistics, finance and administration during emergencies that are increasingly supported by IT solutions for incident reporting and communication (Roeschke, 2005). A centralised incident command also facilitates communication with third parties and the public (Koschare *et al.*, 2007).

In unforeseen situations, *e.g.* water quality incidents and emergencies (American Water Works Association, 2001), operators should do not follow rules blindly (Schulman, 1993), but negotiate the course of action in a collegial manner with experienced operators and supervisors (Roberts *et al.*, 1994b). The operators should form an informal network in decision making when confronted with unexpected situations (Roberts *et al.*, 1994b) which is kept at an optimal size to avoid increasing ambiguity on the due course of action (Rijpma, 1997). More experienced staff have a veto power in negotiating due course of action (Schulman, 1993). The response team to an unforeseen situation is aware of the timing when negotiating due course of action aiming to balance the period of hazard exposure with the time to build confidence in the correct due course of action (Schulman, 1993). If an accurate and complete operating procedure is not available, the operator creates awareness in a situational assessment (Burke *et al.*, 2005).

Operations management aims to learn from failures and incidents (Burke *et al.*, 2005) and incorporates lessons learnt and operational experience (Roberts, 1993) into common practice and SOP. Learning organisations promote the importance of information gathering (Burke *et al.*, 2005). Information systems collect, analyse and disseminate information from near misses and incidents (Reason, 2000a) to support operations with contextual rich knowledge. The accident/incident investigation focuses on processes, not people (O'Hara, 2005).

The HRO is aware of ambiguity and diverging opinions on the many contributing root causes (Weick, 1987; Sagan, 1993; Bovens and 't Hart, 1996) when incorporating lessons learnt. Learning from past experience requires a strategy for data collection and root cause analysis (American Institute of Chemical Engineers, 1994b). The data collection strategy also incorporates near miss reporting (American Institute of Chemical Engineers, 1994b).

The learning process identifies critical tasks, audits critical factors which influence performance and predicts specific errors and their consequences (American Institute of Chemical Engineers, 1994b). Based on this analysis, the organisation selects and implements corrective actions and introduces an error reducing strategy (American Institute of Chemical Engineers, 1994b), *e.g.* in operations, design or maintenance of assets.

In summary, asset operation is a primary organisational function to control public health risks and the HRO principles described earlier may have a positive impact on the organisational reliability in operations. In the next section, maintenance planning in the water sector and its ability to maintain the ability of physical assets to control of public health risks are further considered. This will close the loop to the asset management decision process described earlier.

1.2.8.5 Maintaining physical assets to safeguard operational reliability

In maintenance planning the organisation should understand the reliability requirements in operations and maintains the ability of physical and information assets to eliminate, reduce, isolate and control risks. Maintenance planning requires asset condition data (Heywood and Lumbers, 2001) and, for this purpose, uses tools and techniques to assess the probability and impact of failure, *e.g.* FMEA, HAZOP for the consequence of failure, and specific considerations for assessing the probability of failure and reliability (Lifton and Smeaton, 2003; Lifton, 2005; Hughes *et al.*, 2000; Strutt, 2004; MacGillivray *et al.*, 2006).

A HRO would maintain their physical assets to exceptionally high standards as HROs do not tolerate defective, substandard or malfunctioning equipment (Roberts, 1990b). More realistically, a water supply organisation maintains its assets to maintain its ability of providing services at acceptable risk and cost. In the regulated UK water industry, the regulatory objective in maintenance planning is to maintain and enhance serviceability benefits to customers (UK Water Industry Research Limited, 2002). Water companies in England and Wales are required to appraise their capital maintenance planning in light of past and future maintenance to provide a view on long term trends on investment and financial requirements, whilst considering "*the trade off between cost and risk*" (Office of Water Services, 2000; Drinking Water Inspectorate and Office of Water Services, 2001).

The key elements of maintenance planning is the identification of failure modes with impact on customer service, the environment or cost to the water company if no proactive capital maintenance is undertaken and the development of an estimation method for probability of failure, consequence of failure and cost of failure (UK Water Industry Research Limited, 2002). This approach emphasises the importance of assessing risks in relation to serviceability criteria (Drinking Water Inspectorate and Office of Water Services, 2001).

The assessment of maintenance needs can be challenging: Many water engineering assets have low probabilities but high consequence of asset failure. Furthermore, reactive maintenance planning has, traditionally, aimed to avoid system failure

(Chapman, 2002) and the impact of asset failures on the level of service is difficult to predict because of large redundancies inbuilt to the supply system. Redundancies and low failure history, although a high reliability trait, complicate the assessment of maintenance needs and inevitably limits reliability assessment methodologies and techniques (*e.g.* RCM and Weibull analysis) (Dunn, 2004).

The risk of failure throughout the life-time of an engineering system can be optimised in a regime of inspection and maintenance (Crossland *et al.*, 1992) Many systems deteriorate over time and condition assessment based on inspection supports the assessment of deterioration to estimate the residual life of an asset. The planning of the inspection process has to consider the re-produceability and practicability of the regime, but also the integration into a management and auditing system (Crossland *et al.*, 1992).

Dunn (2004) proposes an asset integrity process which is the meta process of risk management, environmental management, maintenance management and safety management processes. Dunn (2004) defines three root causes for system failures: physical root cause failure of equipment, human root cause failure from human intervention and latent root cause, which finds its origin in the organisational decision making processes described earlier. The latter is a function of organisational processes, leadership, culture and reward systems which interact with organisational ability to manage risks (Dunn, 2004).

The asset integrity assessment is a review of the designed system against current standards and specification using a risk matrix with defined probabilities and categories for consequences for production, environment and safety. The designed operating parameter envelope is reviewed against actual operating parameters to assess the probability and consequence of exceedence. A review of the routine maintenance program is assessed and compared to the asset risk profile from a design and operations perspective down to individual needs for maintaining components (Dunn, 2004).

The outcome of risk assessment methodologies determines the maintenance activity which range of fixed interval tasks, condition based tasks, periodic inspections, continuous monitoring and planned maintenance (Woodhouse, 2001) such as refurbishment and replacement. Reliability centred maintenance (RCM) was developed to direct maintenance towards components critical to reliable operation. RCM considers maintenance cost and loss of production (as a consequence) due to failure when identifying the optimal maintenance intervention for reliability sensitive components (Anderton and Neri, 1990). RCM considers the criticality of components in process equipment and the appropriate maintenance regime which could be (Organ *et al.*, 1997b):

- preventative intervention based on past experience;
- planned maintenance integrated to the business planning system;
- breakdown response maintenance where excess capacity is available or preventative maintenance difficult to forecast or expensive; and
- condition monitoring uses and benefits of vibration analysis, thermography and microscopy but also visual inspection.

Application of RCM for the water industry in the context of cost and benefit was investigated by Fynn *et al.* (2006). They found that "*water utilities will typically derive extensive benefit from utilizing RCM to develop optimised maintenance programs for their asset base"*. Vatn *et al.* (1996) aimed to integrate RCM into the wider context of business operations to demonstrate the relationship between maintenance, safety and economic returns. Safety, health and environmental objectives are assessed in conjunction with maintenance and loss of production costs. Since this model is based on an economic assessment, it requires valuing safety and risk in monetary terms.
Asset maintenance planning also has to consider human error during maintenance activities and 'learning from past failures' is a strategy to identify risks associated to maintenance planning (Health and Safety Executive, 2000).

In this section, the loop of the asset life cycle (with the exception of decommissioning assets) is closed whilst aiming to portrait a reliability-focussed approach to asset and operations management. Reliability of a water supply system goes beyond technical reliability and has to consider the organisational processes in asset management planning but also design, construction, commissioning, operation, incident management and maintenance of physical assets. These processes consider primarily the physical assets but also human 'assets', information and intangible assets which constitute the basis for an organisational culture and public health risk management.

1.2.9 Knowledge gap

The World Health Organisation (2004) characterises trying conditions in the water sector as "*short periods of 'stress'*" after "*long periods of steady state performance"* (World Health Organisation, 2004) that affect customers. These periods of stress need to be identified and characterised to subsequently investigate organisational resilience via incident management based on HRO principles.

High reliability theory in the context of drinking water supply operations has not been investigated in formal case studies and recent academic work suggests that the principles of HRO should be further investigated in context of the water sector. A rich academic literature exists on HROs in other industry sectors and operations, *e.g.* management systems in nuclear power stations and submarines, oil platforms and other high hazard industries. In this thesis, high reliability theory is investigated in the context of water utilities.

The challenge in investigating a high reliability for water utilities is to provide evidence of the successful contribution in terms of 'value for money' of HRO principles towards enhancing the provision of safe and reliable drinking water.

The recent 3rd Edition of the WHO *Guidelines for Drinking Water Quality* places a greater emphasis on proactive risk-based management for drinking water supplies. Risk-based decision-making requires sufficient quality and quantity of risk assessment data to effectively and consistently allocate resources for risk management (*e.g.* via cost benefit analysis). In the literature review it was stipulated that the three perspectives on risk, *i.e.* the economic-rational, the psychological and sociological construction of risk can have a significant impact on the quality of risk data by inducing psychological and sociological biases in the risk models and data. In this thesis, evidence for these biases is sought in the risk data used for asset management decision making. Furthermore, it was stipulated that 'learning from failure' can act as a means to adjust mental anchors (Rutledge, 1993). In this thesis, evidence is sought to enhance the prediction of future risks by statistical comparison between risk data with historical incident data.

The forthcoming study investigates the principles of HRO in the context of incident management. In particular, it aims to identify the presence and effectiveness of high reliability principles to maintain a resilient water supply system "*under trying conditions*" (Weick, 1987). Beyond the immediate management of incidents, opportunities to 'learn from failures and incidents' are sought to enhance risk assessment data that challenge the perception of risk by individual risk assessors who, according to the literature, can be biased by psychological and sociological constructs of risk. The latter study is aimed to enhance the (economic-) 'rationality' of decision making by providing a methodology to remove biases in the mental modes of risk assessors.

1.3 Aims and Objectives

1.3.1 Research question and hypothesis

In the literature review, the main characteristics describing High Reliability Organisations were introduced. High Reliability Theory has two main themes. Firstly, a technical perspective on reliability, and secondly, an operational perspective that describes organisational reliability. The former is concerned with managing technology and system redundancy to manage the failure proneness of technical assets and systems. Its measure is failure frequency, *e.g.* mean time between failures (MTBF), and the impact of failure on organisational objectives. The latter describes organisational strategies for learning from failure, decision making processes as well as communication and training to operate assets and resources in the organisation with a view to avoid failures or contain their impact. In the water utility context, failure relates to incidents that affect the safe and reliable supply of drinking water to customers.

For this project, a hypothesis was developed that builds on the statement that "*most drinking water supply systems are characterised by long periods of steady state performance, and short periods of 'stress'*" (World Health Organisation, 2004). It is hypothesised that the

"***principles of HRO facilitate a) organisational resilience under trying conditions and b) learning from failure to enhance the safety and reliability of drinking water supply***".

1.3.2 Research aim

The research aim of this project is to investigate the benefit of high reliability organisations principles in enhancing the safety and reliability of drinking water supplies.

Three main aspects are investigated: firstly, the nature of incidents and their impact on customers; secondly, building on the review of incidents, the effectiveness and benefit of HRO principles to enhance the organisational capability to manage incidents and contain their impact. Thirdly, learning from incidents to enhance risk assessments that are subsequently used for risk-based asset management strategies that provide and maintain the technical reliability of the water supply system. The relationship of these three themes is conceptualised in Figure 6.

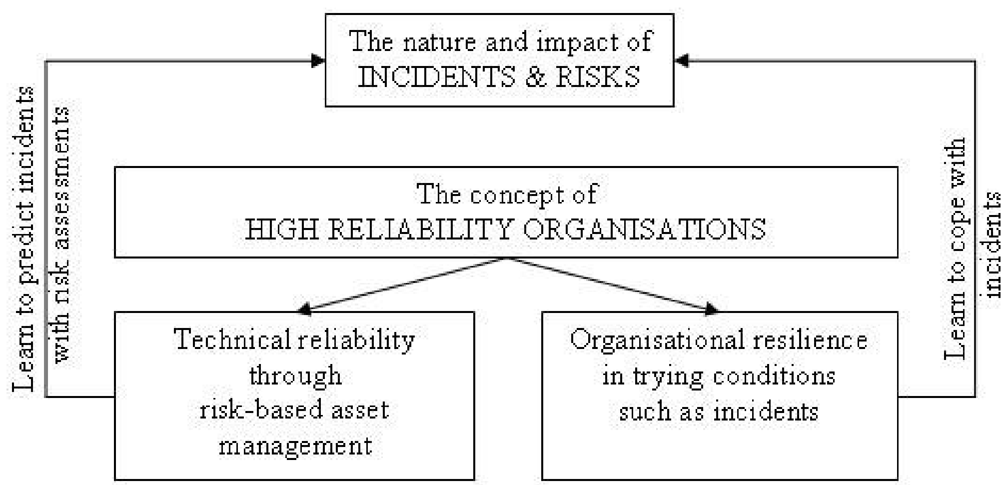

Figure 6 A high reliability organisations' perspective on technical reliability and organisational resilience

From a utility operations perspective, the three themes are further detailed in Figure 7.

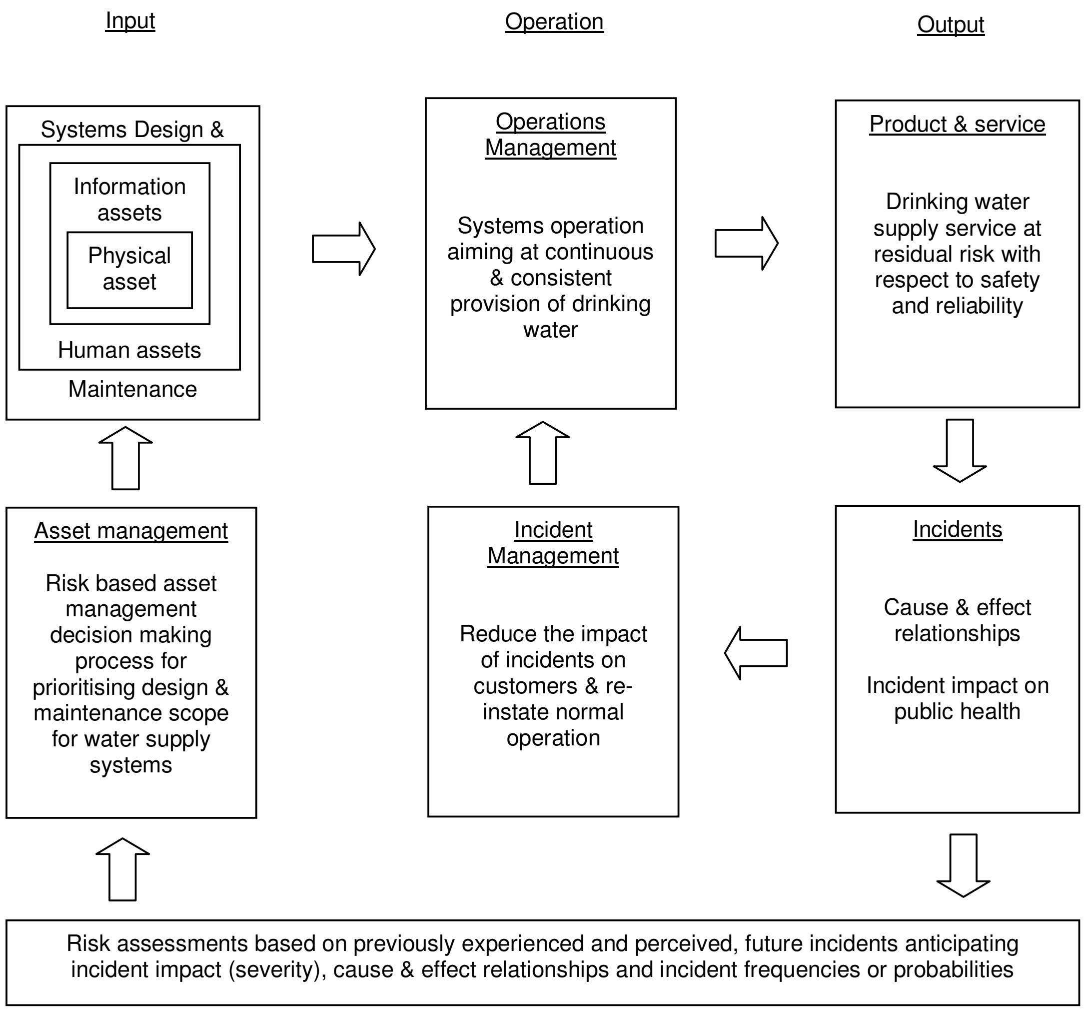

Figure 7 The interaction of operation, incident and asset management via learning from failure

1.3.3 Research objectives

From the above literature review, the hypothesis and the research aim, a number of research objectives have been devised. The specific objectives of this study were identified as:

1. To characterise "*the short periods of stress*" (World Health Organisation, 2004) in an assessment of incident frequencies, cause and effect relationships and impact on customers.

2. To investigate the benefit of HRO principles in incident management, and to correlate incident impacts on customers and impact reductions with observation of high reliability principles under trying conditions.
3. To identify learning opportunities from incident analyses to enhance risk assessments that are subsequently used for asset investment and maintenance decision making in asset management.
4. To investigate the prevalence of incidents from a financial and customer perspective on the "price" of risk and the benefit arising for customers to reduce the frequency or probability of incidents.

1.4 Outline Methodology

1.4.1 Research strategy

The literature differentiates between deductive and inductive approaches to research (Denzin and Lincoln, 1994). Deductive research uses a theory, *e.g.* HRT, to develop a hypothesis that is then used to structure observations. Based on the findings, the hypothesis is accepted or rejected. Inductive research commences with observations to identify patterns that amalgamate into building hypotheses and theories. In practice, the combination of deductive and inductive research methodologies provide a more practical means of addressing a research question and deriving the necessary data to support or reject a hypothesis. This is depicted in Figure 8 which is adapted from Blaikie (1993).

The methodology in this thesis uses the combined approach to research, although individual studies are dominated by deductive or inductive inquiry. These are further detailed below.

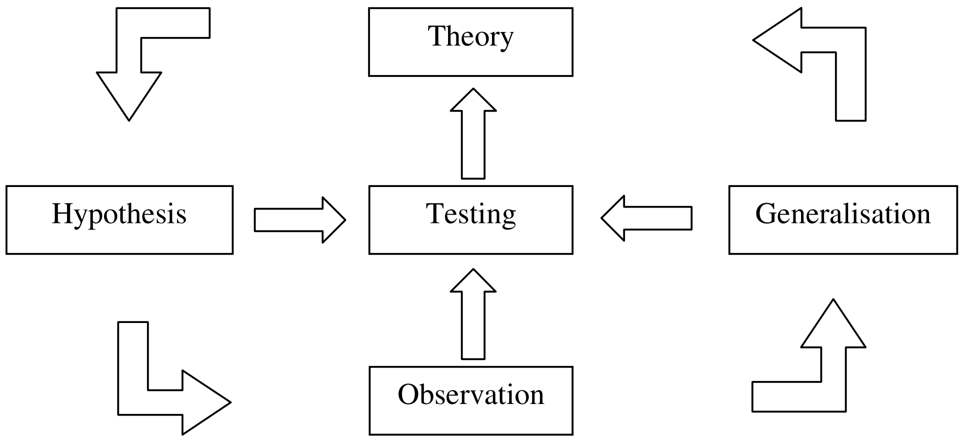

Figure 8 Combined inductive and deductive research strategies

A range of research strategies were considered and used in the design of this project. Ethnography is concerned with specific people or cultural groups to describe a way of life (Denzin and Lincoln, 1994), or in this project's context, the "*the way we do things here*" (Johnson, 1992). As part of the sample group, the researcher interacts with the group. This poses a serious disadvantage since the researcher influences the information obtained in the studies.

Phenomenology studies events and how individuals experience them (Trochim, 2000) and is a method of trying to understand how an individual perceives and constructs their reality (Robson, 2002). This form of research can provide highly detailed data for a specific research question. However, facts and information become highly personalised and subjective experiences (Denzin and Lincoln, 1994). In combination with studies of the external reality (beyond individual accounts) it can provide a definite advantage (Trochim, 2000).

Historical research focuses on the history of reality. It refers to documentation such as company reports and all forms of records that were pre-existing to the research project (Denzin and Lincoln, 1994). Documentation can be highly biased due to the views of the authors and it was even suggested as a form of propaganda (Denzin and Lincoln, 1994). Yet, it holds some weight when combined with other forms of research (Trochim, 2000).

Action research has been promoted by practitioners as a moral responsibility to work socially meaningful in changing a situation for the better by the researchers involvement

(Denzin and Lincoln, 1994; Greenwood and Levin, 1998). It is "*research becoming praxis – practical, reflective, pragmatic action – directed towards solving the problems in the world*" (Denzin and Lincoln, 1994) and has a deliberate interaction with the subject areas of study.

Grounded theory identifies an area of study and allows findings to emerge from systematically collected data (Denzin and Lincoln, 1994). It is data driven with developed methods of collection and analysis that can stand up to rigour, reliability and validity. It is not theory driven and is approached by broad and exploratory search before focussing on emerging findings. According to Robson (2002), grounded theory allows the researcher to cover more territory whilst remaining relevant within the real world. It is a constant comparative approach building on a continual review of new data against previously collected data that help to refine the development of theory (Bogdan and Taylor, 1984) and represents an almost inductive approach to data analysis (Strauss and Corbin, 1997). Theory must fit the real world across a range of contexts, it must be relevant to the people concerned and its theory must be readily modifiable beyond a single project (Glaser and Strauss, 1967). Lee (1999) identifies the eight steps for grounded theory research as

- the generation of ideas, questions and concepts;
- suggestions of potential hypotheses;
- preliminary data acquisition to test potential hypothesis;
- continuous comparison of hypotheses with the wider population;
- theory refinement with integration and simplification of the hypotheses;
- production of theory development and theory refinement;
- detailed data collection and analysis; and
- communicating the research findings.

A number of methodological challenges had to be considered in the design of this project: HRT has not been previously investigated in the water sector context. Although this research builds on existing academic *prior art* in the military-industrial environment, the transfers of knowledge requires an in-depth analysis of HRT in a water utility setting to avoid false assumptions and conclusions biased from the literature. A detailed analysis was required to capture the complex processes and organisational cultures that may prevail in an organisation. It was previously found that HRT interlinks a number of disciplines and functions in an organisation, *e.g.* operations management, asset management, human resource management, etc. Ultimately, this is reflected in the extensive scope of a HRO research project. In addition, the analysis of management theory application requires particular attention to sufficient detail in order to ascertain authentic and trustworthy conclusions (Denzin and Lincoln, 1998). It was decided that an in-depth study of one water utility was required to provide a sufficiently detailed case study. According to Trochim (2000), case studies are widely used and an accepted tool for gathering a broad range of data about a specific, contextual topic.

The selection process of one water utility had to consider a number of criteria. In considering Reason (2000b) who wrote that "*unlike pure sciences, in which theories are assessed by how much empirical activity they provoke, the insights of safety scientists and safety practitioners are ultimately judged by the extend to which their practical application leads to safer systems*". This research project, too, has been initiated from a practical perspective to provide safer water supply systems and it was thought that an investigation of HRO principles in an exceptionally well performing water utility would enhance their capabilities so that the "*practical application [of HRO principles] leads to safer systems*". In a wider perspective of HRO application in the water sector, it could be argued that such a study investigates the ultimate potential or benefit for water utilities arising from HRO principles. Whilst different utilities have different technical systems and organisational cultures, the findings of this research seem eminently transferable across the sector. Subsequent studies would require an investigation how average and poor performing companies could enhance their performance by implementing HRO principles (Bradshaw and Pollard, 2006; Burke *et al.*, 2005).

The economic regulator in England and Wales has systems and procedures in place to monitor the performance of regulated water utilities in accordance with the level of service requirements (Office of Water Services, 1998; Office of Water Services, 2003). Since these level of services reflect the water sector objective of providing safe and reliable drinking water, it was thought that level of service performance assessments are a valid mechanism to select a water utility for this case study.

The water sector in England and Wales has seen a considerable concentration in the number of water utilities with increasingly large utilities serving increasing numbers of customers (Office of Water Services, 1993). From the literature, it was understood that risk assessment tools and techniques were readily available to water utilities to assess their risks. The literature, however, has not sufficiently emphasised the needs and challenges of risk assessment programmes, *i.e.* the risk data requirements for significantly large asset systems, and it was thought that the competence of conducting risk assessments requires a further dimension of consistency in risk data acquisition. Therefore, it was decided to study a significantly large water utility in terms of its asset base and the customers supplied by their water supply system.

In the selection process it was further stipulated that the water utility needs to be willing to learn, *i.e.* a level of curiosity of stakeholders to ascertain interest and engagement with this project, and willing to share information as a data source to underpin this case study. The dimension of learning was thought to be important because it is critical for this project to have access to data that may portray the organisation in an unfavourable light (*e.g.* incident data). Since this project aims to learn from failure, an attitude to 'discard' previous experience, *e.g.* from previous incidents, would have rendered this investigation impossible to conduct.

The methodology of selecting a water utility that complies with all those criteria represents a non-random selection of an "*extreme samples*" (Schnell *et al.*, 1995).

The Regional Water Utility that was chosen for this case study was identified to be within the top three water utilities in the overall performance assessment ranking that compares all water utilities in England and Wales (Office of Water Services, 2003). It has *"continued to improve levels of operational and customer service in Ofwat's Overall Performance Assessment (OPA), with an increase in score for the 9th consecutive year. The report confirmed that the company achieved the highest grades available in all categories of service indicators*"(Regional Water Utility Limited, 2007). "*Ofwat again confirmed [that the Regional Water Utility] has the most efficient water and sewerage company in the UK. The company was awarded four 'A' ratings for the efficient way it runs its water and waste water operations"* in 2007 (Regional Water Utility Limited, 2007). It achieved 'A' band ratings for operational and capital efficiency since 2005. The Regional Water Utility "*achieved platinum status in the Sunday Times 'Top 100 Companies that Count 2007' report, based on Business in the*

Community's corporate responsibility index. The report benchmarks companies' performance against a range of social, ethical and environmental issues. The company, which achieved its highest ever score of 97%, achieved outstanding performance in the areas of community, environmental, workplace and customer management" (Regional Water Utility Limited, 2007). In addition, the Regional Water Utility has won the '*Utility Company of the Year Award'* in three consecutive years between 2004 and 2006. The Regional Water Utility has an active research interest in risk management and its approach to risk-based asset management is considered to operate an advanced risk management and asset investment decision making model (Oakes and Skipworth, 2006). Regarding the large asset base, the Regional Water Utility represents ca. 10 % of customers in England and Wales and operates a vast asset base that will be further described in chapter 4.

Extrapolating from one in-depth case study to draw wider conclusions for the water sector in highly developed countries was deemed unacceptable and in addition to an in-depth study in one water utility, which provides authentic and trustworthy conclusions, less detailed studies in a sample of water utilities were conducted to provide more objectivity and validity in the results. Robson (2002) and Blaikie (1993) argue that with increasing number of consistent dataset the fallibility of a single conclusion drawn from that data reduces dramatically but never to zero, hence, always leaving scope for further research to derive new or conflicting conclusions (Robson, 2002). As a result, it was decided to conduct eight sub-studies: Four projects were designed to address the research question with in-depth studies in the setting of one Regional Water Utility; the remainder focussed on addressing the research question in less detailed studies with contributions from a national and international perspective. This is reflected in the overall methodology of the research design but also in the methodologies of the forthcoming, individual chapters. Four themes were investigated so that each theme had a national or international context and a water utility specific context in the Regional Water Utility. As outlined in the research objectives, the four themes are

- characterising incidents,
- incident management with a particular emphasis on HRO principles,
- asset management with a particular emphasis on 'learning from incidents', and

- valuing the 'price' of risk for risk-based asset management decision making.

These four themes were used to structure this investigation but also this thesis. It can be seen that the study of incidents and incident management is transactional as well as the study of incidents and the derivation of risk data.

Before outlining the eight sub-studies, data acquisition strategies have to be considered. According to Wisker (2001), *"collections of statistics and number crunching are not the answers to understanding meanings, beliefs and experience, which is better understood through qualitative data."* In the research design of the eight sub-studies a number of data collection methods were considered. Trochim (2000) and Robson (2002) argue that a single research project should focus on ideally one data collection method. Others argue that diverse data collection methods as a form of triangulation reduce skewedness of data sets (Denzin and Lincoln, 1994). The latter view has been endorsed in this thesis.

Qualitative data collection uses language, description and expression (Trochim, 2000) and emphasises the human element in a 'real' perspective (Denzin and Lincoln, 1994). Yet, its analysis is inherently complex (Robson, 2002) and provides highly animated, rich and deep information (Trochim, 2000).

One form of qualitative data collection are observational methods to view what groups or individuals do (Robson, 2002). Recording their actions and describing their activities in 'real-world research' (Robson, 2002) offers good advantages, however, there is danger of the researcher influencing the results. Interviews provide a source of data from interacting in a conversation. The spectrum of interviews ranges from unstructured via semi-structured to structured interviews (Robson, 2002). Whereas the former can provide very rich and detailed data with expressive and enlightening information (Wengraf, 2001), it lacks standardisation in its results (Robson, 2002) which is a definitive advantage in structured interviews. Yet, structured interviews lack in the inability to react to emergent topics raised by the interviewee (Robson, 2002).

Surveys and questionnaires are an extension to interviews (Trochim, 2000) and can be designed for quantitative analysis and even for self-administration (Robson, 2002). They offer a time-effective means of data acquisition but questions arise over the quality of data obtained (Robson, 2002), *e.g.* unanswered questions and misinterpretation.

Quantitative research methods use numerical techniques to acquire and process data from surveys and questionnaires but also from 'hard science' experiments that provide numeric data outputs. Another form of quantitative analysis can arise in the coding of language. Means of coding language can be 'open coding', 'axial coding' and 'selective coding' (Lee, 1999). With open codes, the researcher develops new codes for every new concept found in the use of language and can result in significant amounts of coded categories. Axial codes are pre-determined coding categories that are predominantly prescriptive. In selective coding, the researcher selects the most important category and judges all data with the potential to fit that category. If a predetermined model exists, the model can be used to generate initial codes (Trochim, 2000) whilst still allowing for new codes to be generated without changing the strict adherence of one concept to one code (Lee, 1999).

Data analysis has to provide research results that are reversible and repeatable (Lee, 1999). Dozens of diverse methods exist for quantitative data analysis to be used according to different circumstances and distinctive types of results (Rowntree, 1991). They can be found in (Dey, 1993), (Hays, 1993), (Wright, 1996) and (Rice, 1995).

It was decided that the research scope of this project was best studied with qualitative research methods such as participant observation, interviews, surveys, document reviews but also keeping personal learning logs. Quantitative research techniques such as quantitative data analyses based on surveys and coded language were used to underpin the qualitative research findings.

Qualitative research is prone to bias and ambiguity and a methodology was sought to reduce their effect on the research results. It was decided that the design of the overall project should build on triangulation. This is reflected in the design of the sub-studies. As a result, the eight studies were:

- A statistical analysis of incidents that occurred between 2004 and 2006 in England and Wales to explore the causes and effects of incidents and their impact on drinking water customers.

- A statistical analysis of incidents that occurred between 1997 and 2006 in a Regional Water Utility to explore the causes and effects of the incidents and the impacts on drinking water customers. The statistical analysis was enhanced by interviews and further explored with observing unfolding incidents during a research placement in the Regional Water Utility.
- A survey and interviews on 'HRO' with particular emphasis on the value of HRO for incident management with participants from water utilities in the UK, the USA and Canada.
- A survey and interviews on 'HRO' with particular emphasis on incident management with participants from the Regional Water Utility. This study was further enhanced by the research placement in the Regional Water Utility to observe HRO principles.
- A survey and interviews on risk-based asset management with participants from water utilities in the UK, the USA and Canada.
- A study of risk-based asset management with particular emphasis on 'learning from incidents' to enhance risk assessments and risk data quality that is used for decision making. This study was facilitated by a research placement in the Regional Water Utility and enhanced by document reviews, expert interviews and observations
- A statistical analysis of financial data to evaluate the monetary value of asset risk in stock market listed water utilities in England.
- An analysis of the monetary evaluation of public health risks from customers in the Regional Water Utility.

Triangulation does not remove personal and group bias from research participants. The author of this thesis was educated and trained as an engineer to operate within the socio-technical system of water utilities. In this working environment many years of awareness, experience, knowledge and expertise were accumulated that shaped the author's "*heuristic models*" to perceive the world (Gigerenzer *et al.*, 1999; Bazerman, 1998). These heuristic models influence the idiosyncratic understanding of the functions and processes in the water sector. In a further attempt to reduce bias and ambiguity, it was considered to be aware of the research paradigms that are commonly used to interpret research results. They are the

- **Positivistic research paradigm** where "*things, events and people interact and link logically*". Its focus is on "*internal validity, external validity, reliability and objectivity*". In this paradigm, the inquiry does not interact with the truth, facts can only be read in one way and are value free (Denzin and Lincoln, 1998).
- **Relativistic research paradigm** in which our beliefs of the world affect the studying and interpretation of interaction between things, events and people. Their focus is not validity but trustworthiness and authenticity. This research aims for the production of reconstructed understanding (Wisker, 2001).
- **Constructivism** and **critical theory** that "*use a relativistic ontology, transactional epistemology [i.e. knowledge of the world based on one set of action that causes an interaction and responses], and hermeneutic, dialectical methodology"* (Denzin and Lincoln, 1998).

The author's awareness of different paradigms help to challenge own beliefs and understandings of the world. As a result, the research results presented in this thesis are not entirely value-free but also value laden and reflect how the author's and participants' beliefs and perceptions affect the interpretation of research data as an interaction between people, things and relationships (Wisker, 2001). Hence, the focus is not only internal and external validity, reliability and objectivity but also on authenticity and trustworthiness.

In the following section the rationale of the forthcoming studies, the methodologies used and the interpretation of results are summarised. The detailed methodologies of the individual studies are further introduced and presented in greater depth in the subsequent chapters.

1.4.2 Individual study methodologies

The statistical analysis of incidents that occurred between 2004 and 2006 in England and Wales aimed to inductively explore the root causes, effects and the impacts of incidents on drinking water customers. The methodological approach in this study is similar to a study carried out by the Health and Safety Executive (2000) with a view to learn from failure. It considers human and organisational factors, technology as factors in incident propagation (Johnson, 2003). The structured analysis was facilitated by incident data provided by the Drinking Water Inspectorate (Drinking Water Inspectorate, 2005b; Drinking Water Inspectorate, 2006; Drinking Water Inspectorate, 2007) and represents a form of historical research. The study used a number of models to conceptualize and code the unfolding of the individual incidents. The models include

- a Hazard Analysis and Critical Control Points (HACCP) study from catchment to tap (Hrudey and Hrudey, 2004),
- the study of failure modes and an analysis of their effects (FMEA) (Strutt, 2004)',
- an asset systems model that investigates the asset types (*e.g.* physical, information and human assets) (British Standard Institution, 2003) involved during an incident, and
- a model to assess the incident impact on customers.

The latter model uses a methodology described in Deere *et al.* (2001) and was used to derive a comparative measure for incident impacts. The impact on customers was measured as an incident impact score consisting of individual scores for

- the hazard type,
- the affected population, and
- the duration of hazard exposure.

This is conceptualised in Figure 9.

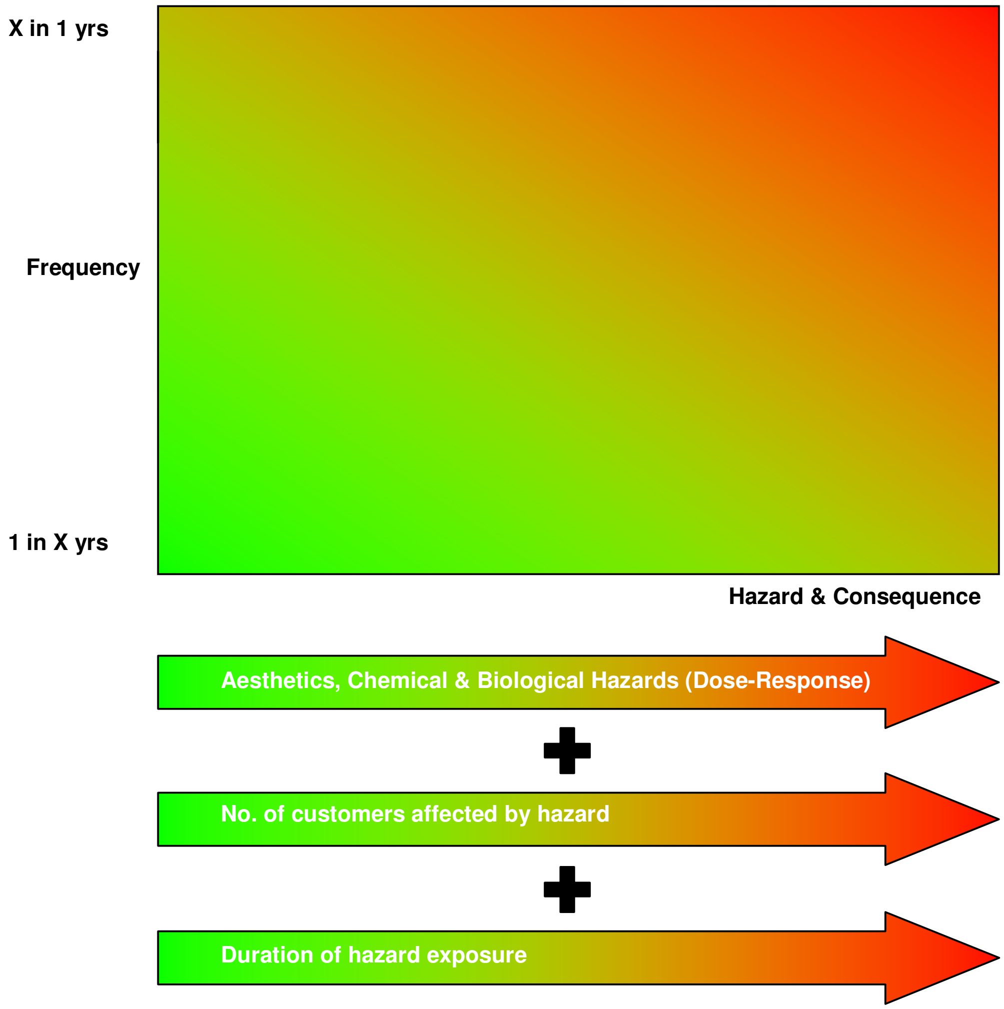

Figure 9 The risk assessment matrix (adapted from (Deere *et al.*, 2001))

Beyond the derivation of individual incident scores, the frequency of incidents with identical hazard types was derived and the average incident impact for those hazard types calculated.

Quantitative analysis is used to compare incident impacts for subsequent years but also to investigate the frequency and impact of incidents relating to specific hazard types. The methodology adapted from Deere *et al.* (2001) is further used in subsequent studies.

The statistical analysis of incidents that occurred between 1997 and 2006 in the Regional Water Utility explores the causes and effects of incidents and their impact on drinking water customers. This historical research was facilitated by an analysis and coding of detailed documentations of incidents. They consisted of incident reports, incident logbooks and personal accounts of staff involved during the incident as well as

- narrative summaries of incidents,
- narrative descriptions of cause for the incidents,
- description of the effect on customers,
- review of the timeline log of events,
- issues arising and further data/investigation required,
- an analysis of what went well and what could be improved during the management of incidents,
- narrative descriptions of lessons learnt and recommendations to senior management, and
- immediate actions arising after the incident.

The level of detail in the incident documentation enabled a thorough analysis of incidents that are subsequently coded using the conceptual models and methodologies previously introduced. The use of primary data significantly improved the quality and robustness of research results. The results of the incident analyses were subsequently used in studies relating to the management of incidents but also in the studies relating to 'learning from failure' with a view to enhance risk assessments.

The statistical analysis was further enhanced by semi-structured interviews with staff who were recently involved in the management of incidents and specialists for specific asset types. The interviews were primarily conducted to understand "*meanings, beliefs and experience*" (Wisker, 2001) but were not used for subsequent coding or quantitative analysis. These interviews were conducted during a 6-month research placement in the Regional Water Utility.

The next two studies investigated 'organisational reliability' in the context of water utilities. For this purpose, an HRO framework specific for water utilities was conceptualised. The framework was developed by deductively setting HRO principles into the context of water utility management with a particular emphasis on contributing to the provision of safe and reliable drinking water. The HRO framework was previously introduced in the literature review and presented in (Bradshaw *et al.*, 2006).

A survey tool (Appendix 4.3.1) was planned and a survey executed that explored HRO principles amongst a selected group of participants - all senior managers - from water utilities in the UK, the USA and Canada. The survey was sent to the participants to identify HRO principles within their own water utilities. In addition, the survey required the participants to evaluate their benefit and the cost of implementing and maintaining those principles. The survey was designed to enable a quantitative analysis using a numerical code or metric (HRO metric) that enabled subsequent statistical analysis. The emphasis of the statistical analysis concentrated on those HRO principles that were regarded to be cost beneficial for the provision of safe and reliable drinking water. Furthermore, it calculated an HRO score for the participating water utilities. This survey was repeated with participants from the Regional Water Utility and a significance test compared both samples.

In the literature it was argued that HROs operate effectively "*under trying conditions*" (Weick, 1987) and a need was identified to identify and validate the presence and effectiveness of high reliability principles to maintain a resilient water supply system during the management of incidents. For this purpose, the HRO framework was specifically adapted to incident management situations (Appendix 4.3.2) and used for a series of structured observational studies in the operational control centre and in the field during the unfolding of incidents. For this study, the author also had access to standard operating procedures, policies, planning and implementation documents for incident, operations and asset management.

The adapted HRO framework (Appendix 4.3.2) was also used in a review of detailed incident documentations described above. The review sought to find evidence of HRO principles in the documentation of incidents. For each investigated incident an HRO score was calculated using the above scoring system. To establish the significance of HRO principles in incident management, two extreme datasets were required, *i.e.* incidents with a significantly low impact on customers and incidents with a significantly large impact. The HRO scores were subsequently correlated with the incident impact score derived in a previous study. The review of past incidents also attributed HRO principles to effective incident impact reduction. Here, it was necessary to estimate the

potential incident impact had the incident management team failed to reduce the incident impact. Again, the documented adherence to HRO principles was correlated to incident impact reduction attributable to HRO principles.
In a series of interviews with staff who were recently involved in the management of incidents, the specific aspects relating to 'learning from failure' with a particular view to enhance risk assessment processes were explored. Again, these interviews were primarily conducted to understand "*meanings, beliefs and experience*" (Wisker, 2001) but were not used for subsequent coding or quantitative analysis.

The next two studies investigated the management of technical reliability via risk-based asset management in the context of water utilities. In a theoretical development, it was identified that the trade-off between assets and risk, *i.e.* the substitution of public health risk with assets that reduce risk, are optimally derived in cost benefit analyses. Here, benefit arises through risk reduction whilst cost denotes the capital and operational expenditures to design, operate and maintain assets. The theoretical/mathematical derivation of this equilibrium was previously introduced in Appendix 1.
In the first study that consisted of a series of semi-structured interviews the understanding, practice and experience in using risk assessments for asset management decision making were explored. A number of participants from a range of water utilities in the UK, the USA and Canada were invited to partake. The interview schedule was designed with a view to understand risk-based asset management and the need for learning strategies from incidents to enhance risk assessments (Appendix 4.3.3).
In the following study, opportunities in the Regional Water Utility to enhance risk assessments by 'learning from failure' were investigated. It was previously argued that a water utility is a low clock speed organisation (Fine, 1998) in which learning opportunities from incidents arise to predict or validate risk assessments for future risks. In a series of data analyses, the accuracy and consistency of risk assessments was investigated. Previously analysed incident data were used as a baseline to evaluate risk assessments that are currently filed in the Asset Risk Database and used for risk-based decision-making. In this study, it was aimed to compare the perceived and explicitly assessed risks with the occurrence of incidents as a proxy for actual risk. The discrepancy between perceived and actual risk is sought to demonstrate that risk

perceptions by risk assessors can significantly vary. This was previously introduced and explained with the psychological and sociological construction of risk as opposed to economic-rationality of risk.

In further action research studies, opportunities to enhance the risk assessment process were sought. The study used document reviews, observation of the asset decision-making processes, case studies, interviews and experiments.

Finally, in the theoretical development of trade-off's between assets and risk it was identified that optimal investments in assets are a function of the 'price' of risk. In the following two studies, the 'price' of risk was investigated a) from a financial perspective and b) from a customer 'willingness to pay' perspective.

The first study investigated the financial evaluation of risk for stock market-listed water utilities in England and Wales. It used publicly available financial data to calculate the asset beta for water utilities. Asset beta is a measure for the volatility in cash flows, which represents business risk. The asset beta or business risk is compared to the incidents that affect drinking water customers.

In the second study, the monetary benefit of risk reduction is investigated from a customer perspective. In a series of surveys, the Regional Water Utility investigated the 'willingness to pay' of customers to reduce the occurrence of future incidents, *i.e.* risks. In a series of case studies, the monetary benefit of risk reduction to customers is compared with the capital and operational expenditures required to reduce particular risk.

1.4.3 Study validation and verification

The project execution for this thesis used a number of strategies to validate and verify the research scope, methodologies and results.

This project commenced in October 2004 with a literature review to scope out the research question and hypothesis. In parallel to studying mandatory taught modules at Cranfield University's School of Management between January 2005 and January 2006, a preliminary research scope was prepared and presented as a poster at a conference on 'Risk analysis strategies for better and more credible decision making' (AWWARF RFP 2939) in Banff, Canada, April 2005. This poster presented early ideas of risk –

asset trade-off's in the context of managing public health risks and water safety (Bradshaw, 2005). At this conference, the research scope was further defined in discussions and formal meetings with water utility professionals, academics and the Project Advisory Committee of the American Water Works Association Research Foundation.

In mid 2005, the first pilot studies commenced, in particular relating to the analysis of incidents.

In April 2006, the author's research scope was presented at a project initiation workshop ('Developing a risk management culture – 'mindfulness' in the international water utility sector' (AWWARF Project 3184)) in London. A number of academics, water utility professionals and the AWWARF Project Advisory Committee were present to peer review the project scope and execution plan. Feedback from the peer review group was evaluated and endorsed in the project execution plan.

In December 2006, the author presented a literature review and the revised project scope in a formal conference paper (Bradshaw *et al.*, 2006) to an audience of water utility professionals and academics at a conference on 'Risk management culture'. The subsequent discussion provided valuable feedback that was incorporated in the research execution plan. In a subsequent project meeting with the AWWARF Project Advisory Committee, the project execution plan was again presented and research progress discussed with the committee.

In December 2007, a formal review meeting was organised with the AWWARF Project Advisory Committee to present the author's preliminary findings.

In January 2008, the author commenced writing his contribution to the final AWWARF Project Report (Pollard *et al.*, 2008), which was subsequently peer reviewed by academics, water utility professionals and the AWWARF Project Advisory Committee. At this time, the author was also invited to present his research findings at an EPSRC sponsored workshop under the title "IDEAS Factory: Scientific uncertainty and decision making; Project title: Rethinking Human Reliability Analysis Methodologies (EP/E017800/1)". The presentation was followed by a discussion and critical analysis by six independent academics from various disciplines and an invited water utility professional.

In April 2008, the author was invited to present his research findings at an international conference on 'Water Contamination Emergencies: collective responsibilities' at The Royal Society of Medicine, London. Here, the author presented his research findings and obtained valuable peer review critique for further consideration in this thesis (Bradshaw *et al.*, 2008).

Throughout the 4-year research programme, regular meetings with academic supervisors provided a peer review mechanism and critical challenges to the proposed scope, methodology and research data analysis.

Furthermore, the research results were presented to staff in the Regional Water Utility.

2 Characterising incidents in the water sector

2.1 Introduction

The WHO states that "*most drinking water supply systems are characterised by long periods of steady state performance, and short periods of 'stress'*" (World Health Organisation, 2004). They are the incidents that affect customers relating to the safety of their drinking water and supply reliability.

For this study historical incident data from the Regional Water Utility between 1997 and 2006 as well as publicly available incident data reported to the Drinking Water Inspectorate (Drinking Water Inspectorate, 2005b; Drinking Water Inspectorate, 2006; Drinking Water Inspectorate, 2007) for England and Wales between 2004 and 2006 were coded and analysed. The objective of this study is to characterise "*the short periods of stress*" (World Health Organisation, 2004) with a view to identify

- the incident occurrence in a catchment to tap model;
- the incident occurrence in the asset life cycle model;
- cause and effect relationships for incidents; and
- frequencies and impact of failure.

This detailed analysis of incidents constitutes the foundation to investigate incident management capabilities in water utilities and to argue for a competent approach to incident management that is capable to manage unforeseen and complex incident scenarios with a view to minimise the impact on customers. It also aims to demonstrate the learning opportunities from previously experienced incidents to enhance the process of identifying and assessing risks.

2.2 Theoretical development

Regulated water companies in England and Wales have procedures in place to report water quality and supply reliability related incidents to the Drinking Water Inspectorate (DWI). The procedure of investigating incidents and their reporting to the DWI is outlined in the Water Undertakers (Information) Direction 2004 (Department for Environment, 2004) and Guidance on the Notification of events (Drinking Water

Inspectorate, 2004). In practice, water utilities are required to document, analyse and report incidents. Since 2004, the reported incident narratives are publicly available (Drinking Water Inspectorate, 2005b; Drinking Water Inspectorate, 2006; Drinking Water Inspectorate, 2007).

The rich body of incident data available in the Regional Water Utility and the incident data published by the DWI were analysed to identify the frequency, cause and effect relationships and their impacts on customers.

Incidents were investigated according to the asset type that failed using a catchment to tap model during the incident and its life cycle. The catchment to tap model consisted of

- catchments including boreholes and river abstraction points;
- water treatment works;
- service reservoir;
- distribution system; and
- customer installations.

In that context, the asset life cycle phases were identified during which the incident occurred. The typical asset life cycle for a physical asset usually commences with its conceptualisation followed by design, construction, commissioning, operation, maintenance and finally de-commissioning. For this analysis, the following categories were used:

- asset design;
- asset construction;
- asset operation; and
- asset maintenance.

Incidents in the category ‘design’ denote a failure to design or upgrade sections of an existing supply system to be fit for purpose. A failure in design suggests that the supply system was not built fit for purpose or the design was outdated to provide safe and reliable drinking water. Incidents in the category ‘operation’ denote a failure to operate sections of a fit for purpose water supply system. A failure in operations suggests that a human intervention based on inadequate information (monitoring and control), training, instruction (*e.g.* work procedures) or supervision through management was the root cause to an incident and, *e.g.*, may relate to the erroneous opening or closing of valves on a distribution water main. Incidents in the category 'maintenance' denote a failure to maintain the fitness for purpose of sections of the water supply system. A failure to maintain water supply assets suggests inadequate re-investment into technically depreciating water supply system. This section also accounts for all physical asset failures which are designed to 'run to failure' and incidents caused by maintenance activity on assets.

Failure Mode and Effect Analysis was used as a methodology to characterise the multiple, contributing causes for individual incidents and the multiple effects an incident can have.

Based on the methodology advanced by Deere *et al.* (2001), a comparative measure of failure impacts was derived that takes into account the hazard type, the affected population and the duration of hazard exposure. It used these key parameters to construct a comparative metric for public health impacts from incidents. This impact assessment model provided a methodology to calculate a comparative incident score. In Table 1, the scores for each parameter 'hazard type', the 'duration of hazard exposure' and the 'size of affected population' are defined. Definitions for the hazard categories are found in Table 2.

The hazard scores adopted for this project are predominantly based on weighting factors proposed in the literature (Deere *et al.*, 2001) but a number of modifications had to be considered. The hazard scores for 'aesthetics' and 'discolouration' of drinking water were reviewed and amended with a view to re-evaluate their potential health impact. According to Tam *et al.* (2005) *"there is some evidence that increases in turbidity of final water are associated with subsequent increases in the incidence of acute gastrointestinal illness"*, in particular due to resuspended deposits in drinking water mains (Korth *et al.*, 2008). A hazard category for 'loss of supply' was introduced. Although 'loss of supply' does not constitute a health hazard but rather a supply reliability issue, it was reasoned that 'loss of supply' coincides with the de-pressurisation of distribution networks and potential for contaminant ingress from groundwater, surface water and leaking sewers (Emde *et al.*, 2006; Korth *et al.*, 2008). A further adaptation was introduced for the potential presence of hazards: In the review of the incident records it was found that a significant number of incidents were presumed hazard exposures but the actual presence of hazards was not confirmed or reported. Consequently, the hazard scores were adapted to represent 75% of an actual hazard presence reflecting the uncertainty of hazard exposure.

Estimate frequency of hazard	**Estimate magnitude of hazard**		**Estimate duration of hazard**		**Estimate no. of customers affected by hazard**	
Score (F) [1]	Hazard type	Score (H)	Duration in days	Score (D)	Customers	Score (P)
1 in X yrs	Aesthetics above guidelines	32	< 0.5	2	0 – 7,500	2
	Unwholesome, potential health effects	48	0.5 – 1	4	7,500 – 15,000	4
	Chemicals present above guidelines	8	1 – 2	8	15,000 – 30,000	8
	Chemicals present above guidelines, health effects envisaged	32	2 – 4	16	30,000 – 60,000	16
	Potential biological pathogens present	6	4 – 8	32	60,000– 120,000	32
	Potential biological pathogens present, health effects envisaged	48	8 – 16	64	120,000– 250,000	64
	Biological pathogens present	8	16 – 32	125	250,000 – 500,000	125
	Biological pathogens present, health effects envisaged	64	32 – 64	250	500,000 – 1,000,000	250
	Loss of supply, potential contaminant ingress	16	64 – 128	500	> 1,000,000	500
X in 1 yr			> 128	1000		
[1] X represents a variable > 1; e.g. X = 50: 1 in 50 years and 50 in 1 year						

Table 1 Coding the impact of incident, after (Deere *et al.*, 2001)

Primary incident effect	Definition
Interruption to supply	Temporary loss of water supply to customers (including low pressure for surrounding areas)
Discolouration	Aesthetic problems with the drinking water to due high colour, turbidity
Potential biological pathogens present	Potential for biological pathogens present in the drinking water for customers on which procedures were instigated to avoid customers from drinking supplied water (Precautionary principle). The presence of pathogens, in hindsight, was neither confirmed or rejected
Chemicals present above guidelines	Exceedance of water quality parameters specified in drinking water quality regulations
Biological pathogens present, health effects envisaged	Confirmed presence of pathogens in drinking water supply. Health effects were envisaged and a “do not drink notice” or “boil notice” was issued to affected customers
Potential biological pathogens present, health effects envisaged	Potential for biological pathogens present in the drinking water for customers on which procedures were instigated to avoid customers from drinking supplied water (Precautionary principle). Health effects were envisaged and a “do not drink notice” or “boil notice” was issued to affected customers
Biological pathogens present	Confirmed presence of pathogens in drinking water supply. No health effects were envisaged and no “do not drink notice” or “boil notice” was issued to affected customers
Aesthetics above guidelines	Aesthetic problems with the drinking water to due taste and/or odour
Chemicals present above guidelines, health effects envisaged	Exceedance of water quality parameters specified in drinking water quality regulations with anticipated short, medium or long-term effects for customer health
low pressure	Low pressure in the distribution network

Table 2 Hazard definitions

The representation of public health impact for individual incidents used the following equation to provide an impact score

$$I = P + D + H$$

with

I = Incident impact score

P = Population impact score

D = Duration impact score

H = Hazard impact score

Equation 1 Public health impact

The annual score for public health impacts was calculated with

$$I_{yr} = \sum (P + D + H)$$

Equation 2 Annual public health impact

Equation 2 can be used to compare the annual impact of incidents on a year-to-year basis.

Based on the definition of a hazard type, incidents can be grouped together to calculate the annual frequency of a particular hazard type to result in an incident. This is shown in Equation 3. Since every incident has its own characteristic impact profile in terms of duration and affected population, an average impact for groups of incidents with identical hazard types was calculated. For each hazard type, the frequency of occurrence and the average impact on customers are expressed with

$$R_{H,yr} = F_H * \frac{\sum(P+D+H)}{n/yr}$$

with

$R_{H,yr}$ = Frequency*Impact of incidents for specific hazard types per year

$F_H = n/yr$

F_H = Frequency of occurrence for specific hazard type

n = number of incidents

yr = year

Equation 3 Annual public health impact for specific hazard types

The incident profile at national or regional level for all incidents per time period is a function of

$$R_{Total,yr} = \sum(F_H * \frac{\sum(P+D+H)}{n/yr})$$

Equation 4 Annual public health impact profile for all incidents grouped according to hazard types

This theoretical development enables a comparative study of individual incidents but also groups of incidents in specific hazard categories. It also enabled a comparative analysis of incidents in one water utility with incidents at national level. For this purpose, the scale of a water utility operation had to be taken into account with a common denominator or baseline. Therefore, the national public health impact profile from incidents can be calculated per capita.

$$R_{Total/TP,yr} = \frac{\sum(F_H * \frac{\sum(P+D+H)}{n/yr})}{TP}$$

with

TP = total population

Equation 5 Standardised incident impact profile per capita

or

$$R_{Total/TP,yr} = \frac{\sum F_H}{TP} * \frac{\sum(P+D+H)}{n/yr}$$

Equation 6 Standardised incident impact profile per capita

From a water utility perspective, the average impact of incidents at national level can be expressed as a water company specific public health impact by scaling national incident impacts to regional level.

$$R_{Total/TP*WCP,yr} = \frac{\sum F_H}{TP} * WCP * \frac{\sum(P+D+H)}{n/yr}$$

with

WCP = population served by the water company

Equation 7 Public health impact profile adjusted to size of a water utility operation

Equation 7 enables a comparative assessment of reported incident impacts at regional level, *i.e.* water utility level, with the national average incident impact per hazard category. Furthermore, it enables the assessment of actual (reported and unreported) incident impacts with the national average incident impacts. The methodology for this analysis is further described in the section below. At first, the methodology outlines the analysis of incidents that were reported to the DWI between 2004 and 2006. The second section describes the methodological approach to investigating incidents in the Regional Water Utility.

2.3 Methodology

For this chapter it was decided to conduct a form of historical research to inductively observe patterns in historical data that allows further generalisation and theory building. The qualitative data contained in historic documents uses language, description and expression and provides highly animated, rich and deep information (Trochim, 2000).
The coding of language provides the facility to identify patterns in the data and it was decided to use selective coding of language based on pre-conceived models and concepts introduced in Chapter 1.4 'Outline methodology'. The methodological approach for these studies were considered to be superior to any other form of research methodology and data analysis: firstly, the use of historical data is perceived to reflect the truth of what was known at the time and removes any attempt to revise knowledge with hindsight ideas or concepts. Secondly, the selective coding of language found in the incident documentations avoided unnecessary open coding of language and enabled the use of well established ideas and concepts to be used to categorise data. Considering the volume of data records used in this research element, selective coding provided the highest benefit in the context of time required to code incidents.
In addition to the historical research, semi-structured interviews were conducted with staff who were recently involved in incidents. This represents a form of triangulation to the historical research and presents a form of phenomenology as a method of trying to understand how an individual perceives and constructs their reality (Robson, 2002). Although this form of research provides highly detailed data based on highly personalised and subjective experiences it was thought that the content analysis based on semi-structured interviews provides rich and detailed data with expressive and enlightening information (Wengraf, 2001) on how staff experience and make sense of incidents despite the lack of standardisation in its results. A further advantage over structured interviews is the ability to react to emergent topics that are raised by the interviewee (Robson, 2002). The results of the content analysis arising from the semi-

structured interviews were grouped in themes and used in the presentation of the results to construct a coherent argument in this chapter.

2.3.1 Incidents in England and Wales between 2004 and 2006

In this section, two methodologies for analyses are presented. Firstly, an analysis of the asset types that failed and caused an incident and, secondly, the impact these asset failures had on customers.

The first analysis was limited to a dataset of incidents that occurred in England and Wales for the year 2005. At the time of commencing this study, data for the year 2006 was not yet available, since the incident reports are made public ca. 7 months after the end of the year. Furthermore, the 2004 data provided little reliable information on specific assets types that failed and caused an incident. As a result, the asset types and the asset life cycle phase were identified for incidents that occurred and were reported in 2005 for England and Wales. In total, 92 reported incidents were studied and analysed. Following a thorough examination of the incident narratives, each incident was coded and classified in a matrix as the most probable asset type and asset life cycle phase that caused the incident. For this purpose, a methodology of subsequently eliminating matrix fields that were unlikely to pinpoint the incident in the matrix was employed. The process is based on eliminating those matrix fields with the lowest probability of being related to the incident until only one matrix field is identified to be the most probable. Where the elimination process was inconclusive and different matrix fields had equal probability to constitute the most probable source of the incident, two or more asset types – asset life cycle phases were listed in the matrix. From the analysis of all incidents in 2005, a matrix distribution was obtained that provides and overview for the types of assets that fail and their asset life cycle phase. In an application of Chi Square testing the matrix is tested for randomness of the data distribution. A comparison between observed incident data and expected data identifies asset types and asset life cycle phases that follow non-random patterns.

The incident impact on customers for incidents that occurred between 2004 and 2006 in England and Wales was further investigated in the following analysis. In this analysis, incident data that were reported to the DWI for the three consecutive years 2004, 2005 and 2006 were analysed. In principle, qualitative, narrative data were converted into semi-quantitative data to enable statistical analyses of hazard types, the size of the affected population and the duration of hazard exposure. For each incident, an incident impact factor was calculated using the theoretical development described above. In total, 279 narrative incident reports were coded and statistically analysed to identify trends in the frequency and impact of these incidents but also trends for the duration of hazard exposures and the population sizes exposed to hazards.

2.3.1.1 Data quality

The data used in this study is limited to the data provided to the public by the Drinking Water Inspectorate (2005b; 2006; 2007) and represents tertiary data. In narrative form, the incidents were described by the DWI to reflect the severity of incidents and the impact the incident had on drinking water customers.

The interpretation of the data analyses requires some caution: After an incident, the water utility will have commissioned an incident investigation. An incident investigator would evaluate the causes, effects and impacts of the incident using his/her expertise and heuristic models to interpret the incident. This process is guided by the Water Undertakers (Information) Direction (2004) and Guidance on the Notification of events (Drinking Water Inspectorate, 2004). An incident report, that summarises the findings, will be sent to the regulator who further evaluates the findings and publishes a short description of the incidents in the annual reports on drinking water quality (Drinking Water Inspectorate, 2005b; Drinking Water Inspectorate, 2006; Drinking Water Inspectorate, 2007). The summary of these incident reports, too, reflect an interpretation of the Drinking Water Inspectorate who use their expertise and heuristic models to communicate the incident to the public. The author, in turn, used the incident summaries to assess incident causes, effects and impacts based on pre-filtered data.

The merit of this study was primarily designed as a trial of the above theoretical developments, methodologies and models for the subsequent detailed incident analysis in the Regional Water Utility.

2.3.2 Incidents in the Regional Water Utility between 1997 and 2006

The Regional Water Utility maintains a database of all its incidents and significant incident data recorded between 1997 and 2006. These detailed, narrative descriptions of cause and effect relationships, failed asset type, population affected, the duration of the incident and the procedures adopted to manage the incident enabled a thorough, structured incident analysis.

In the first study, all of the 419 documented incidents were coded to identify the primary cause and the primary effect of the incident. In the assessment of primary incident causes and primary incident effects a number of categories have been inductively identified which best characterise and code the circumstances on an incident. These categories are presented in Table 3 and Table 4. Although most of these categories are self-explanatory, the tables provide definitions for the cause and effect categories.

Primary incident cause	**Description**
Burst main	Failure of a water main or trunk main
Information Technology failure	Failure of information technology or systems required to operate assets or business processes (*e.g.* computer networks, software programs)
Maintenance work	Maintenance work at or near a water supply systems asset which subsequently caused the asset to fail in providing safe and reliable drinking water supply
Asset failure	Asset failure denotes any asset, equipment or component failure for asset which are not elsewhere specified (*e.g.* as burst main or chlorination asset failure)
Power failure	Power failure denotes failure in the power supply from external suppliers or generates on site of the water utility (*e.g.* uninterruptable power supply)
Operational intervention	Planned or unplanned intervention in the water supply system causing an incident (*e.g.* a valving operation in the distribution network resulting in a discolouration incident)
3rd party	3^{rd} party impact on water utility assets (*e.g.* accidental damage or unauthorised use of hydrants)
Chlorination failure	Failure to maintain uninterrupted chlorination of drinking water due to asset failure specific to chlorination assets, equipment or components
Asset contamination	Ingress of contaminants into water supply system asset *e.g.* ingress of groundwater or sewage in depressurised water mains
Treatment failure	Treatment process failure due to inadequate treatment process design, raw water quality parameters outside the designed boundaries for treatment processes or treatment process asset failures
Raw water quality	Raw water quality outside the specified boundaries for designed assets
Asset damage	Damage to assets due to any circumstances other than 3^{rd} party
Monitoring and Control failure	Failure of monitoring and control assets, equipment or component specific to monitoring and control of water supply assets (instruments, PLC, SCADA)
Severe weather	Unprecedented and unforeseen, extreme weather conditions such as 1 in 50 year flood events
High Demand	Exceptionally high demand for drinking water *e.g.* due to high temperatures
Security	Security breaches and intrusion on utility sites for the purpose of theft or sabotage
Adverse weather	Poor but not extreme weather conditions
Chemical spillage	Chemical spillage due to accidental release or unauthorised discharge of chemicals into or near the water supply system (*e.g.* in the catchment or service reservoir)
Chemical supply contamination	Contamination of chemicals used in treatment processes
Design failure	Conceptual error or failure of an asset which originated in the design phase of the asset
Illegal connection	Illegal connection onto the distribution network
Telemetry failure	Failure of a telemetry system which is used to transfer signals for monitoring and control of water supply assets to a control centre
Water quality	Water quality failure due to unknown circumstances not related to the treatment process or raw water quality

Table 3 Primary incident causes

Primary incident effect	
Interruption to supply	Temporary loss of water supply to customers (including low pressure for surrounding areas)
Discolouration	Aesthetic problems with the drinking water to due high colour
loss of Monitoring and Control	Loss of the ability to monitor and/or control assets without immediate or direct effect on customers
Potential biological pathogens present	Potential for biological pathogens present in the drinking water for customers on which procedures were instigated to avoid customers from drinking supplied water (Precautionary principle). The presence of pathogens, in hindsight, was neither confirmed or rejected
Chemicals present above guidelines	Exceedance of water quality parameters specified in drinking water quality regulations
Biological pathogens present, health effects envisaged	Confirmed presence of pathogens in drinking water supply. Health effects were envisaged and a "do not drink notice" or "boil notice" was issued to affected customers
Potential biological pathogens present, health effects envisaged	Potential for biological pathogens present in the drinking water for customers on which procedures were instigated to avoid customers from drinking supplied water (Precautionary principle). Health effects were envisaged and a "do not drink notice" or "boil notice" was issued to affected customers
Biological pathogens present	Confirmed presence of pathogens in drinking water supply. No health effects were envisaged and no "do not drink notice" or "boil notice" was issued to affected customers
Empty Service Reservoir	Operational failure resulting in empty reservoir with having no immediate impact on customers
Loss of asset	Long-term outage of asset due to failure. Asset write-off.
Damage to asset	Damage to assets owned by water utility as a result of an type of incident cause
3rd party impact (Gas)	Ingress of drinking water into gas distribution assets owned by the gas company. Incident due to burst main or leakage
Aesthetics above guidelines	Aesthetic problems with the drinking water to due taste and/or odour
Environmental	Environmental pollution
Chemicals present above guidelines, health effects envisaged	Exceedance of water quality parameters specified in drinking water quality regulations with anticipated short, medium or long-term effects for customer health
low pressure	Low pressure in the distribution network
3rd part damage	Damage to assets owned by 3rd parties
Disruption To Normal Processing Of Work	Disruption of business processes not treatment processes
Risk of cross contamination	Risk of cross contamination from other assets *e.g.* wastewater cross connection to distribution network
3rd party accident	Accident of a member of the public or other 3rd party
Human safety	Safety of operator, 3rd party is jeopardised
Statutory monitoring failure	Failure in the requirement to provide a statutory sample
Supply of unchlorinated water	Confirmed supply of unchlorinated water to customers
Treatment failure	Treatment process failure without immediate impact on public health objectives for customers

Table 4 Primary incident effects

In a subsequent study, a comprehensive assessment of incidents not only considered the primary causes and effects of incidents but also multiple causes and contributing factors as well as the multiple effects of individual incidents. This analysis focused on incidents between 2004 and 2006. The incident analysis was facilitated by an inductively developed, comprehensive incident assessment tool that enabled the structured coding of incidents. It identified

- asset type;
- asset phase;
- asset and process failures;
- cause and effect relationships during the incident;
- duty standby arrangements for the failed assets;
- intermediate asset between the failed asset and customers;
- the way the incident was notified; and
- human factors that may have contributed as a cause to the incident.

With a view to the subsequent thesis chapter on incident management, the comprehensive incident analysis tool was also used to investigate the prevailing organisational ‘culture’ in the organisation during the management of the incident. In particular, it investigated

- the effectiveness of communication;
- the organisational ability to adapt its structure to the incident management needs;
- the adaptability and flexibility in decision making; and
- the use of redundancy during the incident.

Furthermore, it investigated whether a risk assessment had been previously devised to forecast such an incident. Here, the experienced incidents were compared to risk assessment data stored on the corporate risk database. The template for structured incident analysis is presented in Appendix 3.3.1.

Following the analysis of incident causes and effects, the impacts of incidents on customers were investigated. In this analysis, the incident data for the years 1997 to 2006 were analysed. Based on the previously introduced theoretical development and methodology, the 419 incident were considered for coding. Of these, 95 incidents had no customer impact and were excluded from the study. As a result, 324 incidents were coded and statistically analysed. In a significance test, the frequency and impact of incidents in the Regional Water Utility were compared to the previously analysed incidents in England and Wales. Furthermore, all incidents experienced by the Regional Water Utility are compared to the incidents they reported to the DWI.

In a series of semi-structured interviews with staff who were recently involved in the management of incidents, a number of questions related to the causes, effects and impacts of incidents. The interviews were primarily conducted to understand "*meanings, beliefs and experience"* (Wisker, 2001) but were not used for subsequent coding or quantitative analysis. Where appropriate, extracts of interviews are presented in the body of text. The interview questionnaire is presented in Appendix 4.3.4.

2.3.2.1 Data quality

The main source of data in this study originates from the Regional Water Utility who provided access to a vast repository of documented incidents. The predominant source of data used in this study is historical data and personal accounts of staff involved in recent incidents. In most cases, incident files describing individual incidents contained lengthy logbook entries, detailed incident review minutes, personal communications of staff involved during the incidents, maps and raw data from monitoring and control equipment (*e.g.* SCADA printouts). From a practical perspective, the structured analysis of data consisted of building a number of databases to code, analyse and statistically process the data.

The quality of the incident data analysis depends on the reference models used to acquire and process data. In the literature review and the theoretical development of this chapter a number of models were introduced that facilitated the assessment of incidents. The information and knowledge derived from the analyses were presented to the peer review group for review. The verification and validation process aimed to ensure that the models used to code the data were relevant and applicable to the set research question and to verify the results.

One important aspect in evaluating research results was the awareness that the outcomes of this data analysis also depended on the reference models used by the incident investigator to derive primary incident data. A risk was identified that the data acquisition and collection process within the water utility is subject to cultural bias (Macgillivray, 2008). The models used to analyse incidents may represent heuristic simplifications of complex circumstances that represent a simplified or limited version of a complex reality. Furthermore, according to Denzin and Lincoln (1994), documentation can be highly biased due to the views the authors may had at the time recording data. This is particularly relevant in light of the regulatory requirements to report incidents and it is important to understand the motivation of the authors. On the one hand, a systematic bias may motivate authors to 'misrepresent factual data'; on the other hand, a strong desire may exist to learn from failure driven by a code of professional conduct. At this stage, the quality of data cannot be fully evaluated before understanding the organisational culture and attitudes towards learning from failures and incidents. So far, the organisation provided unrestricted access to historical incident data with a motivation to further learn from documented failures. The subsequent chapters return to evaluate the quality of incident data.

2.4 Results and Discussion of Results

2.4.1 Incidents in England and Wales between 2004 and 2006

The primary purpose of the following analysis was to understand where (asset type) and when (asset life cycle phase) incidents occur. On analysis of the incident narrative, the main cause for the incident was pinned to an (asset) failure in the broad categories 'catchment', 'water treatment works', 'service reservoir' and 'distribution system'. Furthermore, the appropriate asset management phase from 'design', 'operation' and 'maintenance' was identified to which the individual incident causes was attributed. Both models can be presented in a matrix form to record the asset type and life cycle of the asset at which the incident occurred.

In Table 5 the catchment to tap – asset life cycle matrix for the analysed incidents is presented. A total of 159 incident causes were recorded for the 92 incident narratives. The deviation in numbers arises mainly from multiple factors contributing during an incident but also ambiguity in the short incident reports to precisely pinpoint the incident to a specific matrix field.

	Catchment	WTW	SR	Distribution	Sum
Design	6	18	8	3	**35**
Operations	6	19	11	22	**58**
Maintenance	0	10	6	50	**66**
Sum	**12**	**47**	**25**	**75**	**159**

Table 5 Incident classification in catchment to tap - asset life cycle matrix for incident in England and Wales in year 2005

In Table 5 a number of significant observations can be made. First, the results in a catchment to tap perspective are considered: Here, 47% of incidents arose in the distribution networks of the water utilities. This is followed by ca. 30% of incidents occurring at the water treatment capabilities in the water utilities, ca. 16% of incidents originating in service reservoirs and ca. 7% in the catchment.

From an asset life cycle perspective, the majority of incidents were attributed to asset maintenance. As per definition, the category ‘maintenance’ denotes a failure to maintain the fitness for purpose of sections of the water supply system but also accounts for all physical asset failures which are designed to “run to failure” and incidents caused by maintenance work. A total of 41% of incidents were attributed to this category. This is followed by ca. 36% of incidents as a result from failing to operate a water supply system that is otherwise fit for purpose. As per definition, a failure in operations may suggest that a human intervention based on inadequate information (monitoring and control), training, instruction (*e.g.* work procedures) or supervision through management was the root cause to a particular incident. Only 22% of incidents were attributed to the category ‘design’ which denotes a failure to design or upgrade sections of an existing supply system to be fit for purpose. A failure in design suggests that the supply system was not fit for purpose or the design outdated to provide safe and reliable drinking water.

Within the matrix, the largest number of recorded incident causes can be identified for distribution systems maintenance. Here, ca. 31% of incident causes were recorded. This originates primarily from water mains bursts that result in discolouration of the remaining water supply. Ca. 14% of incident causes were recorded as distribution systems operation. The majority of these incidents were caused by valving operations which re-suspended solids in the water mains but also impact from third parties *e.g.* during construction work. Ca. 23% of incidents were recorded for the design and operation of water treatment works. The majority of these relate to design and operation of chemical dosing equipment that was inadequate, *e.g.* non-fail safe, and loss of power supply causing water treatment problems.

Overall, it could be demonstrated that a high level of diversity in the occurrence of incidents prevails. Incidents occurred across the categories from catchment to tap as well as in all asset management life cycle phases and from this observation it can be concluded that water utilities require an incident management system that is capable to manage this diversity of incidents.

In the following analysis, it was aimed to identify common patterns in the distribution of incidents in the catchment to tap – asset life cycle matrix. It was hypothesised that incidents are randomly distributed across the matrix. For this purpose, the Chi square testing methodology was employed to calculate an expected distribution of incident occurrences in the matrix. A random distribution of incidents in the matrix based on the sums for the individual categories is presented in Table 6. The formal calculation and hypothesis testing is presented in Appendix 3.2.1.

	Catchment	**WTW**	**SR**	**Distribution**	**Sum**
Design	2.64	10.35	5.50	16.51	**35**
Operations	4.38	17.14	9.12	27.36	**58**
Maintenance	4.98	19.51	10.38	31.13	**66**
Sum	**12**	**47**	**25**	**75**	**159**

Table 6 Calculated, random distribution of incident occurrences in the asset type - asset life cycle matrix

The Chi square statistic is calculated from the sum of squared differences in each matrix field as $(\text{Observed-Expected})^2/\text{Expected}$. For each matrix field the Chi Square statistic is presented in Table 7.

	Catchment	WTW	SR	Distribution	Sum X_2
Design	4.27	5.66	1.13	11.05	
Operations	0.60	0.20	0.39	1.05	
Maintenance	4.98	4.64	1.85	11.44	
Sum	**9.85**	**10.50**	**3.37**	**23.54**	**47.26**

Table 7 Chi square statistic for incident occurrences in the asset type - asset life cycle matrix

The sum of the Chi square statistic is 47.26. The critical value for 6 degrees of freedom at a significance level SL = 0.05 is $X_2 = 12.59$. Since 47.26 > 12.59, the H0 hypothesis of a random distribution in the catchment to tap – asset life cycle matrix is rejected. Similarly, the critical value for 6 degrees of freedom at a significance level SL = 0.001 is $X_2 = 22.46$. Since 47.26 > 22.46, the H0 hypothesis of a random distribution in the catchment to tap – asset life cycle matrix is rejected. In scrutinising the Table 7 it can be identified that the largest deviation between observed and expected distribution arises for the distribution network. A significantly larger proportion of distribution maintenance issues can be observed than it would be expected assuming a random distribution of incident occurrences in the matrix. Similarly, a significantly smaller proportion of distribution design issues are observed than would be expected.

In the above analyses, valuable insights into the distribution of incidents occurrences for different asset types and their asset life cycle were gained. This analysis was aimed to understand the criticality and priorities for incident management efforts but also to direct risk assessments towards assets and asset management interventions (design, operation and maintenance) that are more likely to cause incidents.

In the following analysis, the impact of incidents on customers is presented by calculating incident impact factors based on hazard type, the size of the affected population and the duration of hazard exposure. Table 8 is a summary of the statistical analysis performed on the incident data that affected customers in England and Wales between 2004 and 2006. The detailed analysis is presented in Appendix 3.2.1.

In Table 8 the following trends can be identified for the years between 2004 and 2006:

- The number of incidents increased by 10% from 89 to 98.
- The average incident impact score increased by 59% from 21.59 to 34.40.

- The average duration of an incident increased from 80.15 hours to 579.82 hours.
- The average population affected during an incident increased by 17% from 38,372 to 44,871, although the number reduced to 36,072 in 2005.

	Duration in hrs	Population	P Score	H Score	D Score	I Score Incident impact on customers
Drinking Water Incidents 2004						
Number of incidents: 89						
Average	80.2	38372.1	15.3	30.2	20.6	21.6
SD	101.8	101868.4	39.0	17.3	23.4	15.5
SE	10.8	10798.0	4.1	1.8	2.5	1.6
CI 95 lower	59.0	17207.9	7.2	26.6	15.8	18.4
CI 95 upper	101.3	59536.2	23.4	33.8	25.5	24.8
Drinking Water Incidents 2005						
Number of incidents: 92						
Average	191.3	36072.0	14.2	30.0	51.0	31.5
SD	472.4	103239.8	32.8	16.9	131.7	47.6
SE	49.0	10705.5	3.4	1.8	13.7	4.9
CI 95 lower	95.3	15089.3	7.5	26.5	24.2	21.9
CI 95 upper	287.4	57054.7	20.9	33.4	77.7	41.2
Drinking Water incidents 2006						
Number of incidents: 98						
Average	579.8	44871.4	17.8	25.9	59.6	34.4
SD	3475.1	149689.4	55.1	17.0	183.2	63.3
SE	352.8	15198.7	5.6	1.7	18.6	6.4
CI 95 lower	-111.8	15082.1	6.8	22.5	23.2	21.8
CI 95 upper	1271.4	74660.8	28.8	29.3	96.1	47.0

Table 8 Statistics for drinking water incidents between 2004 and 2006 in England and Wales

Statistically, the mean time in days between an incident for England and Wales reduced from 4.6 days to 4.0 and 3.7 for the years 2004 to 2006, respectively. Considering the average duration of each incident of 3.3, 8.0 and 24.2 days for the respective years, it could be argued that every day parts of the population in England and Wales were affected by an incident impact from their water supply. Multiplying the number of incidents for the respective years with the average population affected concludes that, statistically, 3.41 million, 3.32 million and 4.39 million customers experienced the impact of incidents in those years. With an estimated population of 53.47 million drinking water customers in England and Wales, this represents ca. 8 % of customers for the year 2006.

Further statistical analysis is required to establish whether these trends are significant in comparison to previous years. In Table 9 the significance tests are presented that compare the incident statistics for incident duration, size of population and incident impact score for 2004, 2005 and 2006. According to this analysis, the trends do not represent a significant increase for the duration of the average incidents, the average affected population and the average incident impact score. The only significant difference arises in the duration score that suggests that the average incident in 2004 has a significantly shorter duration than in 2005. Similarly, the duration score for the average incident in 2004 is significantly lower than in 2006.

Significance testing						
	H0: X1 - X2 = 0			X1: 2004	SL: 5%	
	H1: X1 - X2 <>0			X2: 2005		
	Duration in hrs	**Population**	**P Score**	**H Score**	**D Score**	**Sum**
X1-X2	-111.2	2300.1	1.2	0.3	-30.4	-9.9
Var	2516.4	231204278.7	28.7	6.4	192.6	27.1
SE	50.2	15205.4	5.4	2.5	13.9	5.2
CI 95% (+/-)	98.3	29802.6	10.5	5.0	27.2	10.2
Result at significance level of 5%	**Reject H0, significant**	**Accept H0, not significant**	**Accept H0, not significant**	**Accept H0, not significant**	**Reject H0, significant**	**Accept H0, not significant**
Significance testing						
	H0: X1 - X2 = 0			X1: 2005	SL: 5%	
	H1: X1 - X2 <>0			X2: 2006		
	Duration in hrs	**Population**	**P Score**	**H Score**	**D Score**	**Sum**
X1-X2	-388.5	-8799.4	-3.6	4.1	-8.6	-2.9
Var	126895.5	345606155.1	42.9	6.1	532.3	65.7
SE	356.2	18590.5	6.6	2.5	23.1	8.1
CI 95% (+/-)	698.2	36437.4	12.8	4.8	45.2	15.9
Result at significance level of 5%	**Accept H0, not significant**	**Accept H0, not significant**	**Accept H0, not significant**	**Accept H0, not significant**	**Accept H0, not significant**	**Accept H0, not significant**
Significance testing						
	H0: X1 - X2 = 0			X1: 2006	SL: 5%	
	H1: X1 - X2 <>0			X2: 2004		
	Duration in hrs	**Population**	**P Score**	**H Score**	**D Score**	**Sum**
X1-X2	499.7	6499.4	2.4	-4.3	39.0	12.8
Var	124611.9	347596544.4	48.4	6.3	352.1	44.0
SE	353.0	18643.9	7.0	2.5	18.8	6.6
CI 95% (+/-)	691.9	36542.1	13.6	4.9	36.8	13.0
Result at significance level of 5%	**Accept H0, not significant**	**Accept H0, not significant**	**Accept H0, not significant**	**Accept H0, not significant**	**Reject H0, significant**	**Accept H0, not significant**

Table 9 Significance test comparing incident impact in England and Wales between 2004 and 2006

So far, the incident impacts for individual incidents were determined and the annual average incident impacts were calculated. This was used to compare the annual, average incident impact with the impact from incidents in subsequent years. This analysis was performed to assess the trend of annual incident impacts; however, it does not explain the nature of these incidents. In the following section, these incidents with a specific focus on the different hazard types or hazard categories as identified in Table 1 are investigated. This thesis employed the definitions ‘Aesthetics’, ‘Biological pathogens present’, ‘Biological pathogen present health effects’, ‘Chemical present above guideline’, ‘Chemicals present, health effects’, ‘Unwholesome’ and ‘Loss of supply’ to record incidents according to the respective hazard categories. Incidents in these categories were grouped into a table that was used to identify the annual re-occurrence of incidents in these impact categories. This enabled the calculation of the frequency and average incident impact score for the respective hazard category. For each table containing one incident category, *e.g.* ‘Aesthetics’, the annual frequency of incidents was calculated as well as average, standard deviation, standard error and confidence interval at 95 percentile for the size of population affected, the duration of hazard exposure and the overall incident impact factor. A summary of the frequency and average impact for these hazard categories is presented in Table 10. The detailed analysis is presented in Appendix 3.2.1.

Hazard category	Frequency of occurrence in 2004 (F)	Average incident impact in this hazard category (I)	SE	CI 95% lower	CI 95% upper
Aesthetics	46	21.6	2.2	17.2	26.0
Biological pathogens present	16	16.4	5.1	6.5	26.3
Biological pathogens present, health effects	15	29.9	2.5	25.0	34.8
Chemical present above guidelines	6	19.6	6.3	7.3	32.0
Potential unwholesome medium health effect	2	24.8	2.3	20.2	29.3
Potential Unwholesome, low health effect	2	16.8	0.3	16.2	17.5
Loss of supply	1	11.9	0.0	11.9	11.9
Hazard category	**Frequency of occurrence in 2005 (F)**	**Average incident impact in this hazard category (I)**	**SE**	**CI 95% lower**	**CI 95% upper**
Aesthetics	48	29.1	7.1	15.1	43.0
Biological pathogens present	18	20.3	9.1	2.5	38.5
Biological pathogens present, health effects	15	46.4	12.2	22.4	70.4
Chemical present above guidelines	4	39.0	17.9	3.9	74.0
Chemical present, health effects	3	85.8	52.1	-16.3	187.9
Unwholesome	2	10.3	5.7	-0.8	21.4
Loss of supply	2	19.3	8.0	3.7	35.0
Hazard category	**Frequency of occurrence in 2006 (F)**	**Average incident impact in this hazard category (I)**	**SE**	**CI 95% lower**	**CI 95% upper**
Aesthetics	43	43.7	11.5	21.2	66.3
Biological pathogens present	22	20.5	7.6	5.6	35.3
Biological pathogens present, health effects	11	33.7	7.3	19.4	47.9
Chemical present above guidelines	11	18.2	3.5	11.3	25.0
Chemical present, health effects	4	96.1	82.8	-66.1	258.3
Loss of supply	6	8.7	1.0	6.7	10.6

Table 10 Frequency and average incident impact by hazard categories for the years 2004 to 2006

Table 10 enables a direct statistical comparison of frequency and impact for specific incident categories in subsequent years. This analysis was performed to identify significant differences in customer impact from the frequency and average hazard exposure for the respective hazard categories. The findings are summarised in Table 11, Table 12 and Table 13. The detailed analysis is presented in Appendix 3.2.1.

In the analysis it was found that customer impacts for ‘Aesthetics’, ‘Biological pathogens present’ and ‘Chemicals present above guideline’ have significantly increased over the three years. The ‘Biological pathogens present with anticipated health effects’ has significantly increased from 2004 to 2005 and significantly reduced from 2005 to 2006.

One interesting finding is the low number of ‘Loss of supply’ incidents presented in the data. Primarily, the DWI reports on water quality incidents but not incidents relating to supply reliability. This will be further investigated in the Regional Water Utility.

Significance testing		**H0: X1 - X2 = 0**				**X1: (F*H) for year**				**Legend**	
		H1: X1 - X2 <>0				**X2: (F*H) for year**				**F**	**Frequency of occurrence**
										H	**Average incident impact per hazard category**
X1				**X2**							
2004				**2005**							
	F	**I**			**F**	**I**		**H0**	**SL**		**Comment**
Aesthetics	46	21.6		Aesthetics	48	29.1		Reject	0.05	X2>>X1	**Higher impact in 2005**
Biological pathogens present	16	16.4		Biological pathogens present	18	20.3		Reject	0.05	X2>>X1	**Higher impact in 2005**
Biological pathogens present, health effects	15	29.9		Biological pathogens present, health effects	15	46.4		Reject	0.05	X2>>X1	**Higher impact in 2005**
Chemical present above guidelines	6	19.6		Chemical present above guidelines	4	39.0		Reject	0.05	X2>>X1	**Higher impact in 2005**
Chemical present, health effects				Chemical present, health effects	3	85.8		Reject	0.05	X2>>X1	**Higher impact in 2005**
Potential unwholesome medium health effect	2	24.8		Unwholesome	2	10.3		Reject	0.05	X1>>X2	**Lower impact in 2005**
Potential Unwholesome, low health effect	2	16.8			0	0.0		Reject	0.05	X1>>X2	**Lower impact in 2005**
Loss of supply	1	11.9		Loss of supply	2	19.3		Reject	0.05	X2>>X1	**Higher impact in 2005**

Table 11 Significance testing comparing frequency and impact of incidents in 2004 and 2005

Significance testing		**H0: X1 - X2 = 0**				**X1: (F*H) for year**				**Legends**	
		H1: X1 - X2 <>0				**X2: (F*H) for year**				**F**	**Frequency of occurrence**
										H	**Average incident impact per hazard category**
X1				**X2**							
2005				**2006**							
	F	**I**			**F**	**I**		**H0**	**SL**		**Comment**
Aesthetics	48	29.1		Aesthetics	43	43.7		Reject	0.05	X2>>X1	**Higher impact in 2006**
Biological pathogens present	18	20.3		Biological pathogens present	22	20.5		Reject	0.05	X2>>X1	**Higher impact in 2006**
Biological pathogens present, health effects	15	46.4		Biological pathogens present, health effects	11	33.7		Reject	0.05	X1>>X2	**Lower impact in 2006**
Chemical present above guidelines	4	39.0		Chemical present above guidelines	11	18.2		Reject	0.05	X2>>X1	**Higher impact in 2006**
Chemical present, health effects	3	85.8		Chemical present, health effects	4	96.1		Accept	0.05	X2 = X1	**Equal impact**
Unwholesome	2	10.3			0			Reject	0.05	X1>>X2	**Lower impact in 2006**
Loss of supply	2	19.3		Loss of supply	6	8.7		Accept	0.05	X2 = X1	**Equal impact**

Table 12 Significance testing comparing frequency and impact of incidents in 2005 and 2006

Significance testing		**H0: X1 - X2 = 0**				**X1: (F*H) for year**				**Legends**	
		H1: X1 - X2 <>0				**X2: (F*H) for year**				**F**	**Frequency of occurrence**
										H	**Average incident impact per hazard category**
X1				**X2**							
2004				**2006**							
	F	**I**			**F**	**I**		**H0**	**SL**		**Comment**
Aesthetics	46	21.6		Aesthetics	43	43.7		Reject	0.05	X2>>X1	**Higher impact in 2006**
Biological pathogens present	16	16.4		Biological pathogens present	22	20.5		Reject	0.05	X2>>X1	**Higher impact in 2006**
Biological pathogens present, health effects	15	29.9		Biological pathogens present, health effects	11	33.7		Reject	0.05	X1>>X2	**Lower impact in 2006**
Chemical present above guidelines	6	19.6		Chemical present above guidelines	11	18.2		Reject	0.05	X2>>X1	**Higher impact in 2006**
Chemical present, health effects	0			Chemical present, health effects	4	96.1		Reject	0.05	X2>>X1	**Higher impact in 2006**
Potential unwholesome medium health effect	2	24.8			0			Reject	0.05	X1>>X2	**Lower impact in 2006**
Potential Unwholesome, low health effect	2	16.8			0			Reject	0.05	X1>>X2	**Lower impact in 2006**
Loss of supply	1	11.9		Loss of supply	6	8.7		Reject	0.05	X2>>X1	**Higher impact in 2006**

Table 13 Significance testing comparing frequency and impact of incidents in 2004 and 2006

In the above analysis it is demonstrated how different hazard categories can be compared for subsequent years. In the following analysis incidents that occurred at regional level, *i.e.* incidents in individual water utilities are compared to incidents at national level in England and Wales. In this analysis, it was aimed to identify how regional water utilities perform relative to national average with respect to incidents. In this analysis, the national incident frequencies and average incident impacts for hazard categories represented a baseline against which the performance of the regional water utilities was evaluated. Since the 89, 92 and 98 incidents for the years 2004, 2005 and 2006 respectively, represent the national frequency of incidents, the baseline frequency needs to be adjusted to reflect the regional scale of water utilities. It was thought that an effective means to adjust the national baseline was to scale down the frequency of national incidents according to size of population served by the assets of a regional water utility. A water utility serving 10% of the customers in England and Wales would have a baseline of 9.8 incidents in 2006.

Here, the Regional Water Utility is used as an example: According to the DWI, it supplied 9.09% of all customers in England and Wales in 2004 and 8.74% of all customers in 2005 and 2006 (Drinking Water Inspectorate, 2005b; Drinking Water Inspectorate, 2006; Drinking Water Inspectorate, 2007).

Based on the national incident frequencies presented in Table 10 the scaled down frequencies were calculated as a baseline to reflect the regional size of supplied population in the Regional Water Utility. In order to facilitate the significance testing of regional incidents at water utility level with the baseline data, the water utility specific incidents were identified in (Drinking Water Inspectorate, 2005b; Drinking Water Inspectorate, 2006) (Drinking Water Inspectorate, 2007)and statistically analysed.

Table 14 to Table 16 summarise the comparison of incidents in the Regional Water Utility with incidents in England and Wales for the years 2004 to 2006. It was found that on five counts between 2004 and 2006, the Regional Water Utility generated significantly higher impacts on its customers compared to national average. Similarly, on five counts it generated significantly lower customer impacts on its customers in comparison. The detailed analyses and significance tests are presented in the Appendix 3.2.1.

	X1			X2					H0: RWU H*RWU F = SN H*SN F		
2004	**Baseline (National standard (SN) for RWU**			**Regional Water Utility (RWU) Incident Impact**					**H1: RWU H*RWU F<>SN H*SN F**		
Hazard category	**SN F**	**SN I**		**RWU F**	**RWU I**		**Mean (X2-X1)**	**SE**	**CI 95%**	**H0**	**Result**
Aesthetics	4.2	21.6		12	19.0		**137.3**	2.7	**5.2**	**Reject**	**RWU do worse than SN**
Biological pathogens present	1.5	16.4		2	8.6		**-6.7**	7.3	**14.3**	**Accept**	
Biological pathogens present, health effects	1.4	29.9		3	30.6		**51.0**	3.1	**6.0**	**Reject**	**RWU do worse than SN**
Chemical present above guidelines	0.6	19.6		1	9.2		**-1.5**	6.3	**12.3**	**Accept**	
Potential unwholesome medium health effect	0.2	24.8		0			**-4.5**	2.3	**4.5**	**Accept**	
Potential Unwholesome, low health effect	0.2	16.8		0			**-3.1**	0.3	**0.7**	**Reject**	**RWU do better than SN**
Loss of supply	0.1	11.9		0			**-1.1**	0.0	**0.00**	**Accept**	

Note	
SN F is the national frequency for this category incident scaled down with the percentage of customers served by this utility.	
Legend	
SN	National standard
RWU	Regional Water Utility
F	Frequency of occurrence
I	Incident impact for respective category
SE	Standard Error
CI 95%	Confidence interval at 95%

Table 14 Significance test comparing incidents in the Regional Water Utility with incidents in England and Wales in 2004

	X1			X2					H0: RWU H*RWU F = SN H*SN F		
2005	Baseline (National standard (SN) for RWU			Regional Water Utility (RWU) Incident Impact					H1: RWUH*RWU F<>SN H*SN F		
Hazard category	**SN F**	**SN I**		**RWU F**	**RWU I**		**Mean (X2-X1)**	**SE**	**CI 95%**	**H0**	**Result**
Aesthetics	4.2	29.1		5	17.9		**-32.7**	8.3	**16.2**	**Reject**	**RWU do better than SN**
Biological pathogens present	1.6	20.3					**-32.0**	9.1	**17.8**	**Reject**	**RWU do better than SN**
Biological pathogens present, health effects	1.3	46.4		3	41.2		**62.7**	16.7	**32.7**	**Reject**	**RWU do worse than SN**
Chemical present above guidelines	0.4	39.0		0	0.0		**-13.6**	17.9	**35.0**	**Accept**	
Chemical present, health effects	0.3	85.8		0	0.0		**-22.5**	52.1	**102.1**	**Accept**	
Unwholesome	0.2	10.3		1	4.7		**2.9**	5.7	**11.1**	**Accept**	
Loss of supply	0.2	19.3		0			**-3.4**	8.0	**15.7**	**Accept**	

Table 15 Significance test comparing incidents in the Regional Water Utility with incidents in England and Wales in 2005

	X1			X2					H0: RWU H*RWU F = SN H*SN F		
	Baseline (National standard (SN) for RWU			Regional Water Utility (RWU) Incident Impact					H1: RWUH*RWU F<>SN H*SN F		
Hazard category	**SN F**	**SN I**		**RWU F**	**RWU I**		**Mean (X2-X1)**	**SE**	**CI 95%**	**H0**	**Result**
Aesthetics	3.8	43.7		5	81.1		**241.3**	66.8	**131.0**	**Reject**	**RWU do worse than SN**
Biological pathogens present	1.9	20.5		3	23.9		**32.3**	12.7	**24.9**	**Reject**	**RWU do worse than SN**
Biological pathogens present, health effects	1.0	33.7		0			**-32.4**	7.3	**14.3**	**Reject**	**RWU do better than SN**
Chemical present above guidelines	1.0	18.2		2	12.0		**6.5**	4.4	**8.6**	**Accept**	
Chemical present, health effects	0.4	96.1					**-33.6**	82.8	**162.2**	**Accept**	
Loss of supply	0.5	8.7		0			**-4.5**	1.0	**1.9**	**Reject**	**RWU do better than SN**

Table 16 Significance test comparing incidents in the Regional Water Utility with incidents in England and Wales in 2006

This type of analysis was conducted for all significantly large water utilities in England and Wales. The significantly large water utilities were selected by the size of population they serve. In analogy to the incident analysis for the Regional Water Utility, their incidents were analysed and compared to a specific baseline of national incidents that reflects their population size. In a significance test, it was determined whether they generated incidents in the specific hazard categories that exceeded national average. Figure 10 shows the number of hazard categories for which the frequency and impact assessment of individual water utilities generated significantly better or worse incident impacts in comparison to the national average in England and Wales. If the significance test resulted in accepting H0 at a significance level of 5%, the water utility performance was recorded as 'same performance'. Similar to the analysis for the Regional Water Utility, the results for the years 2004 to 2006 were aggregated. From this analysis, it can be identified that there is a trend suggesting that water utilities with significantly large customer bases outperform the average and small water utilities with significantly lower incident impacts. This can be calculated by the number of significantly lower customer impacts in comparison to the number of significantly higher customer impacts generated by significantly large water utilities.

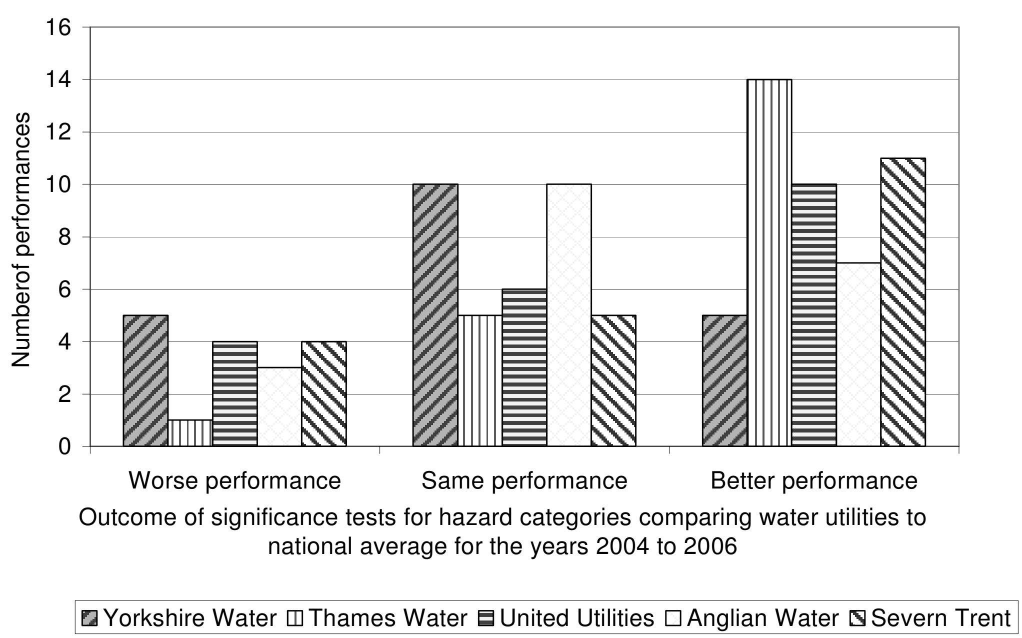

Figure 10 Summary of significance tests comparing water utility performance during incidents to the national average performance for the years 2004 to 2006

In summary of this section, publicly available incident data were used to identify - in a high level assessment - the types of assets that failed and caused an incident. The asset life cycle phase during which the incident occurred was identified and presented in a matrix. It was found that incidents do not occur randomly but significantly affect distribution assets. They commonly occurred due to a lack of maintenance or as a deliberate policy to "run to failure".

In a more detailed analysis, the incident impacts on customers were evaluated. An increasing trend was found in the annual number of incidents but also in the average duration and size of population affected by incidents. The comparative analysis of incidents enables a direct comparison of incidents at regional level with incident data for national level.

In the following section, the incidents between 1997 and 2006 in the Regional Water Utility are presented.

2.4.2 Incidents in the Regional Water Utility between 1997 and 2006

In this following analysis the 419 incidents that occurred between 1997 and 2006 were investigated to understand their cause and effect relationships and to quantify their impact on customers using the previously introduced theoretical developments, methodologies and models. For each analyzed incident, the most significant or primary cause and effect was extracted from the incident narratives discarding any contributing factors or secondary effects of the incident. (These will be accounted for in a subsequent study.)

In Table 17, a histogram of the primary incident causes and primary incident effects is presented for all 419 incidents. The causes and effects are presented in descending order.

Primary incident cause	10 year histogram	in %		Primary incident effect	10 year histogram	in %
Burst main	133	31.7%		Interruption to supply	120	28.6%
IT failure	47	11.2%		Discolouration	115	27.4%
Maintenance work	45	10.7%		loss of M and C	42	10.0%
Asset failure	41	9.8%		Potential biological pathogens present	24	5.7%
Power failure	25	6.0%		Chemicals present above guidelines	23	5.5%
Operational intervention	23	5.5%		Biological pathogens present, health effects envisaged	18	4.3%
3rd party	19	4.5%		Potential biological pathogens present, health effects envisaged	13	3.1%
Chlorination failure	18	4.3%		Biological pathogens present	12	2.9%
Asset contamination	15	3.6%		Empty Service Reservoir	11	2.6%
Unknown	13	3.1%		Loss of asset	8	1.9%
Treatment failure	12	2.9%		Damage to asset	5	1.2%
Raw water quality	8	1.9%		3rd party impact (Gas)	4	1.0 %
Asset damage	4	1.0%		Aesthetics above guidelines	4	1.0%
M and C failure	3	0.7%		Environmental	4	1.0 %
Severe weather	3	0.7%		Chemicals present above guidelines, health effects envisaged	3	0.7%
High Demand	2	0.5%		low pressure	3	0.7%
Security	2	0.5%		3rd part damage	2	0.5%
Adverse weather	1	0.2%		Disruption To Normal Processing Of Work	2	0.5%
Chemical spillage	1	0.2%		Risk of cross contamination	2	0.5%
Chemical supply contamination	1	0.2%		3rd party accident	1	0.2%
Design failure	1	0.2%		Human safety	1	0.2%
Illegal connection	1	0.2%		Statutory monitoring failure	1	0.2%
Telemetry failure	1	0.2%		Supply of unchlorinated water	1	0.2%
Water quality	1	0.2%		Treatment failure	1	0.2%
Total	**419**	**100.00%**		**Total**	**419**	**100.00%**

Table 17 Primary incident causes in the Regional Water Utility between 1997 and 2006

The top 50% of primary incident causes were identified as ‘failed water mains (31.7%)’, ‘IT failures (11.2%)’ and ‘maintenance work (10.7%)’. The remainder is distributed over 21 further categories reflecting the prevailing diversity of primary incident causes resulting in an incident. Similarly, the top 50% of primary incident effects were identified as ‘interruption to drinking water supply (28.6%)’ and 'discolouration/aesthetics (27.4%)'. The remainder is distributed over 22 further categories reflecting the prevailing diversity of primary incident effects.

345 out of the 419 incidents had a direct impact on customers. Their cause-effect relationships are presented in a three-dimensional chart in Figure 11.

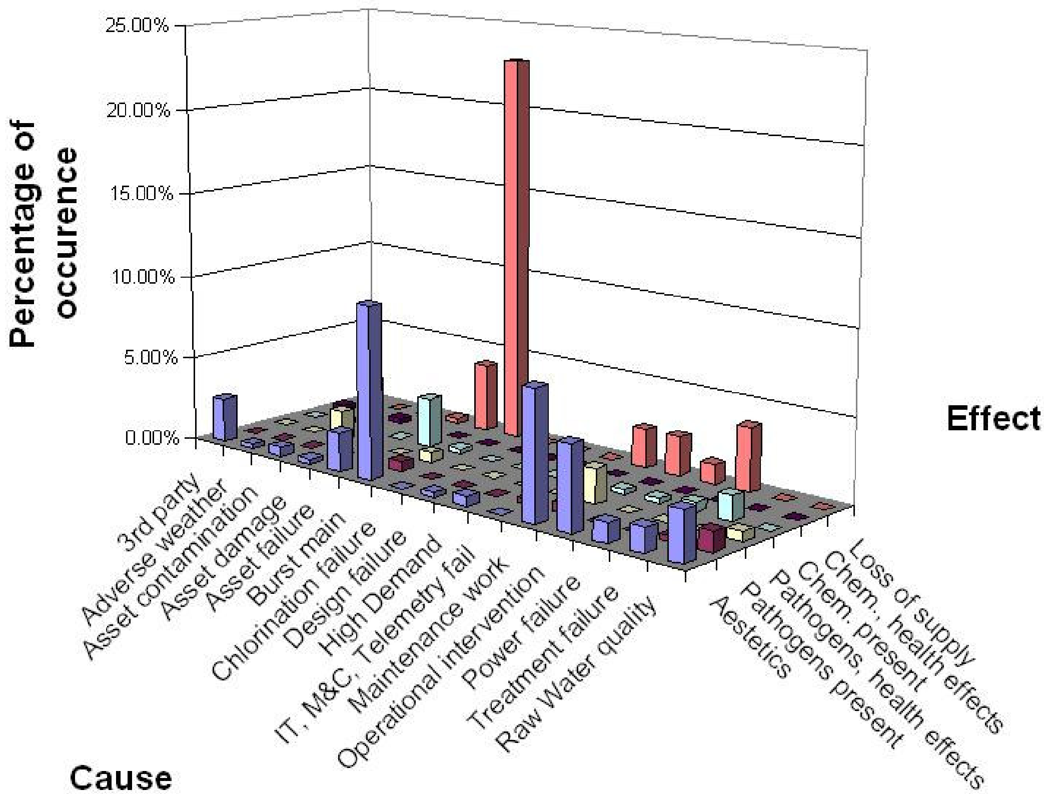

Figure 11 Percentage of incident occurrence for primary cause and effect relationships for incidents between 1997 and 2006 in the Regional Water Utility

In 22.9% of all incidents, a burst main resulted in the loss of supply to customers. In 10.1% of all incidents, a burst main has primarily resulted in aesthetical problems related to the drinking water supplied to customers. 7.5% of incidents were attributed to maintenance work that subsequently led to aesthetical problems with the drinking water. 5.2% of incidents were attributed to chlorination systems failure that led to potential biological pathogens present in the supplied drinking water. All other interrelationships between causes and effects constitute less than 5% of incidents.

In comparison to the data recorded for incidents in England and Wales in 2005, a significantly higher percentage of incidents are attributed to loss or interruption of supply reflecting the DWI strategy of reporting water quality incidents only. Yet, this analysis already confirms that the majority of incidents are associated to distribution network assets.

In the following analysis, it was aimed to understand where and when incidents occur in the asset type – asset life cycle matrix. 324 incidents were considered that had an impact on the safety and reliability of drinking water supply for customers in the Regional Water Utility between 1997 and 2006. Based on the analysis of the incident narratives, the primary incident cause of every incident was classified in the broad categories 'catchment', 'water treatment works', 'service reservoir' and 'distribution system'. Furthermore, the appropriate asset management phase from 'design', 'operation' and 'maintenance' was identified to which the individual incident causes could be attributed.

In Table 18 a catchment-to-tap – asset life cycle matrix is presented. A total of 369 incident causes were recorded for the 324 incident description. The deviation in numbers arises mainly from multiple factors contributing during an incident but also ambiguity in the incident reports to precisely pinpoint the incident to a specific matrix field. Problems of classification also arose when an incident symptom occurred in a downstream asset but originated further upstream in the catchment to tap model. Discoloured water can arise through the deposition of solids in the distribution network. At self-cleaning velocities in the distribution network, these deposits are constantly washed out to customer tap at low concentration and low impact on customers. The deposition of solids could be classed as a treatment problem (design) because the process does not adequately remove the precursors for discolouring precipitates (Iron and Manganese). It could also be classed as treatment (operations) if the process was not optimally operated to remove precipitates. It could be classed as distribution network design problem because deposits were allowed to accumulate in the network until water demand increased the flow velocities to self-cleansing velocity. It could be classed as a distribution operations and maintenance issue because regular flushing and swabbing could have avoided the accumulation of deposits.

	Catchment	WTW	SR	Distribution	Sum
Design	2	38	4	24	**68**
Construction	0	1	2	54	**57**
Operations	2	14	8	33	**57**
Maintenance	0	18	4	165	**187**
Sum	**4**	**71**	**18**	**276**	**369**

Table 18 Incident classification in catchment to tap and asset life cycle matrix for incidents in the Regional Water Utility between 1997 and 2006

In Table 18 a number of significant observations can be made: The results are first considered in a catchment to tap perspective: Here, 74.8% of incidents arose in the distribution networks of the water utilities. This is followed by 20.2% of incidents occurred at the water treatment capabilities in the water utilities. 4.8% of incidents originated in service reservoirs and 1% in the catchment.

From an asset life cycle perspective, the majority of incidents were attributed to asset maintenance. A total of 50.6% of incidents were attributed to this category. This is followed by 18.4% of incidents attributed to the category ‘design’ (which denotes a failure to design or upgrade sections of an existing supply system to be fit for purpose). 15.4% of incidents were attributed as a result from failing to operate a water supply system that is otherwise fit for purpose. Another 15.4% of incidents were attributed to construction work at or near the asset that subsequently failed or resulted in an impact on customers.

Within the matrix, the largest number of recorded incident causes can be identified for distribution systems maintenance. Here, 44.7% of incident causes were recorded. This originates primarily from water mains bursts that result in ‘loss of supply’, ‘low pressure’ and ‘discolouration’. 14.6% of incidents causes were recorded as an impact of construction work on distribution assets. Overall, it could be demonstrated that a high level of diversity in the occurrence of incidents prevails. Incidents occur across all categories from catchment to tap as well as in all asset management life cycle phases.

In the following analysis, it was aimed to identify patterns in the distribution of incidents in the catchment to tap – asset life cycle matrix. It was hypothesised that incidents in the matrix are randomly distributed and the Chi square testing methodology was employed to calculate an expected distribution of incident occurrences in the matrix. The formal calculation and hypothesis testing is presented in Appendix 3.2.2. A random distribution of incidents in the matrix based on the sums for the individual categories is presented in Table 19.

	Catchment	WTW	SR	Distribution	Sum
Design	0.7	13.1	3.3	50.9	**68**
Construction	0.6	11.0	2.8	42.6	**57**
Operations	0.6	11.0	2.8	42.6	**57**
Maintenance	2.0	36.0	9.1	139.9	**187**
Sum	**4**	**71**	**18**	**276**	**369**

Table 19 Calculated, random distribution of incident occurrences in the asset type - asset life cycle matrix

The Chi square statistic is calculated from the sum of squared differences in each matrix field as $(\text{Observed-Expected})^2/\text{Expected}$. For each matrix field the Chi Square statistic is presented in Table 20.

	Catchment	WTW	SR	Distribution	Sum X_2
Design	2.2	47.5	0.1	14.2	
Construction	0.6	9.1	0.2	3.0	
Operations	3.1	0.8	9.8	2.2	
Maintenance	2.0	9.0	2.9	4.5	
Sum	**7.9**	**66.3**	**13.0**	**23.9**	**111.17**

Table 20 Chi square statistic for incident occurrences in the asset type - asset life cycle matrix

The sum of the Chi square statistic is 111.17. The critical value for 9 degrees of freedom at a significance level SL = 0.05 is $X_2 = 16.92$. Since 111.17 > 16.92, the H0 hypothesis of a random distribution in the catchment to tap – asset life cycle matrix is rejected. Similarly, the critical value for 9 degrees of freedom at a significance level SL = 0.001 is $X_2 = 27.88$. Since 111.17 > 27.88, the H0 hypothesis of a random distribution in the catchment to tap – asset life cycle matrix is rejected. It is concluded that the matrix distribution is not random but dependencies exist between the catchment to tap axis and the asset life cycle axis. In scrutinising Table 20 it can be identified that the largest deviation between observed and expected distribution arises for design issues in Water Treatment Works. Here, the observed incident causes are larger than expected in a random distribution. The observed incident causes related to design of distribution assets are lower than expected in a random distribution.

In a further, detailed analysis, the 145 incidents between 2004 and 2006 were coded with the structured incident assessment template previously introduced. In this analysis, the detailed description of the incident enabled a precise identification of the failed equipment and component. In Figure 12, the asset, equipment and component types at which the incidents occurred are shown in percentage of the total number of incidents for the years 2004 to 2006. As seen before, the majority of incidents occur in the distribution network; 33% of the incidents occurred due to the failure of water mains. 13.6% of the incidents occurred as a result of trunk main failures. The second largest asset type causing an incident is equipment for chemical treatment in water treatment works (14.3%). This is followed by incidents due to power failures (10.2%).

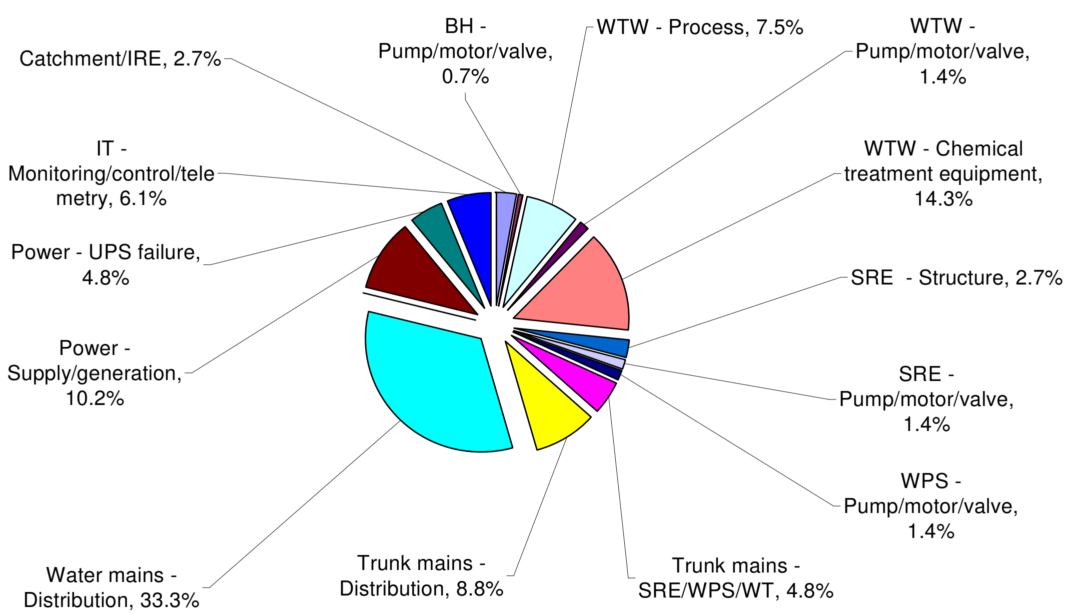

Figure 12 Asset type causing an incident between 2004 and 2006

In Figure 13, the number of attributed asset-related incident causes is shown. In total 316 asset-related causes were identified for the 145 incident. The categories of incident causes presented in this figure are not necessarily mutually exclusive as the analysis allowed multiple categories for the assessment of individual incidents. *E.g.*, a burst water main could be attributed to water mains failure due to material fatigue and corrosion, if this was so identified in the incident documentation for a particular incident. 'Corrosion', 'material fatigue', 'wear and tear', 'age' and 'poor condition' are often the underlying factors for the different types of asset-related failures. 'Asset failure' denotes any failure of an asset which has not been explicitly recorded as 'mechanical failure', 'electrical failure', 'civil failure' or 'water mains failure'. Within the 145 incidents, the largest number of incident causes was recorded as 'water main failures'; this is followed by 'material fatigue', '3rd party impact on assets' and 'corrosion'.

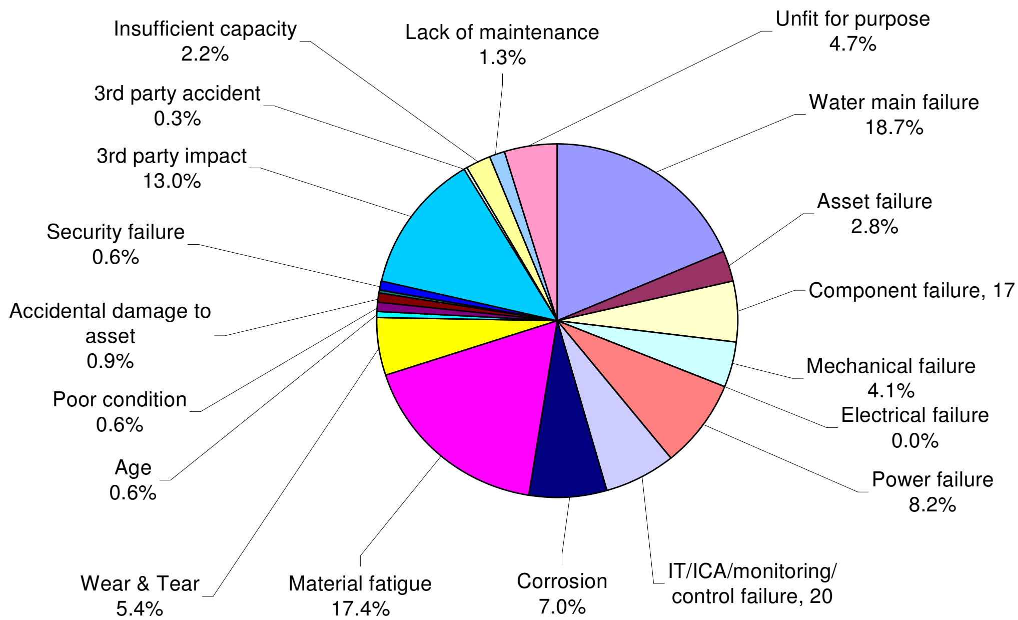

Figure 13 Asset related causes for incidents between 2004 and 2006

A further perspective is provided by investigating the time series of asset failures.

In Figure 14 asset-related incident causes are shown in a time series which relate to asset failures. The incident causes classed as 'asset failures' denote failures of assets, equipment and components other than burst mains and failure of chlorination asset, equipment and components. Due to the high rate of occurrence, 'burst mains' form a distinct group. Similarly, the 'failures of chlorination' (equipment) were recorded separably. The remaining category 'asset damage' denotes a severe impact on an asset that limited its ability to provide a service. In Figure 14, the number of primary incident causes for asset failures, burst mains, chlorination asset failure and asset damage is plotted for the years between 1997 and 2006. For the purpose of illustration, the data points are connected with a line.

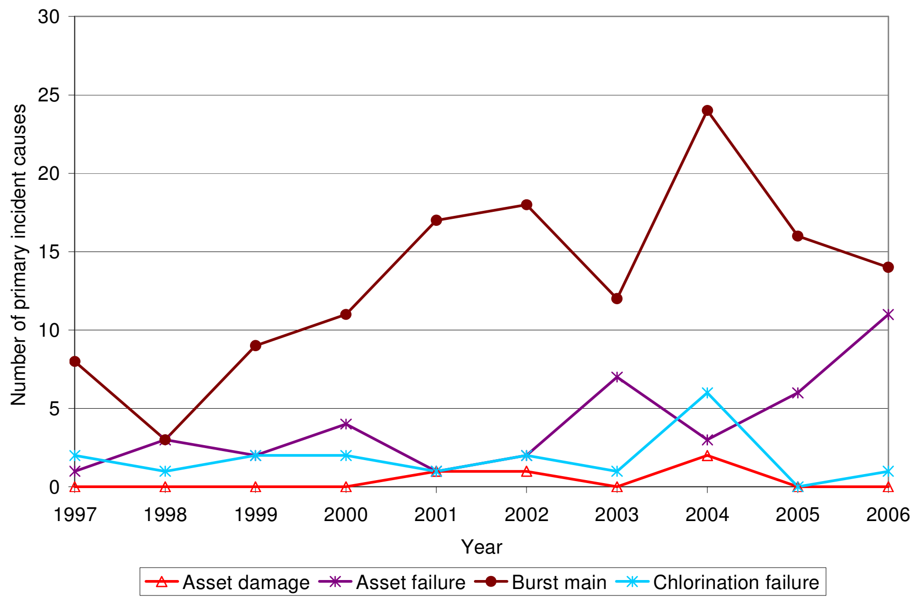

Figure 14 Asset damage, asset failure, burst mains and chlorination equipment failure between 1997 and 2006

A notable trend can be identified of increasing numbers of burst mains to cause an incident. This trend peaked in 2004 at 24 incidents and, since, the number of burst main incidents reduced to 14 in 2006. According to one reporter (participant no.34), the reduction of burst main incidents coincides with targeted mains refurbishment and replacement programmes.

A trend of increasing asset failures can also be identified. Throughout the 10 years, on average four asset failures per year led to an incident. Since 2004, the number of asset failures increased to 6 and 11 for the years 2005 and 2006, respectively.

Failure of chlorination assets, equipment and components resulting in an incident averages at 1.8 failures per year. In 2004, the frequency of chlorination asset and equipment failure peaked at 6 incidents per year. Since then, the number has reduced to zero and one incident in the years 2004 and 2005, respectively.

In Figure 15, the number of primary incident causes for 'IT failures', 'power failures' and 'monitoring, control and telemetry failures' that caused an incident is plotted in a time series for the years between 1997 and 2006.

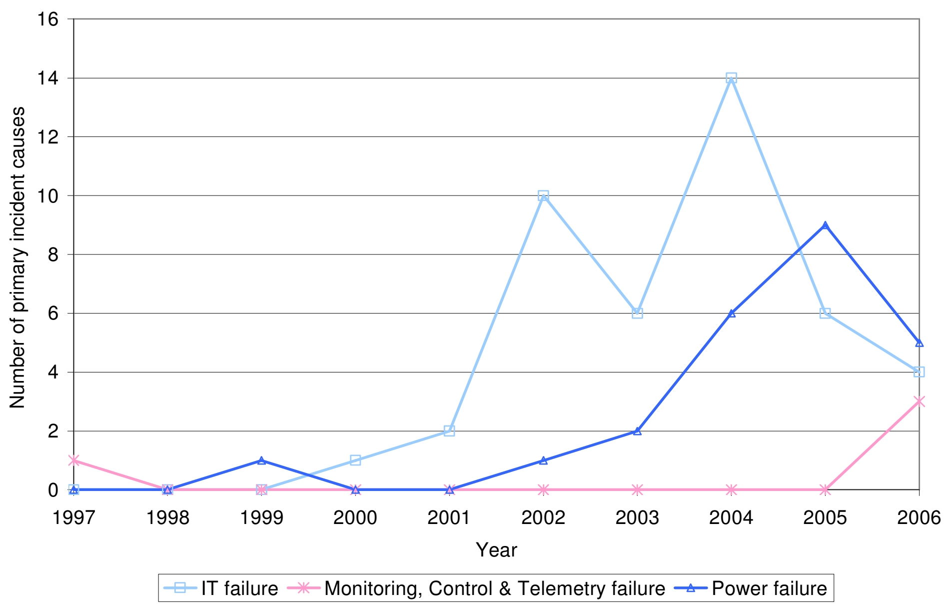

Figure 15 IT, power, monitoring, control and telemetry failures between 1997 and 2006

With respect to IT failure, a significant trend can be observed of increasing numbers of incidents between 1999 and 2005. This can be attributed to an increasing use of IT to manage business processes in the organisation. Since 2004, the number of IT related incidents reduces from 14 to 4 in 2006. According to one IT Manager (participant no. 30), the "*teething problems of introducing new technologies were initially having a huge impact on the business but have now been 'ironed out'*". Similarly, the number of power failures with the effect of an incident has significantly increased since 2001 to 2005. On enquiry, a number of factors were reported to explain this trend: Firstly, the supply of electricity by the electricity company is seen as less reliable nowadays than it

was a few years ago. One reporter (participant no.4) suggested that severe weather events have contributed to the overall reduction in the reliability of electrical supply. Secondly, according to one asset manager (participant no.13), the water utility has increased its use of water pumping stations in favour over water towers and reduced its capacity of gravity-fed water supply systems. In his view, increasing numbers of power-supply dependent water pumping stations correlates with the increasing number of incidents due to power supply failures. This trend is, however, overshadowed by investments in un-interruptible power supply systems. The organisation has increased its investments in un-interruptible power supply based on risk assessments and reliability studies on the power supply company.
In 2006, three incidents were specifically attributed to failures of monitoring and control equipment. This represents a significant increase compared to previous years. Similarly, to the use of IT, a trend can be observed in the organisation for increased use of monitoring and control equipment. This is related to an operational philosophy that requires all water treatment works to be operated from a regional operations and control centre without an operator on-site. This operational philosophy can also be observed for other assets owned by the water utility.

Incidents do not only occur due to asset-related failures. Figure 16 shows the number of attributed process-related incident causes. In total, 110 process-related causes were identified for the 145 incident between 2004 and 2006. Again, the categories are not mutually exclusive and the analysis allowed multiple categories for the assessment of individual incidents, if this was so identified in the incident documentation. Process-related incidents may relate to process issues, impact from the environment but also process-operational issues in utilitizing assets. The three largest process-related incident causes were recorded as ‘water main scouring’, ‘treatment process failure’ and ‘ingress of contaminants’. Water main scouring denotes changes in flow patterns, velocities and pressures in distribution systems that re-suspended deposited solids to cause discolouration incidents. Hydraulic effects, too, are changes in flow patterns, velocities and pressures in a distribution system that may disrupt the continued water supply to customers or dissolves air in the drinking water. ‘Operating environment’ denotes an adverse operating environment for assets.

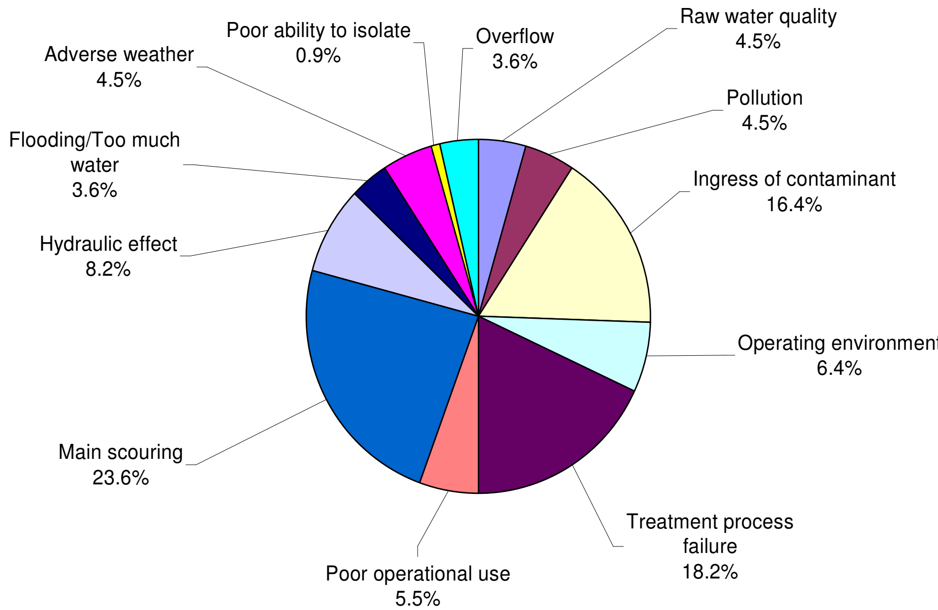

Figure 16 Process-related incident causes for incidents between 2004 and 2006

So far, 426 asset- and process- related incident causes were identified for the 145 incident. On average, 2.9 asset- and process-related incident causes were attributed per incident. This figure indicates that incidents have multiple causes and contributing factors leading to failures and an inability to pinpoint one ‘root cause’.

Beyond asset- and process-related failures, human factor can be taken into account as a contributing element to cause an incident. In 127 instances, a causal relationship between human factors/errors and an incident could be attributed. This represents an average of 0.88 human factors per incident. Although this was not necessarily the main root cause to the incident, the human factor was seen as a contributing factor in the incident. As in previous studies, this analysis allowed more than one contributing factor to be attributed to any one incident. In Figure 17, the numbers of occurrences in the respective categories of human factors are presented. A number of these human factor categories are arguable: ‘Unanticipated effect’ and ‘acted in good faith’ do not necessarily describe an insufficiency in the decision making of an operator but rather denote a ‘lesson learnt’ in hindsight: Had the person involved in the incident known about the potential effect, s/he would probably not have pursued a chosen course of action. Other categories are self-explanatory.

The largest attributed human factor was identified as 'poor design' and 'unanticipated effect'. 'Lack of information' on the potential consequences of action and 'poor outage planning' represent the third and fourth largest group in human factors contributing to incidents.

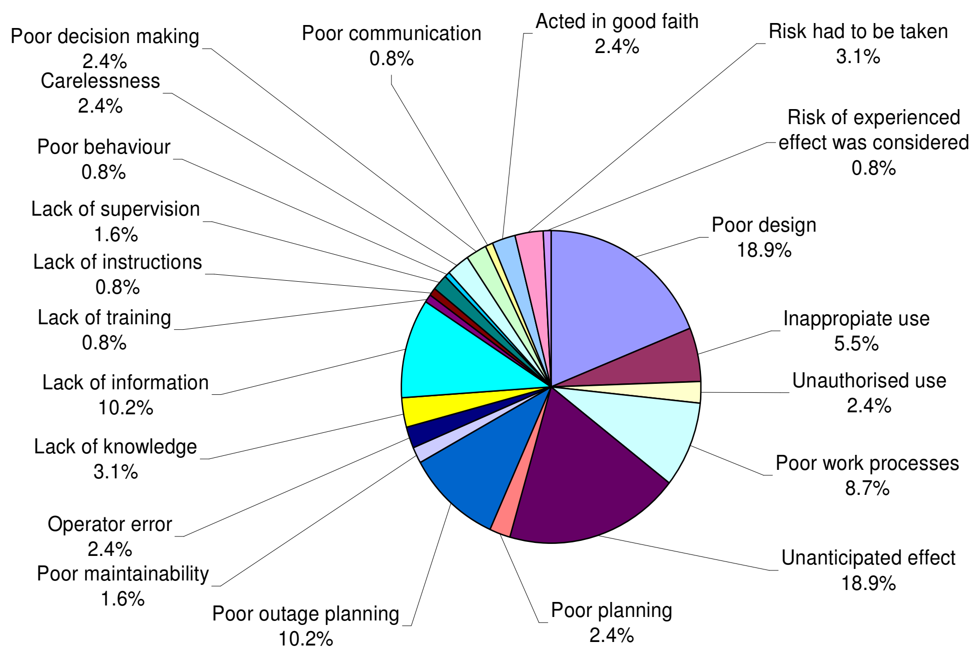

Figure 17 Human factor-related incident causes for incidents between 2004 and 2006

In total, 553 asset-, process- and human factor- related incident causes were identified for the 145 incident. This represents an average of 3.8 incident causes attributed for each incident and demonstrates that incidents are attributable to multiple incident causes and contributing factors as opposed to one 'root cause'.

In Figure 18 incident causes are shown which relate to operational activities on assets in the years 1997 to 2006 and represent human factors in incident propagation. The incident causes are classed as incidents that occurred during maintenance work on assets and due to an operational intervention by utility staff. Again, the data points care connected by a line to illustrate any trends.

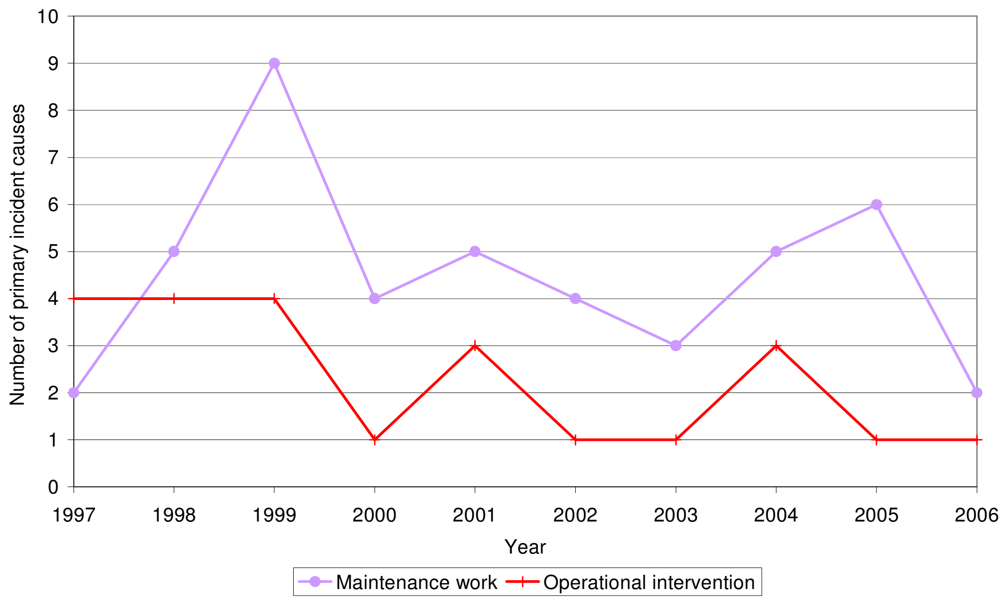

Figure 18 Incidents relating to operational activities on assets between 1997 and 2006

On average 4.5 incidents per year occur during maintenance work on assets. Although a trend can be identified of reducing numbers of incident causes in this category, the main observation suggests some form of periodical increase and decline. 1999 and 2005 represent peaks in the number of incidents occurring. It appears that this periodical trend coincides with capital investment and maintenance spending during the subsequent asset management programmes (AMP). According to one asset manager (participant no.31), 1999 and 2004 are the final years of asset management programmes in which, historically, a considerable amount of investment and maintenance projects are implemented. These implementation phases are "*busy*" periods with many scheduled construction activities being carried out on or near water utility assets.

It appears that operational interventions resulting in an incident has a similar periodic pattern, which almost corresponds with incidents due to maintenance work on assets. There may be a correlation to increased construction activity. However, there was no further data available to test this hypothesis. Providing evidence for this hypothesis would require an assessment of overall operational activity, in particular interventions into the water supply system, as a baseline to compare operational interventions causing an incident. The assessment would further require a measure for construction related activity on or near water supply system assets.

In a series of interviews it was aimed to further illuminate the causes of incidents. A number of operations and asset engineers were asked how specific incidents came about: Quite often interviewees would state "*it was like a bit of a freak occurrence which caused [the asset] to fail", "it was sort of a strange incident*", "*what happened was there was several things linked in*." and "*that fault was just specific to that site and that issue, it was just a one off type thing and it wasn't a generic fault which could occur at any site."* One process engineer (participant no.1) commented: Regarding "*the initial fault, you realise that there's still going to be that unknown, that something can occur which can throw a spanner in the works which it did on this occasion which there's nothing that you could have really done about it, it was like a freak occurrence."*

Commenting on one incident that involved a failure of chlorination equipment, an asset engineer (participant no.2) reported: "*The chlorine problems that happened on site because the site wasn't a fail safe site as such."*

Another process engineer (participant no.32) commented on an incident that involved contaminated chemicals: *"It was down to unforeseen circumstances really that caused [the incident]. Because basically it all stemmed from the supply of the chemical being substandard and causing blockages in our line and we actually ran out of hypo because of it. I mean, hindsight is a great thing. Up until this happening I don't think anybody had considered us getting a chemical that was going to crystallise and block our dosing lines – up until now you think that might happen in the future. I mean, all chemicals should be to an ISO standard, you know, they do come ISO stamped so whether they failed on ISO standards could be questionable. We've had hypo for a lot of years and we've only had it happen the once so something has gone wrong"*

One expert for distribution systems (participant no. 4) further explained the reason for discolouration incidents: *"Well, I suppose it all begins … from the water treatment works output and we don't provide distilled water from treatment works, there's always a level of say materials like iron and manganese that have been distributed into the distribution network. Now, they eventually sort of end up somewhere, I've heard some figures from water treatment works over a year kicking out so many kilograms of iron, for instance, and it's true, if the water is coming out of the treatment works at the level* *of even twenty milligrams per litre of iron then eventually that ends up somewhere. A lot of the iron and manganese ends up as sedimentation. Research now shows that it sticks to the pipe more at the inner surface and then it can just build up and up and, as long as the typical daily flows and velocities are happening in that main then it's quite happily stuck to the pipe and then eventually on some disturbance happening, call it like a hydraulic event, typically a burst, then the sudden increase in the velocity increases what we're calling the sheer stresses on that pipe or sedimentation material and strips those off and, of course, it then gets delivered to customers. When we get a burst, we get big discolouration problems sometimes because of … material has stripped off and some of the figures have shown that it doesn't take much of this to cause massive discolouration problems."* Further research into discolouration incidents and strategies to manage discolouration risk were developed by (Brandt *et al.*, 2004).

In Figure 17, a number of incidents were attributed to human factors. After one incident involving the failure of an acid system, one senior operations manager (participant no.5) commented: *"I think there was a lot of thing about the monitoring of the chemical dosing of the acid systems at the time, I think there was a clear gap in the process and procedures. I think basically [the operators] did a really excellent, top quality job during the day in normal hours and … out of hours and on a weekend they went back to basically a skeleton monitoring exercise and I think that's when the process started to go astray. "* Another operations manager (participant no.6) was more specific about human error: "*I would say that responding to incidents is something that we excel at but, you know, as far as incidents happening there's usually some gap in an operating procedure or it's human error, someone's made an incorrect judgement."*

Incident may also arise from standard operating procedures. The organisation requires stringent adherence to procedures and guidelines aiming for a repeatability of actions and routines. Activities based on decisions that are not defined in procedures are to be taken at a more senior level, for these individuals should have the best overall knowledge of the system. Many incidents that were investigated had unique and novel aspects to consider for which detailed procedures were not available. These arise out of the specific circumstances, *e.g.* the environment in which the incident occurs. The performances of tasks are embedded in formal rules, generalised guidelines and standardised frameworks and are expressed in SOPs, risk assessments and method statements. One process engineer (participant no.1) commented on the adherence to SOP: "*You're relying more and more on your team members to pull their weight to actually do the job correctly and not to drop you in it basically and there is an understanding within teams that you've got to do your job and you've got to follow, if there is a procedure there, you don't follow it and it's proved you don't follow it then that's it, it's your fault for not following the procedure. So it is understood that procedures are there for a reason, they're there to ensure things are done correctly and people are aware that you've got to understand and evaluate all the risks that you're going to come into contact with when you do certain jobs.*

There are jobs on site which you know that you can do with your eyes closed, it's not going to create a problem, but then there's also – especially with being on standby and having site shutdowns and you're there and you've got to start a site up and you've resolved a fault and you know that there's a higher risk involved because the site has been shut down. People are aware that, yeah, you have to ensure you follow procedures and you do everything to the letter and you do see through things thoroughly before carrying out any actions to ensure that you've mitigated all the risks that you can within reason."

One incident manager (participant no.7) criticised the amount of procedures currently in use: "*I think one of the problems we've got is there would be so many procedures people don't read them. I think what we need to do is they need to highlight the critical ' thou shall not ever' sort of thing, they really do need to understand those ones but they're just being hit with that many now. I think that's the problem, they just all merge into each other."*

Care must also be taken when procedures are not updated or fail to reflect actual circumstances on a site. One operations manager (participant no. 8) reported: "*Also, I think some learning [from an incident] that we had [for] the organisation [was], that when certain controls are changed on assets that we need to consider what the whole effect of that is."* A senior operations manager (participant no.5) commented on enhancing SOP following an incident caused by inadequate procedures: "*I think they would have certainly amended the site protocols in terms of the monitoring and control of the acid system.*"

Another operations manager (participant no.6) commented: "*We had some actions that rolled out from that [incident] - a modification to a procedure so, for instance, on start ups, sample transfers, things like that before you actually move water forward into the contact tank, … and I believe there was also some amendments into … alarms as well.*"
Adherence to SOP also features in the incident review meeting. One operation engineer (participant no.1) commented: In the incident review meeting "e*verybody was asked: what was your involvement, what happened at this time, what did you do at this time, did you follow the relevant QMS procedure? So if there's a procedure in place you were asked if you followed it, what did you do with it, it was checked and then, if there are procedures missing do any need writing.*"
More interesting are incidents with multiple incident causes that include human factors: One asset engineer (participant no.9) commented on physical asset failure in combination with human error: *"You've had … [a] communication breakdown, somebody hasn't fully understood the procedure and you've had something that's failed technically."*
Another interviewee (participant no.6) expanded on the multicausality of incidents: "*Usually, it's like I said before with this incident, it's usually when you get two things that align. This, for instance, the incident that we had at [Name of site], the flow switch failing and being modified with PLC codes on its own would have been fine, you wouldn't have had a problem with that if the Process Engineer had checked the sump before he put the water forward.*
It's usually when two or three errors align that you get an incident, one error alone and there's usually thing in place that ensure that, if you do have a failed asset, you have an alarm that picks it up and, if you have a failed alarm, there's usually someone on site.
I would say that we have very robust procedures and our assets are extremely well automated and extremely well alarmed that it usually captures everything and it's usually when there's a gap in something and a couple of those gaps align that you end up with a failure."
One operations manager (participant no.10) commented on the lack of inspection and maintenance that led to a specific incident: "*It would be the lack of inspection and maintenance of the mechanical seals that are used in a particular tank and the fact that we don't do that, therefore, they corroded and it wasn't a proactive replacement*

schedule and, therefore, we ended up with an acid leak." An asset engineer (participant no.11) also commented on the organisational maintenance philosophy: *"I've found that a lot of the issues have come because we don't maintain the assets like we used to, it's as simple as that. We don't have the manpower to do that any more and we've also reduced the practice policies and how many times we maintain things etc".* There are, however, strategies in place to identify investment and maintenance needs. Another asset engineer (participant no.12) reports on ways of investigating problems on site before an incident may happen: *"Well, in my role a lot of identifying the needs has been when we have problems on the site so the Process Engineers will call me…. Some of it's from looking around or looking at trends on SCADA or from breakdowns or, you know, things like pump failures or generator failures or diesel generator failures.* "
The multicausality and often very complex circumstances under which incidents arise were further investigated in a series of case studies based on documented incidents (Appendix 3.1). It was found that minor technical issues can cause cascading errors technical and human errors that amalgamate into major incidents. A number of cases were studied that relate to power failures and subsequently failure of chlorination assets or pumping stations despite being designed with fail safe mechanisms or stand-by power generation. One incident describes an operations controller being over-whelmed by alarms 'flooding' into the operations control centre and disguising the most critical alarm; another case study describes how an alarm from a failed asset is badly communicated to field staff resulting in a prolonged incident duration. One case study reports on the adverse effect of a telemetry failure that led to a site being 'non-visible' for monitoring and control purposes without controllers realising the problem. The detailed case studies are presented in Appendix 3.1.

Before considering the effect of incidents, the use of redundancy has to be considered that has potential to reduce the impact on customers. The entire water supply system builds on duty standby systems or excess capacity to isolate a failed asset and compensate for its loss. The organisation maintains reserve capacity in its technical and organisational system that includes back-up functions, overlapping tasks and responsibilities.

In Figure 19, the immediate availability of redundancy for failed assets that caused an incident is identified. The majority of incidents between 2004 and 2006 that occurred on assets had no immediate redundancy or stand-by available. These duty-only assets were predominantly water and trunk mains. The lack of standby or redundancy is one reason why the incident had an impact on customers and, it could be argued, that the incident impact could have been avoided, if immediate redundancy had been available (unless a common cause failure occurred). This, of course, would have significant cost implications, as it would require the duplication of the entire distribution system. It can also be identified that 29.6% of incidents had immediate standby assets or redundancy that failed in the course of the incident unfolding. This was attributed to duty-standby failures *e.g.* due to a common failure cause.

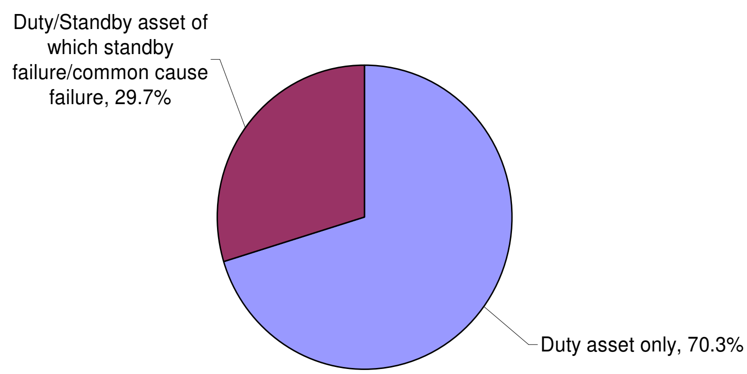

Figure 19 Immediate redundancy of assets that failed during incidents between 2004 and 2006

In Figure 20, the catchment to tap model was used to identify any assets between the asset that caused the incident and the customer. In this analysis, all intermediate assets were identified even if they had no reducing effect on the impact on customers.

It can be seen that in 68% of the incidents an asset failure had an immediate impact on customers without any asset between the incident origin and the customer. These 68%

contain the majority of "burst water and trunk main" incidents. In 8% of the incidents, the rezoning capability of the distribution network significantly reduced the impact on customers. In 15.3% of the incidents, a service reservoir mitigated against the full impact of an incident. As in the example above, the impact of a failure at a water treatment works was largely reduced due to the availability of drinking water in the service reservoir for supply to customers.

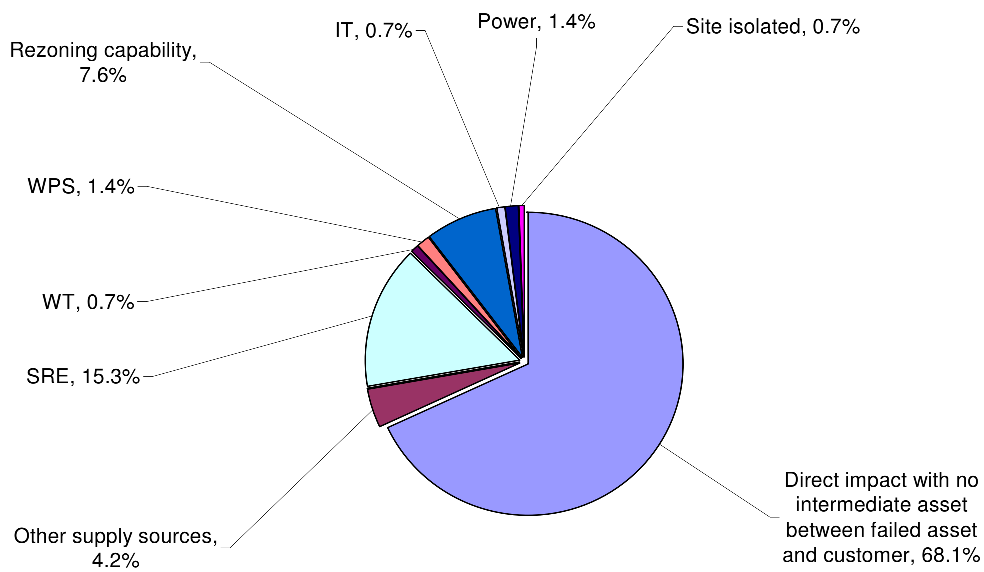

Figure 20 Alternative redundancy in the water supply system between the failed assets and the customer for incidents between 2004 and 2006

Figure 21 identifies the beneficial use of the intermediate assets to reduce the impact of an incident on customers. As shown before, the majority of incidents had no immediate asset between the failed asset and the customer that could have reduced the impact (67.6%). In 9.7% of the incidents an intermediate asset was available, however, it was not designed to or failed to reduce the impact of the incident on customers. In 4% of the incidents, the intermediate asset had a very high effect in reducing the incident impact so that the residual incident impact was minimal. The remainder of incidents had intermediate assets between the failed asset and the customer. Their effectiveness to reduce the impact ranged from very low to high.

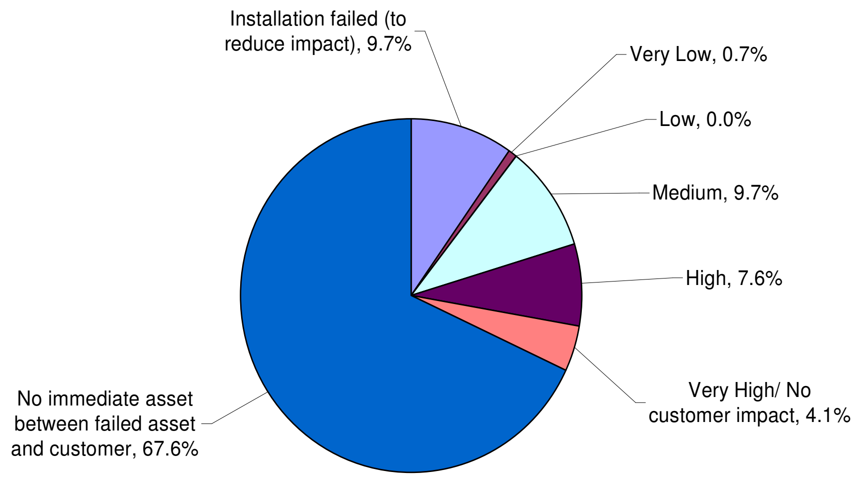

Figure 21 Beneficial use of systems redundancy during incidents between 2004 and 2006

The use of system (as opposed to asset) redundancy was investigated as part of the incident management response. In the previous study, the immediate asset redundancy and downstream redundancy of failed assets in a catchment to tap perspective were investigated. In this study, the emphasis is on alternative supplies that were used to reduce or avoid the impact of incidents on customers. Systems redundancy is defined as any means of water supply capability that could be diverted to compensate for a failed asset or installation. This can arise from using explicitly designed standby systems such as standby boreholes, pumps but also emergency connections between distribution management areas (DMA). This definition considers systems redundancy to originate from fixed installations but excludes bottled water and water tankering. The latter are commonly used to provide customers with an emergency supply of drinking water if no alternative supply can be established.

With reference to Figure 22 it was found that in 55.2% of the incidents no systems redundancy was used or could be used to reduce the impact or avoid customer impact.

In the majority of these incidents, the water utility resorted to the supply of bottled water. In 22.1% of the incidents, the use of systems could not avoid customer impact although it had a reducing effect. In 15.9% of the incidents, the use of systems redundancy significantly reduced the impact of incidents on customers and avoided the impact for a much larger customer base. In 6.2% of the incidents, systems redundancy was available and used but had a low effect on reducing the incident impact.

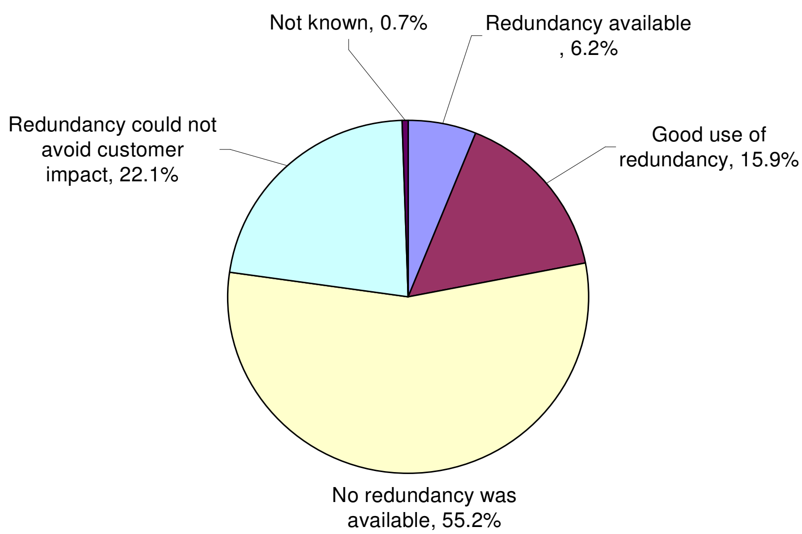

Figure 22 Usage of redundancy during incidents between 2004 and 2006

Sagan (1994) noted that it is important to recognise the counter-productivity of designing redundancy for a system, as back-up functions can increase technical complexity, conceal errors and lead individuals into not performing their required tasks under the assumptions that someone else takes care of his task.

One incident manager (participant no.7) commented on the availability of redundancy for managing incidents: "*I think we're getting a bit close now sometimes, be it …in terms of the capacity of a system in dealing with failure or in terms of the people, it can be a little bit tight but that's indicative of the way we are now. In terms of the systems, we're obviously trying to run an optimum system, people are trying to be careful with the budgets and sometimes there's one pump not working at this site and one pump not* *working at this site and one pump not working and they all come together to – and just one more little thing and, you know, we've got a major problem here. That is part of risk management; you're going to get it wrong, aren't you? And I don't say it was any different to what it was in the past because in the past you would have three standby pumps but if you ever tried to switch them on it didn't work".*

In that context, one asset manager (participant no.13) commented on the rationalisation of redundancy: "*We've spent a lot of time trying to understand what we actually mean by rationalisation, what exactly is it, and the crux of it is can we deliver the same or better service with less assets. Before you can take the assets out you have to understand how the assets perform and how they contribute to a resilient network. If you have a resilient network, in theory, an asset failure doesn't impact on the customer …and … we can build up an understanding [of] asset failure versus network resilience and customer impact.*

One of the things that we are targeting is reservoirs as a whole… Why do we need them, why do we have them, do we really need them, can we avoid spending money on certain service reservoirs and invest it on building a new reservoir in a better area."

The aforequoted incident manager (participant no.7) also commented on concealed errors in technical back-up systems: "*One of the things we have is –say, that water treatment works is at a hundred percent of its capacity and at the minute we're only calling in fifty percent. One of the places we really slip upon, something happens and you say right, I want seventy percent, yeah, you've got an emergency and you want seventy percent. It tends to be then when you find out that at that moment you can actually only do sixty percent. That's what the works is capable of doing but obviously there can be filters out on different things or there can be a problem, there can be a dosing pump that's maybe for repair which means at the moment can only do sixty percent but, because we're only asking as a routine for fifty percent of its capacity, you don't get to know that. If something else fails and we say let's have some more water, that's the point where you find out and that lets us down big style in this organisation of water."*

Technical redundancy has to be available instantaneously during an incident. As suggested by the above incident manager, technical redundancy is also required for technical maintenance. The availability of redundancy to enable maintenance work requires planning. One asset engineer (participant no.14) reports on the planning of maintenance work: *"Any operation which our field team do on the distribution system, they have to do a risk assessment …. Basically… it's like a risk assessment and a method statement so it's basically just saying how they will isolate an asset, whether it be a water main, service reservoir or pumping station…."* The risk assessment for planned maintenance has to consider the availability of redundancy to manage eventual incidents.

Beyond technical redundancy, there is also an element of operator redundancy to prevent incidents from happening. One operations engineer (participant no.15) reported: "*I think people are beginning to realise that, where before they might have been a little bit more lax about things because there were more people around to ensure things were covered. Not that I'm saying that things were done haphazardly, I'm just saying that now teams have become smaller people are aware that, yes, if there's less people to ensure if you 'can't something out' that someone else will do that for me. It's down to 'yeah, I've got to do that because the team is relying on me to do my job properly otherwise I'm going to impact on them further down the line'. There's that possibility and if I do that they're going to have to deal with more risks because I haven't done something the way I should have done it."*

Having considered the causes of incidents and the beneficial use of redundancy, the impact on customers was assessed. In the following analysis, the effects of these incidents are considered taking into account the explicitly stated, multiple effects an incident can have. In Figure 23, the effects of the 145 incidents between 2004 and 2006 are shown. It total 170 incident effects were recorded which equates to 1.17 incident effects per incident. The percentages shown in Figure 23 are based on 145 incidents. For example, 59 out of the 145 incidents were identified that resulted in 'loss of supply' to customers. This equates to 40.7% of incidents.

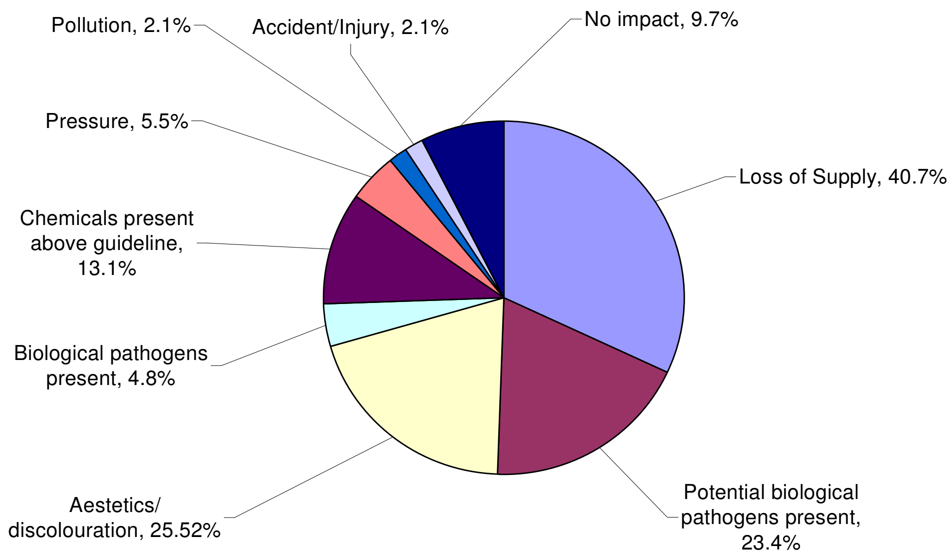

Figure 23 Effects of incidents between 2004 and 2006

Out of the 145 incidents, 107 were recorded to have no impact or only one impact category affecting customers. 37 were recorded explicitly stating two distinct incident effects affecting customers. One incident was recorded explicitly stating three different impact categories affecting customers. In Figure 24 the percentage of incidents are shown with no impact on customers, a single impact on customers and the percentage of incidents with double and triple impact on customers. 26.2% of the incidents were recorded to have a two or more distinct effects on customers. 23.5% of the incidents were recorded for ‘loss of supply’ to customers. 14.5% of the incidents constituted a potential presence of pathogens in the drinking water. 13% of the incidents related to aesthetic issues affecting the drinking water mainly due to discolouration. 9.7% of the incidents had no immediate customer impact. In these incidents, the incident management response was able to avoid any impact on customers.

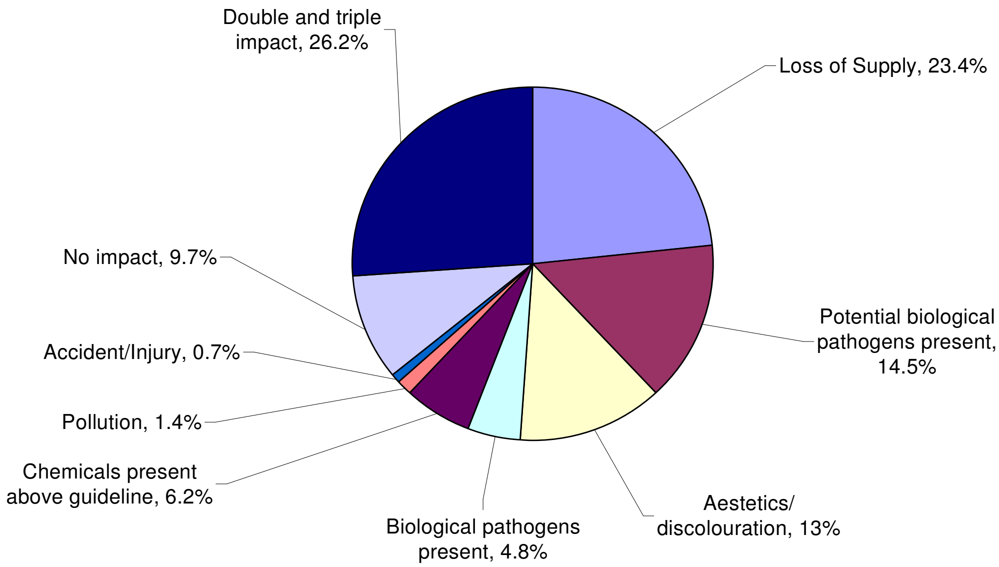

Figure 24 Percentage of single, double and triple effect incidents between 2004 and 2006

In the following analysis, the incidents with two or more incident impacts on customers are further examined. In Figure 25, the percentage of incidents with double or triple impact on customers is shown. 10.3% of the 145 incidents caused a 'loss of supply' to customers followed by aesthetical problems – mainly due to discolouration – on resuming normal operations. 6.2% of the incidents involved potential pathogens present in the drinking water in combination with exceeding chemical parameters above guidelines. 4.8% of the incidents were recorded as 'loss of supply' for customers and subsequently or simultaneously 'low pressures'.

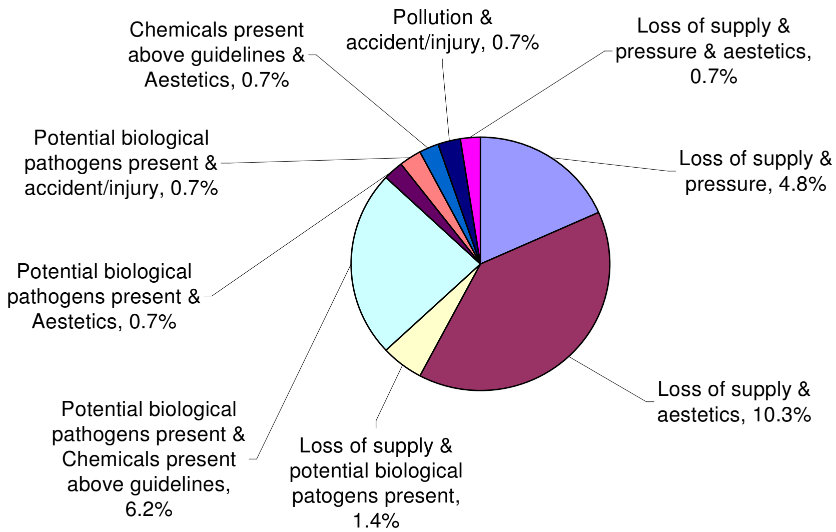

Figure 25 Percentage of incidents between 2004 and 2006 with a multiple incident effect

In the following section, the impact of incidents on customers is further considered. In the Regional Water Utility, a trend of increasing frequency for incidents can be identified between 1997 and 2006. Whereas the number of incidents has gradually increased by an average of 2.3 incidents per year, the average incident impact has marginally reduced. This is presented in Figure 26.

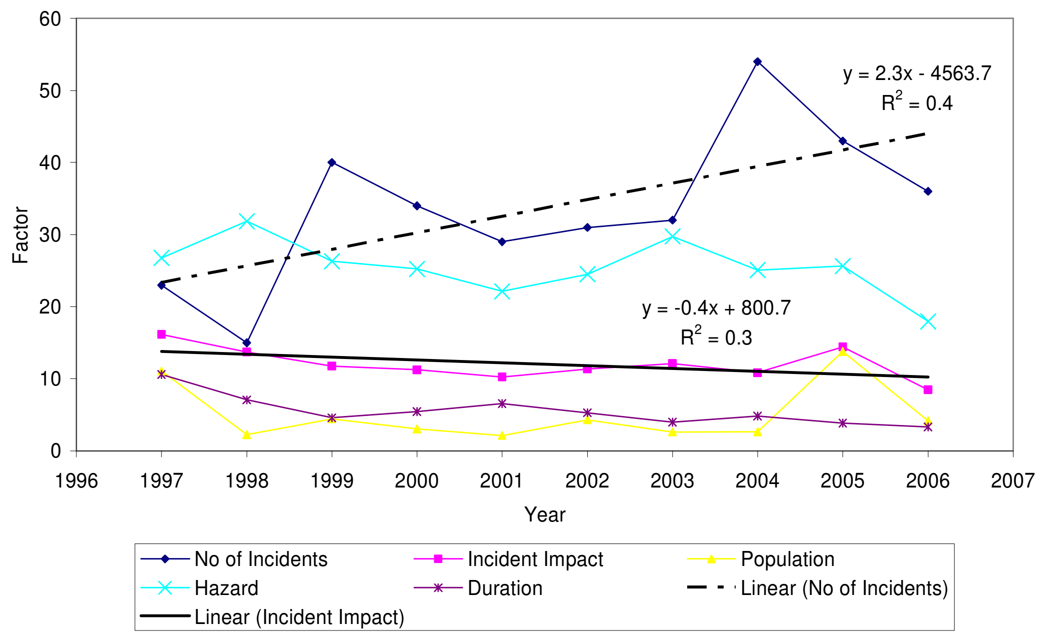

Figure 26 Frequency and impact of incidents between 1997 and 2006

The increase in incidents may have threefold reason: firstly, the threshold for defining an incident may have changed during that time period. Collecting incident data corresponds with a need to report incidents to the Drinking Water Inspectorate. Since 2004, the current definition of an incident is governed by the Water Undertakers (Information) Direction 2004 (Department for Environment, 2004) and the Guidance on the Notification of events (Drinking Water Inspectorate, 2004). If the threshold in the definition of an incident had been reduced, it would reflect in the number of incidents in the incident database. Secondly, the water utility may commit more resources to document incidents. This, in turn, may contribute to an increased availability of incident documents that would, otherwise, not be available. Thirdly, incidents may actually occur more frequently due to increased vulnerability of the water supply system, lack of maintenance, increased 3rd party impacts, etc.

Over that 10 year time period, the annual average impact of incidents reduced marginally. Per definition, the annual average incident impact is derived from three components, namely, the average factor for the hazard type, the average size of the population affected during an incident and the average duration of an incident. Hence, the average size of the population affected by an incident not only indicates the size of a population supplied by individual supply system arrangements but also indicates the ability of the organisation to reduce the affected population during an incident. The average duration of an incident indicates the speed of the incident management team to identify the hazard source and the speed of re-instating normal operations.

In the following Figure 27, the annual, average size of populations affected during incidents is presented. For the purpose of illustration, the data points are connected by a line. It can be seen that the annual average fluctuated between 1,000 and 10,000 customers affected by incidents. In the year 2005, the annual, average peaked at above 100,000 customers due to one extreme event that caused an impact on customers in the entire water supply region. In 2006, the average number of customers has again fallen below the 10,000-customer threshold.

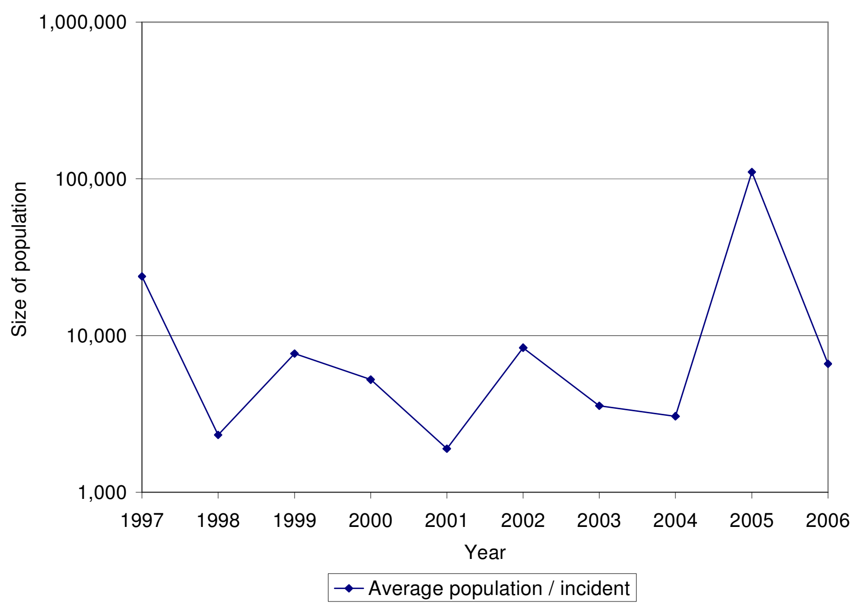

Figure 27 Annual, average population size affected by incidents between 1997 and 2006

Figure 28 shows the average duration of incidents in hours of exposure to hazards. Over the shown years, the incident duration has reduced by more than 50%.

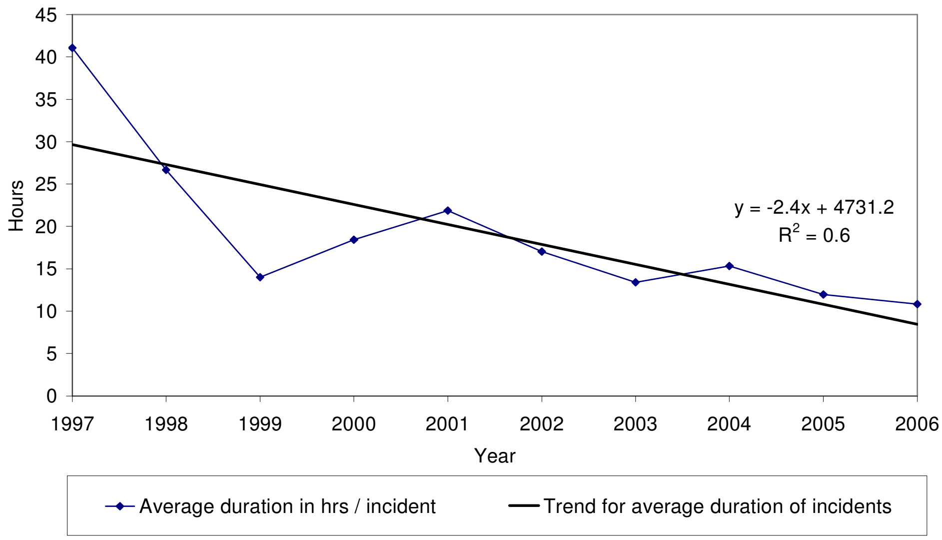

Figure 28 Annual, average duration of incidents between 1997 and 2006

Overall, the comparison of data for subsequent years does not suggest a statistically significant increase or reduction for the duration of the average incidents, the average affected population and the average incident impact score. The only exceptions arose in the analysis of the datasets for 2000 with 2001, 2005 with 2006 and 1997 with 2006. In 2000, the average size of population affected during incidents was significantly larger than in 2001. In 2005, the average hazard score was significantly larger than in 2006. The comparison of the year 1997 with 2006 suggests that the average duration of incidents, the duration score, the hazard score and the calculated incident impact for the year 1997 was significantly higher than in 2006. The detailed statistical analysis and significance tests are presented in Appendix 3.2.2.

In Table 21 further statistical analysis provides evidence of the statistical percentage of customers who experience incidents but also the statistical number of hours the water utility operated under trying condition.

Year	Average population / incident	Average duration in hrs / incident	Number of incidents	Mean Time Between Incident in days	Number of incidents * Population	Statistical percentage of population experiencing incidents	Total incident hours (Number of incidents * Average duration of incidents)	Total incident hours / Total operating hours
1997	23867.5	41.1	23	15.9	548953	11.8%	945	10.8%
1998	2323.5	26.7	15	24.3	34852	0.8%	400	4.6%
1999	7694.9	14.0	40	9.1	307794	6.6%	560	6.4%
2000	5231.1	18.4	34	10.7	177856	3.8%	627	7.2%
2001	1898.2	21.9	29	12.6	55047	1.2%	634	7.2%
2002	8381.3	17.0	31	11.8	259819	5.6%	528	6.0%
2003	3575.9	13.4	32	11.4	114429	2.5%	429	4.9%
2004	3061.0	15.3	54	6.8	165296	3.5%	828	9.5%
2005	110879.0	12.0	43	8.5	4767798	102.0%	514.5	5.9%
2006	6608.2	10.8	36	10.1	237895	5.1%	390	4.5%

Table 21 Statistical percentage of customers experiencing incidents and the percentage of hours operating under incident condition between 1997 and 2006

So far, the incident impact for individual incidents were analysed and determined and the annual average incident impact calculated. This was used to compare the annual, average incident impact with the impact from incidents in subsequent years. This analysis was used to monitor the trend of annual incident impacts; however, it does not explain the nature of these incident impacts on customers. In the following figures, the incidents are investigated with a specific focus on the different hazard types affecting customers.

The overall annual customer impact from incidents in their respective hazard categories is presented in Figure 29. The annual incident impact on customers is calculated as (frequency of incident for hazard category)*(average incident impact for hazard category).

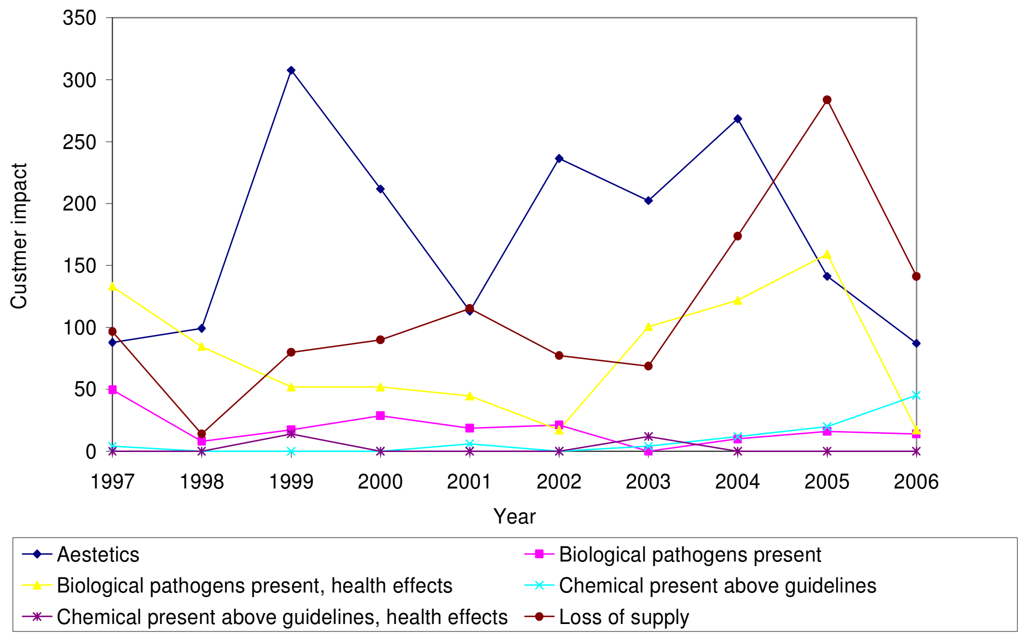

Figure 29 Annual incident impact in specific hazard categories between 1997 and 2006

The incident impact in the specified hazard categories were compared with another and it was found that the highest customer impacts between 1998 and 2004 related to 'aesthetical' unpleasing drinking water quality. Since 2004, this has significantly reduced. Since 1998, a trend can be identified of increasing customer impact from incidents relating to 'loss of supply'. This trend peaked in 2005 and has, since, reduced. The third largest hazard category that affects customers during incidents relate to 'biological pathogens present with anticipated health effects'. Since 1997, a downward trend suggested an improvement in this incident category. Since 2002, the impact on customer in this category increased to a peak in 2005. Since then, it reduced to below a 10-year average.

The frequencies of incidents for the different hazard categories are presented in Figure 30.

As suggested before, it can be identified that the two highest incident frequencies are associated to 'aesthetics' and 'loss of supply'. Since 2004, the frequency of incidents associated to 'aesthetical' unpleasing drinking water quality has reduced significantly whereas the frequency of 'loss of supply' incidents has been steadily increasing since 1998.

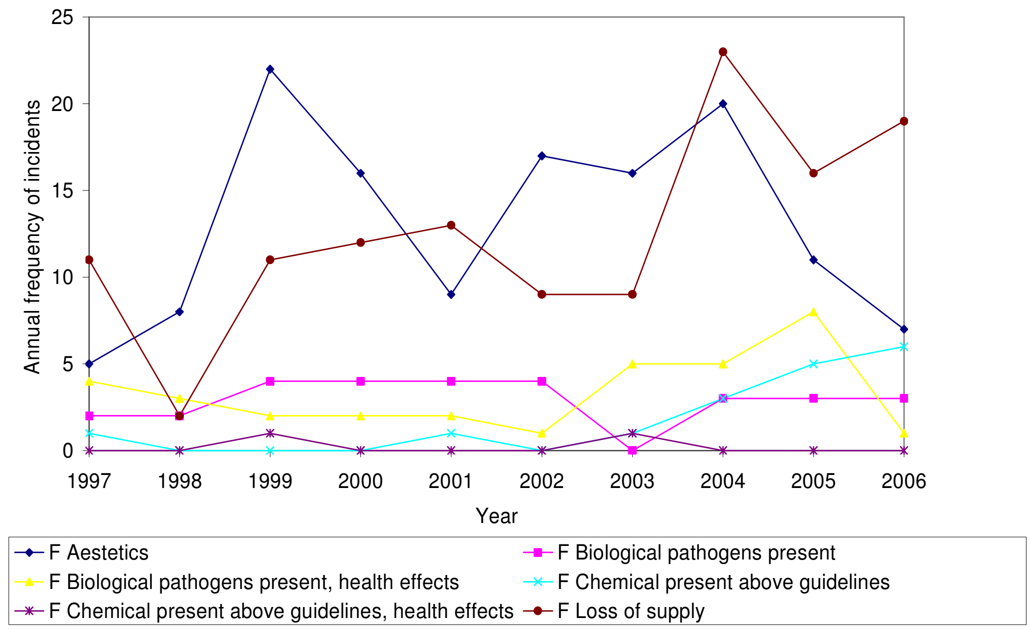

Figure 30 Annual incident frequencies for hazard categories between 1997 and 2006

The average, annual incident impact per incident for the respective hazard categories is presented in Figure 31. It can be identified that the annual average impact of incidents in the respective hazard categories remained largely unchanged. The only exception is identified for the average, annual incident impact related to the hazard category 'biological pathogens present with envisaged health effects'. In this category, a declining trend can be identified that suggests an improving organisational performance

- to reduce the size of the population affected during an incident, and/or
- to reduce the duration of such incident for this particular category.

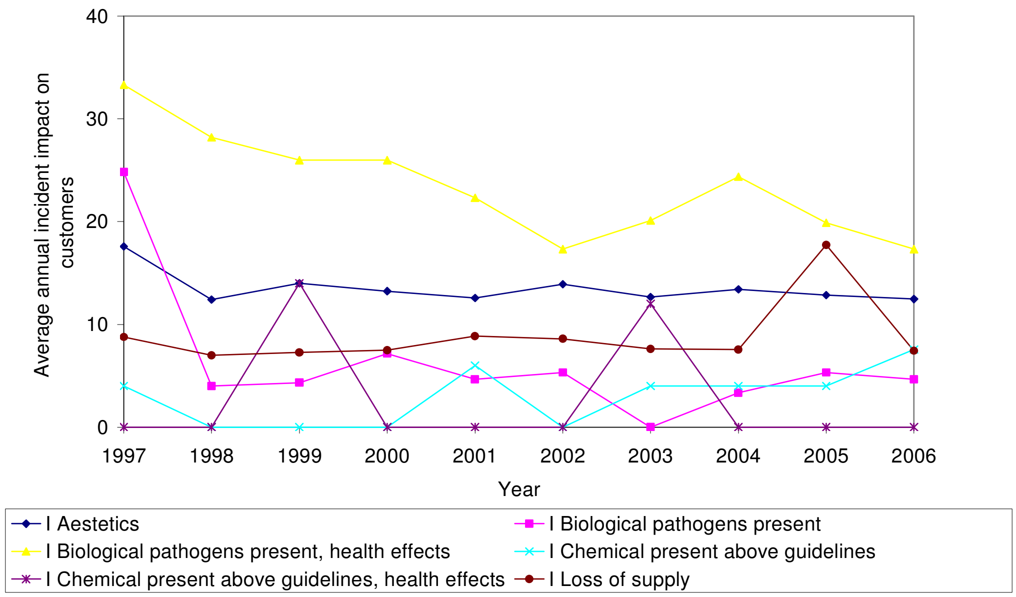

Figure 31 Average, annual incident impact for different hazard categories between 1997 and 2006

The analysis for hazard categories enables a direct statistical comparison and significance testing of frequency and impact for specific hazard categories in subsequent years. In Table 22, the findings for the years 2004 to 2006 are summarised. In this analysis, the hazard categories are compared for subsequent years.

Significance testing			H0: X1 - X2 = 0						
			H1: X1 - X2 <>0						
			SL: 5%						
X1: Year			**X2: Year**						
2004	X1		2005	X2					
	F	I		F	I	**H0**	SL		**Analysis**
Aesthetics	20	13.4	Aesthetics	11	12.8	**Reject**	0.05	X1>>X2	**Reduced impact compared to previous year**
Biological pathogens present	3	3.3	Biological pathogens present	3	5.3	**Reject**	0.05	X2>>X1	**Increase of impact compared to previous year**
Biological pathogens present, health effects	5	24.4	Biological pathogens present, health effects	8	19.9	**Reject**	0.05	X2>>X1	**Increase of impact compared to previous year**
Chemical present above guidelines	3	4.0	Chemical present above guidelines	5	4.0	**Reject**	0.05	X2>>X1	**Increase of impact compared to previous year**
Chemical present above guidelines, health effects	0	0	Chemical present above guidelines, health effects	0	0	**Accept**	0.05	X2 = X1	**Equal impact**
Loss of supply	23	7.6	Loss of supply	16	17.7	**Reject**	0.05	X2>>X1	**Increase of impact compared to previous year**
X1: Year			**X2: Year**						
2005	X1		2006	X2					
	F	I		F	I	**H0**	SL		**Analysis**
Aesthetics	11	12.8	Aesthetics	7	12.5	**Reject**	0.05	X1>>X2	**Reduced impact compared to previous year**
Biological pathogens present	3	5.3	Biological pathogens present	3	4.7	**Accept**	0.05	X2 = X1	**Equal impact**
Biological pathogens present, health effects	8	19.9	Biological pathogens present, health effects	1	17.3	**Reject**	0.05	X1>>X2	**Reduced impact compared to previous year**
Chemical present above guidelines	5	4.0	Chemical present above guidelines	6	7.6	**Reject**	0.05	X2>>X1	**Increase of impact compared to previous year**
Chemical present above guidelines, health effects	0	0	Chemical present above guidelines, health effects	0	0	**Accept**	0.05	X2 = X1	**Equal impact**
Loss of supply	16	17.7	Loss of supply	19	7.4	**Reject**	0.05	X1>>X2	**Reduced impact compared to previous year**

Table 22 Significance testing for hazard categories between 2004 and 2006

As an example, it was identified that incident impacts relating to 'aesthetical' unpleasing drinking water quality significantly reduced from 2004 to 2006. With respect to discolouration and incidents relating to aesthetically unpleasing drinking water quality, the technical expert for distribution systems (participant no. 4) commented on the regulatory response to those types of incidents: ***"****It was a DWI … initiative and information letter that first instigated what all Water companies are doing in DOMS [Distribution Operation and Maintenance Strategy]. So they're really* *concerned with water quality issues of which discolouration is probably the biggest one in terms of customer contact, customer complaints coming in. So all the Water companies are quite focussed on discolouration being the biggest problem but DOMS does actually encompass other aspects like taste and odour and contacts around that and problems associated with it and pH and, you know various other issues as well. So it's quite all encompassing in terms of water quality but they're all naturally a bit biased towards discolouration because it's often such a big problem."* DOMS was developed in a collaborative research project in response to discolouration incidents (Brandt *et al.*, 2004).

Returning to Table 22, incident impacts relating to 'biological pathogens present with envisaged health effects significantly increased from 2004 to 2005 and significantly reduced in the following year.

In the following analysis, incidents in the Regional Water Utility are compared to incidents reported at national level in England and Wales. As in previous analyses, the national incident occurrences and impacts represent a baseline against which the performance of the Regional Water Utility is compared. Table 23, Table 24 and Table 25 summarise the comparison of incidents in the Regional Water Utility with incidents in England and Wales for the years 2004 to 2006.

RWU Incident database			**National Standard (SN) (DWI) customised to RWU (Frequency adjusted over Population)**			**Significance testing**			
						H0: X1 - X2 = 0			
Year						H1: X1 - X2 <>0			
2004						SL: 5%			
						X1	RWU		
						X2	DWI		
	F	I		F	I	H0	SL		**Analysis**
Aesthetics	20	13.4	Aesthetics	4.9	21.6	Reject	0.05	X1 >> X2	**RWU do worse than SN**
Biological pathogens present	3	3.3	Biological pathogens present	1.5	16.4	Reject	0.05	X2 >> X1	**RWU do better than SN**
Biological pathogens present, health effects	5	24.4	Biological pathogens present, health effects	1.4	29.9	Reject	0.05	X1 >> X2	**RWU do worse than SN**
Chemical present above guidelines	3	4.0	Chemical present above guidelines	0.6	19.6	Accept	0.05	X1 = X2	
Chemical present above guidelines, health effects	0	0.0				Accept	0.05	X1 = X2	
Loss of supply	23	7.6	Loss of supply	0.1	11.9	Reject	0.05	X1 >> X2	**RWU do worse than SN**
			Potential unwholesome medium health effect	0.2	24.8	Accept	0.05	X1 = X2	
			Potential Unwholesome, low health effect	0.2	16.8	Reject	0.05	X2 >> X1	**RWU do better than SN**

Legend	
SN	National standard
RWU	Regional Water Utility
F	Frequency of occurrence
I	Incident impact for respective category

Table 23 Comparison between regional incidents against national baseline for 2004

RWU Incident database			**National Standard (SN) (DWI) customised to RWU (Frequency adjusted over Population)**			**Significance testing**			
						H0: X1 - X2 = 0			
Year						H1: X1 - X2 <>0			
2005						SL: 5%			
						X1	RWU		
						X2	DWI		
	F	I		F	I	H0	SL		**Analysis**
Aesthetics	11	12.8	Aesthetics	4.2	29.1	Reject	0.05	X1 >> X2	**RWU do worse than SN**
Biological pathogens present	3	5.3	Biological pathogens present	1.6	20.3	Accept	0.05	X1 = X2	
Biological pathogens present, health effects	8	19.9	Biological pathogens present, health effects	1.3	46.4	Reject	0.05	X1 >> X2	**RWU do worse than SN**
Chemical present above guidelines	5	4.0	Chemical present above guidelines	0.4	39.0	Accept	0.05	X1 = X2	
Chemical present above guidelines, health effects	0	0.0	Chemical present, health effects	0.3	85.8	Accept	0.05	X1 = X2	
Loss of supply	16	17.7	Loss of supply	0.2	19.3	Reject	0.05	X1 >> X2	**RWU do worse than SN**
			Unwholesome	0.2	10.3	Accept	0.05	X1 = X2	

Table 24 Comparison between regional incidents against national baseline for 2005

RWU Incident database			**National Standard (SN) (DWI) customised to RWU (Frequency adjusted over Population)**			**Significance testing**			
						H0: X1 - X2 = 0			
Year						H1: X1 - X2 <>0			
2006						SL: 5%			
						X1	RWU		
						X2	DWI		
	F	I		F	I	H0	SL		**Analysis**
Aesthetics	7	12.5	Aesthetics	3.8	43.7	Reject	0.05	X2 >> X1	**RWU do better than SN**
Biological pathogens present	3	4.7	Biological pathogens present	1.9	20.5	Reject	0.05	X2 >> X1	**RWU do better than SN**
Biological pathogens present, health effects	1	17.3	Biological pathogens present, health effects	1.0	33.7	Reject	0.05	X2 >> X1	**RWU do better than SN**
Chemical present above guidelines	6	7.6	Chemical present above guidelines	1.0	18.2	Reject	0.05	X1 >> X2	**RWU do worse than SN**
Chemical present above guidelines, health effects	0	0	Chemical present, health effects	0.4	96.1	Accept	0.05	X1 = X2	
Loss of supply	19	7.4	Loss of supply	0.5	8.7	Reject	0.05	X1 >> X2	**RWU do worse than SN**

Table 25 Comparison between regional incidents and national baseline for 2006

For the years 2004 to 2006, it was found in the comparison that on eight counts the Regional Water Utility had significantly worse incident impacts on customers than the national average. On 8 counts it was performing not significantly different to national average. In 5 counts customer impact was significantly better than national average.

In this final analysis, the actual incident data in the Regional Water Utility is compared with the data they reported to the DWI. This analysis is an indication for the willingness to report incidents to the regulator. The significance tests that compare actual incidents with incidents reported to the regulator DWI are presented in Table 26.

RWU Incident database			**RWU reported to DWI**			**Significance testing**			
						H0: X1 - X2 = 0			SL: 5%
						H1: X1 - X2 <>0			
Year						X1	RWU		
2004						X2	DWI		
	F	**I**		**F**	**I**	**H0**	**SL**		**Comment**
Aesthetics	20	13.4	Aesthetics	12	19.0	Reject	0.05	X1 >> X2	The actual incident impact is higher than reported
Biological pathogens present	3	3.3	Biological pathogens present	2	8.6	Accept	0.05	X1 = X2	
Biological pathogens present, health effects	5	24.4	Biological pathogens present, health effects	3	30.6	Reject	0.05	X1 >> X2	The actual incident impact is higher than reported
Chemical present above guidelines	3	4.0	Chemical present above guidelines	1	9.2	Reject	0.05	X1 >> X2	The actual incident impact is higher than reported
Chemical present above guidelines, health effects	0	0.0	Chemical present above guidelines, health effects	0	0	Accept	0.05	X1 = X2	
Loss of supply	23	7.6	Loss of supply			Reject	0.05	X1 >> X2	The actual incident impact is higher than reported
Year									
2005									
	F	**I**		**F**	**I**	**H0**	**SL**		**Comment**
Aesthetics	11	12.8	Aesthetics	5	17.9	Reject	0.05	X1 >> X2	The actual incident impact is higher than reported
Biological pathogens present	3	5.3				Reject	0.05	X1 >> X2	The actual incident impact is higher than reported
Biological pathogens present, health effects	8	19.9	Biological pathogens present, health effects	3	41.2	Reject	0.05	X1 >> X2	The actual incident impact is higher than reported
Chemical present above guidelines	5	4.0				Reject	0.05	X1 >> X2	The actual incident impact is higher than reported
Loss of supply	16	17.7				Reject	0.05	X1 >> X2	The actual incident impact is higher than reported
			Unwholesome	1	4.7	Reject	0.05	X2 >> X1	The actual incident impact is lower than reported
Year									
2006									
	F	**I**		**F**	**I**	**H0**	**SL**		**Comment**
Aesthetics	7	12.5	Aesthetics	5	81.1	Reject	0.05	X2 >> X1	The actual incident impact is lower than reported
Biological pathogens present	3	4.7	Biological pathogens present	3	23.9	Reject	0.05	X2 >> X1	The actual incident impact is lower than reported
Biological pathogens present, health effects	1	17.3				Reject	0.05	X1 >> X2	The actual incident impact is higher than reported
Chemical present above guidelines	6	7.6	Chemicals present above guidelines	2	12.0	Reject	0.05	X1 >> X2	The actual incident impact is higher than reported
Loss of supply	19	7.4				Reject	0.05	X1 >> X2	The actual incident impact is higher than reported

Table 26 Comparison of actual incidents and reported incidents for the years 2004 to 2006

In this analysis, it was found that on 13 counts the actual incident impacts for the hazard categories are significantly higher than the incidents reported to the regulator DWI. On

4 counts the incident impacts in the hazard categories are not significantly different. On 3 counts the actual incidents in the hazard categories are significantly lower than reported to the DWI.

2.5 Summary

In the outset of this thesis, the need to characterise the causes, effect, frequencies and impacts of incidents that affect customers was identified. In this chapter, the "*short periods of stress*" (World Health Organisation, 2004) were characterised in an assessment of incidents frequencies, cause and effect relationships and impact on customers.

Drinking water quality incidents were investigated which occurred in England and Wales in the years 2004 to 2006 and incidents in the Regional Water Utility that occurred between 1997 and 2006. A series of data analyses were performed to identify the cause and effect relationships that govern the outcome of incidents, their impact on customers and the frequency or re-occurrence of incidents for distinct hazard categories. It was found that incident in the Regional Water Utility occur frequently rather than exceptionally. A trend was identified of increasing numbers of annual incidents between 1997 and 2006. Considering the mean time between incidents of 8.7 days, it was suggested that incidents and their management are a normal operating routine.

The analysed incidents do not always constitute 'linear' cause - effect relationships with a single incident root cause and a single incident effect. More appropriately, incidents, in many occasions, can be characterised for their diversity of cause and effect relationships, multiple incident causes and interdependencies in the effects of an incident. In the case studies it was shown that they are often a reflection of the complex interaction between physical and information asset and their interface with human 'assets'. From the study of the 419 incidents and the case studies, supporting evidence was found that incidents affecting the safety and reliability of drinking water mirror the complexities of the asset fabric that constitute this large water supply system. This asset fabric consists of the predominantly physical assets and information asset and their interaction with human 'assets' and cultural, intangible assets including organisational policies for systems design, operation and maintenance but also communication, decision making and organisation structures and hierarchies for asset operation and management. It was also found that precursors for incidents can be introduced as early as in the design phase; furthermore, operational intervention and maintenance issues play a major role in contributing or causing an incident.

For each incident the hazard type, the size of the population affected by the incident and its duration was investigated. In a structured analysis based on a methodology introduced by Deere *et al.* (2001) an incident impact factor was calculated to enable a direct comparison between individual incidents but also between groups of incidents which have been aggregated according to hazard categories. This was used to compare incidents in their respective hazard categories but also to compare incidents at water utility level to the national average.

In comparing the causes, effects, frequency and impact of water utility incidents to a national standard, valuable learning opportunities for water utilities to monitor incident frequencies and impact of incidents on customers were demonstrated. Per definition, the impact of incidents is composed from three components: hazard category, duration of the incident and the size of the population. Evaluating the impact of incidents with this methodology enables the monitoring of trends for the above components. During an incident, the incident management function of an organisation could monitor the components 'incident duration' and 'size of exposed population' as the main management emphasis of incident management. The exposure of a population to hazards during the circumstances of an incident requires a water utility to design and maintain effective incident monitoring and response systems and procedures. Monitoring the frequency of incidents for specific hazard types could be the main emphasis of the asset management function in a water utility. This form of analysis can guide a water utility to prioritise management efforts to improve performance in certain hazard categories. For example, a water utility can specifically target asset maintenance to reduce aesthetical problems in a water supply or the frequency of water main bursts. This would be a typical example for risk-based asset management.

In this chapter, the nature of "*trying conditions*" (Weick, 1987) in the water sector were identified. In the following chapter, the organisational capacity to respond to incidents and the ability to manage risk is investigated in the context of the previously introduced

High Reliability Organisations Framework that has been conceptualised to describe the means of creating organisational resilience. So far, it is understood that every incident that occurred required organisational capacities to identify the incident, reduce its impact on customers and processes and procedures to re-instate normal operations. This is primarily a capacity within operations management that assumes the role of managing incidents.

In the following chapter, the organisational preparedness for these short periods of stress is further investigated. Here, the objective is to investigate the benefit of HRO principles in incident management and to correlate incident impacts on customers and impact reductions with observation of high reliability principles under trying conditions.

3 High reliability in incident management

3.1 Introduction

In the literature review, it was identified that high reliability theory has not been researched in the context of providing safe and reliable drinking water to customers. Without an existing knowledge base in this area, it was decided to conduct a series of studies that investigate the familiarity of the water sector with the principles of high reliability organisations. In this chapter, the prevalence of HRO principles in the water sector and their perceived organisational benefit in the provision of safe and reliable drinking water to customers is investigated. The perceived benefit of HRO principles was also investigated in the context of the cost required to implement and maintain the described HRO principles.

High Reliability Organisations (HRO) have been characterised for providing resilience during "*trying conditions*" (Weick, 1987) – in the water sector context this relates to normal operating conditions deteriorating into abnormal events, incidents and significant incidents. At the extreme end, the organisation has to be capable to contain emergencies whilst minimising the impact of public health hazards on the affected population. For the investigation of a water utility under "*trying conditions*" (Weick, 1987), recently experienced incidents were identified for further analysis and research. In a series of incident analyses, it was aimed to identify whether HRO characteristics were observable during the management of incidents. For this purpose, the author had access to the incident control room and staff involved during incidents but also a vast body of documented incident records.

Twofold questions are investigated in this chapter. Firstly, how familiar is the water sector with the principles of high reliability organisations (HRO)? Here, it was aimed to identify the benefit of HRO principles in providing safe and reliable drinking water to customers in the context of the cost to implement, operate and maintain these principles. This represents a form of cost benefit analysis or economic cost benefit trade-off.

Secondly, it is investigated if HRO principles in incident management significantly reduce the public health impact on a population during an incident.

Three main sub-studies were carried out: Firstly, a series of surveys with water utility staff to identify the familiarity of water utilities with HRO principles were conducted.

Secondly, the author acted as an observer in the operations and incident control centre. During unfolding incidents, it was aimed to observe the HRO characteristics during the handling of incidents. These studies were enhanced by staff interviews (Appendix 4.3.4) and document reviews, *e.g.* standard operating procedures, policies, communiqués, etc., to underpin the observations. Thirdly, based on a large number of highly detailed incident analysis documentations, the documented incidents were cross-reviewed against an HRO framework and the impact of incident management correlated against evidence of documented HRO principles.

In this chapter two chapter-hypothesises are used to structure the study. Firstly, it is hypothesised that the water sector is familiar with the principles of HRO in the context of providing safe and reliable drinking water to customers. Secondly, a water utility makes provisions for the "*short periods of 'stress'*" (World Health Organisation, 2004) with the design of incident management procedures that are based on HRO principles.

A number of sub-hypotheses were also used with specific relevance for subsequent chapters in this thesis. In particular, it is hypothesised that

- 'water utilities maintain existing technology to an exceptionally high level';
- 'water utilities use root cause analysis of minor errors and incidents as a source for learning'; and
- 'water utilities develop a collective memory for failures, incidents and root causes of failure to help anticipating future problems'.

3.2 Theoretical development

High reliability theory (HRT) claims to having discovered principles that reduce the accident susceptibility of complex and tightly coupled systems and creates organisational resilience under trying conditions (Weick, 1987). HRT has two distinct pillars: firstly an approach to technical reliability and, secondly, an approach to organisational reliability and resilience. The technical reliability is concerned with the design and maintenance of asset systems including their system redundancy to produce and deliver reliable product and services. Organisational reliability, on the other hand, has been described as an approach for effective decision-making, organisational learning, communication, organisational structures and human resource practices. They are reflected in the culture of an organisation.

The previous chapter that analysed incidents in England and Wales between 2004 and 2006 and in the Regional Water Utility between 1997 and 2006 demonstrated that incidents can present trying conditions to a water utility. These trying conditions require an incident management response to reduce the impact of incidents on customers and to re-instate normal operating conditions. Therefore, water utilities are a suitable candidate to investigate the resilience of an organisation under trying conditions based on HRO principles.

For this purpose, an HRO framework was developed to investigate the prevalence of HRO principles in water utilities. This HRO framework was deductively derived in the literature review and is presented in Table 27 to Table 31. This HRO framework was used to observe and evaluate HRO principles in the water utility context under trying conditions. It was also used to structure surveys, observations, document reviews and interviews.

Organisational culture of reliability	
Ref.	**Description**
A1	In my organisation, staff in operations has a strong sense for the primary mission of the organisation and share a common system of beliefs and perceptions.
A2	In my organisation, the water supply system is continuously monitoring so that failure events are foreseen and understood.
A3	In my organisation, our staff in operations has a highly developed understanding of their contribution to water safety and their role in the system.
A4	In a water quality incident, our staff in operations acts in a collaborative and collegiate manner and the group interaction can be described as collective intelligent interaction.
A5	Our staff in operations is sensitive towards all events where water supply reliability is concerned. Staff knows that a very small initial moment of inattention or misperception can lead to an escalation of failure which can result in a water quality incident.
A6	All our employees take responsibility where problems are identified and immediate corrective action programmes are required.
A7	Our staff in operations is obliged to report their mistakes without fear of punishment.
A8	In our organisation, individual behaviours which jeopardise the primary mission of reliability are labelled as disgrace.
A8a	Our senior management is committed to the reliability of the organisation. This is communicated to all levels in the organisation and demonstrated with investments in technology, processes and personnel.
A9	In our organisation, individuals “monitor, advise, criticize and support” each other, in particular in situations where mistakes are more likely to occur.
A10	In general, our staff is attentive, alert and act with care.

Table 27 High reliability organisations framework

Continuous learning and intensive training	
Ref.	**Description**
B1	In order to facilitate continuous learning and intensive training, our organisation constantly reviews their processes and ways of operating.
B2	In preparation for a job, our staff in operations and maintenance staff receive training on the requirements of maintaining a safe system. These are embedded in formal rules, general guidelines and standardised frameworks.
B3	Our staff in operations must adhere to standard operating procedures but also pro-actively identify potential sources of failure and actions to stop faults from escalating.
X1	Our staff question procedures when in doubt about their appropriateness.
X2	In unforeseen situations, staff in operations doesn't follow rules blindly, but negotiate the course of action in a collegial manner with more experienced staff and supervisors.
X3	During a water quality incident, staff in operations establish an emergency response team for joint decision making in order to avoid overlooking complex circumstances.
B4	All our staff maintains a commitment to continuous learning and seeks the acquisition and improvement of skills.
B5	In our organisation we learn from failures, near misses and mistakes by other utilities and use these as a means to study the failure susceptibility of the own organisation.
B6	In our organisation, even minor errors and incidents provide a source for learning which are assessed through root cause analysis.
B7	Our organisation develops a collective memory for failures, incidents and root causes for failure which helps the organisation to anticipate future problems.
B8	In our organisation, we share a sense that learning from trial and error is not feasible to understand our water supply system. For staff training, we use offline methods of learning which consist of realistic drills, simulations and exercises to replicate potential failure scenarios.

Table 28 High reliability organisations framework (continued)

Effective and varied patterns of communication	
Ref.	**Description**
C1	Our communication system makes our water supply system better understandable, predictable and controllable.
C2	Our organisation operates in an information rich environment. All processes are measured and understood. Data are transparent and made available to all.
C3	Our staff in operations is encouraged to share their experiences relating to the reliability of the system. Communication is designed as bottom up and top down to ensure rapid flow of information through the hierarchy of the system. Rapid dissemination of information helps the organisation to respond to water quality incidents with corrective action aiming to prevent the escalation of failure.
X1	During a water quality incident, the response team maintains "closed loop" communication with all stakeholders within the organisation
X2	During a water quality incident, the organisation maintains "closed loop" communication with the public, regulators and government authorities
C4	In our organisation, communicating information shapes the 'big picture' of our organisational vision, mission and responsibility of individuals towards reliability.
C5	Our organisation uses various channels to transmit different types of data and information relating to monitoring and control of our assets (and ultimately water safety). Direct and complementary information enhance information reliability and provides a form of redundancy.
C6	Multiple monitoring and control data from a variety of sources provide information density which allows individual signals to be scrutinised for fitting into the whole information pattern. Abnormal signals are treated as an indication for latent errors to unfold into failures.
C7	In our organisation, interpersonal communications are formalised in a precise, unambiguous, impersonal and efficient structure, which denies individuals to communicate in their idiosyncratic communication style.

Table 29 High reliability organisations framework (continued)

Adaptable decision making dynamics and flexible organisational structures	
Ref.	**Description**
D1	Our organisation can only prevent outbreaks with a high level of centralisation, because low-level decision makers have insufficient understanding of the inter-relationship between their action and consequences on other elements of the water supply system. During an emergency, control has to be maintained highly centralised in order to maintain overview of the entire system response to action on all sub-units.
D2	In our organisation, decentralisation is required to respond rapidly to unfolding failures. An emergency can be confined to one sub-unit which is subsequently isolated from the entire system. The control over an emergency is decentralised to this subunit until the emergency is cleared.
D1/2a	In our organisation, centralisation at collective level coexists with decentralisation at individual level. The organisation exhibits an adaptive, flexible or organic nature.
D3	Our organisation enforces the stringent adherence to standard operating procedures aiming for repeatability of action and routines.
D4	Our standard operating procedures are constantly updated and incorporate lessons learnt. Formal rules and procedures are effective elements to identify and control risk.
D5	In our organisation, activities which are not defined in standard operating procedures are based on decisions a most senior individual makes as they should have the best knowledge of the system.
D6	Our organisation has a hierarchical structure for decision making which reflects expertise, know-how and seniority. Each level has controls and regulating mechanisms.
D7	Our organisation requires staff to conform to organisational norms and avoids innovative, autonomous or creative behaviours.
D8	Our decision-making processes have slack in-built in order to assess and challenge decisions to avoid faulty decisions to escalate into failure.

Table 30 High reliability organisations framework (continued)

System and human redundancy	
Ref.	**Description**
E1	Our organisation maintains reserve capacity in the system. This includes back-up functions, overlapping tasks and responsibilities.
E2	In our organisation, we are aware that redundancy can be counterproductive. Back-up functions can increase technical complexity, conceal errors and can lead individuals into not performing their required tasks under the assumptions that someone else takes care of his task.
Precise procedures in managing technology	
F1	Our organisation does not use state of the art equipment to ensure that our technology does not add unnecessary complexity to the organisation.
F2	In water supply systems design, our organisation aims to simplify complex technical systems and avoid unnecessary automation.
F3	New technology acquisition is only justified if existing equipment does not perform to required specification.
F4	In our organisation, existing technology is maintained to exceptionally high standards, as we do not tolerate defective, substandard or malfunctioning equipment.
F5	In our organisation, maintenance activity and protocols as well as performance data are used to monitor the healthy operation of the system.
Human resource management practices that support reliability	
G1	In recruitment and selection, our organisation acquires suitable and skilled candidates for the jobs aiming to match the complexity of the environment with an equally complex set of people to understand the system. Diverging backgrounds for staff offer different ways of looking at systems.
G2	Since most people do what is rewarded, our organisation remunerates reliability with incentives, recognition and career opportunities.
G3	In our organisation, job rotation increases networking between teams and helps the organisation to transfer and diffuse knowledge and lessons learnt.
G4	Our organisation has systems in place to monitor the behaviour of staff.

Table 31 High reliability organisations framework (continued)

In the literature review, it was identified that water utilities increasingly use an explicit, risk-based approach to decision-making that uses cost benefit analysis or cost-risk trade-off models to evaluate the merits of investments to reduce or maintain risks. Similar to physical assets, changing the culture in an organisation requires investment and maintenance in training, communication and competence building. For this research, the need to evaluate the perceived benefit of HRO principles in providing safe and reliable drinking water to customers in the context of the cost to operate and maintain these principles was identified. This enables an analysis of the perceived cost benefit or an economic cost benefit trade-off analysis.

The first analysis in this chapter was designed to investigate the familiarity of the water sector with the principles of high reliability organisations. Water utility managers and staff were invited to participate in a survey on HROs. The survey required the participants to observe HRO principles in their organisation and to evaluate the merit of implementing and/or maintaining those HRO principles. The first survey series was conducted with water utility managers from various international water utilities followed by an in-depth survey of managers and staff in the Regional Water Utility. This survey aimed to capture the 'world view' of the organisation as a general perception of staff members on 'how we do things here' with respect to HRO principles.

In the next analysis, the author acted as an observer during a six-month placement in the Regional Water Utility. During this placement, the processes and culture in the operations and incident management department as well as the asset management department were studied. During that period, interviews with staff were conducted and documents and processes studied. This placement also facilitated a review of past incidents for an analysis specific to HRO principles. A series of well-documented incidents were identified and the observance of HRO principles during incident management investigated. These were used to correlate the observed HRO principles with a) the impact of these incidents on customers using the methodology based on Deere *et al.* (2001) and b) with an assessment of an effective incident impact reduction and re-instatement of normal operations.

Finally, a series of case studies were identified to demonstrate how observable HRO principles operated under "*trying conditions*" (Weick, 1987).

3.3 Methodology

In this chapter four different methodologies were used to structure this research aspect. The use of multiple methodologies were thought to provide a form of triangulation for investigating the subject matter of this chapter. The four methodologies adopted were surveys, observations, analysis of historical records and interviews.

The first research element discussed here are the surveys that were conducted to explore the prevalence of HRO principles in the water sector and their cost benefit to provide safe and reliable drinking water for customers.

The HRO survey is a phenomenological methodology aiming to capture qualitative data from a number of participants. Considering the aim to reach out to a significant number of participants the conduct of interviews had to be ruled out and a strategy of self-administrated, structured surveys as a research tool was adopted. The survey questionnaire was deductively derived from high reliability theory and logically applied to the water sector. Surveys offer a time-effective means of data acquisition although problems may arise regarding the quality of data obtained. These problems may arise when questions remain unanswered or are misinterpreted. The form of survey adopted in this research enabled the use of numerical techniques to process the data by coding the results with numerical values for subsequent analysis. The research design envisaged to obtain two sets of data samples that were subsequently compared.

The second methodology adopted in this chapter were observations in the regional water utility. This form of research is best categorised as phenomenology and studies how the researching individual experiences events (Trochim, 2000). It may also be used as a method of trying to understand how an individual perceives and constructs their reality (Robson, 2002). Observational methods can be used to investigate what groups or individuals do and recording their actions and describing their activities offers data rich accounts of real-world research (Robson, 2002). However, there is a danger of the researcher to influence the results, in particular when considering mental frameworks that are shaped by heuristics or expectations.

In addition to surveys and observations, it was decided to extend the form of historical research described in Chapter 2 towards identifying evidence of HRO principles in the records of documented incidents. It was thought that further evidence was required to substantiate the claims made by the participants of the survey and the evidence recorded in the observational study. The content as well as context analysis of recorded incidents sought to identify how these HRO principles are used to reduce the impact of incidents. As described earlier, the qualitative data contained in historic documents uses language, description and expression and provides highly animated, rich and deep information (Trochim, 2000). The coding of language provides the facility to identify patterns in the data and it was decided to use selective coding of language based on pre-conceived concepts introduced in the literature on high reliability theory. The methodological approach for these studies were considered to supplement the other forms of research methodologies and data analyses: firstly, the use of historical data is perceived to reflect the truth of what was known at the time and removes any attempt to revise knowledge with hindsight ideas or concepts. Secondly, the selective coding of language found in the incident documentations avoided unnecessary open coding of language and enabled the use of well established ideas and concepts to be used to categorise data. Considering the volume of data records used in this research element, selective coding provided the highest benefit in the context of time required to code incidents.

In addition to the historical research, semi-structured interviews were conducted with staff who were recently involved during incidents. This represents a further form of triangulation to the historical research and presents another form of phenomenology as a method of trying to understand how an individual perceives and constructs their reality (Robson, 2002). Although this form of research provides highly detailed data based on highly personalised and subjective experiences it was thought that the content analysis based on semi-structured interviews provides rich and detailed data with expressive and enlightening information (Wengraf, 2001) on how staff experience and make sense of incidents despite the lack of standardisation in its results. A further advantage over structured interviews is the ability to react to emergent topics that are raised by the interviewee (Robson, 2002).

3.3.1 The concept of HRO in an international water sector context

Based on the previously deducted HRO framework a survey questionnaire was developed to investigate HRO principles in a range of water utilities. 14 water utility professionals from a range of international water utilities in highly developed countries were invited to participate in this self-administrated questionnaire (Appendix 4.3.1). The selection criteria for inviting participants focussed on risk-, operations- and asset managers who were invited to attend a workshop on risk management culture in December 2006 in Banff, Canada.

The invitees represented a range of water utility sizes and various water utility ownership models. The participants represented

- medium to large-sized, privately owned water utilities from England and Wales;
- a large-sized, corporatized, publicly-owned water utility in Scotland;
- a medium-sized, corporatized, publicly-owned water utility in Canada;

- small to medium - sized, publicly owned and operated water utilities in Canada; and
- a small - sized, publicly owned and operated water utility in the USA.

For the purpose of subsequent analysis, the organisational types differentiated between private and public ownership but also considered its corporate structure. 'Public' denotes public ownership and operated within government administration, 'public corporate' denotes public ownership operated within financially accountable corporate structures and 'private' denotes private/shareholder ownership with a corporate structure. The utility size indicates the number of customers supplied by the water utilities. 'Small' denotes less than 100,000 customers, 'Medium' represents a customer base between 100,000 and 1,000,000 and 'Large' denotes a water utility with more than 1,000,000 customers.

In the first part of the survey, the participants were required to identify and observe the prevalence of the individual HRO principles in their organisation. The questionnaire was designed as an organisational self–assessment and required the participant to record their observation using the legend in Table 32. For further statistical analysis, a scoring system was used that reflects the criteria detailed in the choice of answers. These scores were not visible to the participant.

Choice of answer	**Criteria**	**Score**
Strongly Agree	"This attribute is observable throughout my organisation without any exception!"	100
Agree	"This attribute is observable throughout my organisation with some exceptions!"	80
Disagree	"This attribute is not observable throughout my organisation. There are, however, some exceptions!"	20
Strongly Disagree	"This attribute is not observable throughout my organisation.	0

Table 32 Assessment criteria for HRO survey

In the second part, the participants were requested to evaluate the benefit of each HRO principle in a cost benefit assessment. Here, the participant was prompted to evaluate the merit of the HRO principle in contributing to the provision of safe and reliable drinking water in the context to the cost of implementing and maintaining the HRO principle. A framework was provided to consider the cost implications of implementing and maintaining HRO principles. The framework in Table 33 prompted the participants to consider the capital and operational expenditures for physical assets, human resource management and information assets required to implement and maintain HRO principles in the organisation.

Change management model	Criteria
Policy	Consider the policy required to implement and maintain the described HRO principle.
Organisation	Consider the cost for providing an organisation structure required to plan, implement, monitor, audit and review a policy which facilitates the described HRO principle.
Planning and Implementation	Consider the cost for planning and implementing a policy which facilitates the described HRO principle.
Monitoring	Consider the cost for a monitoring programme required to measure the success of the HRO principle.
Auditing	Consider the cost for auditing requirements to verify the successful operation of the HRO principle.
Review	Consider the cost for review procedures to ascertain the effectiveness of the HRO principle

Table 33 Implementation and maintenance framework for HRO principles in an organisation

The participants were prompted to use the legend presented in Table 34 to answer the cost benefit analysis questionnaire. For further statistical analysis, a scoring system was used that reflects the criteria detailed in the choice of answers. These scores were not visible to the participants.

Choice of answer	Criteria	Score
Highly cost beneficial	The benefits significantly outweigh the costs incurred	10
Balanced cost benefit	Approximate parity between cost and benefits	0
Negative cost benefit	The costs significantly outweigh the benefits	-10

Table 34 Assessment criteria for the cost benefit of HRO principles

The range of answers is reflected the following equations.

Positive cost benefit $= \Delta Benefit - \Delta Cost > 0$

Balanced cost benefit $= \Delta Benefit - \Delta Cost = 0$

Negative cost benefit $= \Delta Benefit - \Delta Cost < 0$

It should be noted that 'benefit' denotes 'risk reduction' and relates to reducing public health impact during incidents or public health risks.

The acquired data enabled a number of statistical analyses: Firstly, it enabled the calculation of scores for the individual questionnaire sections and a total score of observed HRO principles for each participant. The results represent a numerical analysis of identified HRO principles for the individual water utilities.

Secondly, it enabled the calculation of average scores for the individual questionnaire sections and a total average score for all participants. This analysis calculated the average score, standard deviation, standard error and a 95% confidence interval for each HRO principle. The results from this survey were subsequently used for a comparison with an identical survey in the Regional Water Utility.

Thirdly, it enabled the calculation of scores for the individual questionnaire sections and a total score for the cost benefit analysis for all participants. This analysis calculated the average score, standard deviation, standard error and a 95% confidence interval for each HRO principle. These results represent the evaluated cost benefit for each HRO principles in a cross section view for the participating water utilities.

Previous to launch, the survey was tested by fellow students and peer-reviewed by academic supervisors and the AWWARF Project Advisory Group.

Alongside the survey, six international water utility professionals from the above sample were invited to participate in an interview series to enquire aspects relating to the management of water safety, reliability and incidents. The interview series was designed as a pilot study to inform the detailed study in the Regional Water Utility. The questionnaire (Appendix 4.3.3) was previously peer-reviewed.

3.3.1.1 Data quality

The analysis and evaluation of the data aquired in the survey and interview has to consider that participants responded according to individual perceptions and observations. These individuals have their own heuristic frameworks for observations but also motivations to participate in this survey and interviews. Each survey return is a subjective assessment of HRO principles within the boundaries of their, idiosyncratic water utilities. The subjectivity of the survey is illustrated by the following observation: In the survey, two participants were selected to carry out an assessment in one water utility. It was found that their assessment of HRO principles marginally deviated from another.

Although this study provides valuable, initial insights into the culture and philosophies of water utilities, the results of this survey cannot be extrapolated to represent the entire, international water sector of highly developed countries. These participants represent only a little number of water utility segments in terms of their size, country of origin and ownership models. Furthermore, the selection of these individuals was pre-screened by their involvement in an international workshop on “risk management cultures” in Banff in 2005 which also explains the high return rate of completed surveys.

3.3.2 HRO principles in the Regional Water Utility

Based on the HRO framework survey used in the previous study an in-depth survey was prepared and launched in the Regional Water Utility. In total 27 operations managers and operators in the water supply department were invited to partake in this survey. The participants reflect a range of professional experience, office or site locations within the region and different degrees of responsibilities in the provision of safe and reliable drinking water. The invited staff were selected for their recent involvement in the management of an incident dating back no further than 6 months. The statistical analysis of the survey returns enabled a direct comparison with the survey results from the international participants and enabled a significance test between both samples.

Following the survey, structured observations in the organisation were conducted, in particular in operations and incident management. The above HRO framework was used as a guiding document to observe work processes and activities in the operations management department in particular during the management of incidents. As a silent and passive observer, the author monitored and recorded organisational processes and activities during the management of incidents.

Building on the observations of incident management, it was further aimed to correlate the actual impact of incidents on customers with a structured assessment of evidently documented HRO principles observed or adhered to during their management. Based on detailed, narrative accounts of incidents in the incident documentation, individual, well-documented incidents were selected and evaluated against an adapted version of the HRO framework (Appendix 4.3.2). In a statistical analysis, the individual incident impacts on customers were correlated with the documented adherence to HRO principles during the management of incidents. The selection of incidents employed a methodological approach of non-random selection of extreme incident cases (Schnell *et al.*, 1995) that reflect operating *"under trying conditions*" (Weick, 1987): All incidents for the years 2004 to 2006 were identified and a confidence interval at 95% for the incident impacts was constructed. With the confidence interval, those incidents with a significantly lower and higher incident impact as well as incidents with average impact were identified for the individual years. Out of these, 12 incidents per year were selected aiming to reflect four incidents with a significantly high incident impact, four incidents with a significantly low incident impact and four incidents with an incident impact within the range of the minimum and maximum confidence interval. In the selection process of incidents, it was ensured that these incidents were well documented to enable a thorough document analysis. The selection process of incident case studies is further discussed in Appendix 4.2.3.

Individual incident impacts were plotted against the numeric score for HRO principles that were, according to the incident documentation, observed or adhered to during incident management. This analysis was performed for the overall HRO score per incident as well as for the individual groups of HRO principles.

For each of these analyses a coefficient of determination was derived to explain the range of incident impacts as a function of HRO principles. Furthermore, a significance test was performed to compare the average HRO scores for incidents with significantly low incident impacts on customers to the average HRO scores for incidents with significantly high incident impacts. Using significance testing, the results of this analysis were also compared to the results of the previously conducted survey on HRO.

Finally, a series of case studies were identified to demonstrate how HRO principles can operate under "*trying conditions*" (Weick, 1987). In a narrative format, the potential incident impact is compared to the actual incident impact whilst considering the influence of HRO principles as a beneficial contributor to reduce the impact on customers. The assessed impact reduction was correlated with the obtained HRO scores. Alongside the above studies, a series of interviews was launched to explore how the Regional Water Utility prepares for and performs under "*trying conditions*" (Weick, 1987) but also to understand the process of incident investigation.

3.3.2.1 Data quality

The main sources of data in this study originated from the Regional Water Utility who provided access to staff for interviews and surveys but also a vast repository of documented incidents. The predominant source of data used in this study is historical data and personal accounts of staff involved in recent incidents. In most cases, incident files describing individual incidents contained lengthy logbook entries, detailed incident review minutes and personal communications of staff involved during the incidents.

The survey, structured observations, interviews and the study of documented interviews were used as a triangulating technique to reduce personal bias and ambiguity. However, the analysis and evaluation of the survey data and the interviews reflect individual perceptions and observations of the participants. These individuals have their own heuristic frameworks for observations but also motivations for participating in the survey and interviews.

The data quality used for the analysis of documented incidents was previously discussed in the context of characterising incidents. In this chapter, it was aimed to understand the motivation behind the analysis of incidents that are subsequently reflected in the incident documentation. It was previously argued that documentation can be highly biased due to the views the authors may have had at the time of recording data (Denzin and Lincoln, 1994).

3.4 Results and Discussion of Results

3.4.1 The concept of HRO in an international water sector context

In total, the author received 14 completed questionnaires from the participants in the survey. They were returned by email or handed over at the 'Risk management culture' conference in December 2006 in Banff. Two returned questionnaire were only half-completed and, hence, represented exceptionally low data quality.

In Table 35 and Table 36, the observation of the participants in their water utilities is summarised in percentage of all observations. The alpha-numeric reference number refers to the HRO principles in Table 27 and Table 31. It can be identified that HRO principles are not observed homogeneously across the participating water utilities. The majority of observations confirm that a particular HRO principle may be observable by a number of participants, whereas others have not observed them in their organisation. In 40 out of 51 HRO principles, the majority of participants 'strongly agree' or 'agree' to having observed those principles in their organisations. In total, 61% of the overall responses 'strongly agreed' or 'agreed' with having observed the stated HRO principles in the organisations. Thereof, 12.7% of the overall responses 'strongly agreed' and 48.3% of the responses 'agreed' with having observed the stated HRO principles. 34.7% of the overall responses 'disagreed' and 4.2% 'strongly disagreed' with having observed the stated HRO principles in the organisations. Further detailed analyses of the survey data is presented in Appendix 4.2.1.

	Percentage of participants observing HRO principles				
Reference to HRO principle	Combined 'Strongly agree' & 'Agree'	Strongly agree	Agree	Disagree	Strongly disagree
A1	84.6%	38.5%	46.2%	15.4%	0.0%
A2	91.7%	16.7%	75.0%	8.3%	0.0%
A3	91.7%	25.0%	66.7%	8.3%	0.0%
A4	91.7%	50.0%	41.7%	8.3%	0.0%
A5	91.7%	41.7%	50.0%	8.3%	0.0%
A6	66.7%	8.3%	58.3%	33.3%	0.0%
A7	83.3%	16.7%	66.7%	16.7%	0.0%
A8	0.0%	0.0%	0.0%	83.3%	16.7%
A8a	100.0%	16.7%	83.3%	0.0%	0.0%
A9	50.0%	8.3%	41.7%	50.0%	0.0%
A10	100.0%	41.7%	58.3%	0.0%	0.0%
B1	91.7%	25.0%	66.7%	8.3%	0.0%
B2	66.7%	13.3%	53.3%	33.3%	0.0%
B3	71.4%	14.3%	57.1%	28.6%	0.0%
X1	66.7%	8.3%	58.3%	25.0%	8.3%
X2	66.7%	8.3%	58.3%	33.3%	0.0%
X3	91.7%	58.3%	33.3%	8.33%	0.0%
B4	58.3%	0.0%	58.3%	33.3%	8.3%
B5	66.7%	25.0%	41.7%	25.0%	8.3%
B6	33.3%	0.0%	33.3%	50.0%	16.7%
B7	42.9%	0.0%	42.9%	50.0%	7.1%
B8	58.3%	0.0%	58.3%	33.3%	8.3%
C1	66.7%	8.3%	58.3%	33.3%	0.0%
C2	61.5%	7.7%	53.9%	38.5%	0.0%
C3	76.9%	7.7%	69.2%	23.1%	0.0%
X1	57.1%	7.1%	50.0%	42.9%	0.0%
X2	72.7%	9.1%	63.6%	27.3%	0.0%
C4	58.3%	8.3%	50.0%	41.7%	0.0%
C5	91.7%	0.0%	91.7%	8.3%	0.0%
C6	57.1%	0.0%	57.1%	35.7%	7.1%
C7	0.0%	0.0%	0.0%	83.3%	16.7%
			Continued overleaf		

Table 35 Summary of observed HRO principles in percentages of all observations from 14 participants in the HRO survey

	Percentage of participants observing HRO principles				
Reference to HRO principle	**Combined 'Strongly agree' & 'Agree'**	**Strongly agree**	**Agree**	**Disagree**	**Strongly disagree**
D1	23.1%	0.0%	23.1%	76.9%	0.0%
D2	38.5%	0.0%	38.5%	61.5%	0.0%
D1/2/a	76.9%	30.8%	46.2%	23.1%	0.0%
D3	57.1%	0.0%	57.1%	42.9%	0.0%
D4	58.3%	16.7%	41.7%	25.0%	16.7%
D5	33.3%	0.0%	33.3%	66.7%	0.0%
D6	71.4%	0.0%	71.4%	28.6%	0.0%
D7	8.3%	0.0%	8.3%	58.3%	33.3%
D8	54.6%	9.1%	45.5%	36.4%	9.1%
E1	50.0%	25.0%	25.0%	33.3%	16.7%
E2	41.7%	8.3%	33.3%	50.0%	8.3%
F1	30.8%	0.0%	30.8%	61.5%	7.7%
F2	58.3%	8.3%	50.0%	41.7%	0.0%
F3	41.7%	25.0%	16.7%	58.3%	0.0%
F4	33.3%	8.3%	25.0%	66.7%	0.0%
F5	84.6%	15.4%	69.2%	15.4%	0.0%
G1	78.6%	21.4%	57.1%	21.4%	0.0%
G2	53.9%	15.4%	38.5%	38.5%	7.7%
G3	50.0%	0.0%	50.0%	41.7%	8.3%
G4	58.3%	8.3%	50.0%	25.0%	16.7%
Sum	**61.0%**	**12.7%**	**48.3%**	**34.8%**	**4.3%**

Table 36 Summary of observed HRO principles in percentages of all observations from 14 participants in the HRO survey (continued)

Based on the scoring system introduced in the methodology, a numerical analysis of the data was conducted and the average, SD, SE and CI 95% for all survey responses calculated. The averages for the observed HRO principles and the cost benefit analysis were derived by multiplying each observation and cost-benefit analysis with the scoring factors previously introduced in Table 32 and Table 34. The total sum was then divided by the number of observations. Based on the statistical analysis for the cost benefit analysis, those HRO principles were identified that were evaluated by the participants with an average positive cost benefit. In other words, the participants in the survey evaluated these particular HRO indicators to have an average positive cost benefit for effectively contributing to the safety and reliability of drinking water supply. These HRO principles are presented in Table 37 to Table 42. The Tables also record the combined observation of HRO principles in the participating water utilities. The aggregated observation of these HRO principles reflects whether the participants observed these principles being implemented or maintained in their organisations.

Ref	Description	**1) Observable in my organisation**			
Cost Benefit Analysis (CBA): Av>=0		Strongly agree	Agree	Disagree	Strongly disagree
Organisational culture of reliability					
A1	In my organisation, staff in operations has a strong sense for the primary mission of the organisation and share a common system of beliefs and perceptions.	5	6	2	0
A2	In my organisation, the water supply system is continuously monitoring so that failure events are foreseen and understood.	2	9	1	0
A3	In my organisation, our staff in operations has a highly developed understanding of their contribution to water safety and their role in the system.	3	8	1	0
A4	In a water quality incident, our staff in operations acts in a collaborative and collegiate manner and the group interaction can be described as collective intelligent interaction.	6	5	1	0
A5	Our staff in operations is sensitive towards all events where water supply reliability is concerned. Staff knows that a very small initial moment of inattention or misperception can lead to an escalation of failure which can result in a water quality incident.	5	6	1	0
A6	All our employees take responsibility where problems are identified and immediate corrective action programmes are required.	1	7	4	0
A7	Our staff in operations is obliged to report their mistakes without fear of punishment.	2	8	2	0
A8a	Our senior management is committed to the reliability of the organisation. This is communicated to all levels in the organisation and demonstrated with investments in technology, processes and personnel.	2	10	0	0
A9	In our organisation, individuals "monitor, advise, criticize and support" each other, in particular in situations where mistakes are more likely to occur.	1	5	6	0
A10	In general, our staff is attentive, alert and act with care.	5	7	0	0

Table 37 HRO principles with a positive cost benefit

Ref.	Description	Observable in the organisations			
	Cost Benefit Analysis (CBA): Av>=0	Strongly agree	Agree	Disagree	Strongly disagree
Continuous learning and intensive training					
B1	In order to facilitate continuous learning and intensive training, our organisation constantly reviews their processes and ways of operating.	3	8	1	0
B2	In preparation for a job, our staff in operations and maintenance staff receive training on the requirements of maintaining a safe system. These are embedded in formal rules, general guidelines and standardised frameworks.	2	8	5	0
B3	Our staff in operations must adhere to standard operating procedures but also pro-actively identify potential sources of failure and actions to stop faults from escalating.	2	8	4	0
X1	Our staff question procedures when in doubt about their appropriateness.	1	7	3	1
X2	In unforeseen situations, staff in operations doesn't follow rules blindly, but negotiate the course of action in a collegial manner with more experienced staff and supervisors.	1	7	4	0
X3	During a water quality incident, staff in operations establish an emergency response team for joint decision making in order to avoid overlooking complex circumstances.	7	4	1	0
B4	All our staff maintains a commitment to continuous learning and seeks the acquisition and improvement of skills.	0	7	4	1
B5	In our organisation we learn from failures, near misses and mistakes by other utilities and use these as a means to study the failure susceptibility of the own organisation.	3	5	3	1
B6	In our organisation, even minor errors and incidents provide a source for learning which are assessed through root cause analysis.	0	4	6	2
B7	Our organisation develops a collective memory for failures, incidents and root causes for failure which helps the organisation to anticipate future problems.	0	6	7	1
B8	In our organisation, we share a sense that learning from trial and error is not feasible to understand our water supply system. For staff training, we use offline methods of learning which consist of realistic drills, simulations and exercises to replicate potential failure scenarios.	0	7	4	1

Table 38 HRO principles with a positive cost benefit (continued)

Ref.		Observable in the organisations			
	Cost Benefit Analysis (CBA): Av>=0	Strongly agree	Agree	Disagree	Strongly disagree
Effective and varied patterns of communication					
C1	Our communication system makes our water supply system better understandable, predictable and controllable.	1	7	4	0
C2	Our organisation operates in an information rich environment. All processes are measured and understood. Data are transparent and made available to all.	1	7	5	0
C3	Our staff in operations is encouraged to share their experiences relating to the reliability of the system. Communication is designed as bottom up and top down to ensure rapid flow of information through the hierarchy of the system. Rapid dissemination of information helps the organisation to respond to water quality incidents with corrective action aiming to prevent the escalation of failure.	1	9	3	0
X1	During a water quality incident, the response team maintains "closed loop" communication with all stakeholders within the organisation	1	7	6	0
X2	During a water quality incident, the organisation maintains "closed loop" communication with the public, regulators and government authorities	1	7	3	0
C4	In our organisation, communicating information shapes the 'big picture' of our organisational vision, mission and responsibility of individuals towards reliability.	1	6	5	0
C5	Our organisation uses various channels to transmit different types of data and information relating to monitoring and control of our assets (and ultimately water safety). Direct and complementary information enhance information reliability and provides a form of redundancy.	0	11	1	0
C6	Multiple monitoring and control data from a variety of sources provide information density which allows individual signals to be scrutinised for fitting into the whole information pattern. Abnormal signals are treated as an indication for latent errors to unfold into failures.	0	8	5	1

Table 39 HRO principles with a positive cost benefit (continued)

Ref.	Description	Observable in the organisations			
	Cost Benefit Analysis (CBA): Av>=0	Strongly agree	Agree	Disagree	Strongly disagree
Adaptable decision making dynamics and flexible organisational structures					
D2	In our organisation, decentralisation is required to respond rapidly to unfolding failures. An emergency can be confined to one sub-unit which is subsequently isolated from the entire system. The control over an emergency is decentralised to this subunit until the emergency is cleared.	0	5	8	0
D1/2a	In our organisation, centralisation at collective level coexists with decentralisation at individual level. The organisation exhibits an adaptive, flexible or organic nature.	4	6	3	0
D3	Our organisation enforces the stringent adherence to standard operating procedures aiming for repeatability of action and routines.	0	8	6	0
D4	Our standard operating procedures are constantly updated and incorporate lessons learnt. Formal rules and procedures are effective elements to identify and control risk.	2	5	3	2
D5	In our organisation, activities which are not defined in standard operating procedures are based on decisions a most senior individual makes, as they should have the best knowledge of the system.	0	4	8	0
D6	Our organisation has a hierarchical structure for decision making which reflects expertise, know-how and seniority. Each level has controls and regulating mechanisms.	0	10	4	0
D8	Our decision-making processes have slack in-built in order to assess and challenge decisions to avoid faulty decisions to escalate into failure.	1	5	4	1

Table 40 HRO principles with a positive cost benefit (continued)

Ref	Description	Observable in the organisations			
	Cost Benefit Analysis (CBA): Av>=0	Strongly agree	Agree	Disagree	Strongly disagree
System and human redundancy					
E1	Our organisation maintains reserve capacity in the system. This includes back-up functions, overlapping tasks and responsibilities.	3	3	4	2
Precise procedures in managing technology					
F2	In water supply systems design, our organisation aims to simplify complex technical systems and avoid unnecessary automation.	1	6	5	0
F3	New technology acquisition is only justified if existing equipment does not perform to required specification.	3	2	7	0
F5	In our organisation, maintenance activity and protocols as well as performance data are used to monitor the healthy operation of the system.	2	9	2	0

Table 41 HRO principles with a positive cost benefit (continued)

Ref.	Description	Observable in the organisations			
	Cost Benefit Analysis (CBA): Av>=0	Strongly agree	Agree	Disagree	Strongly disagree
Human resource management practices that support reliability					
G1	In recruitment and selection, our organisation acquires suitable and skilled candidates for the jobs aiming to match the complexity of the environment with an equally complex set of people to understand the system. Diverging backgrounds for staff offer different ways of looking at systems.	3	8	3	0
G2	Since most people do what is rewarded, our organisation remunerates reliability with incentives, recognition and career opportunities.	2	5	5	1
G3	In our organisation, job rotation increases networking between teams and helps the organisation to transfer and diffuse knowledge and lessons learnt.	0	6	5	1
G4	Our organisation has systems in place to monitor the behaviour of staff.	1	6	3	2

Table 42 HRO principles with a positive cost benefit (continued)

It can be identified that the number of HRO principles has reduced from 51 HRO principles in the HRO framework to 44 HRO principles with an average, positive cost benefit. In 36 of the 44 HRO principles, the majority of respondents ‘strongly agree’ or ‘agree’ to having observed the stated HRO principle in their organisation

In Appendix 4.2.1, those HRO indicators with the minimum 95% confidence interval for cost benefit analysis exceeding the value zero are also presented. These HRO principles are considered to have a 97.5% chance of being cost beneficial. Here, the number of HRO principles has significantly reduced to 18 in comparison to the initial HRO framework of 51 HRO indicators. It should also be noted that HRO principles relating to 'organisational culture of reliability' now forms the largest group of relevant indicators. For all indicators (18 out of 18), it can be identified that the majority of responses 'strongly agree' or 'agree' to having observed the stated HRO principle in their organisation.

In Appendix 4.2.1, the individual responses from the survey participants were further analysed. For each participant the HRO scores for observable HRO principles are presented. Since the data was anonymised, the participants are described by the size of their water utility and the asset ownership model.

A number of sub-hypotheses were initially formulated with a view to underpin subsequent studies in this and the following chapters and the series of interviews aimed to explore some of those HRO principles in more detail. One of the HRO principles relates to 'staff in operations and maintenance staff receive training on the requirements of maintaining a safe system' and in this context one senior manager (participant no.16) commented on the role of operator training to manage the potential for human error: *"Previously the UK water industry had no formal training processes for its operators so, in that extent, we were lagging, for instance, the American Water industry but our company has established a national and vocational qualification training course and got that accredited through the appropriate bodies. … [Name of] University …run training courses on our behalf. The outcome of which can be an NVQ up to Level 4 qualification in Water Process Control, for instance, and each of our operators either has or will go through that process and, dependant on their appointment to positions of particular responsibility, we would not put them in that position until they'd had the appropriate training and accreditation. So it's what we call a licence to operate; that licence is periodically reviewed so they should understand the processes that their plant that they operate or maintain is intended to perform, the implications of that plant operating in a sub optimal or defective manner and the procedures that they should* *institute or trigger to recover that situation and, as the situation goes outside a particular envelope of compliance. What they have to do to escalate awareness of that event within the organisation. So they are empowered to control the plant to make a range of decisions directly to record and report what they've done but they understand the boundaries of that empowerment and the need to escalate up any non-compliances."*

With respect to incident preparedness, one senior asset manager (participant no.18) reported: *"We have regular [incident training] - it must be every few months we seem to have dummy incidents. The real big incidents … are done less frequently obviously because they take a huge amount of time to organise with the Emergency Services and everything but we do have mock up incidents where we get the Fire Brigade and the Police and everyone involved……but more regularly we have in-house incidents where you know when something's going to happen, you don't know whether it's going to be a burst or a tanker spill or something, you just know that something is going to happen on that day and it will be a full blown sort of incident…All the team leaders will have incident management training in terms of a small mission command type training. You will be trained, if you're an operator or a team leader. You'll be trained in what will be expected of you."*

It was hypothesised that organisations 'learn from failures, near misses and mistakes by other utilities and use these as a means to study the failure susceptibility of the own organisation.' In the survey, it was identified that 25% of the survey participants strongly agreed to having observed this HRO principle in their organisation. 41.7% of the participants agreed, 25% of the participants disagreed and 8.3% of the participants strongly disagreed to having observed this HRO principle in their organisation. In the cost benefit analysis it was identified that the survey group considered this HRO principle to be beneficial in the context of the cost involved to implement and maintain this HRO principle. It can be concluded that the HRO principle to 'learn from failures, near misses and mistakes by other utilities and use these as a means to study the failure susceptibility of the own organisation' is a cost beneficial HRO principle and the majority of participants strongly agreed or agreed to having observed this principle in their own organisation. The hypothesis is accepted. Considering the 'type 2' error, the test is not significant.

It was hypothesised that organisations 'even minor errors and incidents provide a source for learning that are assessed through root cause analysis.' In the survey, it was identified that 33.3% of the survey participants agreed to having observed this HRO principle in their organisation. 50% of the participants disagreed and 16.7% of the participants strongly disagreed to having observed this HRO principle in their organisation. In the cost benefit analysis it was identified that on average the survey group considered this HRO principle to be beneficial in the context of the cost involved to implement and maintain this HRO principle. However, the survey group rejected the positive cost benefit at the 95% confidence interval. It can be concluded that the HRO principle to 'learn from failures, near misses and mistakes by other utilities and use these as a means to study the failure susceptibility of the own organisation' is - in the average opinion of the survey participants - a cost beneficial HRO principle, yet, the majority of participants disagreed or strongly disagreed to having observed this principle in their own organisation. The hypothesis is therefore rejected. Considering the 'type 1' error, the test is significant. With respect to learning from failure, one interviewee (participant no.16) reported: *"We have a post incident review process and part of that is to identify lessons learned. There are recommendations for improvement which require to be signed off by the responsible General Managers and the budget holders so we don't make recommendations that are unfunded and never get done as a result. So recommendations for improvement action are agreed and they are tracked subsequently through to completion by the Emergency Planning Manager's team. So we have a log going back – I instituted this about seven or eight years ago, so we can track all of the incidents that have occurred in the business that have been formally declared as incidents."*

It was hypothesised that organisations 'develop a collective memory for failures, incidents and root causes for failure which helps the organisation to anticipate future problems.' In the survey, it was identified that 42.86% of the survey participants agreed to having observed this HRO principle in their organisation. 50% of the participants disagreed and 7.14% of the participants strongly disagreed to having observed this HRO principle in their organisation. In the cost benefit analysis it was identified that on average the survey group considered this HRO principle to be beneficial in the context of the cost involved to implement and maintain this HRO principle. However, the survey group rejected the positive cost benefit at the 97.5% confidence Interval. It can be concluded that the HRO principle that ‘organisations develop a collective memory for failures, incidents and root causes for failure which helps the organisation to anticipate future problems’ is - in the average opinion of the survey participants - a cost beneficial HRO principle, yet, the majority of participants disagreed or strongly disagreed to having observed this principle in their own organisation. The hypothesis is therefore rejected. Considering the ‘type 1’ error, the test is significant. One interviewee (participant no.16) commented on developing a collective memory for failures: *“Where I would say we are relatively weak is in translating [learning from incidents] into a lessons learned database. We’ve had several attempts at this and I think … most of the focus has been on IT based systems and I’m increasingly sharing the view that that isn’t necessarily the best way to go and you need something which is softer and more culturally based than something which is a hardware solution. That said, I think hardware solutions have a part to play. One of the things we do is, through lessons learned and post incident reports [is to] to cascade discussion and awareness of the root causes of incidents through team briefings. We have, or we should have, a regular team briefing infrastructure within the business.”* Learning from incidents as a subset of training staff and incident preparedness will be further discussed in the context of the Regional Water Utility.

With a view to the next chapter on asset management, it was hypothesised that ‘existing technology is maintained to exceptionally high standards as we do not tolerate defective, substandard or malfunctioning equipment’. In the survey, it was identified that 66% of the survey participants disagreed to having observed this HRO principle in their organisation. 25% of the participants agreed and 8.3% of the participants strongly agreed to having observed this HRO principle in their organisation. In the cost benefit analysis it was identified that the survey group considered this HRO principle to be not beneficial in the context of the cost involved to implement and maintain this HRO principle. It can be concluded that ‘existing technology is not maintained to exceptionally high standards’ and the hypothesis is rejected. Considering the ‘type 1’ error, the test is significant.

In conclusion of this study, it was found that many HRO principles are not novel to the water sector. Although the sample size used in this survey is insignificant to the vast number of water utilities in the highly developed world, it can be concluded that the surveyed water utility managers and professionals are familiar with many HRO principles and were able to observe many of them in their organisations. In this study, the survey participants evaluated the benefit and cost of implementing HRO principles in their organisation. In the analysis of the survey responses, it was found that a positive correlation exists between the observation of HRO principles and their perceived benefit in context of cost. The study of individual responses identified a range of observed HRO principles in the respective organisations. Whereas a number of participants identified many of the HRO principles in their organisations, others were less able to do so.

3.4.2 HRO principles in the Regional Water Utility

3.4.2.1 The HRO survey in the Regional Water Utility

With regard to the HRO survey, the author received 12 completed questionnaires from the participants in the survey after a number of ‘reminders’ were sent out to all invited participants to prompt participation. The majority of the surveys were received by post after conducting the interview series with the majority of survey participants. In Table 43 and Table 44, the observation of HRO principles of the participants in the Regional Water Utility is summarised in percentage of all observations. The alpha-numeric reference number refers to the HRO principles in Table 27 to Table 31. The detailed data analyses are presented in Appendix 4.2.2. It can be identified that HRO principles are not observed homogeneously across the Regional Water Utility. The majority of observations confirm that a particular HRO principle may be observable by a number of participants, whereas others have not observed them in their specific work environment. In 28 out of 51 HRO principles, *i.e.* 54.9%, the majority of participants ‘strongly agree’ or ‘agree’ to having observed those principles in their working environments. In total, 57.9% of the overall responses ‘strongly agreed’ or ‘agreed’ with having observed the stated HRO principles. Thereof, 19.2% of the overall responses ‘strongly agreed’ and 38.8% of the responses ‘agreed’ with having observed the stated HRO principles.

33.9% of the overall responses ‘disagreed’ and 8.2% ‘strongly disagreed’ with having observed the stated HRO principles.

	Percentage of participants observing HRO principles				
Reference to HRO principle	Combined ‘Strongly agree’ & ‘Agree’	Strongly agree	Agree	Disagree	Strongly disagree
A1	100.0%	50.0%	50.0%	0.0%	0.0%
A2	66.7%	16.7%	50.0%	33.3%	0.0%
A3	100.0%	63.6%	36.4%	0.0%	0.0%
A4	100.0%	66.7%	33.3%	0.0%	0.0%
A5	100.0%	41.7%	58.3%	0.0%	0.0%
A6	66.7%	8.3%	58.3%	33.3%	0.0%
A7	41.7%	8.3%	33.3%	41.7%	16.7%
A8	25.0%	0.0%	25.0%	33.3%	41.7%
A8a	75.0%	25.0%	50.0%	25.0%	0.0%
A9	41.7%	8.3%	33.3%	50.0%	8.3%
A10	66.7%	33.3%	33.3%	33.3%	0.0%
B1	66.7%	33.3%	33.3%	33.3%	0.0%
B2	75.0%	25.0%	50.0%	25.0%	0.0%
B3	75.0%	33.3%	41.7%	25.0%	0.0%
X1	41.7%	0.0%	41.7%	41.7%	16.7%
X2	58.3%	8.3%	50.0%	41.7%	0.0%
X3	91.7%	58.3%	33.3%	8.3%	0.0%
B4	58.3%	25.0%	33.3%	41.7%	0.0%
B5	41.7%	16.7%	25.0%	58.3%	0.0%
B6	46.2%	7.7%	38.5%	53.9%	0.0%
B7	18.2%	0.0%	18.2%	63.6%	18.2%
B8	33.3%	0.0%	33.3%	50.0%	16.7%
C1	91.7%	33.3%	58.3%	8.3%	0.0%
C2	66.7%	16.7%	50.0%	33.3%	0.0%
C3	50.0%	8.3%	41.7%	41.7%	8.3%
X1	66.7%	8.3%	58.3%	33.3%	0.0%
X2	33.3%	0.0%	33.3%	50.0%	16.7%
C4	66.7%	25.0%	41.7%	33.3%	0.0%
C5	25.0%	0.0%	25.0%	66.7%	8.3%
C6	25.0%	8.3%	16.7%	41.7%	33.3%
C7	8.3%	0.0%	8.3%	50.0%	41.7%
		Continued overleaf			

Table 43 Summary of observed HRO principles in percentages of all observations from 12 participants in the Regional Water Utility

	Percentage of participants observing HRO principles				
Reference to HRO principle	Combined 'Strongly agree' & 'Agree'	Strongly agree	Agree	Disagree	Strongly disagree
D1	50.0%	8.3%	41.7%	41.7%	8.3%
D2	58.3%	16.7%	41.7%	41.7%	0.0%
D1/2/a	100.0%	58.3%	41.7%	0.0%	0.0%
D3	83.3%	41.7%	41.7%	16.7%	0.0%
D4	75.0%	16.7%	58.3%	25.0%	0.0%
D5	66.7%	25.0%	41.7%	33.3%	0.0%
D6	41.7%	8.3%	33.3%	41.7%	16.7%
D7	33.3%	0.0%	33.3%	58.3%	8.3%
D8	83.3%	33.3%	50.0%	16.7%	0.0%
E1	83.3%	33.3%	50.0%	16.7%	0.0%
E2	16.7%	0.0%	16.7%	33.3%	50.0%
F1	33.3%	16.7%	16.7%	50.0%	16.7%
F2	33.3%	0.0%	33.3%	58.3%	8.3%
F3	66.7%	25.0%	41.7%	33.3%	0.0%
F4	8.3%	0.0%	8.3%	41.7%	50.0%
F5	83.3%	25.0%	58.3%	16.7%	0.0%
G1	75.0%	16.7%	58.3%	25.0%	0.0%
G2	50.0%	0.0%	50.0%	50.0%	0.0%
G3	41.7%	8.3%	33.3%	41.7%	16.7%
G4	50.0%	16.7%	33.3%	33.3%	16.7%
Sum	57.9%	19.2%	38.8%	33.9%	8.2%

Table 44 Summary of observed HRO principles in percentages of all observations from 12 participants in the Regional Water Utility (continued)

In Table 45 the survey results are summarised and represented in the 7 categories of HRO principles 'organisational culture of reliability (A)', 'continuous learning and intensive training (B)', 'effective and varied patterns of communication (C)', 'adaptable decision making dynamics and flexible organisational structures (D)', 'system and human redundancy (E)', 'precise procedures in managing technology (F)' and 'human resource management practices that support reliability (G)'.

From this table it can be identified that 71% of the responses 'strongly agree' or 'agree' to having observed an 'organisational culture of reliability (A)' in their work environment. 55.3% of the responses 'strongly agree' or 'agree' to having observed 'continuous learning and intensive training (B)'. 48.1% of the responses 'strongly agree' or 'agree' to having observed 'effective and varied patterns of communication (C)'. 65.7% of the responses 'strongly agree' or 'agree' to having observed 'adaptable decision making dynamics and flexible organisational structures (D)'. 50% of the responses 'strongly agree' or 'agree' to having observed effective use of 'system and human redundancy (E)', only 45% of the responses 'strongly agree' or 'agree' to having observed 'precise procedures in managing technology (F)' that are found in HROs. Finally, 54.2% of the responses 'strongly agree' or 'agree' to having observed 'human resource management practices that support reliability (G)'.

	Percentage of participants observing HRO principles				
	Strongly agree	**Agree**	**Disagree**	**Strongly disagree**	**Total counts**
Group A					
Sum	38	55	30	8	131
Percent	29.0%	42.0%	22.9%	6.1%	
Group B					
Sum	25	48	53	6	132
Percent	18.9%	36.4%	40.2%	4.6%	
Group C					
Sum	12	40	43	13	108
Percent	11.1%	37.0%	39.8%	12.0%	
Group D					
Sum	25	46	33	4	108
Percent	23.2%	42.6%	30.6%	3.7%	
Group E					
Sum	4	8	6	6	24
Percent	16.7%	33.3%	25.0%	25.0%	
Group F					
Sum	8	19	24	9	60
Percent	13.3%	31.7%	40.0%	15.0%	
Group G					
Sum	5	21	18	4	48
Percent	10.4%	43.8%	37.5%	8.3%	

Table 45 Summary of HRO survey results presented in HRO sub-categories

Based on the scoring system introduced in the methodology, a numerical analysis of the data was conducted and the average, SD, SE and CI 95% for all survey responses calculated. The averages for the observed HRO principles and the cost benefit analysis were derived to conduct a significance test that compares the observations of HRO principles within the Regional Water Utility to the HRO survey results from the international water utility managers. The statistical data analysis and significance test is presented Appendix 4.2.2.

It was found that 44 observations in the Regional Water Utility out of the 51 observable HRO principles were not significantly different in comparison to the HRO survey of the international water utility managers. In two instances, the responses for observing HRO principles in the Regional Water Utility was significantly more positive, *i.e.* the participants agreed stronger than the international sample. In 5 instances, the responses for observing HRO principles in the Regional Water Utility were significantly more negative, *i.e.* the participants agreed less than the international sample.
The former are:

- ‘In our organisation, centralisation at collective level coexists with decentralisation at individual level. The organisation exhibits an adaptive, flexible or organic nature (D1/2/a)’; and
- ‘Our organisation enforces the stringent adherence to standard operating procedures aiming for repeatability of action and routines (D3)’.

The latter are

- ‘Our staff in operations are obliged to report their mistakes without fear of punishment (A7)’;
- ‘In general, our staff are attentive, alert and act with care (A10)’;
- ‘During a water quality incident, the organisation maintains “closed loop” communication with the public, regulators and government authorities (CX2)’;
- ‘Our organisation uses various channels to transmit different types of data and information relating to monitoring and control of our assets (and ultimately water safety). Direct and complementary information enhance information reliability and provides a form of redundancy (C5)’; and
- ‘In our organisation, existing technology is maintained to exceptionally high standards as we do not tolerate defective, substandard or malfunctioning equipment (F4)’.

In analogy to the previous study, the cost benefit of implementing and maintaining HRO principles was investigated and it was identified that the number of HRO principles reduced from 51 HRO principles to 36 when only considering an average, positive cost benefit. For 27 of those 36 HRO principles, the majority of respondents 'strongly agreed' or 'agreed' to having observed the stated HRO principle in their organisation. Furthermore, the number of HRO principles that are considered to have a 97.5% chance of being cost beneficial reduced to 18. For 14 out of those 18 HRO principles (77%) the majority of respondents 'strongly agreed' or 'agreed' to having observed the stated HRO principle in their organisation. This is higher in comparison to the entire HRO framework or the HRO principles with an average positive cost benefit. The detailed analysis is presented in Appendix 4.2.2.

Finally, the standard deviations of the observed HRO principles in the Regional Water Utility with the HRO survey of international participants were compared. For this analysis, the author considered all HRO principles as well as those HRO principles with an average, positive cost benefit and a significantly (97.5%) positive cost benefit. In all three cases, the standard deviation and standard error of observed HRO principles within the Regional Water Utility is higher in comparison to the international HRO survey.

	Average	SD	SE	CI 95% lower	CI 95% upper
All HRO	57.0	35.3	1.5	54.1	59.8
CBA Av>0	65.9	33.0	1.6	62.8	69.0
CBA CI 95%lower>0	71.7	30.8	2.1	67.6	75.8

Table 46 Statistics for observed HRO principles in the Regional water utility

	Average	SD	SE	CI 95% lower	CI 95% upper
All HRO	58.3	33.2	1.3	55.7	60.9
CBA Av>0	62.7	31.9	1.4	60.1	65.4
CBA CI 95%lower>0	73.7	27.2	1.8	70.1	77.2

Table 47 Statistics for observed HRO principles in the international study

It was anticipated that the standard deviation and standard error within the Regional Water Utility would be significantly lower than in the international survey. It was assumed that the perception of HRO principles within one organisation would converge towards a common view within one company (possibly based on the principles of 'groupthink' (Janis, 1972)). It seems that the perceptions within the Regional Water Utility are diverse and suggest that more than one common perception prevails on the 'culture' of the organisation. In the interpretation of the results, it has to be considered that personnel from various departments and functions in the Regional Water Utility were invited to partake. Furthermore, the invited participants were all involved in recent incidents. Gigerenzer *et al.* (1999) aimed to explain diverging perceptions with the concept of constructing heuristic models that people use to reduce complex environments into understandable models of reality and explained heuristics as a range of simplifying and confidence-sustaining mental short-cuts that enable quick decisions in circumstances when pausing to undertake a full analysis would be unwise (Gigerenzer *et al.*, 1999). Using a number of simplifying strategies, or rules of thumb, to make decisions whilst working through the questionnaire may have contributed to this standard deviation in the survey results. In particular, availability heuristics (people pay more attention to information that is easily available, *e.g.* from recent incidents) and retrieveability heuristics (overweight memories that are more easily retrievable either because they are emotionally vivid or have personal relevance) may be a factor to consider in the evaluation of results. The HRO principles introduced in this study may be highly subjective and individual participants may have interacted and corresponded to the survey using their heuristic understanding of their working environment to make sense of the HRO principles.

In the following section the principles of operations and incident management are described. For this study, the author acted as a passive and silent observer in the operations – and incident control centre. Since the operations control centre is an access-controlled environment, an explicit permission or invitation was required from the operations manager on duty to observe operations and incident management in the control centre. As a result, two incidents could be observed in the control room and four more at the site of the incident. In addition, the author was invited to attend one incident review meeting. The HRO framework was used to record and document observations. The detailed findings of the observational studies can be found in Appendix 4.2.4. In addition, interviews with staff were conducted who were involved during some of these and other incidents. Extracts of these interviews are presented where appropriate in the context of the author's observation and incident case studies are used complementary to the findings. Findings from the detailed analysis of documented incidents that occurred between 2004 and 2006 are also presented in the following section.

3.4.2.2 Observing HRO principles in incident management

In the observational study it was found that the operations management department uses the water supply system aiming to deliver safe and reliable drinking water to customers. It meets demand for drinking water by operating the physical asset base and actively manages human and intangible 'assets' of the organisation. It was observed that staff are constantly aware that the water supply system is prone to failure and they actively sought to identify signs and indicators of failure. On detection of abnormal operating conditions, the incident management procedures were invoked until a safe and reliable drinking water supply is re-instated. The incident management processes and procedures were invoked in response to the awareness of a failure scenario that is defined by the organisational objectives (level of service). The incident management organisation used systems redundancy to reduce the impact of the incident on customers and re-instate the safe operation of the water supply system.

Based on the analysis of 145 incidents that occurred between 2004 and 2006, the means of identifying incidents were identified. With reference to Figure 32, it was found that the majority of incidents were notified to the water utility by customers reporting an unusual observation relating to their drinking water supply. The majority of these customer contacts referred to 'loss of supply' and 'aesthetical problems' due to discolouration. 17.9% of the incidents were escalated from an operator to the incident management team. 17.2% of the incidents were detected on Supervisory Control and Data Acquisition (SCADA) units, *i.e.* IT-based monitoring and control. 8.3% were reported by contractors who worked on or in close proximity of the asset that caused the incident.

5.5% of the incidents were identified via water quality laboratories confirming the pollution or contamination of drinking water. With a turnaround duration of 12 to 24 hrs for bacteriological test for drinking water quality parameters it has to be assumed that contaminated water has, in the meantime, passed beyond the customer tap. Therefore, the majority of incident notifications including 'customer contact' and 'water quality laboratories' indicates that customers were exposed to hazards before reactive incident mitigation can be carried out by the incident management team. Both methods of incident identification are well established business processes: in particular, for customer contacts, a dedicated call centre has been established to identify and characterise symptoms of an incident.

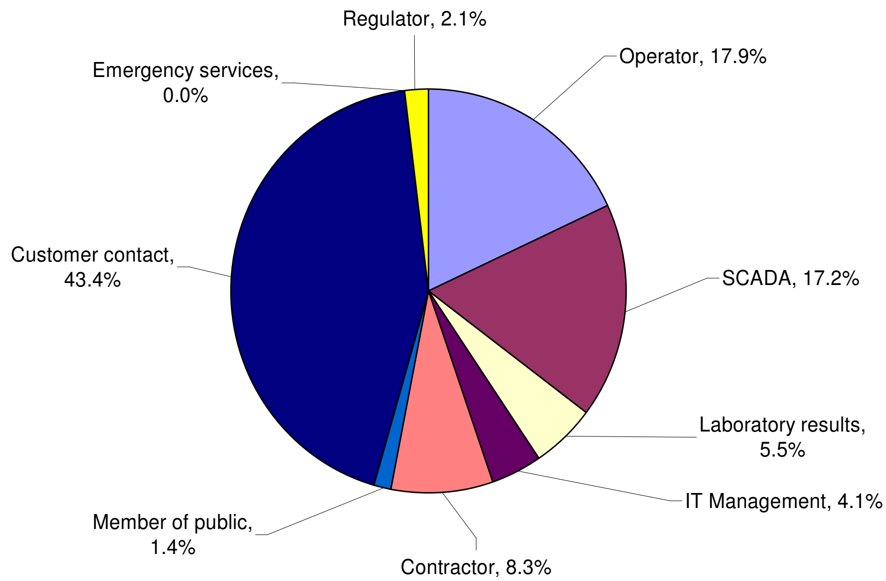

Figure 32 Identification of incidents between 2004 and 2006

There is a heavy reliance on customers to report their experiences to the water utility, in particular relating to incidents in the water distribution network. Efforts are underway to reduce the reliance on 'end of tap' reporting for incidents. A test trial is currently planned to provide sufficient pressure and flow monitoring devices to increase the incident detection capability in an area distribution network. With this arrangement, any deviation of observed pressure and flow patterns from expected patterns will raise an alarm in the control centre so that an incident investigation team can be dispatched to investigate the source of the abnormality. This system will enable the reduction of the response time to an incident considerably. One incident manager (participant no.22) reported: *"If a burst takes a water supply away then that is such a big burst that you'd think we'd be able to spot it before it became such a big burst. So we're looking … at getting telemetry right across our network. We have a pilot ... where we're getting in what we call alerts rather than alarms; alerts are just saying there's a slight variance on the flow or we've got a drop in pressure … that needs investigation. So potentially,* *we're getting a lot closer to knowing real time if there's something starting to happen before it becomes customer impacting. It's actually measuring live-flows and pressures and taking those against historic values and creating some what we call alerts against those either dialogue patterns or the average flow patterns, profiles against a day and a week at different days of the week."*

After an incident was detected, the organisation responded by assuming an organisational incident management structure for decision making with a centralised command and control hierarchy. From the control room, the incident manager co-ordinated efforts to reduce the impact of the incident and to re-instate safe water supply. From here, the incident manager monitored the entire systems response to the incident and the incident management efforts. The incident manager led the incident management team within the control room but also field staff who perform the required tasks at the source of failure or within the area affected by the incident. The incident manager directed all resources at his disposal, *e.g.* additional staff and systems redundancy, towards reducing the incident impact and re-instating safe operations.

Additional staff from departments other than operations and operations management can be called upon during an incident. One asset engineer (participant no.14) reported on the role of the asset management team during an incident: *"Basically, we act as like a support to our field teams or to the [Incident] Manager down in the [incident control centre] - either if they've got an ongoing incident and that we get involved - either, in fairness, at a fairly late stage just before it hits the fan instead of getting involved at an early stage. We do a standby rota anyway, an asset management consultancy sort of role, and the [Incident] Manager will phone us up out of hours…. Sometimes it's not an incident, sometimes they just phone us up for advice …. Usually it's either, if there's an ongoing discolouration incident they might phone up for some advice whether to either let it run or to go out and do some proactive flushing or, if they're overrunning say on a burst repair and they look like they might be failing the DG3, see if there's any way that we can rezone and get some water.*

The field technician on site sometimes might phone us up directly like he has done this morning to say contractors have damaged a twelve inch main…."

During large-scale incidents, the organisation was capable to decentralise to respond to rapidly to a unfolding failure. During a major storm event which had significant impact on many technical subsystems due to wide-spread power failures, a number of incident managers were called up to respond to particular aspects of the region-wide incidents. Although centralisation is essential in this tightly coupled technical systems where interdependencies are high, it was capable to de-couple the system so that decentralisation in the incident management response provided for action at the point of need. During large scale incidents affecting the entire region, the organisation demonstrated a centralised incident management response in order to maintain an overview of the entire system but also decentralisation where particular incident aspects could be confined to one sub-unit which is then isolated from the entire system.

The organisation has set definition for escalating an incident to more senior managers who would assume the role of the incident manager. With respect to escalating an incident to a more senior manager, one reporter (participant no.7) commented: *"In terms of that [incident] it was managed by myself because it didn't go beyond, it stopped. Had that contaminated water got into [Name of] reservoir and gone on into the supply then all sorts of people would have been here but it was manageable by myself. [Name of a colleague], who was in as well that day, had another incident going on and he took charge of that with somebody out on site so I just focussed on this fault with the alarm."*

With reference to Figure 33, the incident documentation was studied to identify the ability of the organisation to adapt its organisational structure to respond to the needs arising during an incident. It was found that in 88.3% of the incidents, the organisation assumed an effective organisational structure to place it in the best possible circumstance for effectively reducing the incident impact on customers and to re-instate normal operations. In 9.7% of the incidents, the assumed organisational structure was deemed 'adequate considering the circumstances'. In this category, a number of improvements could have led to better performance in reducing the impact of the incidents or the re-instating of normal operations. A number of incidents in this category reflect highly challenging or trying conditions and the incident management response demonstrated a reasonable successful outcome. In only 2.1% of the incidents, the incident management organisation was rated as 'inflexible' suggesting that the organisational structure assumed during the incident was inadequate to manage the complexity of the incident situation.

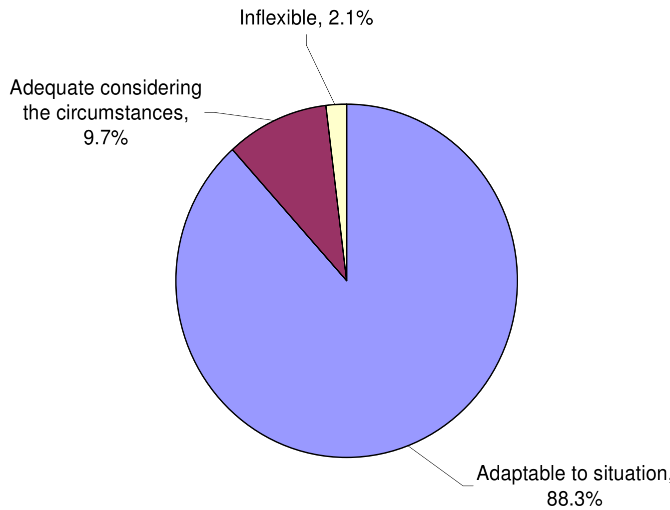

Figure 33 Adaptability of the organisational structure to the incident situation for incidents between 2004 and 2006

Detailed SOPs would not exist for every incident scenario although procedures are in place for many aspects of incident management and for frequently occurring failures, *e.g.* water mains failures. In unforeseen or unique events, the decision making process required to devise an action plan to recover a failed system and to re-instate normal operating conditions. The process had in-built slack for critical decisions in order to assess and challenge decisions by a more senior member of staff. Furthermore, the incident manager had specialist staff at his disposal to guide his decisions.

The assessment of incidents between 2004 and 2006 also focussed on the effectiveness of decision making. With reference to Figure 34 it was found that 64.8% of the incident management efforts could be characterised for ‘good decision making’. The decision taken during the incident significantly and pro-actively contributed to reducing the impact on customers and to re-instate normal operations as soon as possible. In commenting on one incident an operations engineer (participant no.3) noted: *“It was all* *coordination pulled together and decisions were made in the correct manner. I believe that the incident was dealt with quite well and professionally. I believe that the majority of all the people involved did everything, you know, by the book and correct really."*

One operations manager (participant no.6) commented: "*I think once we realised the error of what had happened then I think the organisation put things into place quite quickly. We got scientists involved and we were working out what the impact on the customer would be and exactly what had happened and things like that. So I felt that was quite effective. It was what created the incident was the problem, I think normally with this company when we do have incidents or once we've recognised that something's gone wrong there's usually a very good response from every department to pull it round and rectify it."* An asset engineer (participant no.2) stated: *"I think in general the decisions that we were made when the problem was identified were very appropriate and the right decisions made at the time."*

In 24.8% of the incidents, the decision making was 'responsive to needs' meaning that the incident management efforts pursued an effective course of action by reasonably practical means. The remainder of the incidents were, in hindsight, characteristic for poor judgement, poor decision making and non-adaptive to the incident situation. These were identified as being ineffective to recover the incident situation to normal operation as soon as possible and provided scope to learn lessons for enhancing the incident management response. Overall, the organisation demonstrated that decision making under trying conditions effectively drew the necessary and correct conclusions from the data presented to the incident management team during an incident. This is also reflected in the assessment on data availability during an incident but also on the competence of the decision makers involved during an incident. In 10.3% of the incidents scope for improvements in data availability and/or competence in decision making were identified.

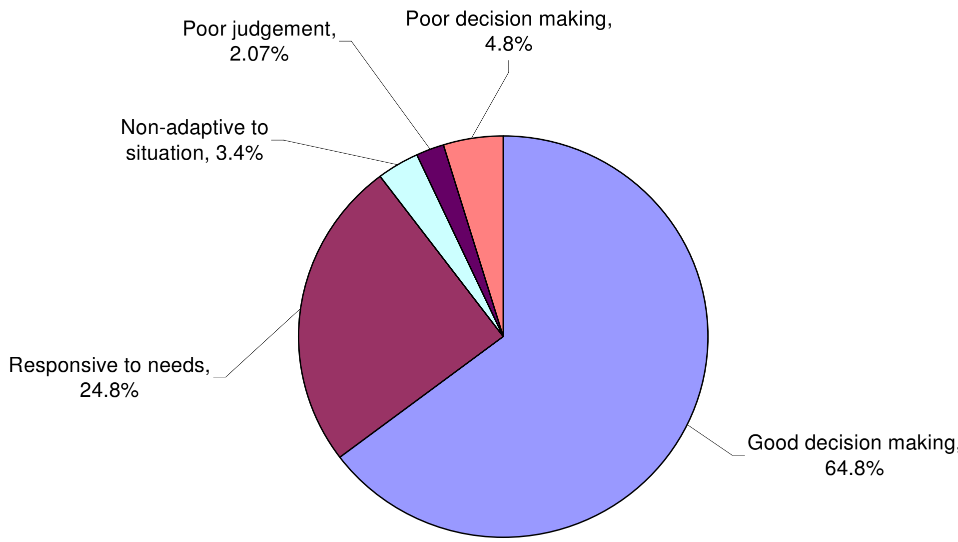

Figure 34 Characterisation of decision making during incidents between 2004 and 2006

In concluding this section on 'decision making' during incidents, it was found that the organisation aimed to recruit and select suitable and skilled candidates that match the complexity of their working environment. Suitability, skills and competencies are defined by the functional role individuals occupy in the organisation. An incident manager has to be able to cope with highly uncertain situations and demonstrate rational decision making under 'trying conditions'. An incident manager has to be able to communicate effectively with the staff and stakeholders involved in incidents. S/he requires the ability to demonstrate decisiveness and firm leadership to remain in control of adverse situations. S/he also requires a good understanding of the entire water supply system whilst drawing on the expert knowledge in the incident management team.

A critical aspect in effective incident management is 'communication'. Effective communication facilitates a complex system to become more understandable, predictable and controllable. With the rapid developments of information technology, water supply systems are increasingly fitted with advanced monitoring and control instruments. They are part of an effective communication strategy to maintain safe and reliable drinking water supplies. In the organisation, the monitoring and control philosophy has been advanced to a stage where physical assets such as water treatment works are no longer operated with staff on site. Monitoring and control is performed with ‘Process Logic Controls’ and ‘Supervisory Control and Data Acquisition’ in the remote control centre. The control centre is the hub for managing drinking water supply for the entire region. However, information technologies have their disadvantages. In the first years of implementing the strategy of advanced monitoring and remote control of water supply assets, an increase of incidents due to the failure of such technologies was observed (Figure 15).

Secondly, too much data can overload the process and grouping alarms together may be considered to manage data overload without jeopardising critical data availability during critical situations. Data overload may result in critical alarms being ‘lost’ or not acted upon. Similarly, grouping alarms together in alarm groups make the identification of the precise incident causes difficult to identify. Having the right information available at the right time in the right place was an important aspect of water utility incident management.

Where monitoring and control equipment fails, the status of a system becomes unknown. One operations engineer (participant no.1) commented on one incident *“I wouldn’t say [the incident] could have been avoided but there was another alarm which came in beforehand which wasn’t acted upon because it was misunderstood. It was a very vague alarm and sometimes you get alarms which are very clearly defined like ‘pH low’ so you know your pH is low but then other times you get grouped alarms which are very obscure. So you could get a sample pump failed but it might just come up as a Group 3 alarm. Until you go to site and actually look on SCADA and actually go to the Group 3 alarm section there might be fifteen alarms grouped under that one generic alarm. Then it’s up to the person on standby to make that decision whether they go in or not and, unfortunately, on this occasion it wasn’t acted upon and that alarm in turn meant the link between SCADA and [the control centre] was down so there was a sort of a dead band in the alarms until I got in during the morning.*“

During the management of incidents, the incident manager took control over assets and resources. A number of databases provide an overview the available water supply resources and assets. One incident manager (participant no.7) also commented on the challenges of data overload to manage an incident: "*You can have twenty six databases open at the same time and my reaction to that, I've never had twenty six but it's interesting because the fact is you could have twenty six databases open to do with that incident, that's appalling because you can't possibly deal with that.*"

During an incident, inter-personnel communication was designed as both bottom up and top down to ensure rapid flow of information through the hierarchy of the incident management team. Rapid dissemination of information helped the organisation respond to an incident, with corrective action aiming to prevent the escalation of the incident into an emergency. One critical commentator (participant no.23) reflected on effective communication: "*I mean, to be honest, as you're well aware that most incidents occur or escalate and get worse because of the communication so that tends to still be one of the biggest things.*"

In an analysis of documented incidents, the effectiveness of communication during the incident management response to the incident was investigated. In Figure 35, 72.4% of the incident management responses were characterised for 'effective communication'. Here, the communication between the stakeholders involved in an incident generated 'a big picture': observations, decisions and water supply systems performance were effectively communicated to all relevant staff and external bodies which enabled comprehensive judgement on the due course of action. These actions were effectively communicated to staff and their implementation communicated back to the decision maker.

One interviewee (participant no.1) commented on communication during a major incident: "*The Control Room was informed of what was happening all the time, of how we were progressing because they needed … [to be] informed of how long before the site was back operational. Yeah, it was just like a normal process, that you keep Control informed. In hindsight, from looking back you think, yeah, there was this, this and this which occurred which whatever should have happened but at the time it was a case of 'we're getting on and starting the plant up, we're aware of what's happening and we're informing the System Controllers on the production capability of the site and when it should be back online'.*

In 6.9% of the incidents, the incident documentation identified aspects of excellent communication that significantly contributed to the effectiveness of the incident management response. One operations manager (participant no.10) noted: "*I was involved right from the beginning and it was escalated to all the appropriate levels and the appropriate people were actually involved. I can say that confidently, yes, [the incident] was very effectively communicated.*"

In 13.1% of the incidents some areas of improvements were identified which meant that the incident was unnecessarily prolonged. In 6.2% of the incident, 'poor communication' had a significantly, adverse impact on the overall performance of the incident management response. One senior operations manager (participant no.5) commented on poor communication: "*There were some communication issues …; I think we didn't get all the feedback that was helpful. I happen to remember we didn't always get … certain bits of key information updates which are business critical and I did remember that I think we were trying to find out what was happening at certain times…. There was a little bit of a void of information not coming back into the Centre.*" Another operations manager (participant no.8) commented on the lack of communication from a site perspective where the incident occurred: "*I think some learning about the incident was that we could have communicated better with the [Incident] Manager earlier on. I got in touch with the [Incident] Manager after I'd initially heard about [the incident] but I think there was some wording to say we could have got in touch with him earlier.*" The Incident Manager (participant no.22) who was managing this incident reported: "*A lot of the times people just think the company needs to know about it and they escalate it at the right time but, in this case and in a number of other cases, they tend to contact us when they've run out of ideas. They've been desperately trying to manage it on site, trying to keep it quiet and mitigate all these results like whereas if they'd contacted us, in this case two days beforehand, they could have done a lot more to prevent it being the incident it was. So the main learning outcome is getting as much information as you can on the first call. They'd tried to keep it under their hat locally. So I think it's not a learning point for me so much in the role but just generally from other people to trust the [Incident] Managers. That's the element of it: they don't want to be seen as failing so they keep it as local as they can.*"

In commenting on one incident, an asset engineer (participant no.2) even suggested that the incident was avoidable if communication had worked better: *"There were a number of learning outcomes and I think the major one was around getting the communications* *right, so around identifying the problem, communicating the problem correctly so that appropriate remedial action could have been taken. I think communications fell down in identifying the incident in a, I guess, in a sufficiently timely manner. I mean, essentially if communications had happened when they should have happened then the incident potentially wouldn't have happened."*

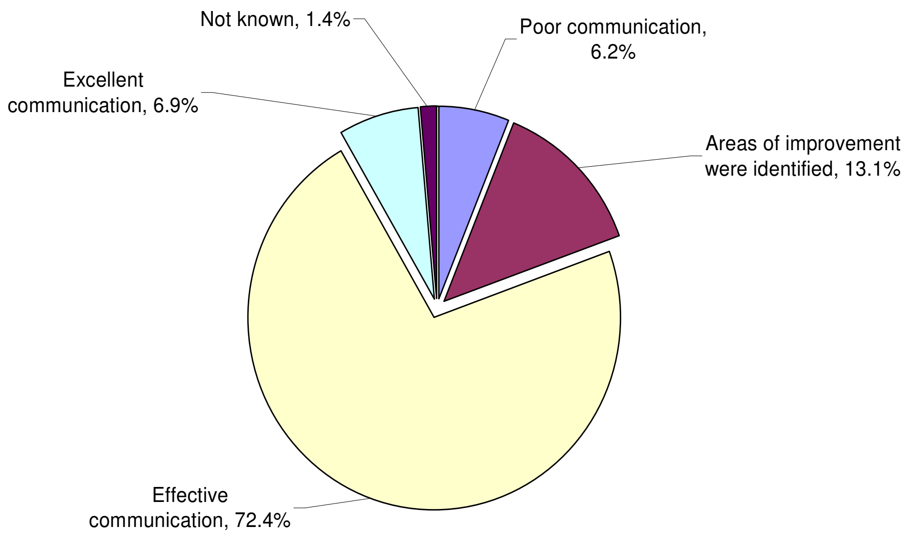

Figure 35 Assessment of communication during incidents between 2004 and 2006

Communicating information allowed staff to shape and share the 'big picture' of the organisations vision, mission and responsibility of individuals towards reliability. It was found to be important for integrating asset management teams into the <u>daily</u> operation of the water supply system so that effective working relationships emerge under trying conditions. One asset engineer (participant no.33) reported: "*Well, I think we have a good working relationship and when things are addressed then we try to deal with them collectively."*

The asset engineers require the information input from operators to assess asset risks. Via risk assessments, resources may be made available for asset investment or maintenance. One operations engineer (participant no.3) commented on the communication between operation management and asset management teams: "*If we* *think we've got an asset deficiency or a problem, we would raise that with Tech Support and discuss it with them and then if they agreed with us then they would probably take it forward to one of the meetings with Asset Management and raise it there."* An asset engineer from Tech Support (participant no.24) responded: "*Part of the job is providing technical support to field operations on a day-to-day basis and we do all the system configurations on zone work and things like that in configuring the distribution and leakage controls."*

One operations engineer (participant no.1) explained the role of asset engineers in his team: "*There's normally a good communication between them [asset management teams and operations management] because you've got like a technical support guy who's [in] 'Production' but his role takes him into the asset side of the job. Basically, you've got your Production guys supported with your operation manager who's there to manage the team and then you've also got a technical support guy there who is like a grade above Process Engineers basically and he's there to offer technical support to the team and put forward improvements to site, like raise risks and get involved in the Asset side of things. You have to use [risk assessments] but it tends to be down to the Tech Support guy doing the [risk assessments] and the Production guy giving him the support and the information he needs to get a successful [risk assessment] through to ensure that all the risks are highlighted and covered.*

'Production' and 'Asset' do need to work together closely anyway on the day to day role. So, yeah, there's normally good cooperation between the teams …." According to one asset engineer (participant no.24): "*We work closely with the field teams. They're run separately from us but we've a close relationship with the teams. We're not based with the teams, the teams are based at the depots within the area but we're based at [Name of site], we're not directly based with the field teams. And the other thing is we do a standby rota as well, out of hours standby to support field guys as well and the Control Room. We would do investigations as well, if there was a problem on the system that wasn't apparent to the field at the time, if we were struggling from say an instance where we got high head losses in the system or we're failing pressure standards and things like that, we would investigate those issues and that would then result in us possibly have to do a capital scheme through the capital system, the [risk assessment] system."* Other asset engineers have only peripheral interfaces with

operations management. According to one asset engineer (participant no.11): "*I'm not so involved with the day to day running, it's more around fitting the capital working around the constraints of running the sites and the distribution system.*"

Returning to the management of incidents, one operations manager (participant no.10) commented on the role of asset engineers during incident review meetings: The asset engineer's "*role was to understand what had gone wrong to actually then take the appropriate actions and next steps to carry out audits at other sites that may be similarly affected, to actually be proactive in addressing those in the future.*" Another operations engineer (participant no.1) commented: "*They [asset engineers] had the same goal of finding out what happened, why it happened and trying to pin it down and to make sure it wasn't a fault which was going to happen on other sites, that fault was just specific to that site and that issue, it was just a one off type thing and it wasn't a generic fault which could occur at any site.*"

The next section focuses on learning from failure and incidents. Here, the processes and learning capability from incidents in the organisation were investigated. Simultaneously, it was sought to uncover sociological factor, i.e. normative, coercive and mimetic pressures that contribute to providing safe and reliable drinking water. The organisation has processes in place to review incidents, failures, near misses and mistakes and uses these as a means to study the failure susceptibility to avoid future incidents. Even minor errors and incidents provide a source for learning which are assessed through root cause analysis. In dedicated incident review meetings an incident is analysed for potential learning opportunities.

According to one senior operations manager (participant no.5) "*there's a standard agenda we go through [after an incident].*" The agenda of the incident review meeting takes the form of 'identifying who was present, an update and the current situation of the incident, ongoing effect on the customer, a review of the log events, issues arising and further data/investigation requirements, identifying issues that went well, what has occurred that could be done better, lessons learnt and recommendations arising and confirmation of next steps'. Actions arising are recorded on a business process database that tracks the progress and monitors the completion of actions.

During the incident review meeting the incident log book was scrutinised. The incident log captures data and information on physical, information and human assets involved during the incident. It captures the incident impact on customers and 3rd parties with particular emphasis on the hazard types, the size of affected population and the timing between incident occurrence and incident awareness as well as the incident response times. It records data of the condition and performance of the drinking water supply system and assets, the planning, implementation and operation of an incident response, actions taken to reduce the impact of the incident, monitoring data and information relating to the water supply systems response to any intervention but also any actions, behaviours and actions by incident management team members, operators, field staff and 3rd parties.

During the review meeting, the actions and activities prior to and during the incident were evaluated. It identified causes and contributing factors in the build-up to the incidents and, secondly, the effectiveness and efficiency of reducing the incident impact and re-instating of normal supply. One operations manager (participant no.6) reported: "*You start off by explaining the normal mode of operation to give a background into how the plant operates, what should happen under normal circumstances, what are our operating parameters. Then you'll do a time line of the day or maybe start it from the day before, who attended site, what time, what actions they took, that type of thing. The investigation then will look at maintenance that's gone on site over that week, we'd go through the jobs that were put on the system for our maintenance providers in case there's been any other breakdowns that might be linked. We'd analyse all the trends on site our SCADA systems and we'd go through RTS reporting for alarms that had been generated.*"

In commenting on one incident, one asset manager (participant no.23) reported: *"We look at absolutely everything that contributed to it but then come up with what we feel is the most significant feature. And then obviously after we've identified what the learning is, [we identify] … what's gone well, what could have gone better, I produce a table of actions and who is the responsible person for dealing with that action and a date to complete it."*

According to the senior operations manager (participant no.5), the incident is recorded by the Emergency Planning team: *"Normally we ask that Emergency Planning do the* *administrative minuting of all the statements of what went wrong and just confirm all the points of action in the log or the diary and then we go onto what was the cause of the problem as we understood it at that point, recognising what the impact on regulation was or what the customer impact were and then we like get them trying to find out what went well and what didn't go so well and then document the actions and learning as an output which is then tracked by the Emergency Planning team."*

According to the senior operations manager (participant no.5), not only incidents but also 'near misses' or near failures are analysed: *[In the incident review], "we probably pick up quite a few near misses as well, they've have not quite got there but we've listed them up anyway and we qualify through the learning and review process whether they are definitely a significant incident or just an ordinary incident. There are occasions where we would actually raise incidents as well where we know they're not significant but we value the learning from the event that took place. … we can pick up any learning points locally and then look at trying to share those across the business.*

I think we've come across quite a few what we would term near misses; it's creating the visibility and the right learning approach for that. There is actually something particularly within the distribution arena which is looking at service failures and operational issues where there's a new database just about to be launched called the 'Events Service Failure Database'. I'm quite keen on making sure we get the learning process right.

We're looking at an adjustment from what we currently work to - towards a more bespoke specification about saying 'at this classification event we will undertake a significant review, at this classification event there will be an incident and we will have a joint review still' and there as a third aspect which might be deferred more as well, it's not caused any breach or anything but it's something that shouldn't have happened, we've got to stop – we've not only got to make sure that we've picked that up but share that across the rest of the businesses and develop some action plans out of that."

The thoroughness of the incident review is partly due to the regulator. After an incident, they may even review the particular risk assessment and risk management protocol to investigate the causes for the incident. According to the expert on distribution network assets (participant no.4): *"[The regulator] now want to see that the DOMS is referred back to whenever there's an incident in the company. So it's the instruction to us that,* *right you've written this, we want to see that you're using this and this is underpinning day-to-day operations and your planning to make sure that this is what you're following and, if you have an incident, we'll be coming back to you and saying "in your DOMS you say that you're tying in", you know, your policy of what you're doing so why didn't it happen during that incident". So it's a bit of a change and a bit of an instructive that you need to be doing what you say you're going to be doing. So what I think the DWI are saying, say every incident that happened that will come into [the Regional Water Utility] as part of their investigation and say, right we've had your DOMS, they've got this, and they'll specifically say "on page 85 you say that you're aware of the risks posed by the operation of sluice valves on trunk mains and we've taken that into account as part of your day to day policy procedures with appropriate training for field staff, they should not operate valves until they're signed off to do it so what went wrong". And so they go round the table saying why didn't you follow that, why didn't you follow your own DOMS strategy."*

Care has to be taken to avoid 'blaming' involved staff without jeopardising the enforcement of accountability of individual responsibilities. One asset engineer (participant no.24) pointed out: *"The meetings I've attended have tended to be what I call factual and not, if you will, finger pointing…– I don't treat them as a witch hunt, if you will, they're dealt with in a factual manner trying to prevent things happening in the future."* One operations engineer (participant no.1) pointed out: *"… we don't want to find a culprit and pin it down on somebody but sometimes do people do feel as though it's a case of if I don't cover my own backside enough by ensuring I do everything correctly even if it means taking twice as long over something and you're being pressurised to perform all the time, it is getting to that stage and people are aware of it so it's only a good thing. If it can help people realise that you've got to think of everything you do nowadays, you've got to think in-depth because you are at the front line."*

Another asset engineer (participant no.11) reported: *"I've seen a few incident reviews where people have come out of it feeling like it was a finger pointing exercise, in other words, it was on human error and they weren't looking at the actual truth - across the business risk and what happened to cause the incident in the first place. But the ones that I've been involved with, I've not allowed them to point the finger, I've said we're* *here to review so, before you start pointing fingers, that's the last thing you want to be doing, it's more around did we follow operating procedures, do we need to make any amendments to the operating procedures, does this need to be resolved by capital spend or can it be resolved by operation maintenance or, you know."* According to one asset engineer (participant no.14): *"Some people view it as trying to find either a scapegoat … for it going wrong but I've not had that sort of experience when I've 'gone up'. I mean, they've usually been quite thorough, you know. There's always a lot – what I've always found with the hindsight, you know, with the incident review, there's always a lot of hindsight. It's a wonderful thing, isn't it, because then you think "oh yeah, we could done it different like that in hindsight". They review the whole incident, see what you could have done better and then hopefully next time if you have a similar situation, nothing goes wrong, you hopefully learn from some of the reviews." You know, some of them are incident reviews and everything's gone great, we've done as much as what we possibly can so there's no sort of blame culture as such. Some of them are, you know, our fault where we've either shut a main off and not sort of either thoroughly gone in and looked at the implications of doing that and some of them are caused by our contractors, you know, which a lot of them are out of our control, we've only got involved obviously when it has caused a problem as such. I must admit, every one that I've been to there's never sort of been "oh right, he were to blame for this" and "he shouldn't have done that" sort of thing, you know what I mean, no sort of finger pointing or anything like that. It were "right, what do we think caused it" and say do a bit of an analysis on that."*

One asset engineer (participant no.11) reported: *"As an Operations person I used to feel: I was controlling, I was coordinating that day, did I fill out the log properly and one thing and another and you're in a bit of a panic to make sure that you followed all your procedures when the incident took place. So, I mean, it does feel like that for the people that run the assets but for Asset Management I would have said it's not a finger pointing exercise, it's more of a what can we do to improve it, is it something that we need to maintain more often, a procedure we should have been following that hasn't been written properly, that needs reviewing, you know, things like that.*

Actions that were agreed in the incident review meeting are recorded on a database and monitored for pursuit and completion. According to one operations manager (participant no.6): "*We have an action tracking system, basically that's a database where the - I believe it's the Emergency Planning team who put actions on the system for us. So they would facilitate the incident review, the outcome of the review would be a number of actions and learning points … well, that would go on the action tracking system with a deadline and after the deadline it flags up that the deadline has been exceeded and that usually goes – I think that now actually goes to you and your manager. We've had incidents before where we've had a dosing line failure, a loading value failure, and so the action on Asset Management would but to have all dosing lines and make sure that it couldn't happen anywhere else, for instance. That would be given to an engineer and he would probably then work with field process engineers to gather that data and sign that action off."*

One incident manager (participant no.7) commented on tracking actions and learning from failure for a wider audience: "*I don't think we're very good at completing [actions] properly, we used to be and this is something in this environment that's gone. There were certain actions I identified that day and I don't think that anybody particularly owns them. There is a chance that we're not as good at that as we should be. I think where we get it wrong is that it's learning through all the people that were involved but the other people that weren't involved don't necessarily get it so they can sometimes make the same mistakes again. I think that's where we slip up a bit but we try to avoid that. There's not too many new things really if you think about it, all the incidents that come along are just a version of another one in a slightly different format so people have learned over time. I don't think we're as slick as probably we should be."*

According to the principles of the action tracking system, failures in one part of the organisation can be used as a means to study the failure susceptibility of the entire organisation or, at least, of other, similar sub-systems. According to one operations manager (participant no.6): *"… we'd assess what we feel the root cause was and then put some learning points and actions in place to make sure it doesn't happen again and that would then normally be rolled out to all of the teams in the company."* One incident manager (participant no.22) provided an example for this type of learning. Following an incident on one site, other sites were investigated "*We're only talking* *about probably thirty five plants but the records were scoured and onsite checks were made to make sure that this couldn't reoccur at other places."*

A total of 2,830 actions are currently listed on the database. These actions were investigated using a string search. Key words were used to identify the number of actions that features those strings. It was found that only 83 actions contained the words 'asset' or 'asset management', 56 actions the word 'maintenance', 44 actions the word 'inspection, 34 actions the word 'review', 31 actions the word 'incident', 12 actions the word 'risk' or 'risk assessment' and merely 11 actions the word 'failure'. Although a business process is in place to cascade learning outcomes from incident reviews into the business and, in particular, to the asset management function, the process – it seems - is hardly utilised. One asset engineer (participant no.12) reports: *"I'm very, very critical of the company on that because certainly within the last two years there's been several failures of my sites that could have happened on similar sites with similar assets and we've decided to invest where we've had the incidents on my sites but we haven't looked at similar equipment and similar assets throughout the company. Certainly, I can think of one or two incidents where we've had health and safety near misses where we have addressed it on the site in question but we haven't looked at the whole company and I've, you know, I've made people aware of that in [Regional Water Utility] but, you know, at the end of the day that's all I can do, it's not my role to look at the whole company's asset strategy, I'm just responsible for one of five areas."*

From an asset management perspective, the asset engineer who attends the incident review meeting would focus on the technical issues arising from that incident. One asset manager (participant no.12) reported: *"I would normally just take away technical issues. All sorts of operator issues or human error issues would be - they'd be managed or investigated by the operation manager. I sometimes get involved in revising operating procedures but that tends to be more done by the process engineers within the field team."*

The asset strategy following an incident may have different stages to provide a short terms solution and subsequently a long-term solution. According to one asset engineer (participant no.11), *"usually you'll have an incident review straight away and then you'll have a post incident review to say how you're going to go forward with this. The Asset Engineers, they will sit down with Operations and say what went wrong, why did* *it go, you know, what do we need to do on a permanent basis, what can we do short term. Then you have a review which then how we go forward with this, how quickly can we get the risk assessment through [the process of making an asset investment or maintenance decision];, can we get a scheme this year, can it be fitted into the capital programme this year because obviously every time that fits - something else … [in] the capital programme has to drop out. So it's got to be a bigger business need than the rest of the capital programme for it to have the focus of getting its attention."*

Learning outcomes for incidents are as diverse as the causes for incidents. With the majority of incidents being a result of distribution water mains failures and discolouration it was thought to further expand on learning outcomes for such incidents. With respect to water main failures, the predominant root causes for mains burst are 'age', 'material' and 'soil conditions' that govern corrosion and, ultimately, failure. The structured collection and analysis of water mains failures enables multi-regression analysis for the derivation of risk profiles for the entire water distribution network as previously described in (Oliphant *et al.*, 1997; Emde *et al.*, 2006; Herz, 2005). These models are used to prioritise maintenance and replacement programmes (Mcall and Green, 2005). Similarly, from an operational maintenance perspective, DOMS [Distribution Operations and Maintenance Strategy] are used to derive optimal network cleaning and flushing strategies to prevent discolouration. According to the expert on distribution network assets (participant no.4), *"DOMS is ever evolving; it's something which is now just starting to come into the company. There's going to be what they're calling the DMA service plans - one of those elements is the … proactive cleansing of DMA where you have discolouration problems. That is flushing work that specifies the velocities that can clean the mains out and then strip the material out and hopefully we don't have to go back into that mains for several years because we've given it a good clean through. That's one type of planned intervention which has now been prioritised from the quarterly DOMS process as we're running it. A lot of pages in [the DOMS assessment for DMA's] are focussing on the policies and procedures and how water quality may be affected by any of those policies and procedures themselves.* "

Learning outcomes from incidents are also a component in staff training schemes. In addition to operators being required to gain professional accreditation in form of college certificates as a license to operate a water supply system, learning from previous incidents and failures are communicated to staff and emphasise the requirements for maintaining a safe system. There are, however, commercial restraints that limit the ability to provide extensive training for operators: One incident manager (participant no.7) reported: "*We give a lot of training and we have the licence to operate but, again, because of the pressures to move forward, that's one of the things that's creaking a little bit. I would say we do recognise that the way to learn is not to keep cocking it up but that's the problem we've got, we're not doing enough offline [training]. They get a lot of training before they get released on their own; normally we have about three months before somebody works on their own in a shift.*"

On the other hand, asset engineers require a very different skill set and have different training needs. The asset engineer requires analytical skills and competencies in assessing technical systems as well as the technical means to provide and maintain safe and reliable drinking water supplies. Their job role is reactive in learning from incidents and pro-active in assessing potential sources of failure. Increasingly, the asset engineer has to consider technical system risks and communicate them in systematic risk assessment to the custodians of the risk management process. The asset engineer requires good communication skills, in particular to communicate with operators and operations management. One asset manager (participant no.23) commented: "*I'm quite fortunate within my Asset team - they're quite multi skilled in that a lot of them have come from an operational type background and worked their way up so, therefore, they have an ability already and a skill that they've already been there and done that job, they can have the input and bounce ideas off the people in Operations who are coming up with the risks and stuff and, therefore, can help influence what we need to do to manage a risk. So they can offer quite good complex operational solutions to problems as well as looking at what we need to do for capital investment, if required.*"

In-house training and training on the job are important components of continuous professional development. Recently, a risk training programme was launched to provide staff with a better understanding of risk identification and assessment skills. It made participants aware of the risk perception horizon people have and develop over time. Risk training not only explores the economic-rational perspective on risk used for decision making in the organisation but also 're-frames' psychological and social construction and understandings of the organisational risk concept. The training is aimed for reducing the deviation in quality of risk assessments with a view to enhance the consistency of investment and maintenance decision making. In that sense, the communication of incidents to staff helps the organisation to communicate the failure proneness and future risks of the system to its staff. The general interest in this training scheme demonstrates that staff maintain a commitment to continuous learning and seeks the acquisition and improvement of skills. This training programme has been recognised as industry leading and earned a number of industry awards.

Taken together, all of these dimensions were observed to contribute to the effective management of incidents affecting water safety and reliability in this organisation. In the web of organisational culture (Johnson, 1992) some key findings of this research component (Figure 36) are summarised.

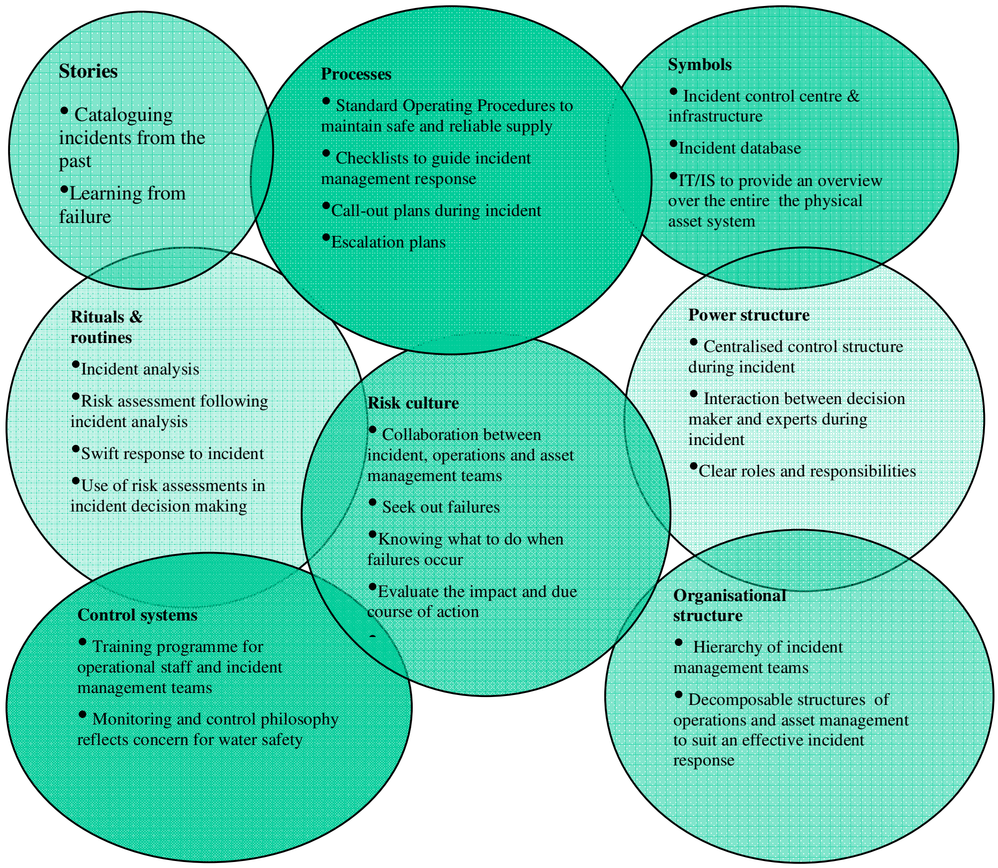

Figure 36 A cultural web of organisational culture in operations and incident management

3.4.2.3 Evaluating the effectiveness of HRO principles in the management of incidents

In the following analysis, the impact of incidents is correlated with an assessment of observed HRO principles during the management of incidents. The assessment was carried out in a review of documented incidents aiming to find documented evidence for adherence to HRO principles during their management. In this analysis, it was aimed to explain the residual incident impact on customers as function of observed HRO principles during the incident management. For the years 2004 to 2006, 36 well documented incidents were selected that represent significantly high, average and significantly low incident impacts. The incidents were reviewed for evidence relating to the HRO principles identified in the HRO framework.

In Figure 37, three data sets are presented: firstly, the incident impacts of 36 selected incidents were correlated with the average score for observed HRO principles based on all HRO indicators: the average score was calculated from the 51 HRO principles if sufficient data in the incident documentation was available to score individual HRO principles. Secondly, the incident impact of 36 selected incidents was correlated with the average score for observed HRO principles using only those principles that were previously identified to have an average, positive cost benefit. Thirdly, the incident impact of 36 selected incidents is correlated with the average score for observed HRO principles using only those principles that were previously identified to have a significant cost benefit, *i.e.* indicators with the minimum confidence interval of 95% exceeding zero.

It can be identified that all datasets have a minimal, positive correlationship between the incident impact on customers and the average score for observed HRO principles. Considering all HRO principles regardless of their cost benefit, a positive correlation described with y=0.41x + 62.8 between the incident impact and the average score for observed HRO principles can be identified. The coefficient of determination R^2=0.0454 only explains 4.5% of the variation in the average score for observed HRO principles as a function of the incident impact.

Considering those HRO principles that were previously evaluated with an average, positive cost benefit, a positive correlation described with y=0.30x + 71.3 between the incident impact and the average score for observed HRO principles can be identified. The coefficient of determination R^2=0.019 only explains 1.9% of the variation in the average score for observed HRO principle as a function of the impact scores.

Finally, considering those HRO principles that were previously evaluated with a significant positive cost benefit, a positive correlation described with y=0.32x + 74.3 between the incident impact and the average score for observed HRO principles can be identified. The coefficient of determination R^2=0.021 only explains 2.1% of the variation in the average score for observed HRO principle as a function of the impact scores.

In all three datasets, the y-axis intercept ranges between 62.8 and 74.3. This suggests, as previously enquired in the survey of water utility managers, that HRO principles form part of the organisational culture during normal operations (at zero adverse impact on customers) but also during an incident.

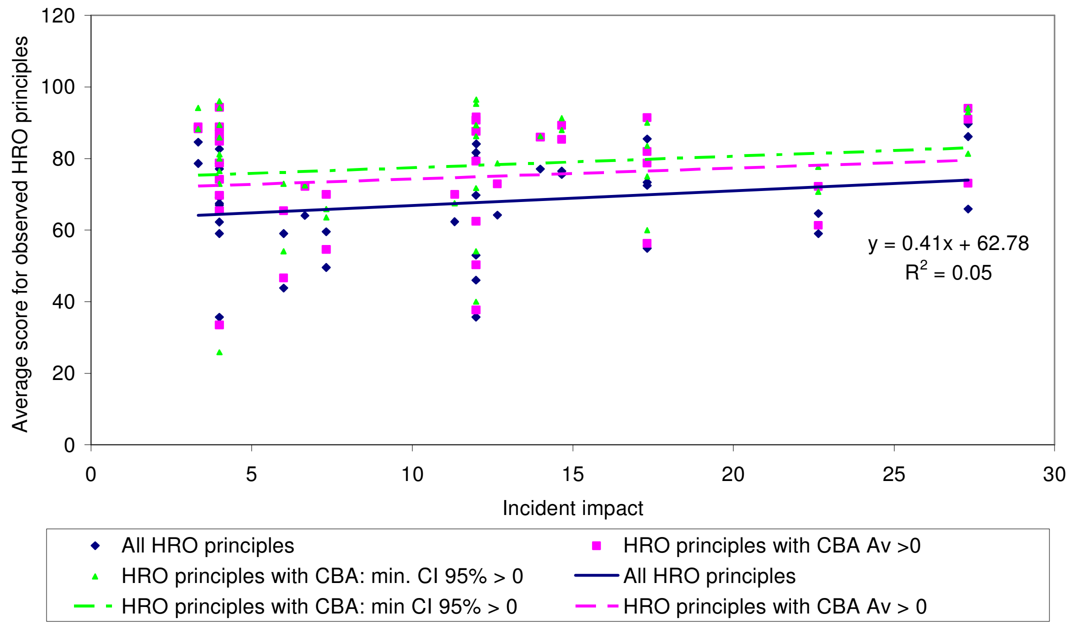

Figure 37 Correlating the incident impact on customers with average scores for observed HRO principles

The marginal, positive relationship between increasing incident impact and average scores for observed HRO principles is an interesting finding because it was initially hypothesised that a higher incident impact would negatively correlate with the scores for observed HRO principles. In other words, it was assumed that low observance of HRO principles would have an adverse impact on customers, *i.e.* prolonging the incident or aggravating the hazard exposure of the population. It is not believed that a causal relationship between increased observation of HRO principles and increased incident impact exist. This would mean that increased scores in HRO principles would have an aggravating effect on customer impact from incidents. To the contrary, it is stipulated that a higher perceived or potential threat to customers during an incident triggers a more focussed incident management response that resembles the characteristics described with the HRO principles. Another attempt to explain the findings may also arise from the quality of data used in the survey. It may be argued that higher impact incidents are better described and the HRO principles are more evident in the incident documentation. A further source for error may arise from incidents that resorted to well tried and tested incident management routines as opposed to novel incident situations. For example, a pipe burst with impact on customers ('loss of supply, 'low pressure and 'discolouration') frequently occurs in the organisation and the incident management response for such a scenario is a well established incident management procedure, whereas truly 'trying conditions' arise in unprecedented and unforeseen situations that were never experienced before.

In conclusion, the coefficients of determination below 4.5% are too low to explain the variation in the average score for observed HRO principles as a function of the impact scores. It is concluded that the incident impact on customers does not correlate with the observation of HRO principles.

In a follow-up analysis, the scores for individual groups of HRO principles (A – G) were correlated with the impact of incidents. Throughout this analysis the coefficient of determination did not exceed 15% and in most instances did not exceed 1%. This suggests that variation in the average score for observed HRO principles can hardly be explained as a function of the incident impact scores. The detailed analyses are presented in Appendix 4.2.3.

It has been previously argued that the effectiveness of incident management requires a measure of reduction in incident impact, *i.e.* deducting the actual incident impact from the potential impact. In the previous study, the <u>ultimate</u> or final incident impact was correlated with the observed HRO principles without taking into account the <u>potential</u> incident impact that could have arisen without effective incident management. So, in this study, a number of incidents were selected to anticipate the potential incident impact in perspective of the actual incident impact on customers. Hence, the reduction of incident impact was correlated with the score average for observed HRO principles identified in the review of documented incident management responses. The incidents were chosen from the trying conditions that were used to compare HRO scores with the ultimate incident impact scores. The narratives and the analysis of these incidents are presented in Appendix 4.1 as case studies; for each year between 2004 and 2006, 4 incidents were selected that represent significantly low as well as significantly high incident impacts on customers. The findings are presented in Table 48 and Figure 38. In this correlation, a positive relationship between observed HRO principles and incident impact reduction can be identified. However, the coefficient of determination only explains 26% of the variation in incident impact reduction as a function of HRO principles.

Incident year	Actual incident impact	Incident impact score	Potential incident impact	HRO score	Impact reduction attributed to HRO principles (Score)
2004	High	27.3	Significantly higher	89.7	Medium (3)
2004	High	27.3	Significantly higher	86.1	Medium (3)
2004	Low	3.3	Significantly higher	84.6	High (4)
2004	Low	4	Significantly higher	67	Very high (5)
2005	High	27.3	Insignificantly higher	65.9	Low/Medium (2)
2005	High	3.3	Significantly higher	78.6	High (4)
2005	Low	4	Significantly higher	78.6	High (4)
2005	Low	4	Insignificantly higher	62.3	Low/Medium (2)
2006	High	12.7	Insignificantly higher	64.2	Low/Medium (2)
2006	High	12.0	Insignificantly higher	53.0	Low/Medium (2)
2006	Low	6.0	Medium	43.8	Low/Medium (2)
2006	Low	4	Significantly higher	67.5	High (4)

Table 48 Correlating the reduction in incident impact with observed HRO principles

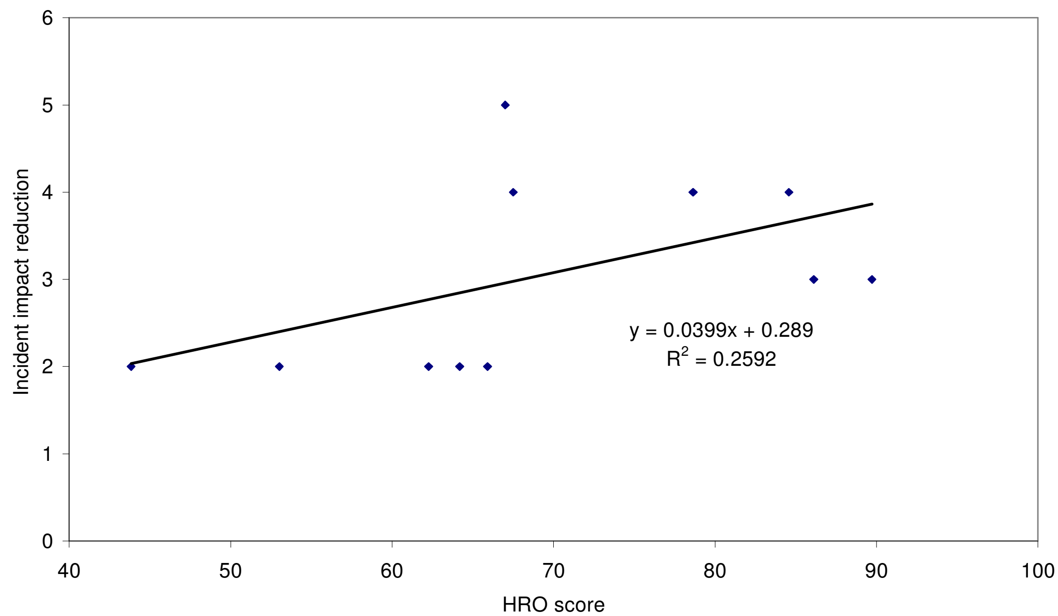

Figure 38 Correlating the reduction of incident impact with observed HRO principles

3.5 Summary

The studies in this chapter were designed to investigate the benefit of HRO principles in incident management and to correlate incident impacts on customers and impact reductions with observation of high reliability principles under trying conditions. A survey series was conducted with water utility staff to identify the familiarity of water utilities with HRO principles. As an observer in an operations and incident control centre, the author watched the management of unfolding incidents. The observational studies were further enhanced by staff interviews and document reviews, *e.g.* standard operating procedures, policies, communiqués, etc.

The author set out to investigate the familiarity of the water sector with the principles of high reliability organisations (HRO). It was aimed to identify the benefit of HRO principles in providing safe and reliable drinking water to customers in the context of the cost to implement, operate and maintain these principles. Here, it was found that many principles of HRO could be readily observed in operations and incident management of the water utilities that participated in the HRO survey and the Regional Water Utility.

Secondly, the author was interested if HRO principles in incident management have a significant effect reducing the public health impact on a population during an incident. Based on the documentary study of incidents and their management it could be demonstrated that HRO principles have a positive effect in reducing the incident impact on customers (Figure 38).

Two hypothesises were used to structure the investigation. Firstly, it was hypothesised that the water sector is familiar with the principles of HRO in the context of providing safe and reliable drinking water to customers. Secondly, a water utility makes provisions for the "*short periods of 'stress'*" (World Health Organisation, 2004) with the design of incident management procedures that are based on HRO principles.

The results of this study confirmed that a significant number of HRO criteria are readily observable in the investigated water utilities and that many HRO principles were considered cost beneficial in contributing to the management of a safe and reliable drinking water supply. It was found that the Regional Water Utility makes provisions for the "*short periods of 'stress'*" (World Health Organisation, 2004) with the design of an incident management capability that are based on many HRO principles. In the study of incidents, it was found that the Regional Water Utility is well positioned to manage incidents and many HRO principles can be readily identified as management practice under 'trying conditions'. It was found that the observance of HRO principles significantly contributes to the resilience of the organisation to provide and maintain a safe and reliable drinking water supply. The incident management procedures are tried and tested procedures: Considering the frequency of incidents that occur in the Regional Water Utility, a dedicated team of incident managers are available 24 hours/day, 7 days a week to oversee efforts of reducing the impact of incidents on customers and to re-instate 'normal operation'. In a number of incident cases, the Regional Water Utility demonstrated a competent approach to manage unforeseen and often complex incident circumstances.

A number of sub-hypotheses were used that are specifically relevant for subsequent chapters in this thesis. In particular, it was hypothesised that

- ‘water utilities maintain existing technology to exceptionally high level’;
- ‘water utilities use root cause analysis of minor errors and incidents as a source for learning’; and
- ‘Water utilities develop a collective memory for failures, incidents and root causes for failure to help anticipating future problems’.

It was found that the majority of survey respondents ‘disagreed’ or ‘strongly disagreed’ that ‘maintenance of technology to exceptional high standard’ could be observed in the participating water utilities. They also considered this to be not beneficial in the context of the cost involved. In the previous chapter, the frequency of incidents per year associated to asset failures suggested that organisations must develop some form of organisational competence to manage incidents. The frequency of asset failures corresponds with the observations in this study that incident management is a highly routinised job and it could be argued that incident management forms part of the normal operation in the Regional Water Utility. It could also be argued that technical reliability of physical assets is substituted by organisational reliability in incident management to reduce the impact of incidents on customers and to re-instate ‘normal’ operations.

With respect to learning organisations, the HRO principle of ‘learning from failures, near misses and mistakes as a means to study the failure susceptibility of the organisation’ was perceived as cost beneficial and, according to the surveys, was observable in the majority of water utilities. Root cause analysis of minor errors and incidents was identified to provide a source for learning and ‘developing a collective memory for failures, incidents and root causes for failure to help the organisation anticipating future problems’ was perceived as cost beneficial. Evidence was found that the Regional Water Utility uses detailed incident review procedures and thorough incident analysis techniques to investigate incidents. In an incident review meeting the circumstances of incidents are investigated considering technical issues as well as human factor. It evaluates the performance of the technical system but also organisation and individual performance prior to and during an incident.

In theory, learning from incidents is facilitated by a process of identifying root causes, agreeing actions to consider the prevention of re-occurrence and communicating learning outcomes to the wider business, in particular were similar incidents could occur. A number of interviewees in the Regional Water Utility shared the view of this process being effective, whereas others were more critical about the learning capability from incidents. On the other hand, the incident review meeting enforces the adherence to standard operating procedures because the explicit investigation of human error drives out poor behaviour by individuals. In that sense, sociological pressures help the organisation to promote safe actions and interventions in the technical system.

The primary purpose of the incident documentation is to report individual incidents to senior management and the regulator. Documented incidents are stored in an incident database that underpinned the majority of the above analyses. After an incident, learning opportunities are immediately communicated to relevant staff in the organisation but then the incident documents end up on the incident database, which is merely a repository of incident records. So far, limited evidence was found that the organisation uses the incident database for structured analysis as performed in the previous chapter. One major exception is the structured analysis of water main burst data that is used to predict the failure susceptibility of water mains in the future. In regressional analyses the occurrence of water main bursts are correlated to 'material type', 'age of the asset' and 'soil conditions' as well as other factors.

Organisational learning, in particular from incidents, in the context of asset management decision making is the subject of further investigations. The forthcoming chapter introduces decision-making processes for risk-based asset investment and maintenance and incorporates 'learning from incidents' to enhance the process of identifying and assessing risks.

4 Learning from failure in risk-based asset management

4.1 Introduction

In the introduction to this thesis, three main aspects were introduced for investigation in this project: firstly, the nature of incidents and their impact on customers; secondly, the need for an organisational capability to manage incidents and its role in maintaining a resilient water supply system that minimises the impact of incidents on customers. Thirdly, risk-based asset management strategies that provide and maintain the technical reliability of the water supply system with a particular emphasis on opportunities to enhance the perception and understanding of risk. The latter aspect is the subject of this chapter.

In the previous chapter, the HRO framework was introduced with a specific section on ‘precise procedures in managing technology’. In the surveys, it was found that the majority of survey respondents disagreed or strongly disagreed that ‘maintenance of technology to exceptional high standard’ could be observed in their water utilities. They also considered this to be not beneficial in the context of the cost involved. In practice, water utilities are now embarking on an explicit trade-off between investment cost and risk for asset investment and maintenance decision making (MacGillivray *et al.*, 2006). Formalised cost risk trade-off mechanisms are becoming common practice (Lifton and Smeaton, 2003; MacGillivray *et al.*, 2006; Pollard *et al.*, 2004) that use risk registers and cost benefit analysis (CBA) in asset investment and maintenance decision making to evaluate the benefit of risk reduction in the context of the cost for asset investment and maintenance. This places risk assessments at the centre of investment and maintenance decision making.

In the previous chapter, it was enquired if ‘water utilities use root cause analysis of minor errors and incidents as a source for learning’ and if ‘water utilities develop a collective memory for failures, incidents and root causes for failure to help anticipating future problems’. These HRO principles are thought to be an effective learning strategies to verify, validate and enhance risk assessments based on learning from previously experienced incidents. In this chapter, the derivation and use of risk assessments in decision making are investigated with a particular focus on the risk data quality to derive effective decisions. Previously experienced incidents are used to validate the risk model and to verify the data derived in risk assessments as a means to learn from failure.

The objective of this chapter is to identify learning opportunities from incident analyses to enhance risk assessments that are subsequently used for asset investment and maintenance decision making in asset management. The sought learning opportunities arise from comparing perceived future risks to actual incident data.

4.2 Theoretical development

From an economic perspective (Bonart and Peters, 1997), a water utility uses technologies to transform input factors into outputs. The three main input factors are capital, labour and natural resources. The management process considers which production factors to use, how to combine these production factors and the prices for production factors and outputs. Similar to capital, labour and natural resources, risk can be allocated an incremental unit and a price or cost. Increasingly, risk assessments are used in the water sector to identify the units of risk in water supply systems (Deere *et al.*, 2001) and commercial or monetary evaluation methods are used to derive the cost of risk (Lifton and Smeaton, 2003; Abell, 2005). The incremental units of risk and their 'market price' can take the form of opportunity cost that a water utility customer is willing to pay in order for a risk event not to occur (UK Water Industry Research Limited, 2002) This methodology for non-market valuation of benefits aims to generate estimates of customer benefit and preferences for different service attributes and their associated risks (Bateman *et al.*, 2002). In that sense, risk becomes the fourth production input factor in a water utility production function.

A production function describes the quantitative correlation between production input factors and outputs (Bonart and Peters, 1997) and in substitutional production functions the input factors can be substituted within a reasonable area of the function (Bonart and Peters, 1997). As with the other substitutional input factors, risk i_1 can be substituted by the production factors labour, natural resources and capital without an effect on the overall output. In Figure 39, the Cobb-Douglas function is such a production function

(Bonart and Peters, 1997) that describes the explicit trade-off between unit risk (Deere *et al.*, 2001) and the units of assets required to reduce risks. A number of examples were added to explain the trade-off concept.

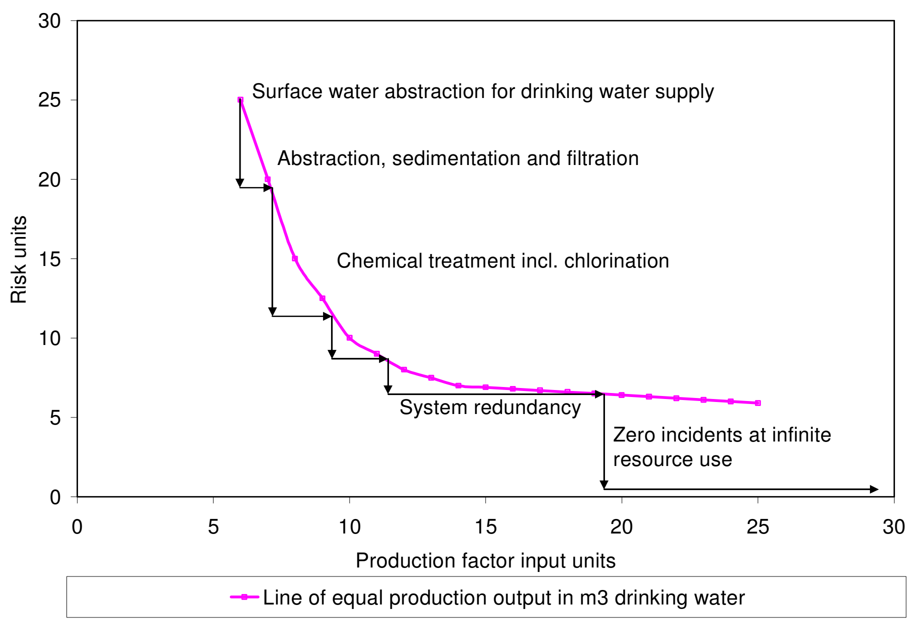

Figure 39 The trade-off between risk and water supply system assets

So far, this relationship between units of risk and assets has not considered the price or cost for risk and assets. Assuming the need to maximise benefit (or profit) the optimal equilibrium between risk and assets is governed by their respective 'market' prices or costs. Based on this principle, Equation 8 describes the rate of technical substitution between risk (di_2) and assets (di_1) to be the negative ratio of their production input factor prices (p_{i1} and p_{i2}) (Bonart and Peters, 1997).

$$\frac{di_2}{di_1} = -\frac{p_{i_1}}{p_{i_2}}$$

Equation 8 The optimal rate of technical substitution

It suggests that the optimal rate of substitution for production input factors is directly dependant on their factor prices (Bonart and Peters, 1997). This is the governing principle of economic-rationale cost risk trade-off in decision making. A detailed derivation of Equation 8 can be found in the Appendix 1.

Since the privatisation of the water industry in England and Wales (Office of Water Services, 1993; Parker, 2004), 26 regional water companies now serve between 400 and 8,231,000 customers (Drinking Water Inspectorate, 2007). The Regional Water Utility investigated in this project provides water and wastewater services to 4.7 million customers and represents a significantly large customer base in comparison to all water utilities in England and Wales. Over 95% of its customers are linked into an asset network of water resources, treatment and distribution pipes. The network of interconnected assets has over 1,200 major elements including 147 reservoirs, 5 river sources, 80 boreholes, 86 water treatment works, 300 pumping stations, over 650 treated water storage reservoirs and 32,000 km of distribution pipelines to satisfy a daily drinking water demand of 1,250 Ml.

Currently, the Regional Water Utility has ca. 86,000 risk assessments collected in an asset risk database. In these risk assessments, the failure of an asset is assessed as a probability to have an impact on customers. Impacts on customers relate to water quality, discolouration, low pressure, loss of supply, etc., *i.e.* reflecting the objective to provide safe and reliable drinking water to customer (International Water Association, 2004) and more specifically the 'level of service' indicators set by the regulator (Office of Water Services, 1998). Considering the vast asset base of regional water supply systems and a centralised decision making process of financial resource allocation for investment and maintenance, high consistency in risk assessments is required to effectively and optimally allocate capital and operational expenditures across the asset base. Based on Equation 8, the economic effect of inconsistencies in risk assessments can be explained with the conceptualised Figure 40.

At individual asset level, the over-estimation of risk attracts excess cash for risk reduction, whereas underreported or underestimated risks for assets attract deficient amounts of resources. Across the entire asset base, a large standard deviation in the assessed units of risks introduces a similar standard deviation in the rate of technical substitution between risk (di_2) and assets (di_1) (Bonart and Peters, 1997). Over- or underestimating as well as over- or underreporting risks distorts the economic optimal allocation of cash resources and imbalances the optimal risk-asset equilibrium. Hence, a consistent approach to risk assessments is required that builds on consistent risk assessment processes and a common understanding and perception of risk is required that shapes the individual's psychological and heuristic constructs of risks towards the organisational standard or norm.

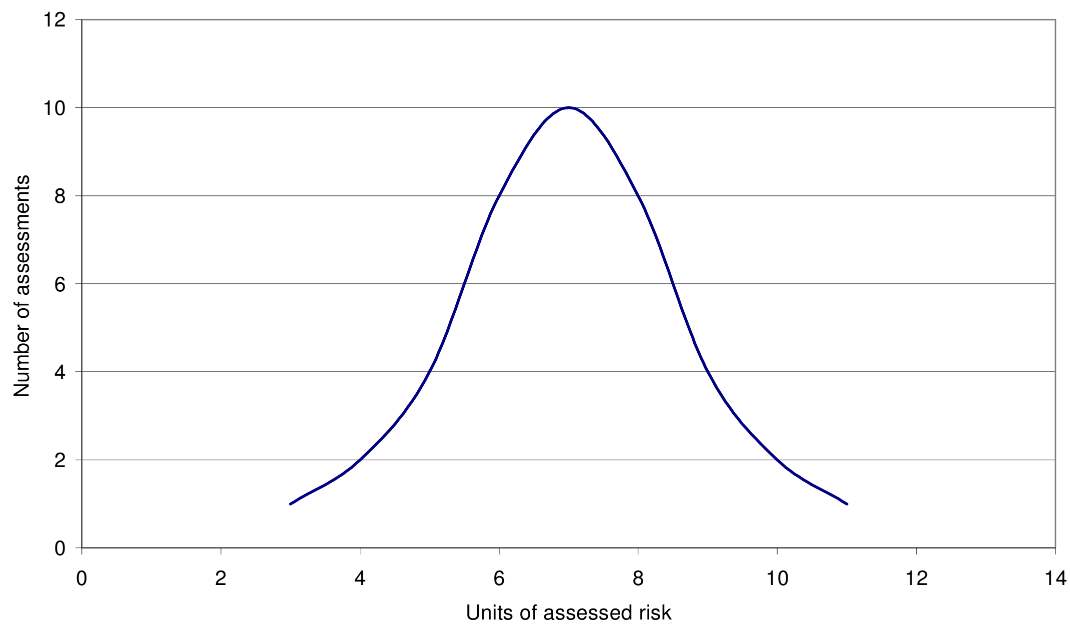

Figure 40 Inconsistency in risk assessments for one asset

In this chapter, the quality of risk assessments is investigated and opportunities to enhance risk assessments based on learning from previously experienced incidents identified.

4.3 Methodology

This chapter methodology is dominated by an action research strategy that has been promoted by practitioners as a moral responsibility to work socially meaningful in changing a situation for the better by the researchers involvement (Denzin and Lincoln, 1994; Greenwood and Levin, 1998). It is "*research becoming praxis – practical, reflective, pragmatic action – directed towards solving the problems in the world*" (Denzin and Lincoln, 1994) and has a deliberate interaction with the subject areas of study. The object of action research was to statistically analyse the incident data previously derived in Chapter 2 with risk assessment data held by the Regional Water Utility and to identify and to improve the gaps in the risk assessment and management process. The former object of study consisted of a quantitative statistical data analysis to compare risk assessments as they are perceived by individual risk assessors with actual past incidents. With respect to the latter object of study, it was thought that action research provided the distinct advantage of using the researchers skills and expertise in an interactive process with experts in the Regional Water Utility to explore the processes of risk analysis and assessment and its interaction with staff, in particular relating to their perception of risk. The research results of this study were documented in similarity to the previously conducted observational studies on HRO principles in incident management and recorded how the researching individual experiences events, actions and processes. Furthermore, observational methods were used to investigate what groups or individuals do and recording their actions and describing their activities offers data rich accounts of real-world research (Robson, 2002).

Although an acclaimed advantage of action research, there is the obvious danger of the researcher to influence the results of the object of study, in particular when considering mental frameworks that have shaped his/her expectations or heuristic models.

In addition to the action research component, semi-structured interviews were conducted with staff who are engaged in the risk-based asset management process. This represents a form of triangulation to the action research programme and represents a form of phenomenology as a method of trying to understand how individuals perceive and construct their reality (Robson, 2002). Although this form of research provides highly detailed data based on highly personalised and subjective experiences it was thought that the content analysis based on semi-structured interviews provides rich and detailed data with expressive and enlightening information (Wengraf, 2001) on how staff experience and make sense of the risk assessment process despite the lack of standardisation in its results. A further advantage over structured interviews is the ability to react to emergent topics that are raised by the interviewee (Robson, 2002).

4.3.1 Risk-based asset management in an international water sector context

Six water utility professionals from a range of international water utilities in highly developed countries were invited to participate in an interview series. The interviews were designed as a pilot study to further define the scope of the in-depth, main study in the Regional Water Utility. The selection criteria for inviting participants focussed on risk-, operations- and asset managers who were attending a workshop on risk management culture in December 2006 in Banff, Canada. The invitees represented a range of water utility sizes and various water utility ownership models. The participants represented

- large-sized, privately owned water utilities from England and Wales (participant no.16 and 17),
- a large-sized, corporatized, publicly-owned water utility in Scotland (participant no.18),
- medium-sized, corporatized, publicly-owned water utility in Canada (participant no.19 and 20), and
- a small to medium - sized, publicly owned and operated water utilities in Canada (participant no. 21).

In the first part of the questionnaire, the participants were required to identify their organisational objectives followed by questions relating to public health, asset management and, finally, questions relating to incident management. The questionnaire (Appendix 4.3.3) was peer reviewed by academic supervisors and the AWWARF Project Advisory Committee.

4.3.1.1 Data quality

In this study, a limited number of interviews were conducted with participants from a range of water utilities in an international context. The number of interviews is not representative for the water sector. Secondly, the interviewee group was potentially biased for their common professional interest in risk management and their attendance at the risk management workshop. Furthermore, the interviewees may express their opinions based their professional experience that shaped their heuristic beliefs and understandings of their environment.

4.3.2 Risk data quality in risk-based asset management decisions

The main study was carried out in the Regional Water Utility during a 6 month research placement. In this placement, the author conducted structured observations and data analyses in the strategic asset management department. Based on the theoretical developments above, the design of the asset risk management system was studied as well as work processes, procedures and activities relating to asset investment and maintenance planning. This time, the author had a more active role in the organisation that could be described as action research: The Regional Water Utility had an interest to enhance their risk management capability and the author applied his technical and organisational expertise to evaluate and enhance the socio-technical and socio-economic business concept of risk-based asset management in the organisation. As an external to the organisation, the author aimed to remain independent in thought and action.

In a series of case studies, it was investigated how the organisation assesses and incorporates future "*trying conditions*" (Weick, 1987) in risk assessment for asset investment and maintenance decision making. For this purpose, a number of roles were assumed – as an analyst of business processes, a risk assessor, an asset engineer/ manager, consultant and facilitator of a risk experiment - to capture a holistic understanding of the risk model.

A major component of this chapter was to evaluate the quality of risk data as perceived by risk assessors in the organisation. The risk data were available in a risk database. In a structured analysis, these risk data were compared and correlated with findings previously obtained, analysed and evaluated in the chapter characterising incidents. Findings of the data analysis were triangulated with observations and document reviews. A series of interviews was also conducted to understand the perception of risk assessors on the user-ability of the current risk assessment model and the means of learning from previous incidents. These interviews guided the author in the analysis of data, confirmed understanding and facilitated the interpretation of research results. The questionnaire is presented in Appendix 5.3.1.

4.3.2.1 Data quality

The main source of data in this study originated from the Regional Water Utility who provided unlimited access to a vast repository of documented incidents and risk assessments. The predominant source of data used in this study are risk assessment files, documents, reviews, communiqués and personal accounts of staff involved in risk assessments. The risk files describing individual risk scenarios contained detailed technical analyses and personal communications of staff. The motivation of providing unrestricted access to data can be explained by the Regional Water Utility's interest to enhance their risk assessment capability.

The structured analysis of the data consisted of building a number of databases to code, analyse and statistically process data. The information and knowledge derived from the analyses were reviewed by representatives from the Regional Water Utility to validate the methodological approach and to verify the results. The verification and validation process aimed to ensure that the models used to code the data were relevant and applicable to the set research question.

One important aspect in this process was the awareness that the outcomes of this data analysis depend on the reference models used to collect incident and risk data. Since only one source of data is used in this analysis a risk was identified that the data acquisition and collection process within the water utility is subject to cultural bias. Although it was a primary objective to identify bias in the process of assessing risk, this analysis used a number of triangulating techniques to reduce the bias and ambiguity of the author. Case studies, interviews and observations were used to investigate, analyse and evaluate the risk-based asset management system. The use of multiple approaches for this research (triangulation) aimed to reduce personal bias whilst aiming to understand processes and the cultural norms in the organisation.

4.4 Results and Discussion of Results

4.4.1 Risk-based asset management in an international water sector context

In this inquiry, approaches to risk-based asset management were investigated. Firstly, it was aimed to identify how prevalent risk-based asset management strategies are across the participating water utilities. It was found that asset management capability ranges from not existent to very advanced. On asking one utility manager (participant no.21) if they use public health risk assessments or whether they have an asset management decision process, the manager replied: "*I'd have to say really not. Our agenda has been driven mostly by regulations*" and "*by dealing with particular risks that we either perceived or knew through testing. We are entering into an area where we are looking at asset management*." "*Now we're implementing a system where we actually have an asset management database in GIS that we will use to make decisions on. So we're certainly going in that direction".*

Another reported (participant no.19): "*We've got a very formal risk management process that we have to go through and set objectives and look at the risks associated with it and that's tied into our budget process. Asset management then decide where we're going to spend our capital dollars. Part of our budget process is actually to highlight what the risks are, what are our current mitigations, what the residual risks are and then what we're doing in terms of our budget, you know, both in terms of kind of resources to address the issues of our capital expenditures to address the issues of the process."*

The traditional engineering approach to asset management was reported from this interviewee (participant no.20): "*For a long time our Engineering Department has done asset management on the pipe infrastructures - so for about twenty five years we've been keeping track of break history." "We've done enough work that we know the life of our infrastructure, you know, what the demographics of it are and we've got a capital plan to support the sustainable renewal rate."*

One reporter (participant no.18) from an advanced water utility highlighted how their public health risk assessments are integrated into asset management plan: *"At high level it's in the drinking water safety plans …. Prior to drinking water safety plans, it was more discrete risk assessments so – but now we have drinking water safety plans - it's a source to tap risk assessment. So, within the drinking water safety plans, you … have DOMS which is another version of a process – you've got a process procedure, …you have written procedures, written work instructions so – but drinking water safety plans at a high level is the methodology we use to monitor and manage public health risks and that's continuously updated and within drinking water safety plans we have*

SWARM which links back to the business impact." The interviewee (participant no.18) also reported on the process of deriving risk assessments and decision making: "*So, SWARM is like the heart of drinking water safety plans and that allows you to evaluate risk in the catchment, treatment [and] transmission down to the customer. SWARM isn't just about capital interventions, within SWARM an intervention might be write a new procedure or put extra staff on them, greater surveillance. SWARM is very effective now … – because we're looking at failure modes, potential failure modes source to tap, and then you're looking at intervention measures for each failure mode and, as I said, a failure mode doesn't have to have happened, it could be a possible thing on the horizon which means you'll have the likelihood. So because we're cash constrained we have a set amount of money. SWARM … will come out with a big long list of interventions and you have to just draw the line when the money runs out. So you're getting your best bang for your buck, you're getting the best risk reduction for that amount of money and that's for all above ground assets. …because our risk reduction is in pounds, in theory, the closer (the cost benefit ratio) to zero obviously the better value it is. If you get [a cost benefit ratio] of one, it means that you're spending four million pounds for avoiding a four million risk which is still pretty good. It's balanced but you might be happier if you were spending four pounds to get rid of a four million pound risk so the closer to zero your risk reduction index is the more likely you'll invest in it."*

However, there are challenges and weaknesses in the cost benefit approach: "*SWARM is a system and you need operator intervention - you need someone, some person to have a look at it because if you just used the risk reduction index you could end up doing a whole load of cheap schemes which gives you big risk reductions but you may leave some big risks on there, huge risks to companies that – it makes the index look very expensive to get rid of.."*

Another utility manager (participant no.16) reported on their decision making tool: "*We do, in making any investment decisions now, apply what we call our 'trade off diamond' for investment decisions related to the water infrastructure. So the 'trade off diamond' looks at alternative options for achieving improvements through project investment and compares options for what we call 'whole life costs' so the capital cost and the maintenance cost in capital terms and the operating cost in revenue terms with the benefit in risk reduction that you achieve through selection of one of the competing* *options. So we're able by looking at the impact and the probability – or the probability of occurrence and the frequency of individual events reoccurrence. Over the life of that asset and, if we're looking at different assets so concrete and steel versus wrinkly tin kind of thing which have different asset lives, we bring those to a common base. We've got a good idea of what we call the 'probable cost of risk' associated with choosing a particular investment option over a standard lifetime which might be thirty or forty years, for instance.*

So the impact criteria have a number of different consequences. We use water quality, public health, legal, regulatory are some examples of the impact criteria that we use. So we're able by doing that analysis and bringing those together to form a view of what benefits we're getting through risk reduction vis a vis the investment we're making on a particular option. So we're able to incorporate public health risk assessment in the wider risk assessment associated with choosing between investment options or choosing not to invest at all. Cost is the lowest common denominator so we reduce everything into an equivalent in cost terms." For the assessment of consequential cost, he reported to "*use in lieu of data" – "and this is where [the Regional Water Utility] are more advanced than we are because <u>they started a data acquisition process far earlier than we have done</u> ."*

The interviewees were asked to comment on the acceptable level of risk: *"What is still not as mature as I would like is an understanding of what represents a tolerable level of risk within the organisation and I'm just promoting discussions to more clearly understand the distinctions between hazard tolerance, control acceptance and opportunity appetites really which are the three subsets of what is generically known as risk appetite* (participant no.16)*."* On that issue, the previous interviewee (participant no.18) reported: "*I must admit we haven't got a very good act on this one. We've sent through the statistical analysis of the water policy risks to determine the site specific risk to achieve an overall corporate risk level. It is very data hungry and all we can hope for at the moment is we try to maintain our risk levels the same because we can score all our sites through SWARM and come up with this site here is three hundred and twenty, that site there is two hundred and forty. We don't say we need to get both sites down to two forty, all we say at the moment is we'll invest to keep that site at three forty, this site at two forty and so we're not trying to move them all towards an* *equivalent level of risk across [Name of Water Utility]. We're trying to hold them at the moment until we've got a lot more data to understand. All we can do is saying the plants we operate are offering a sufficient level of service at the moment and we'll invest to maintain that."*

To the contrary, another (participant no.20) reported: *"Really we don't assess the risk that's tolerable, the risk's not tolerable. So we don't get into decisions like what's the risk of not having a spare pump there versus a spare pump here. We say if we're going to need a spare pump in both places, then we'll provide it."*

Regarding lesson learnt, one interviewee (participant no.16) reported: "*In terms of lessons learned, we conduct post incident reviews from each incident that occurs so if there are lessons learned there then we attempt to build those into our controls and our corporate knowledge but … retention and accessibility of corporate knowledge is something that is a challenge for all Water companies. [More] recently … we were concerned about whether the learnings within the group that did the incident review … were not getting broadcast out far enough. What we've actually done is we set up a group and on a monthly basis we've used this when an incident has occurred across the corporation - these are not just water quality but safety and environment - and then basically we quickly go through and review it."*

Regarding the implementation of changes after an incident one interviewee (participant no.19) reported: "*I mean, some of the incidents are just very particular to a certain site and a certain location but, if there's themes in terms of incidences or an incident that would be applicable to a bunch of other sites, that is brought out and then basically the group meets, reviews these and then has to put up the key learnings that came out of all the incidents that went down. That's set out in the review. Depending on how significant the result is … there's a control process [for] changing a procedure… Part of that is coming up with a plan. If you're going to go in and change a procedure, then you have to come up with a plan on how you're going to do that. It might be something that just affects a small group so then you want to have a small training session with ten people. It might be something that's corporate wide or there might be more of a formal roll out process of how you do it."*

In conclusion, it was found that risk-based asset management strategies range from very little capabilities towards very advanced risk-based asset decision-making processes.

Whereas some (smaller) utilities struggle to even set up adequate accounting practices for asset depreciation and re-investment to sustain a stable accounting value of assets, others are advancing beyond the traditional model of asset depreciation and re-investment towards trade-off's between risk reduction and capital as well as operational spending. Risk assessment processes were described in a couple of advanced water utilities that require the acquisition of risk data to underpin decision making.

A few interviewees described the process of 'learning from failure' as a mechanism to identify investment needs but also needs to change business processes and procedures. These themes were further investigated in the Regional Water Utility.

4.4.2 Risk data quality strategies in the Regional Water Utility

4.4.2.1 The risk assessment model

The Regional Water Utility implemented a risk assessment and management system to prioritise capital and operational expenditures in asset creation, operation and maintenance. It conceptualised a risk assessment framework aimed at identifying risks relating to not delivering service to customers with its current asset base. Risks are expressed as a function of *probability* (p), *severity* (s) and *quantity* (q), which are defined as:

p = probability of at least one service failure occurring

s = severity of the impact on the customer

q = scale of the impact in terms of people affected

For the management of these risks, the organisation identifies

- solutions to risks;
- estimates of the benefits from undertaking a solution (risk reduction); and
- assessments of the costs involved in undertaking a solution.

According to one asset planning manager (participant no.25) "t*he organisation has a system in place to estimate the cost of solutions using unit cost models contained within a unit cost database. The process allows an assessment of alternative solutions to reduce the same risk. Each solution usually requires different levels of CAPEX and*

OPEX and has potentially different effects on risk reduction. Optimal solutions in terms of CAPEX, OPEX and risk reduction are modelled in a cost benefit assessment."

Currently, the organisation uses the following severity scales for impact assessment (Table 49).

Risk effect	**Severity score**	**Description**
Water quality	Very low	Compliance but customer complaint
	Low	Trivial sample failure
	Medium	PCV failure leading to an undertaking
	High	Prosecution by regulator. Boil order as risk of illness through drinking water
	Very high	Public health effect. Illness through drinking water
Discolouration	Very low	1-2 complaints per 1000 properties, < 50ug/l Iron and no events - Slight discolouration noticed in customer bath
	Low	2-4 complaints per 1000 properties, 50-100 ug/l Iron and no events. Particulate material visible in clear water
	Medium	4-7 complaints per 1000 properties, 100-150ug/l Iron or minor events. Translucent and discoloured resembles orange juice or lager.
	High	7-10 complaints per 1000 properties, >150 ug/l or notable events. Opaque and discoloured resembles weak milky tea.
	Very high	>10 complaints per 1000 properties, >200ug/l Iron or DWI reportable incident. Highly discoloured, resembles beer or Guinness
Interruption to supply	Very low	<3 hours
	Low	3-6 hours
	Medium	6-12 hours (6 hrs is reportable)
	High	12-24 hours
	Very high	> 24 hours
Low pressure	Very low	Not defined
	Low	Not defined
	Medium	Property added to register (<15m pressure)
	High	No flow upstairs at peak demand period (<10m pressure)
	Very high	No flow at peak demand period (<5m pressure)
Leakage	Very low	<10%, small leaks on mains and services <2 l/prop/hr
	Low	10-20%, 2-4 l/prop/hr
	Medium	20-25%, few visible leaks with failures on mains and services infrequent - 4-6 l/prop/hr
	High	25-35%, 6-8 l/prop/hr
	Very high	>35% high levels due to severe weather conditions, numerous visible leaks - >8 l/prop/hr
Security of supply	Very low	Loss of yield < 0.5 ML/d or increased grid costs or increased tankering to rural zones
	Low	Loss of yield 0.5 - 0.99ML/d or move to alternative grid systems
	Medium	Loss of yield 1 - 9.99ML/d or voluntary restrictions *e.g.* publicity campaign(local press and radio)
	High	Loss of yield 10 - 50ML/d or no practical alternative supply or compulsory restrictions *e.g.* hose pipe ban and closure of car washes
	Very high	Loss of yield >50ML/d or emergency restrictions *e.g.* rota cuts, standpipes

Table 49 Impact assessments for risks

These severity scales directly reflect the level of service indicators set by the water industry regulators (Office of Water Services, 1998; Drinking Water Inspectorate and Office of Water Services, 2001) – an approach previously criticised by Dunn (2004) for not necessarily obtaining full potential to reach "*asset wisdom*".

The organisation uses three distinct processes to identify risks. According to a senior asset manager (participant no.26): "*We've got three main processes, one is the automatic failure prediction, the second one is the source to tap type approach which is very much focussed on people's views and current risks, and then the third is just manual entry of as and when problems arise or people are surveying a water treatment works.*" "Risks *which occur for reasons other than asset death but lead to service failures are captured in Source to Tap studies. These are facilitated events where above and below ground assets of a catchment are studied in detail by operational and asset management teams. The teams review historical data and knowledge to identify and assess risks and to propose conceptual solutions to reduce risks. Asset capability risks are assessed for assets and asset groups that are incapable to meet future obligations such as regulatory and statutory requirements. This risk type also includes supply and demand imbalances arising in growth areas or e.g. areas of industrial decline.*"

The acquisition of risk data involves a number of sub-processes: For the purposes of asset death related risk the Regional Water Utility periodically conducts site surveys to collect asset data for each site and assets. It has developed an asset register to ensure consistency in data collection. An assessment record lists all elements of a facility (*e.g.* a Water Treatment works) down to equipment level (*e.g.* pumps, valves and actuators). Depending on the asset type and its function in the water supply system, the number of equipment can range from 7 for a borehole, 16 for a water pumping station, 70 for a service reservoir to 700 on a water treatment works. The assessment is undertaken utilising the expert opinion of the asset management and operation teams, who deal with these assets on a day-to-day basis. In terms of data quality, the organisation has introduced the use of 'technical approach' manuals as a guide to conduct asset assessments. These set out the detailed requirements of the data, formats for collection, and definitions for assets. Staff are trained 'on the job' to carry out these assessments.

Based on the acquisition of asset data, the probability of asset death is calculated: The senior asset manager explains (participant no.26): "*It's based on the likes of a Weibull* *curve or a risk tree in the scoring system and that's based on static asset data, dynamic performance data, looking at the two and coming up with a scoring system. That's then validated against performance data, actual bursts or actual breakdowns at a water treatment works, that kind of thing."*

One senior asset manager (participant no. 28) explained the use of Weibull functions: "*It's a standard deterioration curve recognised that uses minimum and typical life and age to … draw a curve and deteriorate an asset through its condition grade until failure"*.

The majority of risk data in the risk database use Weibull distribution curves and network model derived assessments. For asset death, the risk data identifies the probability of asset failure for equipment at any given point in time using mathematical failure distributions, hence allowing it to identify current and future probability of failure for particular assets. However, the asset failure does not necessarily impact on customers due to system redundancy. One senior asset planning manager (participant no.25) noted: A "*pump failure may not always lead to an impact because of standby or storage or flow rate or normal mitigation etc. and this is not always clear in the thinking of those scoring the probability. There are many instances where the probability is clearly that of the asset failing and the impact is assumed to have a 1 to 1 relationship. This separation requires the two parts to be thought of individually and should lead to more accurate and consistent scoring*." The probability of impact on customer objectives requires a water supply systems assessment. For this purpose, the organisation recently introduced a two stage probability assessment to account for redundancy in the systems design. Hence, the probability of an asset is assessed at equipment level whereas the probability assessment of impact uses a customer perspective.

The assessment procedure for non-Weibull probability assessment is depicted in Figure 41. This is a structured assessment based on a decision tree.

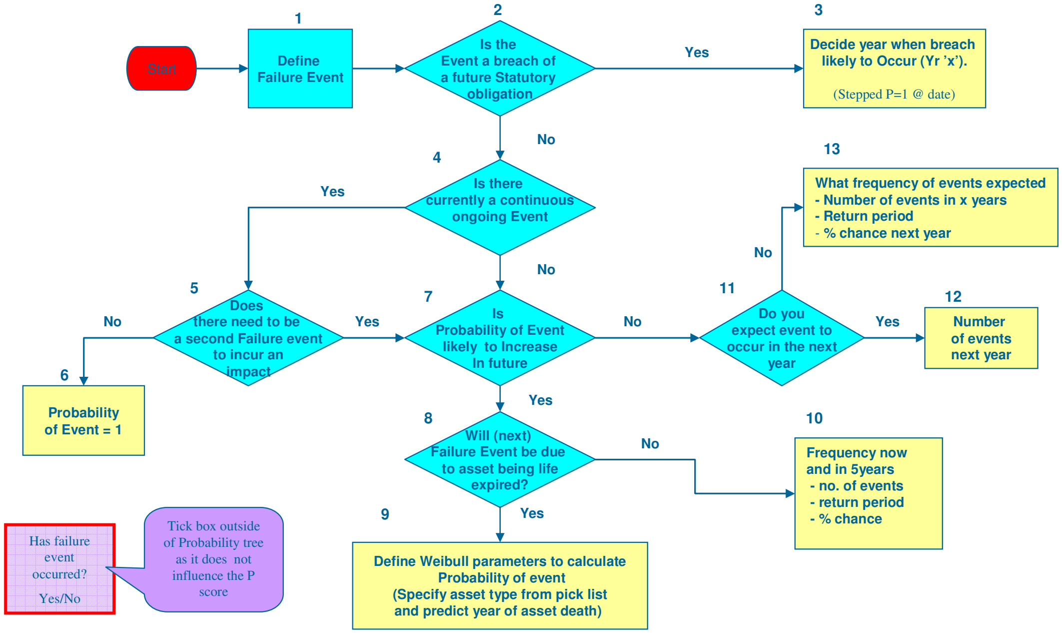

Figure 41 Probability assessment for risks

The assessment procedure to derive the impact probability on customers is depicted in Figure 42. In addition, the severity of the risk has to be 'manually' assessed using Table 49.

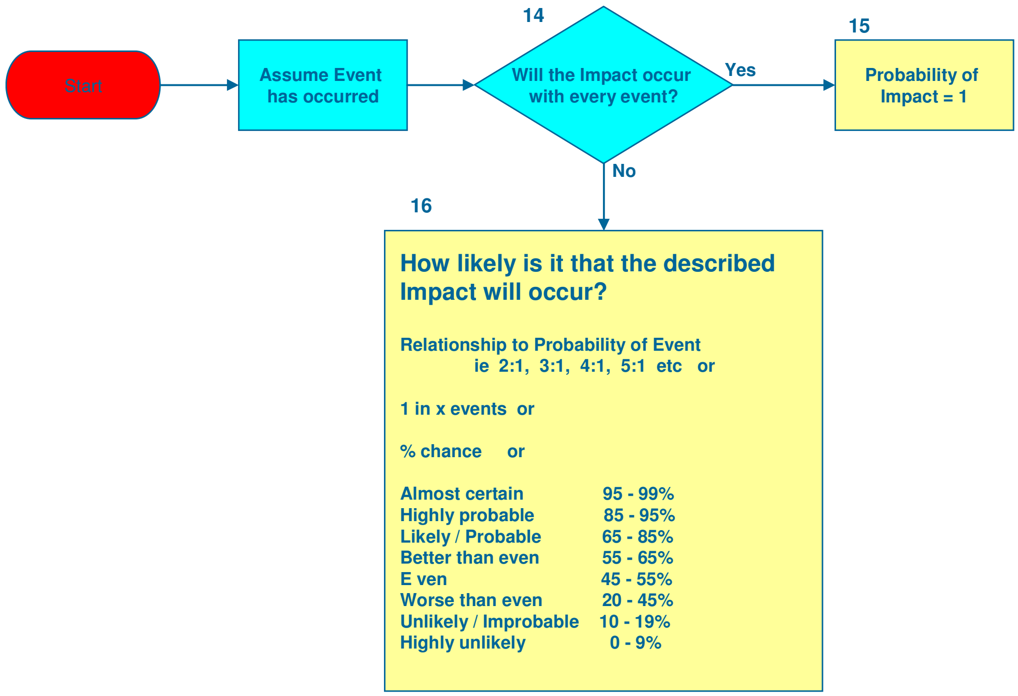

Figure 42 Probability of customer impact assessment

Due to the hidden nature of below ground assets, the derivation of distribution network risk assessments use burst data records, the analysis of Geographical Information System (GIS) and other spatially related data to model the probability and consequence of water main failures. One interviewee (participant no.26) reported that computer simulated models also model leakage, pressure, discolouration and water quality risks and use "*failure mode trees*" to derive failure probabilities and impact on customers. An example of a 'failure mode tree' for a catchment pressure model is presented in Figure 43.

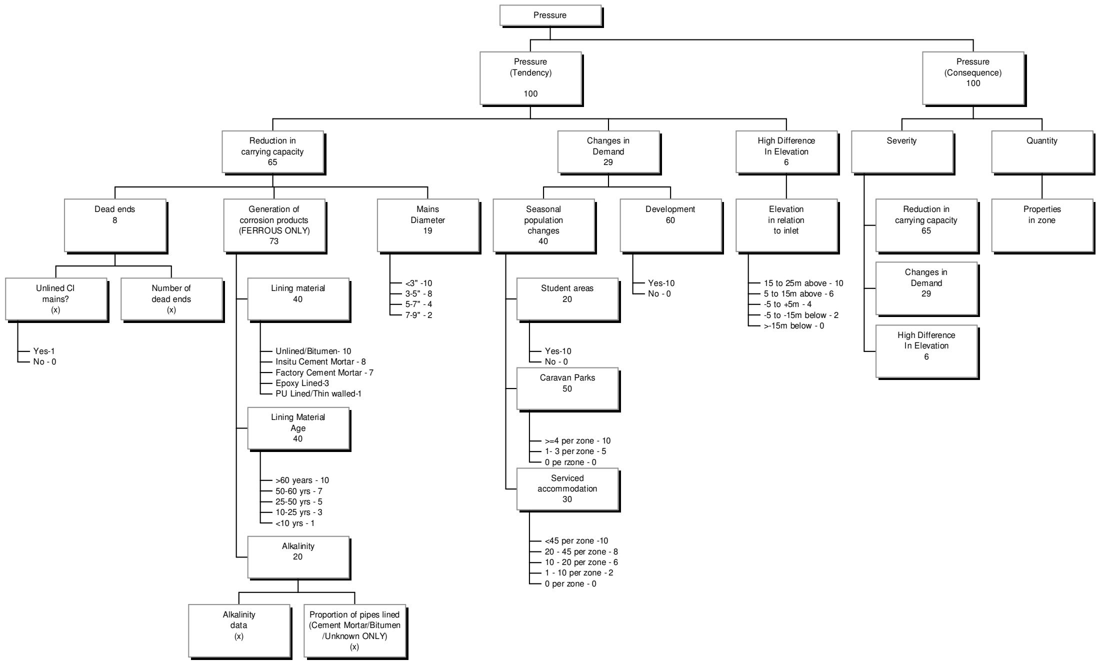

Figure 43 Example for risk assessment decision tree

Despite increased use of statistical derived probability and severity data in risk assessment programmes, a significant number of assets require ‘manual’ determination in terms of their failure modes and how that risk may impact on service provision to customers. Although processes are defined and the organisation has experience in using its risk assessment methodology for assets, it relies on the competence of asset engineers to identify and assess risks. These risks are recorded in defined cause – effect relationships. The current choice of cause effect relationships is presented in Table 50.

Causes of failure to be assessed as probability of occurrence	Risks relating to water safety and supply reliability to be assessed as probability of impact and the severity of impact on customers
A) Physical *i) Asset* *component level* Asset failure Civil failure Water mains failure Mechanical failure Electrical failure Site level Power failure Process failure Security failure Hydraulic effect Fitness for purpose Insufficient capacity Change in demand *ii)Environment* Raw water quality Adverse weather Pollution 3rd party **B) Information** Control systems failure **C)Human** Operator error	Drinking Water Quality (Biol./Chem.) Drinking Water Quality (Discolouration) Interruption to Supply Low Pressure Leakage Security of Supply

Table 50 Cause - effect relationships in risk assessments

Once risk assessments and notional solutions are filed on the database, the cost benefit (risk reduction) analysis tool will determine the viability of an investment. In the following section, the use of the model, the motivation of risk assessors and its user-ability from a risk assessors' perspective are further investigated.

4.4.2.2 Usage and user-ability of the risk assessment model

Risk-based decision making requires the acquisition of risk data. That, in turn, requires risk assessors to identify, assess and record risks on the risk assessment database for subsequent decision making. In a series of interviews the use of the model, the motivation of risk assessors and its user-ability from a risk assessors' perspective were inquired. It was also sought to uncover the heuristic models risk assessors have when engaging in the risk assessment process.

One senior operations manager (participant no.10) commented on the need of having a risk assessment database: *"I think the fundamental drive is that you get the risk on the system, how they're actually scored is important, but it comes later. It's actually making sure that it's flagged up as a risk."* One risk assessment model user (participant no.27) reported: *"I use [the risk assessment model] occasionally to solve problems and to make a bid for money. When I put the problem on, I know we've got a problem and I understand that there isn't enough money to solve everybody's problem. [The risk assessment model] is a way of deciding which problems are the worse and which we'd get the most benefit from."*

According to one operations manager (participant no.10), there seems to be a misunderstanding on the purpose of the risk assessment model: *"It is actually a receptacle for both OPEX and CAPEX derived solutions, not just CAPEX. I think that's a misconception that a lot of people in our company have. I think lots of people use the [risk assessment] system to attract capital funding but it's not actually for that, it's to log risk whether it's OPEX or CAPEX or whatever scale and I think that is not clearly understood."*

From a strategic perspective, one senior asset manager (participant no.28) reported on the implementation of the risk assessment models and the challenges they faced: *"I think initially before when we introduced [the risk assessment model], we had a big struggle in … [in the] strategic asset management [and] investment planning [departments] to incentivise people to put problems and risks onto [the risk assessment model]. As we've moved on, I think people have gradually bought into the process.*

We've had a number of investment criteria rules that have caused problems such as the red [high] risk policy. When people started learning that, as a business, we only really want to invest in red risks, that drove bad behaviours because people over scored risks to get them into the red." He expanded on the incentives to use the risk assessment database: "*In terms of recording problems and short term risks that we want to spend capital on…, I think there's plenty of incentive now to get them on [the risk database],*

… and I think people are incentivised to do that. Obviously now we're beginning to get a bit short on cash."

From an asset-risk trade-off perspective, the 'red risk policy' contravenes the spirit of cost benefit analysis since medium risks could be reduced with very little capital and operational expenditure if the monetary benefits of reducing risks exceed cash requirements. The policy was introduced to increase spending to reduce high risks. The 'shortage' of cash has distinct effects on the risk management policy in the organisation, in particular relating to maintenance. According to one asset engineer (participant no.24): "*The situation we have at the moment is a lot of the time we're doing reactive work, i.e. things that have already gone wrong, … we can still put [pro-active] schemes into [the risk assessment model] but obviously if they don't score in the red. At the moment it's not likely that there will be funding available. So the difficulty that I see with that [risk assessment model] is in the 'predicting' [i.e. pro-active maintenance]. You're supporting schemes that impact on the customer that are causing immediate problems, aren't you and all [the risk assessment model is] going to be [is] a method of dividing that money up, you know. It's not going to be predictive, is it? If you were doing it properly you wouldn't want any in the red risk, would you, because one it's gone into the red you should have sorted it out before really."*

Other engineers and managers commented on the scoring system for risks. One asset engineer (participant no.14) noted: The risk assessment model "*is only a database for storing problems what we identify through the asset management work, you know, either reactive or proactively. Basically, the risk matrix and the scoring system on [the risk assessment model] for customer problems is a load of rubbish…in true fairness because we'd naturally be failing standards of service, i.e. we're failing our standards on flow at the boundary or we're failing standards on pressure and it would still only come out as a medium risk. So basically, what we have to end up doing is trying to get it into the red risk category. We … have to try and frig it to try and get stuff through and we shouldn't have to do that when you're getting assets which are failing or customers who are phoning up saying they haven't got any water and you've gone out and proved that they are failing at the boundary, they've got insufficient flow and then you go into [the risk assessment model], you put your information in and then it still comes out as a* *medium risk and it doesn't score into the red. So there's something drastically wrong somewhere with that and I've told them about it but I might as well just talk to a wall."*

He also commented on the need to raise multiple risk assessments and failure scenarios for individual assets (participant no.14): "*A reservoir, it can either be a water quality problem either ingress through a roof so then you put it as a water quality problem in [the risk assessment model] for a service reservoir and then it might not score [red] so then you have to then try and raise it then as either a 'health and safety', either 'structurally unsound' and then it might not still score red again … so you're ending up having to raise about four different failure scenarios and attach it to the solution …. And we have the same problem on structural mains - they're bursting all the time. [The risk assessment model] for Asset Management wants a bit of an overhaul to get it to score correctly based on the customer's standards of service, OFWAT's standards of service and [the Regional Water Utility's] standards of service as well and it doesn't."*

One operations manager (participant no.6) also commented on the scoring factors: "*I think it's a good tool for capturing risk but I'm not sure whether the scoring system is all that effective sometimes. He [his asset engineer] knows that for my team it is a 'red' risk, he sometimes finds it hard for the [risk assessment model] to show it as a red risk. I mean, for me, my team, my area team, that issue is red risk definitely, it does have problems but when you put it through [the risk assessment model]"* is doesn't score as such.

Another asset engineer reported (participant no.12): *"[The risk assessment model], I think overall it seems a reasonable system to me. I don't have any problems in the way, you know, getting things through 'Challenge'. The only criticism I do have with [the risk assessment model] is that I don't think that the risk matrix for health and safety risks is accurate enough.*"

One interviewee (participant no.11) reported: *"Well, I mean, the problem with the … risk [assessment] model is everybody has their own interpretation of risk and I think what you find within this system is that, I could review a risk and when I do the review I might only review it as 'high' on the list but someone from Operations team, because they work with the asset and they believe that they're sick of being on the bore list as an operational issue could say it's a red risk and they could over-exaggerate that risk. So, I mean, for me it's open to risk interpretation…. I don't know how many times we've* *done this, we've come to pick a scheme up and have actually looked at the risk and what's come through as a 'red' risk I've actually re-evaluated it and said "hang on a second, this is an amber risk, do we need to spending money on this at this stage" and we have actually kicked schemes out for that reason."*

Another asset engineer (participant no.9) commented on the customer perspective of risk assessments and the effect of system redundancy: *"The only issue I see with the business risk model is if you're trying to evaluate something that doesn't have a direct impact on a customer. So, for instance, if it's boreholes etc, they don't tend to score high because usually you have an alternative supply say from the grid and so it's hard to score that on its own merits."*

One asset engineer commented on an improvement initiative to enhance the risk scoring system (participant no.14): "*I've sat down and had a couple of meetings with people who've come round with ways to improve [the risk assessment model] and what have you and is it in the scoring system and I put it all down with our suggestions and that, you know, and it all seemed to tie in correctly with the [the Regional Water Utility's] levels of service, standards of service and what have you, and then she came back and said "yeah, they've altered all the scoring", tried it again, basically it were even worse than it were before."*

The user-ability of the risk assessment model was inquired and interviewees were asked how long it takes to assess a risk scenario. One asset engineer (participant no.24) reported: *"I mean, it could be a couple of hours to a day or so. It depends on how much information you've got to seek and how big the scheme is because, to be honest, [the risk assessment model] is a panacea for everything so it could be a hundred yards of main or it could be a completely new treatment works … .*" Another (participant no.24) reported: *"Yeah, it's quite a long process even for small schemes. I mean, I shouldn't say but in some cases it's perhaps a sledge hammer to crack a nut."* One asset engineer reported (participant no.12): *"It is quite time intensive but then again it is forming the basis of project contracts for contractors. I mean, there are a lot of fields to fill in on the solution. I can't really see a way around that, to be honest. It's not something that I get worked up about, you know."*

One operations manager (participant no.10) reported: "*It's absolutely horrendous, it's populating information for information's sake."* It has got "*too many fields"* to fill in …

"*if they took half the fields out that might help*." One asset engineer reported (participant no.27): "*It is that it's a bit of a sledge hammer to crack a nut, because I'm having to fill in things to do with finance and accounting so I presume somebody has decided that we will fill finance and accounting things in. Sometimes I have a struggle filling boxes in with a meaningful explanation. There seems to be more emphasis on filling the [risk assessment data] in correctly than in solving the problem that the [risk assessment model] is designed to do. I struggle filling some of the fields. I like collecting data and all the rest of it, what I struggle with is then making it fit into the [risk assessment] system. There's no money, no matter how complex they set the [risk assessment model] entries and all the rest of it, if there's no money there's no job gets done, bottom line. So why does it need to be so complicated?"*

Another asset engineer (participant no.11) explained:" … *it's all these extra forms that you have to fill out now that go along with the [risk assessment model] that have to go to site. These OPEX forms, you have to go round site finding out speeds of motors of what you're replacing so that you can work out what the OPEX cost is up front as well as so you'll have an OPEX saving on the scheme and it's all good information which I need, it's not information that's readily available."*

Finally, one reporter (participant no.24) commented the data requirements to predict future risks: "*It's using some sort of judgement assessment. You can rank the severity because that's really against – a lot of those are against particular standards e.g. loss of supply, iron content in water, water quality issues and you can rank those because you've got that information. The probability is more difficult because you've having to make an assessment. If you were trying to say 'we think there's a risk here', it's predicting that risk accurately in terms of assets and having the information to do that. How do you have the information to determine whether a section of main will break or be defective in five years time and how do you get from reactive to proactive?"*

4.4.2.3 Deriving the required quantity of risk assessments for consistent decision making

The quantity of risk assessments supporting decision making is a factor to consider. In the following analyses, the risk assessments filed on the risk database are reviewed in the context of assets managed by the Regional Water Utility and incidents that previously occurred on these asset types. In Table 51, the number of risk assessments per asset type filed on the risk database is presented and the percentage of total risk assessments calculated. Here, 55.6% of the risk assessments were conducted for the distribution management areas (DMA) and 15.9% for Water Treatment Works.

Asset type	Borehole	River	Impounding reservoir	Water treatment works	Service reservoir	Water tower	Water pumping station	DMA
Sum of Risk assessments	1174	9	2383	4201	1315	350	2133	14696
Percentage of all risk assessments	4.4%	0.03%	9.0%	15.9%	5.0 %	2.0%	8.1%	55.6%

Table 51 Current number of risk assessments per asset type

In chapter 2, the asset types that caused incidents between 2004 and 2006 were identified. They are summarised in Table 52. Here, only 42.2% relate to the distribution management areas, whereas 23.1% relate to water treatment works. Major discrepancies arise for boreholes and impounding reservoirs. Only 0.7% of incidents involved boreholes, yet they represent 4.44% of the risk assessments. Similarly, only 2.7% of the impounding reservoirs caused an incident, yet they represent 9.0% of the risk assessments.

Asset type	Percentage of all incidents between 2004 and 2006 involving the specified asset type
Catchment/IRE	2.7%
BH - Pump/motor/valve	0.7%
WTW - Structure	0.0%
WTW - Process	7.5%
WTW - Pump/motor/valve	1.4%
WTW - Chemical treatment equipment	14.3%
SRE - Structure	2.7%
SRE - Pump/motor/valve	1.4%
WPS - Pump/motor/valve	1.4%
Trunk mains - SRE/WPS/WT	4.8%
Trunk mains - Distribution	8.8%
Water mains - Distribution	33.3%
Distribution- Pump/motor/valve	0.0%
Power - Supply/generation	10.2%
Power - UPS failure	4.8%
IT - Monitoring/control/telemetry	6.1%

Table 52 Previous incidents per asset type

The introduction of Weibull distributions for asset failures and risk assessment models for distribution networks has significantly contributed to the availability of probability data. According to the official guidance note on risk assessments: "*In terms of quantity of data, the appropriate degree of resolution is of significance and much consideration has been placed on what asset level gives sufficient resolution for consistency with project delivery, at the same time as not overloading the asset management processes.*" The organisation has selected the '*element component*' level as the general level for risk assessments. The asset hierarchy for a water treatment works as an example is depicted in Table 53.

Site	Installation	Process Group	Process	Element	Element Component
Name	WTW	Primary Treatment	Filtration	Building	Component 1
				Civil Structure	Component 2
					Component 3
				M & E	Component 4
					Component 5
				Process	Component 6

Table 53 Asset hierarchy used in risk assessments

From a theoretical perspective the number of possible risk assessments for the entire regional water system was determined if this policy is fully implemented. In Table 54, it is estimated that the total number of possible risk assessments at component level may raise to ca. 770,000 risk assessments at component level for water supply assets. All anticipated combinations of cause and effect relationships (Table 50) are considered for each component in the water supply system. However, this number does not yet include risks assessments for the 32,000 km of water mains in the distribution network. In comparison, the organisation has ca. 86,000 risk assessments logged on their database for water and wastewater assets. These risk assessments include above and below ground assets and, hence, incorporate assessments for the distribution network. From a theoretical perspective, a major discrepancy between actual and potential risk assessments arises from the data.

Asset type	Number of assets	Typical number of element components	Number of possible risk causes	Number of possible risk effect	Risk assessment per site	Total number of risk assessments at element component level
Impounding Reservoirs	147	35	11	6	282	41,454
River Intake	5	7	13	6	114	570
Borehole	20	7	15	6	114	2,880
Water Treatment Works	86	700	17	4	4,278	367,908
Water Pumping Station	300	16	12	4	150	45,000
Service Reservoirs	650	70	17	5	480	312,000
Total	**1,208**	**115,820**				**769,812**

Table 54 Theoretical number of risk assessments

From a practical perspective, it is unlikely that the organisation will ever assess perceivable 770,000 risks for above ground assets at 'element component' level. Means of prioritisation are required to guide the risk assessor to assess risks of importance or criticality. The discrepancy between the number of risk assessments and the total number of possible assessments indicate a problem of consistency in assessing risks.

The following Table 55 shows the average number of (current) risk assessments per asset and per component. It shows the average number of risk assessment per asset and per component varies significantly between different asset types and highlights the inconsistent application of the risk assessment procedure across the asset base. For example, boreholes are recorded to have an average of 2 risk assessments per component whereas water treatment works have only 0.1 risk assessments per component.

Asset type	Borehole	River	Impounding reservoir	Water treatment works	Service reservoir	Water pumping station	DMA
Number of risk assessments	1,174	9	2,383	4,201	1,039	2,133	14,696
Number of assets	80	5	147	86	650	300	32,000
Estimated number of components	7	7	35	700	70	16	
Average risk assessment per asset	14.7	1.8	16.2	48.9	2.0	7.1	0.5
Average risk assessment per component	**2.1**	**0.3**	**0.5**	**0.1**	**0.03**	**0.4**	**0.5**

Table 55 Current number of risk assessments per assets and component

From an economic viewpoint, inconsistent numbers of risk assessments across the asset base distorts the true representation of actual risk in the asset decision-making process leading to higher assessed risks for assets with many risk assessments. On the other hand, assets with low numbers of risk assessments are evaluated with a comparatively lower risk. The decision-making process requires an optimal number of risk assessments whilst considering the cost and benefit of deriving risk assessments. The value of increased numbers of risk assessments for asset decision making has to balance with the organisational cost to identify, assess and process risk assessments. According to one interviewee (participant no. 34), this presents an enormous problem to the organisation. Currently, there is no clear definition for the number of risk assessments to be conducted whilst the asset failure predictor (Weibull) generates more and more asset failure predictions that are not linked to customer impacts. Furthermore, some asset engineers have figured out that increasing the numbers of risk assessments for one asset increases the benefit of a solution aimed to reduce risk (*e.g.* boreholes). Hence, with increasing benefit the chance of implementing an engineering solution rises. If asset engineers have incentives built into their salary or receive annual boni on performance of their assets or dread being associated to failed assets, the assessment of multiple risks per asset will increase the cash spending and, hence asset performance. On the other hand, one interviewee reported that there are also discouraging elements in the risk management process. As mentioned before, the organisation only makes investment and maintenance resources available for high risks. One risk assessor reported (participant no.29): *"I might do a risk assessment but I know it won't come out as a red (high) risk. I already know that no cash is going to be allocated towards my asset. Why would you do a risk assessment if your asset comes out as amber [medium] risk? Where is the point of doing the assessment?"*

In this section it was found that discrepancies exist between risk assessments and past incidents but also between the theoretical and actual number of risk assessments.

Not only the quantity of risk assessments per asset distorts the asset decision making process but also the quality of risk assessments. In turn, the perceived causes, effect, probabilities and impacts of assessed risks in the risk database are reported.

4.4.2.4 The cause and effect relationships assessed in risk assessments on the risk database

During the characterisation of the 145 incidents that occurred between 2004 and 2006, the risk database was searched for risk assessments that predicted the particular incidents to occur. For the purpose of this assessment, only the primary incident causes and primary incident impact categories were considered. It was identified that 44% of the assets involved in the incident had been previously assessed for the incident-specific type of failure scenario. The remainder of assets had no risk assessment filed for the particular failure scenario at this asset.

In the following analysis, the cause and effect relationships assessed by risk assessors are reported. These risk assessments indicate how risk assessors perceive incidents to unfold. In Figure 44, risk assessors identified those assets that were perceived to cause a water quality incident. Figure 44 is based on 4,912 risk assessments.

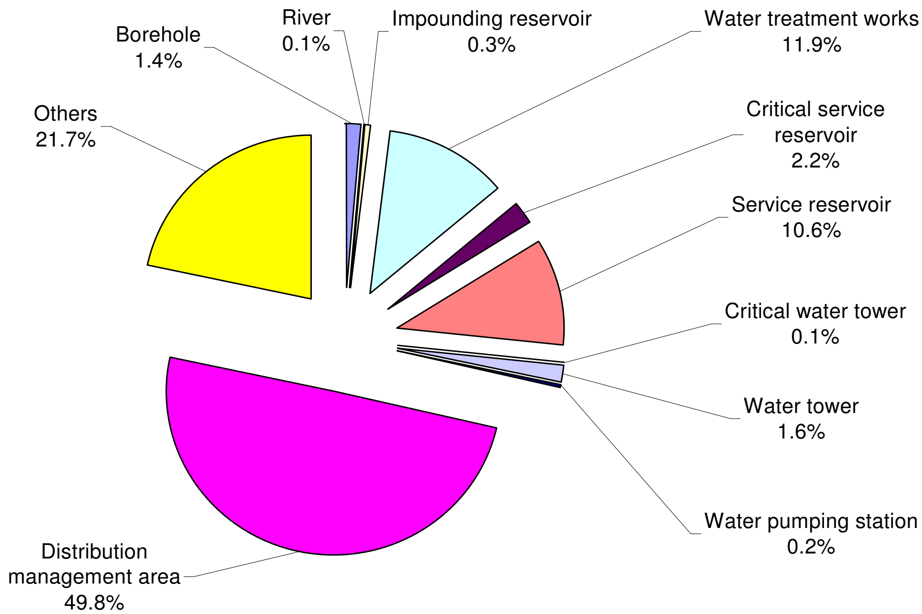

Figure 44 Identified assets attributed to water quality risks

In comparison, 93 out of 426 incidents that occurred between 1997 and 2006 were water quality incidents. The asset types that caused this incident are presented in Table 56. 52.6% of incidents were related to water treatment works, yet, only 11.9% of risk assessments were filed for this type asset. Distribution management areas caused 34.4% of all water quality incidents in that time period. In comparison, 49.8% of risk assessment relate to this asset type. Service reservoirs are also overrepresented in risk assessments in comparison to actual incident caused by that asset type.

Asset type	Percentage
Water treatment works	52.6%
Distribution Management Area	34.4%
Service reservoir	5.4%
Borehole	2.2%
Water tower	1.0%
River	1.0%
Unknown	3.2%

Table 56 Asset types that caused water quality incidents

In Figure 45, the perceived causes for water quality incidents in the risk database are identified.

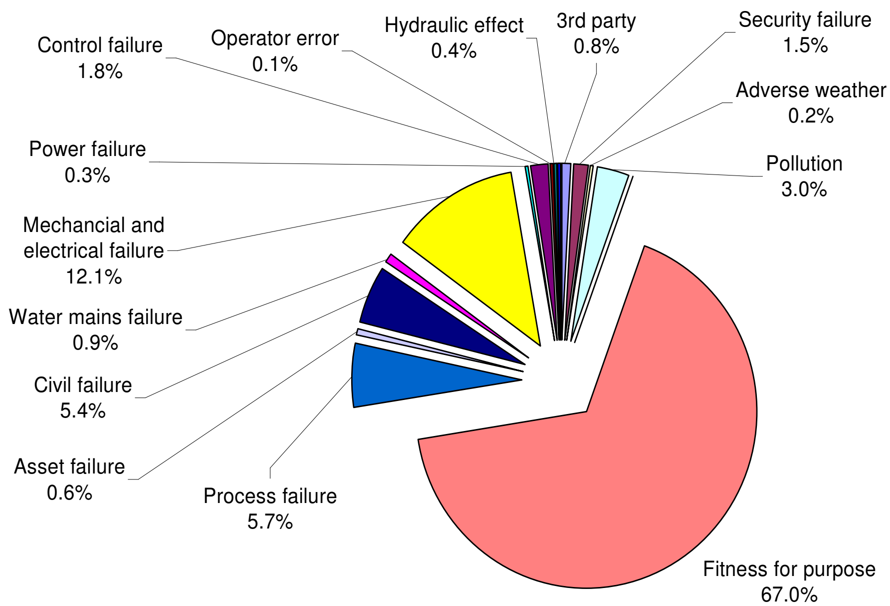

Figure 45 Perceived causes for water quality risks in risk assessments

The identified causes for water quality incidents between 1997 and 2006 are presented in Table 57. 19.3% of all incidents were attributed to chlorination failures which could be regarded as mechanical failure of equipment. Risk assessors only identified 12.1% of all perceived future incidents to be caused by mechanical and electrical failures. This figure, however, includes all mechanical equipment across all assets, whereas chlorination failures commonly affect water treatment works only. The majority of risk assessments state a lack in ‘fitness for purpose’ as the main cause for water quality incidents. This category is a generic description for various failure causes.

Incident cause	Percentage
Chlorination failure	19.3 %
Asset contamination	13.9 %
Asset failure	12.9%
Asset maintenance	11.8%
Power failure	2.0%
Adverse weather	2.0%
Monitoring and control failure	2.0%
Unknown	18.3%

Table 57 Causes for past water quality incidents between 1997 and 2006

A total of 2,835 risk assessments were conducted for water discolouration. Of these, 94% were assessed for distribution management areas. The remainder were conducted for water treatment works (0.5%), Service reservoir (0.2%), water towers (0.2%), and impounding reservoirs (0.04%). 4.8% of the risk assessments did not specify an asset.

In comparison, 115 out of 426 incidents that occurred between 1997 and 2006 were discolouration incidents. The majority of these incidents (74.7%) were associated to the distribution management areas, 12.2% to water treatment works and 13% to water towers, service reservoirs and water pumping stations. It can be identified that risk assessments for distribution management areas disproportionately dominate the risk database, whereas discolouration risk for water treatment works are underrepresented.

The perceived causes for discolouration incidents in the risk assessments were identified as lack of 'fitness for purpose' (93.3%), water mains failure (3.3%) and hydraulic effects (2.3%). In comparison, the identified causes for discolouration incidents between 1997 and 2006 are identified in Table 58.

Incident cause	Percentage
Burst main / reactive maintenance	52.2 %
Operational intervention	14.8 %
Asset failure	4.3%
Treatment process failure	4.3%
3rd party intervention	3.5%
Power failure	3.5%
3rd party impact/damage	2.6 %
Unknown	14.8%

Table 58 Causes for past discolouration incidents between 1997 and 2006

A total of 7,078 risk assessments were conducted for 'interruption to supply'. In Figure 46, risk assessors identified those assets that were perceived to cause an 'interruption to supply' incident.

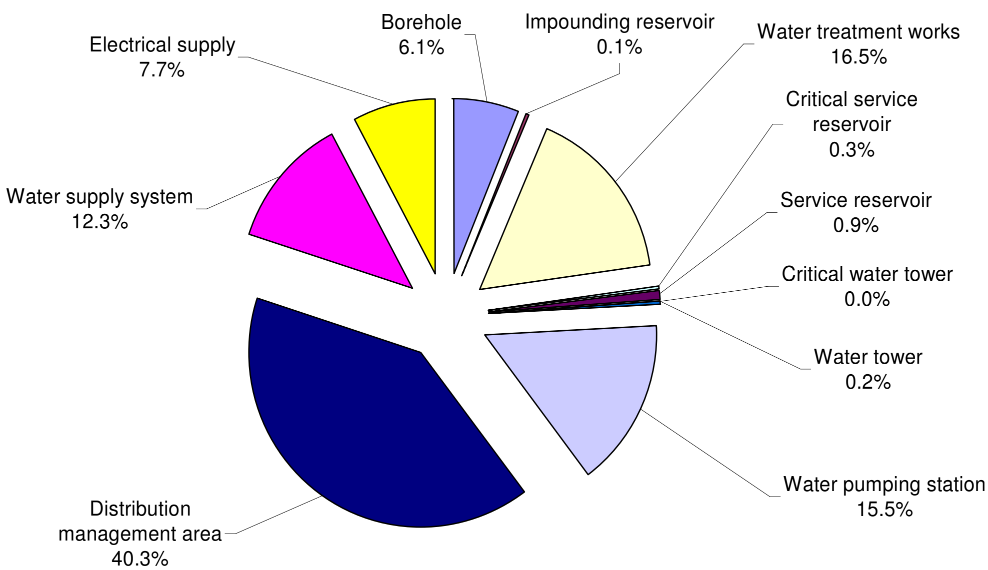

Figure 46 Identified assets attributed to 'loss of supply' incidents

In comparison, 121 out of 426 incidents that occurred between 1997 and 2006 were loss of supply incidents. The asset type that caused this incident is presented in Table 59.

Asset type	Percentage
Distribution Management Area	59.5%
Water pumping stations	11.6%
Water treatment works	10.7%
Service reservoirs	10.7%
Power failure	3.3%
Water Tower	1.6%

Table 59 Assets types that caused 'loss of supply' incidents between 1997 and 2006

Lastly, the perceived causes for interruption to supply incidents in the risk assessments were identified as water mains failure (40.1%), mechanical and electrical failure (30.4%), civil failure (14.0%), 'fitness for purpose' (6.9%), asset failure (2.8%) and power failures with 1.1%. In comparison, the identified causes for interruption to supply incidents between 1997 and 2006 are identified as burst main and reactive maintenance (71.0%), asset failure (9.9%) and operational intervention (2.5%). Again, major discrepancies between perceived risk and actual experience can be identified in comparing the risk assessments with past incident data.

4.4.2.5 Probability and outage assessments on the risk database

In the following analysis the accuracy of the probability assessments on the risk database were evaluated. For this purpose, the structured incident assessment tool that was used to characterise the 145 incidents between 2004 and 2006 had a feature that multiplied the previously assessed probability of failure or incident frequency with the actual outage of that asset due to a failure. This figure represents the anticipated non-availability of an asset to provide service. The calculated factor for anticipated non-availability of an asset was compared to the actual asset outage during the incident. From this comparison, it was found that only 10 (15.9% of the available risk assessments) risk assessments accurately predicted the non-availability of the asset due to an incident. 53 risk assessments (84.1%) were deemed to underestimate the non-availability of the asset due to an incident.

From another perspective, the probability of asset failure in the risk assessments were converted into a frequency using Equation 9.

$$F = \frac{100\%}{P}$$

with

F = frequency as 1 in X years

P = probability [in %] to fail per year

Equation 9 Probability frequency relationship

The obtained frequency was used to search the incident database for re-occurrence of asset failures for specific assets to cause an incident. This analysis presented a serious challenge, in particular for low probability assessments. A probability of 5% equates to a failure return period of 1 in 20 years and exceeds the time length of the incident database. Furthermore, an asset failure may not have resulted in an incident and the re-occurrence of a water mains failure may not have been recorded on the incident database. This is particularly relevant for below ground assets such as water mains. Despite these constraints, it was found that probability assessments were more accurate than previously anticipated. The probability assessments for water mains failures were ca. 60% accurate, *i.e.* the probability assessments converted into burst frequencies resembled the actual return period for specific main failures. For water mains, this can be explained by the derivation of probability assessments. Here, network models use previous burst data in multi-regression analyses that correlate age, soil properties and asset condition to compute the probability of future failure.

4.4.2.6 Incident impact assessments for risks on the risk database

In the following analysis, the impact of future, perceived incidents in risk assessments as perceived by risk assessors is compared to the actual impact of previously experienced incidents. For this purpose, all incident impacts in the risk assessments of the Regional Water Utility were converted to match the impact assessment previously used to assess the impact of incidents (chapter 2). In this process, data on hazard type and affected population were readily available in the risk assessments of the organisation. However, the anticipated duration for an incident does not feature in the current format of risk assessments. Hence, a duration of 28 hours for hazard exposure relating to water quality incidents was assumed. This was estimated from the average water quality incident duration between 1997 and 2006. Here, the average is 27.7 hours and the maximum confidence interval at 95% is 32.1 hours. For discolouration events, a duration of 13 hours for hazard exposure relating to discoloured water was assumed. This was estimated from the average discolouration incident duration between 1997 and 2006. Here, the average is 13.4 hours and the maximum confidence interval at 95% is 14.7 hours.

The converted risk assessments and the previously experienced incidents that occurred between 1997 and 2006 were plotted into a probability – impact matrix. The previously experienced incidents were plotted at 100% probability (representing a realised risk). Figure 47 shows the anticipated impacts for water quality risks in the risk database and the impacts of past water quality incidents, respectively.

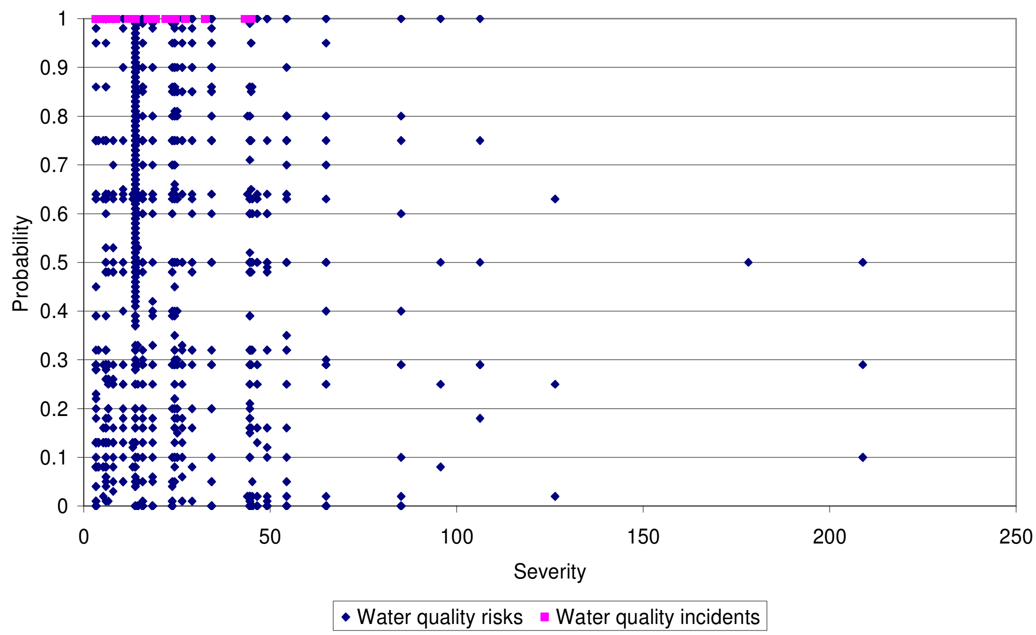

Figure 47 Comparison between incident impacts and risk impact assessments for water quality

In Table 60, a significance test formally compares both datasets. It can be identified that the risk assessments significantly over-evaluate the impact of water quality risks in comparison to previously experienced water quality incidents and it is believed that risk assessors have not considered the effect of incident impact reduction via the capability of the incident management team and the use of redundancy.

Risk statistics (A)	Hazard score (H)	Population	Population score (P)	Duration score (D)	Severity score (I)
Count	4900	4912	4901	4912	4912
Av	38.6	22205.7	10.0	8.0	18.6
SD	30.7	102841.8	29.7	0.0	15.5
SE	0.4	1467.4	0.4	0.0	0.2
CI 95 % lower	37.7	19329.6	9.2	8.0	18.2
CI 95% upper	39.5	25081.7	10.8	8.0	19.1
Incident statistics (B)					
All years	H	Pop	P	D	Sum
No	82	82	82	82	82
Average	27.8	6293.9	4.1	8.0	13.3
SD	24.8	37575.5	14.0	10.6	10.7
SE	2.7	4149.5	1.5	1.2	1.2
CI 95 % lower	22.4	-1839.2	1.1	5.7	10.9
CI 95 % upper	33.1	14426.9	7.1	10.3	15.6
Significance testing					
Mean A - Mean B	10.8	15911.8	5.9	0.1	5.4
Var A + Var B	7.7	19371725.3	2.6	1.4	1.5
SE (A,B)	2.8	4401.3	1.6	1.2	1.2
CI 95% lower	-5.4	-8582.6	-3.1	-2.3	-2.4
CI 95% upper	5.4	8626.6	3.1	2.3	2.4
Test result	A>>B	A>>B	A>>B	A=B	A>>B

Table 60 Significance test comparing incident impacts and risk impacts for water quality

Figure 48 shows the impacts for discolouration risks in the risk database and past incident impacts, respectively.

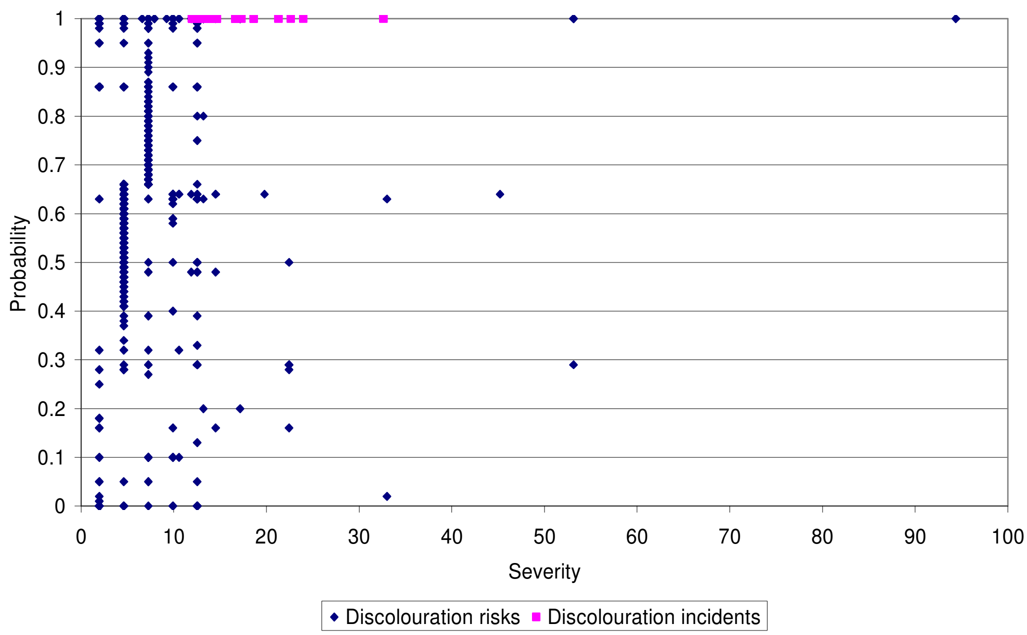

Figure 48 Comparison between incident impacts and risk impact assessments for discolouration

In Table 61, a significance test formally compared both datasets. It can be identified that the risk assessments significantly under-rate the impact of discolouration risks in comparison to previously experienced discolouration incidents.

Risk assessments for discolouration (A)	Hazard score (H)	Population	Population score (P)	Duration score (D)	Severity score (I)
Count	2835	2835	2835	2835	2835
Av	11.5	1544.0	2.5	4.0	7.3
SD	7.4	20500.8	7.0	0.0	3.6
SE	0.1	385.0	0.1	0.0	0.1
CI 95% lower	11.2	789.3	2.2	4.0	7.1
CI 95% upper	11.8	2298.6	2.7	4.0	7.4
Incidents affecting aesthetics (B)					
All years	H	Pop	P	D	Sum
No	131	131	131	131	131
Average	32	7508.7	4.1	4.2	13.4
SD	0	15272.9	7.1	3.9	2.8
SE	0	1334.4	0.6	0.3	0.2
CI 95% lower	32	4893.3	2.9	3.5	12.9
CI 95% upper	32	10124.1	5.3	4.8	13.9
Significance testing					
Mean A - Mean B	-20.5	-5964.7	-1.6	-0.2	-6.2
Var A + Var B	0.02	1928858.1	0.4	0.1	0.1
SE (A,B)	0.14	1388.83	0.63	0.34	0.25
CI 95% lower	-0.27	-2722.11	-1.24	-0.83	-0.49
CI 95% upper	0.27	2722.11	1.24	0.83	0.49
Test result	B>>A	B>>A	B>>A	A=B	B>>A

Table 61 Significance test comparing incident impacts and risk impacts for discolouration

Finally, Figure 49 shows the risk assessments and impacts for loss of supply risks and past incident impacts in that category, respectively.

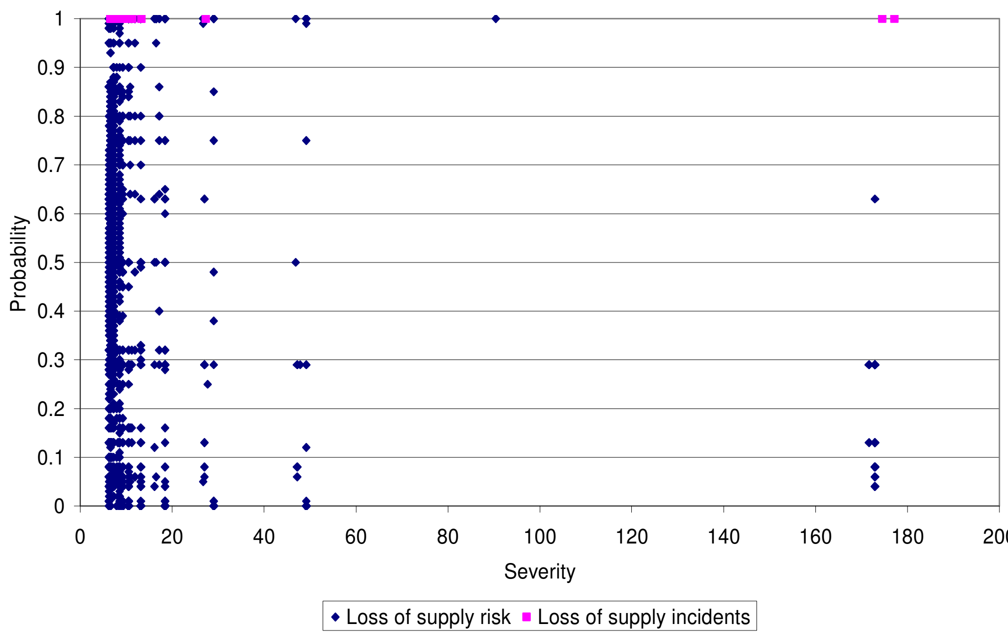

Figure 49 Comparison between incident impacts and risk impact assessments for 'loss of supply'

In Table 62, a significance test formally compared both datasets. It can be identified that the risk assessments and incident impacts are not significantly different at the significance level of 5%

Risk statistics (A)	Population	Duration	Population score (P)	Hazard score (H)	Duration score (D)	Severity score (I)
Count	7056		7055	7056	7056	7056
Av	21475		8.2	16	4.6	9.5
SD	151863.4		39.7	0.0	2.9	13.3
SE	1807.9		0.5	0.0	0.03	0.2
CI 95% lower	17932.1		7.3	16	4.5	9.2
CI 95% upper	25019.1		9.16	16	4.6	9.8
Incidents Loss of supply (B)						
	Pop	Dur	P	H	D	Sum
No	127	127	127	127	127	127
Average	77583.0	14.7	10.8	16	4.4	10.4
SD	584395.6	19.0	62.2	0.0	6.2	21.1
SE	51856.7	1.7	5.5	0	0.6	1.9
CI 95% lower	-24056.2	11.4	-0.02	16	3.4	6.7
CI 95% upper	179222.1	18.0	21.6	16	5.5	14.1
Significance testing						
Mean A - Mean B	-56107.4	-14.7	-2.6	0	0.1	-0.9
Var A + Var B	2692388710.1	2.9	30.7	0	0.3	3.5
SE (A,B)	51888.2	1.7	5.5	0	0.6	1.9
CI 95% lower	-101700.9	-3.3	-10.9	0	-1.1	-3.7
CI 95% upper	101700.9	3.3	10.9	0	1.1	3.7
Test result	A=B	N/A	A=B	A=B	A=B	A=B

Table 62 Significance test comparing incident impacts and risk impacts for 'loss of supply'

In conclusion, it was found that the anticipated impact of future incidents relating to water quality and discolouration varies significantly from past experience and it was demonstrated how incident data from past incidents could be used to benchmark risk assessments that anticipate future incidents. Although a methodological problem arises in comparing past events with future event, significant differences were evident. The methodology assumes that future risks mirror past incidents although demographic, socio-technical and socio-economic developments, technological advancements, investment and maintenance in assets and changes in the operations and asset management philosophies and procedures change the nature and character of a water utility. Despite this limitation, it was previously argued that the slow clock-speed of physical water utility assets allows some comparison between future risks and past incidents.

In the next section, the risk perceptions that risk assessors have when evaluating risks was further explored. It was aimed to identify how consistent risk assessments are conducted by a number of people for an identical asset.

4.4.2.7 Risk perception in risk assessments

In this experiment, six risk assessors evaluated a water main for its probability to have adverse impacts on customers. The participants used the risk assessment procedure prescribed by the Regional Water Utility.

Across the six obtained risk assessments, evidence was found for inconsistencies in the assessment of risk. A varying range of risk assessments had been constructed to assess the probable consequences of perceived failure scenarios for that specific asset. A number of risk assessments were constructed identifying one cause and effect relationship. Others used multiple cause and effect relationships to assess the overall risk for that asset. In some cases, confusion was identified regarding the definitions of severity categories: One example is 'leakage' and 'loss of supply'. The definition for leakage anticipates continuous leakage rather than being instantaneous due to a water main burst. Both indicators have been used to assess the impact of a water mains burst. It was also observed that some risk assessors only derived the probability of the asset to fail but not the probability of this asset failure to have an impact on customers.

From this experiment it was concluded that biases and ambiguities in the methodology are evident that can lead to inaccurancies and inconsistencies in risk assessments. A more detailed analysis of this experiment can be found in the Appendix 5.1.

Staff in the Regional Water Utility acknowledged that inconsistencies can arise in the risk assessments and a number of strategies have been adopted to enhance personnel's perception and understanding of risk.

One strategy pursued by the organisation to enhance the quality of risk assessments is risk training. This was previously introduced in the preceding chapter. The organisation planned and implemented a staff development programme specifically for risk appreciation. Risk training not only explores the economic-rational perspective on risk used for decision making in the organisation but also (participant no.25) *"re-frames psychological and social construction and understandings of the organisational risk concept"*. It is aware that risk assessors have their own understandings and knowledge of risk and the training is aimed to reduce the deviation in quality of risk assessments with a view to enhance of consistency in investment and maintenance decision-making. Furthermore, the asset and operations management teams organise regular joint meetings to discuss operational issues which may have implications for asset design and maintenance. These meetings are aimed to provide an information exchange between asset engineers, operators, operations managers and general managers aiming to disseminate the organisational understanding of risk and best practice in risk assessment and management techniques.

In the previous chapter, it was found that learning from failures provides one form of 'reframing' risk perceptions and failures, near misses and mistakes provide opportunities to learn via incident analysis and disseminating findings into the wider business. Whenever information on failures, near misses and mistakes become available, they can provide an opportunity to review assets, processes and effectiveness of operations and asset management. Learning from failure requires skills to identify multi-causalities and interdependencies in the build up and during the incidents. Complex cause and effect relationships can be disguised by an array of contributing factors and circumstances. Appropriate learning models are required to investigate incidents – a number have been used to structure the analysis of incidents in chapter 2. In the literature, it was found that scientists used different 'heuristic' models to reduce and interpret complex incident circumstances into more understandable scenarios. Similarly, risk assessment models also use simplified cause and effect relationships to assess the probability and impact of adversity on a defined objective. Embedded within a system wide framework, only systematic and consistent risk assessments provide a basis for effective operations, investment and maintenance decision making. In the Regional Water Utility, it was found that learning from incidents is limited to the direct actions that were identified after individual incidents. In the previous sections it was demonstrated how water utilities can validate their risk models and verify the data using a meta-process of statistical analysis of all incidents experienced in their company.

In the above analyses and experiment, it was identified that the assessments of probability and impact of perceived, future incident can significantly vary. In the next section, the existing risk assessment process and procedure is further analysed from a business process perspective.

4.4.2.8 A business process review of the risk assessment model

As an evaluative tool to review the risk assessment and management model, the Johnston and Clark (2005) matrix was adapted that has been proposed to characterise processes in operations management. It maps out process definition, process variation against economies of scale and volume of processes. The four corners of the matrix were defined as capability, consistency, complexity and simplicity. In Johnston and Clark (2005) it was suggested that only the axis between capability and consistency are viable for effective organisational processes. On this axis, 'decision context types' were introduced (Figure 50).

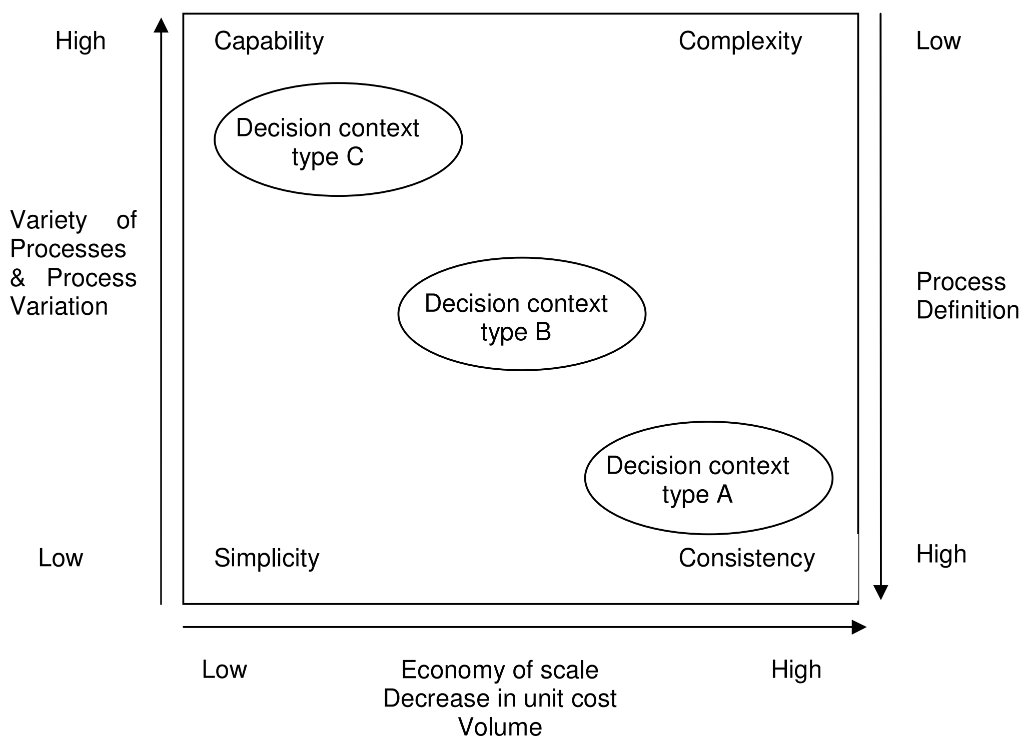

Figure 50 Process characterisation for risk assessments

The design of the risk assessment model adopted in the Regional Water Utility can be characterised for decision context type C. A significant number of highly variable processes were used to forge a capable and competent approach to risk management. A significant number of mathematical, economic and technical considerations were identified and selected to provide a system which is capable to process risk assessment data in a cost benefit trade-off. During the design phase of the model, processes were hardly defined and relied on the expertise of professional risk managers, mathematicians, economic analysts and business managers. An information system was designed to log risks on a risk database. The model had to be capable to process high volumes of data since the database also houses risk data derived in statistical analyses on distribution network assets. The risk assessment model was implemented in a top down approach.

During the design phase, it was considered that the operation and use of the model is highly decentralised with data input interfaces for field asset engineers and asset managers cum risk assessors who report and file risks bottom up from asset level to a strategic asset management level. One concern in a decentralised risk assessment system and database is the consistency in captured data, if data acquisition and data recording is not highly defined and controlled. It had to be considered that the model user requires high process definition with low process variation to consistently process large numbers of asset risk assessments. The model user requires an interface with the model which is characteristic for decision context type A. Hence, the user interface requires high process definition and a low variety of processes to conduct in identifying and assessing risk. Currently, the user interface is semi-structured to guide the risk assessor in providing reasonably accurate and consistent risk assessments.

Although risk assessments have to be conducted following a guided structure, inconsistencies in the number of risk assessments per asset arise and the quality of these assessments can significantly vary. For this reason, the strategic asset management group introduced a 'quality assurance' system for the data stored in the database. *"Company experts review the assessment of risks and solutions to ensure that processes and procedures have been followed in line with technical approach guidance issued to the asset management teams.* (participant no.28)*"*. Currently, the risk assessment process relies on the competency, skills and experience of asset managers and asset engineers to identify and evaluate risks accurately. Deviations from accurate and consistent risks reported on the risk database are reactively sought out with quality assurance procedures.

A first-time-right approach to enhance the quality of primary risk data is to provide a highly structured risk assessment procedure that removes process variations and increases the process definition for risk assessments. During the assessment of incidents between 2004 and 2006, an inductive incident investigation methodology was developed to characterise incidents. In analogy to this incident assessment model, a structured risk assessment methodology was developed that better resembles the causes, effects, probabilities and consequences of future incidents. A structured root cause analysis and effect analysis was developed to characterise the impact on customers. The root cause analysis for future perceived incidents allows the risk assessor to identify a number of incident causes, as opposed to the current model. They range from asset failures and process failures to human error. The risk model allows the user to identify multiple impacts of incidents. *E.g.*, a burst main can be assessed to cause 'loss of supply' for one group of customers, 'low pressure' and 'discolouration' for others. The model incorporates the current two-stage probability assessment for asset failure probability at asset component level and customer impact probability, whilst explicitly considering asset and systems redundancies that reduce probabilities of impact on customers.

In the current risk assessment model, the probability is defined as "*the occurrence of at least one service failure within the next year (participant no.25)*". If a service failure is guaranteed to occur within the next year, the probability is 100%. If that service failure is perceived to occur more than once, *e.g.* 4 main bursts, within the next year, the probability is still only 100%. As a result, the new probability assessment was extended to allow the assessment of frequency of failure. In addition, the new methodology considers the outage of an asset due to failure, since considering the outage of an asset further prioritises the risk. For example, a water mains failure can be fixed within 12 hours. However, the structural failure of a rapid gravity filter will take months to replace. Considering the outage of an asset does not necessarily correspond to the hazard exposure of the population because the incident management team can use system redundancy to reduce the impact of an asset failure on customers. This is also accounted for in the new model. Finally, the model incorporates the current severity assessments whilst using hazard type, size of population and duration of perceived future incidents as weighting factor. This is shown in Table 63

Estimate frequency of hazard	Estimate magnitude of hazard		Estimate duration of hazard		Estimate no. of customers affected by hazard	
Score (F)	**Hazard type**	**Score (H)**	**Duration in days**	**Score (D)**	**Customers**	**Score (P)**
1 in X yrs	Aesthetics above guidelines, >200ug/l Iron or DWI reportable incident. Highly discoloured, resembles beer or Guinness	32	< 0.5	2	0 – 7,500	2
	Aesthetics, >150 ug/l or notable events. Opaque and discoloured resembles weak milky tea.	24	0.5 – 1	4	7,500 – 15,000	4
	Aesthetics, 100-150ug/l Iron or minor events. Translucent and discoloured resembles orange juice or lager.	16	1 – 2	8	15,000 – 30000	8
	Aesthetics, 50-100 ug/l Iron and no events. Particulate material visible in clear water	8	2 – 4	16	30,000 – 60,000	16
	Aesthetics, < 50ug/l Iron and no events - Slight discolouration noticed in customer bath, Compliance but customer complaint	0	4 – 8	32	60,000 – 120,000	32
	Unwholesome, potential health effects	48	8 – 16	64	120,000 – 250,000	64
	Chemicals present above guidelines, Trivial sample failure	8	16 – 32	125	250,000 – 500,000	125
	Chemicals present above guidelines, health effects envisaged, PCV failure leading to an undertaking	32	32 - 64	250	500,000 – 1,000000	250
	Potential biological pathogens present	6	64 – 128	500	> 1,000,000	500
	Potential biological pathogens present, health effects envisaged	48	> 128	1000		
	Biological pathogens present, Trivial sample failure	8				
	Biological pathogens present, PCV failure leading to an undertaking	32				
	Biological pathogens present, health effects envisaged, Boil order as risk of illness through drinking water	64				
	Biological pathogens present, Public health effect. Illness through drinking water	125				
	Loss of supply, potential contaminant ingress	16				
X in 1 yr						

Table 63 Enhanced risk impact assessment model

In the assessment of incidents, a simpler version of Table 63 was used and a re-evaluation of the hazard scores, population scores and duration scores may be required to reflect customer or public health specialist priorities for water safety and reliability.
The proposed enhanced risk assessment model was presented to the Strategic Asset Management Department in the Regional Water Utility. A number of considerations are required to evaluate the benefit and costs of implementing and operating the new model. Firstly, the current risk model already houses ca. 86,000 risk assessments. Their risk impact assessments need to be re-configured and incorporated into the new model. Secondly, the new model captures significantly more data; hence, the risk assessor requires more time to perform risk assessments. In light of some interviewee comments about the user-ability of the existing model, this may be a major obstacle. Thirdly, the new model has significantly more structure and could be perceived to be inflexible to adapt for novel risks or future business requirements. A major advantage of the model is its enhanced reflection of real incidents as they previously occurred. According to a number of risk assessors, the old model is perceived to be too abstract and the severity categories were designed on the back of regulatory performance measures but do not reflect how water incidents in reality unfold.

4.5 Summary

HROs have been described to maintain existing technology at exceptionally high standards and there is zero tolerance of defective, substandard or malfunctioning equipment (Roberts, 1990b). The Regional Water Utility does not maintain its system to highest standard but takes a more differentiated, risk-based view in resource allocation in line with the 'Common Maintenance Framework' (UK Water Industry Research Limited, 2002). In this point, the Regional Water Utility significantly differs from the theory of HROs. Maintenance decisions are based on risk assessments and a trade-off between cost of maintenance and perceived, monetary value of risk reduction. The organisation provides monetary resources for maintenance in circumstances where the monetary value of risk reduction (benefit) exceeds the monetary requirements for maintenance, if that risk is classed as a high risk. This process heavily relies on accurate and consistent risk assessments - accurate, for a 'true' representation of 'real' risks, and consistent, for company-wide, comparative assessments.

In the outset of this chapter, it was suggested that previously experienced incidents provide learning opportunities to anticipate future risk and to enhance risk assessment processes. It was identified that incident review data provide a means of learning to anticipate future incidents and risks. A business process is in place that creates actions for staff to review assets, procedures and policies as well as operator behavior. These learnings are based on individual incidents but little evidence was found that the Regional Water Utility uses the incident database for structured analysis of incidents. One exception is the structured data analysis for water main bursts. The high frequency of distribution asset failures enables a multi-regression analysis that correlates water main age, condition, material and soil condition with burst data. In computer models, probabilities for water mains failure are derived and various customer impacts determined. These customer impacts are 'loss of supply', 'low pressure' and 'discolouration'. Increasingly, Weibull functions are used to determine the failure probability of asset components. The determinants for the Weibull functions are often based on professional judgment and the expected asset life.

This chapter was designed to identify learning opportunities from incident analyses to enhance risk assessments that are subsequently used for asset investment and maintenance decision making in asset management. With a major emphasis on risk in decision making, the quality of risk assessments was investigated and various methodologies to enhance risk assessments suggested. A particular emphasis was placed on learning from failure to enhance risk assessments and a methodology was introduced to validate the risk model and verify risk data. Significant inconsistencies in the quality of risk data were identified when comparing risk assessments in the risk database with past incidents. These inconsistencies relate to the number of risk assessments conducted for water supply assets but also to the cause and effect relationships for perceived, future incidents and their impact on customers. Unless the actual risk profile has significantly changed, there is little rational explanation for these discrepancies. It is believed that the current risk assessments reflect the psychological and sociological perceptions of risk rather than a rational explanation. Based on the review of incidents in Chapter 2 an enhanced risk assessment methodology was introduced which aims to enhance the quality and consistency of risk assessments.

In Johnson's (1992) web of organisational culture (Figure 51), the main findings of this chapter describing an effective organisational risk management culture are summarised.

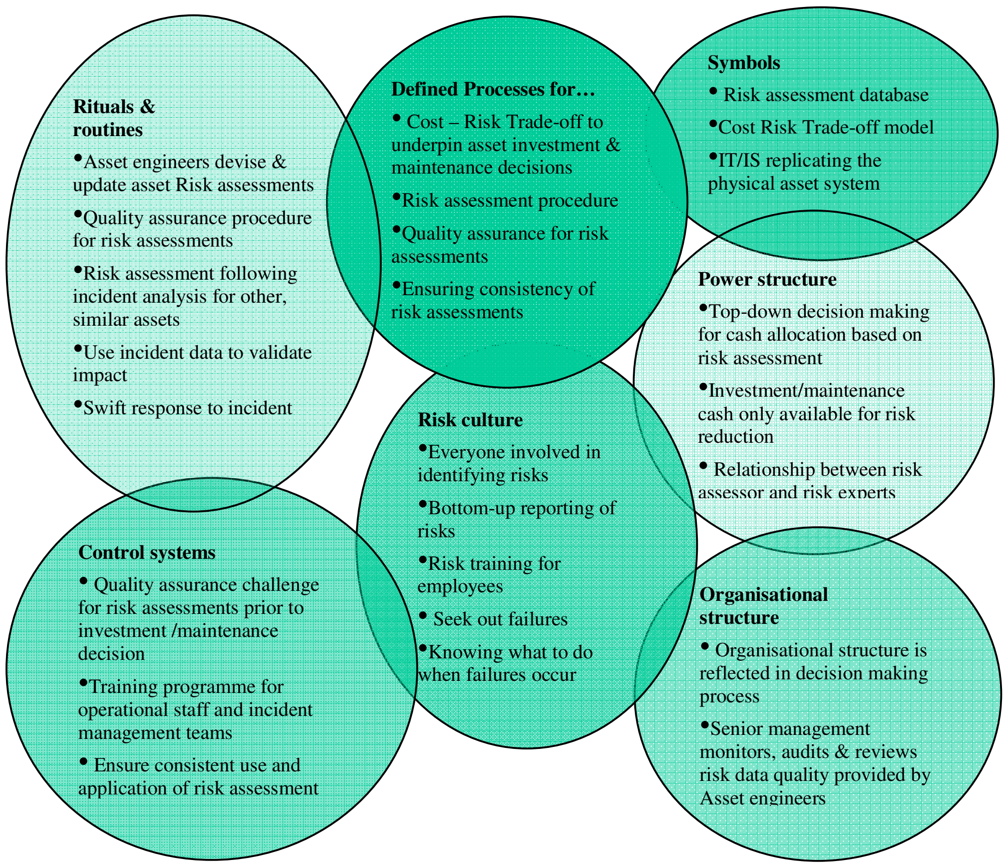

Figure 51 A cultural web for risk-based asset management

So far, the author was unable explain why incidents happen. It was found that risk based decision making uses cost benefit analysis to compare the benefit, *i.e.* perceived value of risk reduction, to the cost of reducing risk. One possible explanation is that the benefit of risk reduction is insufficiently valued to deem risk reductions economically viable. Different strategies have been adopted by water utilities to assess the benefit of risk reduction. In the Common Maintenance Framework, the concept of 'willingness to pay' has been proposed to evaluate the benefit of risk reduction and the Regional Water

Utility has adopted this approach for non-market valuation of benefits (Bateman *et al.*, 2002). Other water utilities consider their internal benefit from reducing the frequency and impact of incident. Here, the opportunity cost, *i.e.* the costs avoided that would be incurred by an incident, defines the benefit of risk reduction (Lifton and Smeaton, 2003; Lifton, 2005). The following chapter investigates the valuation of risk from a financial and customer perspective. Firstly, it is investigated how company share markets evaluate the business risks of privatised, stock-market listed water utilities. Secondly, it is investigated how customers perceive the value of risk.

5 The price of risk and incidents in the water sector

5.1 Introduction

In order to achieve the water sector's objective (International Water Association, 2004), water utilities invest in capital assets that form a barrier between the source of hazards and the consumer. A number of these assets also introduce new hazards (*e.g.* chemicals) that require appropriate management. Failure to provide or maintain such assets may correspond with chronic exposure to hazard or incidents, respectively. From an economic perspective, the exposure to hazards, pathogens or incidents are consequential 'costs' to society. The consequential 'costs' of a pathogen outbreak leading to disease in the population range from loss of life as moral cost, cost of hospitalisation, compensation, cost for law suits, criminal charges leading to imprisonment, fines, the impact on the economy such as health services, lost time (Hughes and Ferrett, 2003) and, finally, the costs for reinstating a safe drinking water supply. These are direct, often non-monetary costs to society and to a water utility. Two further perspectives for valuing public health risk can be considered: a financial perspective representing the owners of water utility assets and a customer perspective. These are considered in this chapter with the aim to explain why incidents still occur in highly developed water supply systems.

This chapter evaluates business risks in the water sector from a stock market perspective and, secondly, public health risks from a customer perspective. The objective of this chapter is to investigate the prevalence of incidents from a financial and customer perspective on the 'price' of risk and the benefit arising to customers from reducing the frequency or probability of incidents.

5.2 Theoretical development

5.2.1 Water utility business risk

From a financial perspective, a firm aims to maximise the value of a business (Bonart and Peters, 1997; Myddelton, 2000) for its shareholders. According to financial theory, the value of a business is reflected in the share price multiplied by the number of shares issued to shareholders. The current value of a business represents the net present value (NPV) of anticipated, future cash flows. These cash flows incorporate future revenues and costs of the business. The financial evaluation of a business is conceptualised in Figure 52 (Myddelton, 2000).

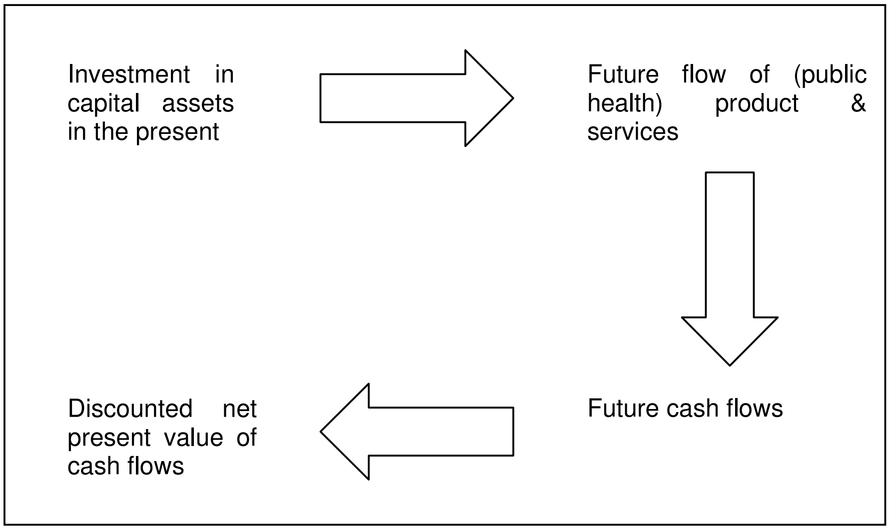

Figure 52 The value of capital assets

Accordingly, in Figure 53, the deterministic method to evaluate a business or an asset is to discount future cash flows to NPV with an appropriate interest rate (Myddelton, 2000). The relevant cash flows are shown in Figure 53. In order to determine the value of the equity in a business, company debts are deducted (Myddelton, 2000).

Function	Net Present Value of Future Cash Flows at 'weighted cost of capital' discount rate	Comments
	Operating profit + Depreciation - Increase in working capital (Debtor, Stocks, Creditors) - Interest payable - Tax payable - Dividends payable	Revenue from providing services (e.g. safe drinking water) Re-investing depreciation cash in capital maintenance theoretically maintains serviceability of capital asset base perpetually at steady state
Investment	- Purchase of fixed assets + Proceeds of fixed assets	Investment in new capital assets to enhance serviceability (e.g. more stringent regulatory compliance criteria)
Finance	+ Proceeds from issuing share capital + Proceeds from long-term borrowing	
Cash	Surplus/Deficit	

Figure 53 Cash flows for the derivation of the value of assets

The interest rate used to discount future cash flows represents the cost of capital. They reflect shareholder expectations for economic returns (Myddelton, 2000) that can be explained with the Capital Asset Pricing Model (CAPM) or the Dividend Growth Model (DGM) (Myddelton, 2000). Both models use the underlying assumption that an investment generates shareholder wealth whilst taking "*time preference, inflation and risk*" into account (Myddelton, 2000). In the CAPM, risk is a measure of the volatility of a share's return in dividends and capital gain and is measured as a beta factor (Myddelton, 2000) which is a retrospective measure of cash flow volatility or the volatility of the shareprice (representing the expected, future cashflows) in the past 60 months (Myddelton, 2000). Cash flow volatilities arise from revenues and costs in a water utility and in this chapter the effect of incidents on cash flows are investigated.

In the CAPM, the required return of a particular equity share has a definite relationship to the return of an investment in the market as a whole (Myddelton, 2000). Therefore, the beta value is a measure for one stock in relation to the whole market (Vernimmen, 2005). This methodology eliminates the systemic risk arising in the market and derives a representation for the risk of an individual company. The underlying calculation method for beta is a least square linear regression over a period of 5 years (60 months) using the monthly change in the share price for one stock J (stock return) plotted against the monthly change in the stock market index M (market return) (Datastream, 2005). The share price is regressed against the respective total market index using log changes of the closing price on the first day of each month (Datastream, 2005).

Statistically, the beta of a stock J is defined as (Brealey *et al.*, 2006)

$$\beta_J = \frac{\sigma(r_J, r_M)}{\sigma^2(r_M)}$$

with

$\sigma(r_J, r_M)$ = Covariance between stock J’s return and the market return

$\sigma^2(r_M)$ = variance of the market return

Equation 10 The Definition of Beta

and in more detail (Vernimmen, 2005)

$$\beta_J = \frac{\sum_{i=1}^{n}\sum_{k=1}^{n} p_{i,k} * (r_{J_i} - \bar{r}_J) * (r_{M_k} - \bar{r}_M)}{\sum_{i=1}^{n} p_i * (r_{M_i} - \bar{r}_M)^2}$$

with

r_J = expected future return of stock J

r_M = expected future return of the market M

$p_{i,k}$ = probability of joint occurrence (correlation coefficient of returns)

p_i = probability of each of the possible return occurring

Equation 11 Equity beta

Beta corresponds to the slope of the regression of the stock J’s return with that of the market M. The resulting equity beta is a geared beta coefficient (Datastream, 2005) and relates to the cost of equity capital in a geared company using shareholder capital and loans. Hence, the equity beta represents financial and business risk (Myddelton, 2000). The asset beta that only represents business risk is derived by extracting total debt figures from the company accounts (Datastream, 2005) to calculate the debt ratio (Reid and Myddelton, 2000). The relationship between asset beta, equity beta and the dept ratio is shown in Equation 12.

$$\beta_A = \beta_E \frac{E}{(E+D)} \text{ or } \beta_A = \beta_E * (1 - \frac{L}{A})$$

with

β_A = Asset beta

β_B = Equity beta

E = market value (equity)

D = Total debt

L = Long-term liabilities

A = Total assets less current liabilities

Equation 12 Asset beta

As a result, the asset beta is obtained that reflects the expected future volatility of cash flows based on retrospective analysis of shareprices in a water utility.

Based on previous incident analyses of incidents reported to the DWI (Drinking Water Inspectorate, 2005b; Drinking Water Inspectorate, 2006; Drinking Water Inspectorate, 2007), it is investigated how incident in water utilities affect the stock market evaluation of asset risks, *i.e.* the volatility of their cash flows.

5.2.2 Customer risk evaluation

In a further perspective, it is investigated how water utility customers evaluate risk. According to Abell (2005), the Regional Water Utility determined the "*willingness to pay*" (UK Water Industry Research Limited, 2002) for service enhancements, *i.e.* the reduction of risk. The methodology adopted for these studies originated from a guideline for non-market valuation (Bateman *et al.*, 2002) that aims to generate estimates of customer benefit and preferences for different service attributes and their associated risks. The Regional Water Utility conducted a three step choice experiment consisting of

- a qualitative research phase to determine general priorities for service attributes;
- a semi-quantitative research phase to evaluate the perceived customer benefit from different levels of services, *i.e.* from different levels of risk, and to identify customer priorities for risk reduction within the group of service attributes identified in the qualitative research phase; and
- a quantitative data analysis to derive the optimal customer benefit expressed in the water price, and a calculation of the price or cost of risk based on the preferences expressed for risk reduction.

According to the documentation of the organisation, "*the qualitative phase consisted of 8 focus groups to discuss service issues generally before focussing on the water services experienced*." Based on the customer surveys, the service areas or risk to service of importance to customers are indicated in the Table 64 below.

Risks relating to water safety and supply reliability
Inadequate Mains Pressure
Interruption to Supply
Security of Supply
Drinking Water Quality (Biological/Chemical)
Drinking Water Quality (Discolouration)
Leakage
Pollution
Personal Injury

Table 64 Service priority for customers

The quantitative phase consisted of 1,500 face-to-face interviews aiming to cover representative samples of domestic and business customers. Each participant was offered a series of service attributes, each with a combination of decreasing, improving or stable levels of risk. These service attributes were 'traded-off' against potential impact on the water price.

The derived function provides monetary values for changes in the level of service provided and changes in the probability and severity of service impacts are incorporated as weighting factors representing level of service changes. The monetary value for benefits from risk reduction of an investment programme to the average customer is described by equations similar to the one below.

$$WTP = \alpha + \sum_{j=1}^{N}\left(\alpha_j + \beta_j\left[\sum_{i=1}^{M}\Delta R_{ij}Q_{ij}\right] - \gamma_j\left[\sum_{i=1}^{M}Q_{ij}\right]\left[\sum_{i=1}^{M}\Delta R_{ij}Q_{ij}\right]\right)$$

with

α = current water price

j = service areas (*e.g.* water quality)

i = solutions (*e.g.* water quality improvement)

ΔR = Risk reduction due to changes in severity and probability

Q = quantity of service in m^3 drinking water provided

N = number of service measures represented in the WTP equation

M = total number of Solutions in the portfolio being evaluated

Equation 13 Customer benefit equations derived from 'willingness to pay' studies

The β and γ are coefficients that were derived for the perceived utility of customers for individual service attributes. As result, equations were derived that calculate the perceived customer benefit for risk reductions relating to water quality, loss of supply, low pressure and discolouration.

In this chapter, a number of case studies are presented that demonstrate how the average customer values risk. The case studies also demonstrate how the risk may reduce after the implementation of a technical solution.

5.3 Methodology

5.3.1 Water utility business risk

In the following study, the business or asset risk for five privatised, stock marked listed water companies in England and Wales was evaluated. Financial data provided by Datastream (Datastream, 2005) was used to calculate a time series of assets betas. The London Stock Exchange 'FTSE All share' is used as the reference market. The 'FTSE

All share' aggregates 803 shares listed from ten industry sectors and 39 sub-sectors (Myddelton, 2000).

A Datastream software application was used to calculate a time series for equity beta between April 1995 (ca. 6 years after privatisation) and April 2005. In order to calculate the asset beta, the debt ratio published for all water companies in company accounts was used to calculate the asset betas. These are plotted as a time series and analysed.

The analysis focuses on the volatility of cash flows that determine the market evaluation of asset beta. The findings are compared to the findings of the incident analysis from chapter 2.

5.3.2 Customer risk evaluation

From a customer perspective, a number of case studies were selected to demonstrate the willingness to pay of customer to reduce risk. In a number of cases, the cost benefit (*i.e.* risk reduction) of engineering schemes is used to show how the average customer valued the monetary benefit for those particular schemes. The case studies also reflect on the perceived risk reduction from a water utility perspective. The trade-off model in Equation 14 that describes the rate of technical substitution between risk (di_2) and assets (di_1) to be the negative ratio of their production input factor prices (p_{i1} and p_{i2}) (Bonart and Peters, 1997) is used to calculate the cost benefit. In this trade-off model p_{i2} represent the willingness to pay. The Regional Water Utility provided the benefit equations that were used for the numerical analyses.

$$\frac{di_2}{di_1} = -\frac{p_{i_1}}{p_{i_2}}$$

Equation 14 The optimal rate of technical substitution

5.4 Results and Discussion of Results

5.4.1 Water utility business risk

Five time series of asset betas for stock-market listed companies were calculated. They are presented in Figure 54. A number of significant observations can be made. Throughout the time series for all water companies, the asset beta is generally below the portfolio market risk with the asset beta < 1. Since 1998, the asset beta reduced considerably and stabilised at around an asset beta of zero. Since 2004, a marginally upward trend can be identified.

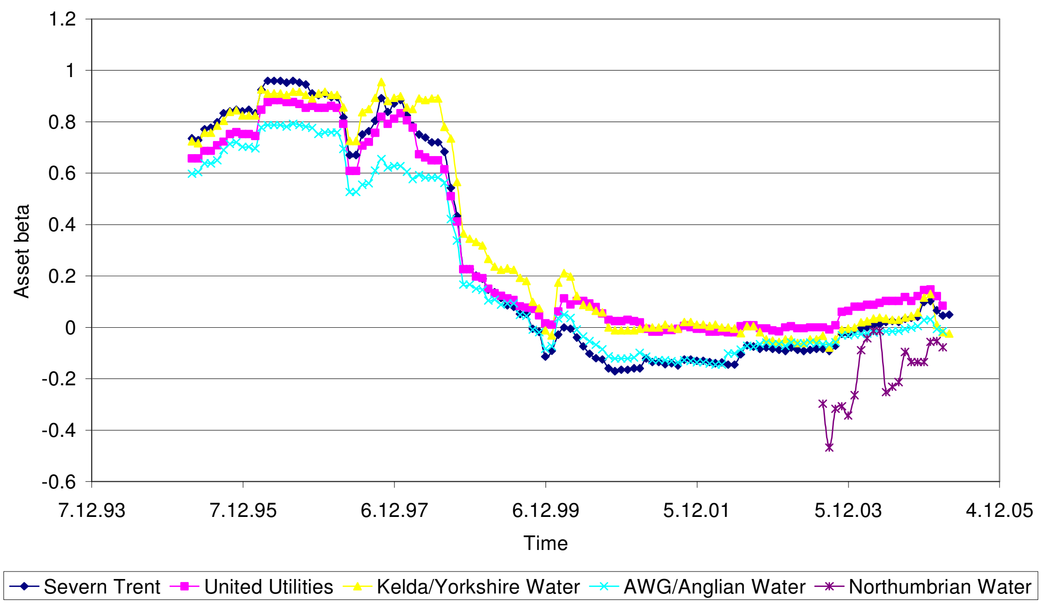

Figure 54 Time series (1995 – 2005) of asset beta for UK stockmarket listed water companies

From an asset owner perspective, the above water utilities operated in a near-risk free business environment between 2000 and 2004 relative to the portfolio market. This can be largely explained with two major influences: Firstly, water companies in England and Wales have a reasonably steady and predictable inflow of cash in their revenues. The product 'water' follows a predictably steady demand pattern for which water companies charge customers periodically. Secondly, the water price is not subject to changes in demand and supply but rather capped by the industry regulator (Office of Water Services, 1993) who will periodically review the water prices for customers in 5 year cycles. From an investor's perspective, the main source of volatility in cash flow arise in the business costs of providing product and services. That also includes the consequential cost of incidents.

In the previous analysis of incidents, it was found that the above water utilities frequently experience incidents. In 2006 alone, Severn Trent, United Utilities and Yorkshire Water reported ten incidents each. Anglian Water and Northumbrian Water reported eight and five incidents, respectively. The consequential cost arising from these incidents incur cash flows *e.g.* to operate and maintain an incident management infrastructure but also direct, consequential cost. At that rate of incident frequency, the consequential costs become normal operating expenditure associated to managing these incidents that do not seem to affect the volatility of cash flows. As a result, incidents do not seem to affect the evaluation of business risk in the asset beta.

It was previously argued that chronic exposure to hazard and instantaneous incident represent an often non-monetary cost to society. The Drinking Water Inspectorate is the regulating body watching over water utilities in their performance of duties, *i.e.* they ensure that the 'cost' to society from public health incidents and risks are controlled in accordance to public interest. Between 1993 and 1996, a total of 36 successful prosecutions were led against water companies in England and Wales of which 95% of the offences related to drinking water supplied unfit for human consumption (Drinking Water Inspectorate, 2008). From Table 65, the average fine of £13,770 imposed on successfully prosecuted water utilities represents the internalised externality of 'social cost' (Endres, 1994).

	Average	**SD**	**SE**	**Minimum Confidence Interval at 95%**	**Maximum Confidence Interval 95%**
Fines	£13,770	13,932	2,231	£9,397	£18,142
Legal cost	£10,857	13,758	2,2,03	£6,539	£15,175

Table 65 Regulatory fines for incidents

The five stock-market listed companies reported 547 incidents to the Drinking Water Inspectorate between 1998 and 2005. Of these, 19 prosecutions were initiated and completed (Drinking Water Inspectorate, 2008). This represents a ratio of 3.5%. Considering the average fine imposed on successfully prosecuted water utilities, the average 'social cost' per incident amounts to £478.29 in addition to the direct cost for the water utility for reinstating a safe system and damages.

In the previous chapter, the asset risk trade-off model described the rate of technical substitution between risk (di_2) and assets (di_1) to be the negative ratio of their production input factor prices (p_{i1} and p_{i2}). Legal fines are one factor in the price of risk and, in considering the trade-off between risk and assets to reduce risk, low fines shift the equilibrium towards accepting higher (public health) risk as an optimality criterion.

From a cost risk trade-off viewpoint, a higher price paid for incidents by the water utilities would encourage further risk reduction, if that was in the interest of the public and customers. The effect of increasing the price of risk can be demonstrated with an initiative by OFWAT to reduce the risk of abusing the bounded rationality of the regulator arising from the monopoly position of water utilities. In April 2004, Ofwat launched "*a consultation over new powers it will have to fine water companies. Companies could face a financial penalty if they breach their licence conditions, or fail either to deliver required customer service standards or meet their legal obligations*" (Office of Water Services, 2004). Since April 2005 Ofwat can impose financial penalties of up to 10% of turnover where a company contravenes its licence or appointment conditions or fails to meet required standards in performing its duties (Department for Environment *et al.*, 2005) and since then it has fined *e.g.* Thames Water 0.7% of turnover (£9.7 million) for misreporting information and delivering poor service to customers in April 2008 (Office of Water Services, 2008a) and Southern Water a total of £20.3 million for deliberately misreporting information and delivering poor service to customers in February 2008 (Office of Water Services, 2008b). More recently, it confirmed its intent to fine Severn Trent Water 3% of its turnover - a total of £35.8 million - for deliberately providing false information to the regulator and providing a poor service to its customers (Office of Water Services, 2008c). These measures are designed to increase the price of risk to ensure that water utilities do not abuse their monopoly position. In analogy to fines for mis-reporting company performance data, an increase in fines for incidents would increase the price of risk and shift the equilibrium of the trade-off model towards reducing risks and, hence, incidents from occurring. This would, however, have an impact on the overall water price as further investments for risk reduction would be required that need to be financed.

Increasing fines as an incentive to enhance performance also draw criticism: Law professor Bruce Welling (1991) describes the logic from a shareholder perspective: *"The practical business view is that a fine is an additional cost of doing business. A prohibited activity is not inhibited by the threat of a fine so long as the anticipated profits from the activity outweigh the amount of the fine multiplied by the probability of* *being apprehended and convicted. Considering the amount of the average fine, deterrence is improbable in most cases. The argument is even more obvious regarding prevention and recidivism. The corporation, once convicted and fined, will simply have learned how to cover its tracks better."*

5.4.2 Customer risk evaluation

From a customer perspective, the Regional Water Utility evaluated the benefit of risk reduction for customers. In 'willingness to pay' studies, the price for one unit risk was determined and this price is used to evaluate the benefit of risk reduction schemes. The risk asset trade-off model is used to compare the cost of engineering schemes with the benefit derived for customers.

In the following Table 66, the monetary benefit for reducing one unit of risk is stated for a number of service measures. It can be identified that customers have different preferences for risk reduction for the various levels of service provided by the Regional Water Utility.

Service Measure	Willingness to pay for reduction of one risk unit in £ p.a.	£ NPV over 40 years at 6.0% discount rate
Security of Supply	0.1549	2.03
Drinking water quality	0.0018	0.02
Inadequate Mains Pressure	1.4566	19.11
Interruptions to Supply	0.0023	0.03
Leakage	78.8249	1033.84
Drinking water Discolouration	0.0299	0.39

Table 66 The price of risk from a customer perspective

Based on the willingness to pay by customers for risk reduction, real investment scenarios can be considered. In Table 67, a project to reduce discolouration in a drinking water main is considered. The project reduces the risk of discolouration by 9.27 risk units. The customer benefit from this project is valued at £91, whilst the cost of the project amounts to £115,000. In conclusion, the project was not cost beneficial, hence the benefit cost ratio is below 1.

Drinking water Discolouration										
Pre Prob.	Post Prob.	Pre Sev.	Post Sev.	∆Risk	£PV of customer benefit	work type	units (m)	unit cost	NP Cost	Benefit / Cost Ratio
0.7	0.55	0.160	0.035	9.28	91.01				115000	0.00079
						cleaning	2461	6.70	16500	
						Scrape & reline	911	44.69	40719	
						cleaning	833	41.15	34284	
						Scrape & reline	14	166.64	2333	
						overheads			21164	

Table 67 Investment scenario based on the price for risk

In the following case study, an incident was triggered by a burst water main. The main was repaired only to find another burst further down the water main. Due to the fragility of the water main, another burst occurred a few hours later. The refurbishment of the water main was previously considered for reduction of leakage and interruption to supply in the risk database. Based on the overall benefit cost ratio of 0.03 (Table 68), pro-active maintenance was not pursued.

Leakage / Interruptions to Supply									
Pre Prob.	Post Prob.	Pre Sev.	Post Sev.	∆Risk	£PV of customer benefits	units (m) water mains replacement	unit cost per m water mains replacement	NP cost	Benefit / Cost Ratio
0.76	0.71	0.07	0.00	5	5240.13	173.56	131.00	22736.00	0.02
0.35	0.34	0.72	0.72	1	1.26	1193.00	130.52	155710.00	0.00
Total					**5241.39**	**1366.56**		**178446.00**	**0.03**

Table 68 An investment scenario assessed previous to an incident

In another incident, a burst occurred; this was brought to light by a number of customers from the village ringing in with ‘no water’. A technician was dispatched to site but the burst proved very difficult to find in the rural location and was finally found in a field. The contractor attended with a mini digger however, due to the depth of the main and the ground conditions being extremely boggy, the mini digger got stuck and the work was delayed while a JCB got to site. The interruption to supply lasted for up to 10 hours.

Pro-active maintenance of the water main was previously considered but rejected as non-beneficial (Table 69). It should also be noted that the reduction in incident probability from pro-active maintenance amounted to 0.08 units, according to the risk assessment.

Leakage and interruption to supply							
Pre Prob.	Post Prob.	Pre Sev.	Post Sev.	∆Risk	£PV of customer benefits	NP Cost	Benefit / Cost Ratio
0.67	0.59	1	1	8	8,270.74	23,000	0.027
0.79	0.79	1	1	0	0	52,000	0

Table 69 An investment scenario assessed previous to an incident (2)

In this incident, a regulatory sample from a service reservoir was reported as failing with counts of 3/3 for E. coli. The usual precautionary slug dosing and investigation sampling was done. The following day, the resample failed with counts of 6/6 from the service reservoir and 1/1 from one of the distribution samples. The risk was previously assessed in the risk database with two investment options. Both options were rejected due to a low benefit cost ratio (Table 70).

Drinking Water quality enhancement								
Pre Prob.	Post Prob.	Pre Sev.	Post Sev.	∆risk	£PV of customer benefit	Investment option	NP Cost	Benefit / Cost Ratio
0.86	0.29	1.00	1.00	57	1,354.22	Replace seals	8,100.00	0.17
0.75	0.10	0.10	0.10	6	52.58	Replace SRE	294,994.00	0.00

Table 70 An investment scenario assessed previous to an incident (3)

In another incident, heavy rainfall resulted in very poor raw water to a water treatment works. The treatment process on site cannot treat highly turbid raw water and, hence, turbid water was passed forward into the clean water tank. In addition, the turbidity used up more chlorine than usual resulting in low chlorine residuals coming off the plant. Process enhancements were previously considered but rejected due to a low benefit cost ratio (Table 71).

Treatment process enhancements								
Pre Prob.	Post Prob.	Pre Sev.	Post Sev.	∆Risk	£PV of customer benefits	Investment options	NP cost	Benefit / Cost Ratio
0.85	0.85	0.73	0.73	0	0	Option 1	255,700	0
0.95	0.5	1	0.73	59	4.19	Option 2	20,925	0.00
1	0	0.73	0.73	72	8611.63	Option 3	136,3000	0.01
0.99	0.2	0.73	0.46	62	11.87	Option 4	38,000	0.00

Table 71 An investment scenario assessed previous to an incident (4)

In this incident, a treatment works shut down however the chlorine dosing continued due to a lost link between SCADA and the control centre. The result of this was super-chlorinated water was making its way into the distribution network once the works started up. Over the next two days, this resulted in a number of taste and odour complaints. In Table 72, the benefit cost ratio rejected a pro-active installation of failsafe chlorination equipment.

Water quality enhancement / Failsafe chlorination							
Pre Prob.	Post Prob.	Pre Sev.	Post Sev.	∆Risk	£PV of customer benefit	NP cost	Benefit / Cost Ratio
0.6	0.0	1.0	1.0	6.0	36,519.67	354,718.00	0.008

Table 72 An investment scenario assessed previous to an incident (5)

The above case studies demonstrate that there are instances where risk assessments were carried out and the cost of risk reduction considered. However, the benefit of reducing that risk was deemed too low to pursue pro-active maintenance or investment. With deriving the value of risk reduction from a customer perspective, a water utility has a strong position to defend the number of incidents that occur in their water supply area. From a shareholder perspective, the number of incidents that customers experience is in the customer interest, because the customer is not willing to pay for reducing that risk. Following that logic, customers are willing to accept risks even when they are realised in the unfolding of incidents. Yet, water utilities are required to maintain levels of service to customers (UK Water Industry Research Limited, 2002) and, in chapter 2, evidence in the Regional Water Utility was found that the number of incidents increased by an average of two incidents per year between 1997 and 2006. Furthermore, the

Regional Water Utility forecasted the number of high risks on their risk database for assets in the next ten years. According to this forecast, the number of high risks for water quality will increase by 36% between 2007 and 2018 if the organisation is unable to finance investments and maintenance (Figure 55).

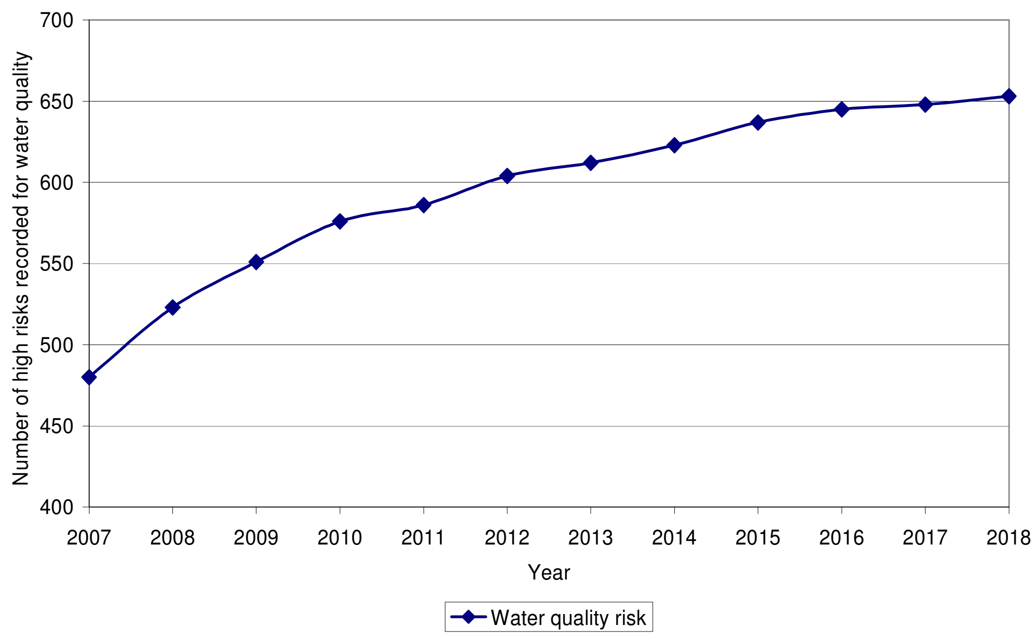

Figure 55 Forecasted high risks for water quality from 2007 to 2018

As a policy, the Regional Water Utility aims to maintain the number of high risks at its current level rather than maintaining (or reducing) the number of incidents. This is a rather odd parameter considering the current weaknesses with the risk data acquisition process.

Either way, the organisation has to finance investment and maintenance programmes to maintain or reduce the number of incidents and to maintain the overall risk profile for assets stable. The current rhetoric of customer 'unwillingness to pay' will not release water utilities to fulfil their statutory obligations. Despite that, there are a number of weaknesses in 'willingness to pay':

Firstly, as introduced in the methodology, the derivation of customer preferences is an interpolation of a limited number of scenarios, *i.e.* lower service, maintaining service and service enhancement in perspective of the anticipated impact on water prices.

Secondly, the ‘willingness to pay’ is an average for all customers. A customer who is regularly affected by incidents may have a much higher ‘willingness to pay’ for service improvement. However, individual preferences are ‘averaged out’ and high risks affecting individuals cannot be financed. In using ‘willingness to pay’ it ought to be considered to use a higher water price that reflects the upper standard deviation or the maximum confidence interval at 95% to ensure that a higher ‘willingness to pay’ above average is adequately recognised.

Thirdly, ‘willingness to pay’ does not consider the direct consequential cost for the water utility. In the above case studies, the regional water utility had to mobilise resources to manage the impact of the incident and to repair and re-instate the water supply system. Incidents were managed via an incident management infrastructure that already represents a ‘sunk cost’ and represents an organisational overhead in business costs. Eliminating all incidents would also eliminate the need for these ‘overheads’.

Fourthly, the ‘willingness to pay’ by customers is also dependent on the way the questions are put to customers. Relating to water quality the Regional Water Utility explained to survey participants: Water quality *“is about how good the tap water is in relation to chemical and biological (bacteria) content. Currently 144 of the company’s water quality samples fail the Drinking Water Inspectorate’s requirements for chemical and biological content, which is equivalent to a pass rate of 99.95%. With increased investment this could be reduced to 75 failed samples (equivalent to 99.97% passing), 50 failed samples (99.98% passing) or 25 failed samples (99.99%). With reduced investment this could increase to 1,500 failed samples (99.43% passing).”* The explanation for water quality does not explicitly mention water quality incidents that have arisen instantaneously in the past or their effects on customers. The Regional Water Utility rather uses the pass rate of 99.95% for water quality samples as a base line. The customer question is further biased by setting the water quality sample record into context of the investments required for reducing the chronic exposure to contaminants and makes no mention of asset reliability to prevent instantaneous asset or processes failures that could lead to an incident. They state: *“Because of the intensive treatment processes needed to control the chemical and biological content of your tap water, <u>even remaining at the current level</u> of service would result in a <u>small increase in your charges</u>.”*

Considering the funding for investment and maintenance programmes, there are several more sources of funding, namely profits and dividends exceeding the risk-free return on investments, loans and efficiency savings. With respect to the latter, the theoretical asset risk trade-off model assumes highest possible efficiency whereas, in reality, the regulator periodically identifies efficiency savings that are reflected in the periodic determination of the water price (Office of Water Services, 2008d) and indentifies opportunities to operate more efficiently.

In re-considering the investment scenarios in the above case studies, another interesting observation was made: It was previously identified that the stock-market listed water utilities have an asset beta at or near zero. In effect, that represents zero business risk or the risk for shareholders to lend money at 4% interest. It appears that the Regional Water Utility charges an extra risk premium of 2% on capital projects to calculate their revenues and cost cash flows.

5.5 Summary

The objective of this study was to investigate the prevalence of incidents from a financial and customer perspective on the 'price' of risk and the benefit arising for customers to reduce the frequency or probability of incidents. From a financial perspective, it was found that shareholders in stock market-listed water utilities can expect a risk-free rate of return on their investment. This was explained to be the result of a number of factors. Firstly, water utilities provide an essential service to customers. Continuous provision of drinking water guarantees a steady cash flow of revenues charged for service provided. Secondly, the water utilities appear to have steady cost cash flows to operate their business. As a result, the volatility of profits converges towards zero. This is reflected in the asset beta of water utilities.

The impact of incidents on a water utility was investigated and it was found that the periodic occurrence of incidents also seem to represent a steady cash flow that does not increase the volatility of profits. From a regulatory perspective, the consequential cost of incidents was investigated and the regulatory fines evaluated that follow successful prosecutions of water utilities. It was found that the average imposed fines are considerably low (Table 65). As a result, the occurrence of incidents is accepted by the water utility because of the 'prohibitive' cost of reducing the number of incidents via cost benefit analysis for asset investment and maintenance.

From a customer perspective, the use of 'willingness to pay' data in the context of investment decision making was investigated. In the Regional Water Utility, it was found that customers were given the opportunity to evaluate their benefit of risk reduction. These represent the unit cost of risk that is used to compare investment proposals with the perceived benefit of risk reduction. In a number of incident cases, it was found that the risk and the benefit of risk reduction have previously been assessed. Based on low benefit cost ratios, service enhancements, *i.e.* risk reduction, did not warrant an investment decision. From an economic-rational viewpoint, the customer was better off accepting the probability of an incident to occur, although consequential 'costs' were incurred during and after the incident.

6 General Discussion

This thesis set out to investigate the hypothesis that the "*principles of HRO facilitate a) organisational resilience under trying conditions and b) learning from failure to enhance the safety and reliability of drinking water supply"*.

A number of research objectives were formulated to structure this thesis and to investigate the components of this research project. They were identified as:

- To characterise "*the short periods of stress*" (World Health Organisation, 2004) in an assessment of incidents frequencies, cause and effect relationships and impact on customers.
- To investigate the benefit of HRO principles in incident management and to correlate incident impacts on customers and impact reductions with observation of high reliability principles under trying conditions.
- To identify learning opportunities from incident analyses to enhance risk assessments that are subsequently used for asset investment and maintenance decision making in asset management.
- To investigate the prevalence of incidents from a financial and customer perspective on the "price" of risk and the benefit arising for customers to reduce the frequency or probability of incidents.

Each objective is discussed in turn.

6.1 The nature and impact of incidents

In chapter 2, the objective was to characterise "*the short periods of stress*" (World Health Organisation, 2004) in an assessment of incident frequencies, cause and effect relationships and impact on customers. In the review of incidents that occurred in England and Wales between 2004 and 2006 as well as incidents in the Regional Water Utility between 1997 and 2006, a methodology was introduced that enabled a direct comparison of incident impacts on customers. This methodology was used throughout this thesis a) to evaluate individual incident impact, b) to evaluate the effectiveness of incident management responses and c) to evaluate and enhance risk assessment capabilities in the Regional Water Utility.

Incidents were investigated for their cause and effect relationships based on the availability of historical data and personal accounts of staff involved during incidents. Based on detailed descriptions and documentation of incidents it was aimed to identify not only single root causes of failure but also contributing factors in terms of assets (Figure 12), processes (Figure 16) and human factors (Figure 17) that contributed to the unfolding of incidents. It was found that the majority of incidents arise as failures of drinking water distribution assets that led to 'loss of supply' and 'discolouration' of drinking water (Table 17). The second largest category of asset failures were associated to the failure of chemical treatment equipment in water treatment works causing a deterioration of drinking water quality due to the loss of chlorination (Figure 12).

Beyond asset failures and process failures, the human factors were considered that contributed to the unfolding of incidents. Human factor considered any adverse influence of decision making during the design and operation of physical assets and processes. Some incidents were reported as a result of incomplete or outdated operating procedures. One interviewee pointed out that the sheer volume of operating procedures is also a factor to consider explaining the non-adherence to operating procedures. This has to be regarded in the context of fewer field staff that are increasingly looking after more and more water supply assets. This may induce time pressures that contribute to 'corners being cut'. On the other hand, the thorough review of incidents emphasises that operators and field staff work according to standard operating procedures.

The analysis of incidents considered the positive effect of asset and systems redundancy during the management of incidents and their effectiveness to reduce the impact of incidents on customers (Figure 19 - Figure 22). It was found that many incidents have no immediate redundancy available (*e.g.* water distribution mains) or redundancy was ineffective due to common cause failures. In a number of case studies, it was found that redundancy did not operate effectively despite being specifically provided for the failure scenarios that occurred. The provision of diesel generators as a means of uninterruptable power supply did not – in some instances – operate due to technical problems that were traced back to their design.

Considering the availability and usage of redundancy, the impact on customers was evaluated (Figure 23 - Figure 25). This impact assessment commenced from identifying the single highest impact on customers towards the evaluating multiple customer impacts an incident can have.

An interesting finding in the Regional Water Utility was an increasing trend of the number of incidents that occurred between 1997 and 2006. It was found that the number of incidents increased by ca. two incidents per year on average (Figure 26), despite a regulatory requirement to maintain or enhance the level of service for customers (UK Water Industry Research Limited, 2002).

A critical issue in the design of this research element was the availability and quality of data. The review of incidents in England and Wales used tertiary data that was pre-filtered by the reporting water utilities and the Drinking Water Inspectorate to report incidents to the lay public. However, it provided sufficient detail to evaluate the impact on customers and the failing asset type causing an incident. In the Regional Water Utility, the author had access to primary and secondary data. It has processes in place to review every incident that occurs and the author had access to detailed, documented incident records. These included log books, detailed incident minutes, personal communications of staff involved during the incidents, maps and raw data from monitoring and control equipment. One important aspect in evaluating research results was the awareness that the outcomes of the incident review meeting as described in the incident documentation may be subject to cultural bias. The models used to analyse incidents may represent heuristic simplifications of complex circumstances that represent a simplified or limited version of a complex reality. Furthermore, according to Denzin and Lincoln (1994), documentation can be highly biased due to the views the authors may had at the time recording data. This is particularly relevant in light of the regulatory requirements to report incidents. It is important to understand the motivation of the organisation to investigate incidents. On the one hand, a systematic bias may have motivated authors to 'misrepresent factual data'; on the other hand, a strong desire may exist to learn from failure driven by a code of professional conduct.

It was found that pressures and conflict can arise in the attribution of root causes to error. A common concern amongst individuals involved during incidents and subsequent incident review meetings is the issue of blame, in particular when human factors were considered that might have led to the incident. MacGillivray (2008) recently pointed out that *"incident investigations are all too often contaminated by political interests, social forces, and psychological biases"* and that *"organisations are generally intolerant of dissent, and so employees often fear the negative repercussions of speaking up, and may not believe that doing so would make any difference"*. He further points out that *"this is amplified in that management often feel threatened by negative feedback, and so try to avoid receiving it, and when they cannot, they may try to ignore it, dismiss it as mistaken or attack the credibility of the source."*

Political factors are not so easily reduced to a nihilistic viewpoint on inability to learn from failure. A number of factors and safeguards have been identified in the Regional Water Utility that prevent - or at least reduce - abuse or biased learning from failures and false reporting of incidents. Firstly, the incident review meeting is attended by a complex set of people. These are operators, operations managers, asset engineers, asset managers and emergency planning officers who are less likely to submit to coercive pressures. The incident review process deliberately plays out conflicting opinions on the causes of incidents. Operators are skilled workers trained at BTEC/NVQ level in Water process control. Their educational background primarily reflects asset operation and public health considerations should asset fail and provides them sufficient understanding of technical and organisational issues to deliver their account of an incident. Secondly, undue 'finger pointing' at operators can have adverse impacts on the working relationship between operators and management which, in turn, can lead towards operators working only 'to the book', *i.e.* the minimum required hours and only following instructions and procedures. As a general observation, it was found that the conflict between operators and management is best described as 'co-opetition', *i.e.* a symbiosis of competition and co-operation. This relationship plays out in the review of incidents and was evidenced in the series of interviews that were conducted in the Regional Water Utility.

Thirdly, the management of a water utility has an interest to identify the 'true' causes of failures - not only from a public health perspective but also from a shareholder perspective. It was demonstrated in chapter 4 that learning from failure provides an opportunity to anticipate future risks. This, in turn, makes the performance of a water utility more predictable and, hence, enables enhanced investment and maintenance decision making. 'Short-termism' to boost the share price of a water utility whilst managing long-term investments in physical assets is a problem to consider: One interviewee (participant no.7) pointed out that *"our senior management understand that the industry we're in now there's a game to be played, there's a bit of gloss here and there's a bit of reality here but they understand what the gap is …. They don't pretend there isn't a gap, they understand that for all the investment we've got we're still short of what we'd like to do and I think what we have to deal with is we can't 'bleat on generic' we're about to close gaps, it's a case of this one has dropped through, we need to take some action and generally speaking we make a selection."*

A further form of safeguard arises in the punishment of water utilities to miss-report incidents to the regulators. The introduction of heavy fines by the Office of Water Services aim to reduce the risk of miss-reporting. The recent case of Severn Trent mis-reporting data demonstrates how uneconomic cheating can be, unless significantly higher returns on investment can be achieved (Welling, 1991).

A much more interesting political factor that drives the understanding of incidents and risks arises from the introduction of 'willingness to pay'. In the Regional Water Utility, it was found that root cause for failures are increasingly identified by 'customer expectation', *i.e.* the customer and the regulator are not 'willing to pay' for preventing these incidents since the budget for investments and maintenance spending are constrained by the water price set by the OFWAT. Although this is a highly simplified explanation of the regulatory mechanism, it has set foot in the belief of a number of staff.

MacGillivray (2008) makes a valid point in suggesting that incident investigations <u>can</u> be *"contaminated by political interests, social forces, and psychological biases"* but significantly more evidence is required that these distortions actually play out in water utilities. From having reviewed a significant number of incidents with access to primary data and from the interviews conducted with staff who attended incident review meetings, little evidence was found that 'groupthink' and 'blame culture' inhibited learning from failure. It was found that incident reviews are facilitated meetings which enabled the thorough scrutiny of multiple incident accounts of staff who were involved. The primary purpose of the meeting that the author attended was to provide an objective and valid as well as trustworthy narrative of the incident for internal and external reporting. Internal reporting, to some extent, aims to prevent identical incidents to re-occur and external reporting to inform the public health regulator of the problems that were identified and the measures put in place to prevent re-occurrence. As a suggestion for further research it is proposed to study conflicting interests, social forces and psychological biases in the conduct of incident review meetings.

This thesis set out to enhance the learning opportunities beyond individual incidents to improve risk assessments that anticipate future incidents. Before returning to the opportunities to 'learn from failure', the findings with respect to incident management capabilities to identify and manage incidents are discussed.

6.2 Incident management and high reliability principles

In chapter 3, the objective was to investigate the benefit of HRO principles in incident management and to correlate incident impacts on customers and impact reductions with observation of high reliability principles under trying conditions.
The following sections discuss the observed HRO principles in incident management.

6.2.1 Organisational culture

A strong organisational culture of reliability was a stipulated requirement as a bulwark against failure resulting in catastrophic consequences. In observations and staff interviews it was observed that staff in operations and incident management have a strong sense of the primary mission of the organisation. These were commonly expressed as 'providing a safe and reliable drinking water for customers in line with regulatory requirements'. Operations managers, engineer and operators share a common system of beliefs and perceptions when water safety is concerned. The water supply system is constantly monitored for any abnormal operating condition. In the observation of unfolding incidents, it was found that staff have a highly developed understanding of their contribution to water safety regarding their role in the technical system and in the decision making process. In particular during incidents staff act in a collaborative and collegiate manner.

Constant vigilance and concern for water safety and reliability dictates the behaviour of staff. This is particularly relevant to field operators but also control room staff who act with alertness, attentiveness and care in monitoring the healthy operation of the entire water supply system. Employees are encouraged to take responsibility, in particular where problems are identified and immediate corrective action programmes are required. On first sight of a problem with a particular aspect of the water supply system, an alarm is raised and the need for instigating the incident management procedures is assessed. With the introduction of information technology and automated monitoring and control system, the majority of asset failures are picked up by monitoring equipment and an alarm is raised. One major exception is the identification of water mains burst and water discolouration arising in the distribution network. Here, the organisation relies on customers to call in and report their service experience. Here too things are starting to change with the use of online, real time monitoring of flows and pressures in the distribution system in an attempt to identify potential issues before they become customer impacts.

The commitment of senior management to water safety and reliability of the organisation is communicated to all levels in the organisation and demonstrated with investments in technology, processes and personnel as long as the conflicting objectives of public health and shareholder value align. In our observations and in interviews, members of staff have communicated their strong sense for collective needs and goals. Individuals 'monitor, advise, criticize and support' another, in particular during critical incidents which are immensely stressful situations and quick decisions have to be taken.

6.2.2 Adaptable decision making dynamics and flexible organisational structures

As pointed out before, Perrow (1999) argues that complex and tightly coupled systems can only prevent accidents with a high level of centralisation because low level decision makers have insufficient understanding of the inter-relationship between their actions and consequences on other elements of the system (Rochlin *et al.*, 1987). Perrow's definition of systems referred to technical assets such as nuclear power plants. Here, it is not claimed that technical systems in the water sector are complex technologies, yet, it is the combination of physical, information, human and intangible assets that form socio-technical systems with increased levels of complexity. Complicated designs of technical systems, monitoring and control philosophies, significant human machine interfaces and significant interfaces with the environment, potential for human error and difficult decision making processes in incident, operations and asset management characterise the complexity of the large water supply system operated by the Regional Water Utility.

It was found that during an incident, the organisation assumed a centralised command and control hierarchy. This is reflected in the organisational structure in operations management in which process and performance data of the technical system are reported to a centralised control room. From this control room, the incident manager co-ordinated efforts to reduce the impact of the incident and to re-instate safe water supply. From here, the incident manager will monitor the entire system’s response to the incident and the incident management efforts. The incident manager leads the incident management team within the control room but also field staff who perform the required tasks at the source of failure or within the area affected by the incident. The incident manager directed all resources at his disposal, including systems redundancy, towards reducing the incident impact and re-instating safe operations. During large scale incidents, the organisation was capable to decentralise if this is required to respond to rapidly unfolding failures (Figure 33). During a major storm event which had significant impact on many technical subsystems, a number of incident managers were called up to respond to particular aspects of the region-wide incidents. Although centralisation is essential in tightly coupled technical systems where interdependency is high, it was possible to de-couple the technical system so that decentralisation in the incident management response provided for action at the point of need.

The organisation requires stringent adherence to procedures and guidelines aiming for a repeatability of actions and routines. Activities based on decisions that are not defined in procedures are taken at a more senior level. Every incident that was investigated had unique and novel aspects to consider for which detailed procedures were not available. These arise out of the specific incident circumstances, *e.g.* the environment in which the incident occurs. Since many of these incidents occurred in unforeseen circumstances, only high level principles and guidelines are available to direct incident response efforts as particular SOPs would not exist for such particular scenarios. In such events, the decision making process had in-built slack in order to assess and challenge decisions by a more senior member of staff. Furthermore, the incident manager had specialist staff at his disposal to guide his decisions.

In the review of past incidents, it was found that the organisation in the majority of incidents effectively adapted its organisational structure to respond to the needs arising during an incident (Figure 33). However, there were also cases where the inadaptability of the organisational structure prolonged the incident. The incident assessment also focussed on decision making during the incidents. It was also found that - in the majority of cases – the decision making process could be characterised for 'good decision making'(Figure 34). The decision taken during the incident significantly and pro-actively contributed to reducing the impact on customers and to re-instate normal operations as soon as possible. Yet, there were also cases that could only be described for 'poor decision making' These were identified as being ineffective to recover the incident situation to normal operation in a reasonable time-frame and provided scope to learn lessons for enhancing the incident management response.

6.2.3 System and human redundancy

The organisation maintains reserve capacity in its technical and organisational system that includes back-up functions, overlapping tasks and responsibilities. As it was seen in chapter 2, in many cases, the organisation is capable to isolate the source of hazard whilst using other asset types to compensate for the loss. These situations would prevent an incident to occur and are, hence, not classed as an incident. For example, the distribution network has re-zoning capability to isolate a burst main and provide water supply from other sources. During major power failure incidents, the organisation can mobilise stand-alone power supply units to critical water supply assets if they have no on-site power generation.

The majority of the water supply system builds on duty standby systems, excess capacity and inter-connectivity to isolate a failed asset and compensate for its loss. The use of systems redundancy was investigated as part of the incident management response. It was found that in the majority of incidents no systems redundancy was used or could be used to reduce the impact or avoid customer impact. This figure predominantly arises from water distribution main failures. In the majority of these incidents, the water utility resorted to the supply of bottled water. In many cases, the use of systems could not avoid customer impact although it had a reducing effect or significantly reduced the impact of incidents on customers and avoided the impact for a much larger customer base. These figures have to be regarded in context of undocumented ‘near failures’ and ‘near misses’ where redundancy avoided the unfolding of an incident altogether.

As mentioned before, it is important to recognise that designing redundancy for a system can be counterproductive, as back-up functions can increase technical complexity, conceal errors and lead individuals into not performing their required tasks under the assumptions that someone else takes care of his task (Sagan, 1994). System redundancy also affects maintenance policies that could be regarded as counterproductive. Based on observations in the Strategic Asset Management department and following the logic of cost benefit analysis in maintenance decision-making, it is believed that maintenance decisions can be deferred due to multiple technical redundancy in-built into the supply system: duty standby systems considered as a system have a significantly reduced probability of failure. Such type of risk assessment considers the probability of asset failure <u>and</u> the probability of that asset failure to have an impact on customers. Considering redundancy in the risk assessment may lead to an assessment of low systems risk and, hence, low priority in maintenance spending.

6.2.4 Effective and varied patterns of communication

Effective communication facilitates a complex system to become more understandable, predictable and controllable. With the rapid developments of information technology, the Regional Water Utility’s supply system is increasingly fitted with advanced monitoring and control instruments. They are part of an effective communication strategy to maintain safe and reliable drinking water supplies. In the organisation, the monitoring and control philosophy has been advanced to a stage where physical assets such as water treatment works are no longer operated with staff on site. Monitoring and control is performed with ‘Process Logic Controls’ and ‘Supervisory Control and Data

Acquisition' that relay data to remote control centre. The control centre is the hub for managing the entire water supply system. In the first years of implementing the strategy of advanced monitoring and control, an increase of incidents due to the failure of such technologies could be observed. Where monitoring and control equipment fails, the status of a system becomes unknown but since then technological developments – such as status monitoring for control and monitoring equipment – have reduced these incidents over the last few years.

Processes in water production and distribution are measured and understood, with data made transparent and available to all. An interesting observation we made is the need to manage potential overload of information during critical situation in an incident. Having the right information available at the right time in the right place is an important aspect of water utility incident management.

During an incident, inter-personnel communication is designed as both bottom-up and top-down to ensure rapid flow of information through the hierarchy of the incident management team. Rapid dissemination of information helps the organisation respond to an incident, with corrective action aiming to prevent the escalation of the incident into an emergency.

It was found that there is a heavy reliance on customers to report their experiences to the water utility, in particular relating to incidents in the water distribution network (Figure 32). Efforts are underway to reduce the reliance on 'end of tap' reporting for incidents. A test trial is currently planned to provide sufficient pressure and flow monitoring devices to increase the incident detection capability in an area distribution network. With this arrangement, any deviation of observed pressure and flow patterns from expected patterns will raise an alarm in the control centre so that an incident investigation team can be dispatched to investigate the source of the abnormality. This system will enable the reduction of the response time to an incident considerably.

Communicating information allows staff to shape and share the 'big picture' of the organisations vision, mission and responsibility of individuals towards reliability. It was found that integrating asset management teams into the daily operation of the water supply system was considered to be important. The asset engineers require the information input from operators to assess asset risks. Via risk assessments, cash may be made available for asset investment or maintenance. Furthermore, the asset engineer can provide technical support during incident management.

In the analysis of documented incidents, the effectiveness of communication during the incident management response to the incident were investigated. In the majority of cases, the incident management responses were characterised by 'effective communication' (Figure 35). Here, the communication between the stakeholders involved in an incident generated 'a big picture': observations, decisions and water supply systems performance were effectively communicated to all relevant staff and external bodies, which enabled comprehensive judgement on the due course of action. Yet, there were also cases where some areas of improvements were identified which meant that the incident was unnecessarily prolonged. Only the minority of incidents, 'poor communication' had a significantly, adverse impact on the overall performance of the incident management response.

6.2.5 Continuous learning and intensive training

The performances of tasks are embedded in formal rules, generalised guidelines and standardised frameworks. These are expressed in SOPs, risk assessments and method statements. Yet, the emphasis is not merely on adherence to SOPs but also on identifying potential sources of failure and actions to stop faults from escalating. In order to facilitate continuous learning and intensive training, the operations management function review their processes and standard operating procedures (SOPs), in particular after an incident in an incident review meeting. In these meetings, the incident is scrutinised, 'lessons learnt' are identified and communicated to relevant parties in the organisation. The water utility learns by studying the failures, near failure and mistakes that occur within the organisation which are identified using 'root' cause analysis. It was found that the investigation of incidents, in particular analysing human error, enforces normative expectations to comply with standard operating procedures.

If necessary, actions for the asset engineer to review a particular system or actions for an operations manager to review a particular procedure can be formulated and their progress and completion monitored. Poor behaviour by staff that led to an incident is identified and countered with additional training. Failures in one part of the organisation could be used as a means to study the failure susceptibility of the entire organisation or, at least, of other, similar sub-systems. However, limited evidence was found that incident review meetings are designed to highlight and prompt cross organisational learnings in other parts of the business.

One effective cross-learning strategy from incidents arises from water mains failures: In the Regional Water Utility, the majority of incidents affect the distribution network in form of mains bursts (Table 17). Root causes for mains burst have many contributing factors such as age, material, soil condition and the operating regime (Figure 13). The structured collection and analysis of water mains failures enables multi-regression analysis for the derivation of risk profiles for the entire water distribution network. These models are used to prioritise maintenance and replacement programmes.

Other than that, little evidence was found that cross-learning initiatives from incidents informed the risk assessment process for other assets, although a business process is in place to communicate 'learnings' to a wider audience in the organisation. The author will return to this issue in a subsequent section.

Staff training is extensive and focuses on the requirements for maintaining a safe system. In the organisation, operators are required to gain professional accreditation in form of college certificates as a license to operate a water supply system. This training scheme is a customised training programme for operators in that particular region. In-house training and training on the job are also important components of continuous professional development. Recently, a risk training programme was launched to provide staff with a better understanding of risk identification and assessment skills. This training programme has been recognised as industry leading and earned a number of industry awards. It made participants aware of the risk perception horizon people have and develop over time. The general interest in this training scheme demonstrates that staff maintains a commitment to continuous learning and seek the acquisition and improvement of skills. The training programme was rolled out to over 170 people in the first year and included representatives from all areas of the business including contract partners.

6.2.6 Human resource management practices that support reliability

Suitability, skills and competencies are defined by the functional role that these individuals occupy in the Regional Water Utility. An incident manager has to be able to cope with highly uncertain situations and demonstrate rational decision making under "trying conditions". The incident manager has to be able to communicate effectively with the staff and stakeholders involved in incidents. S/he requires the ability to demonstrate decisiveness and firm leadership to remain in control of adverse situations. S/he also requires a good understanding of the entire water supply system whilst drawing on the expert knowledge in the incident management team. On the other hand, an asset engineer requires a very different skill set. The asset engineer requires analytical skills and competencies in assessing technical systems as well as the technical means to provide and maintain safe and reliable drinking water supplies. Their job role is reactive to incidents and pro-active in assessing potential sources of failure. Increasingly, the asset engineer has to consider technical systems risks and communicate them as a systematic risk assessment to the custodians of the risk management process. The asset engineer requires good communication skills, in particular to communicate with idiosyncratic operators and operations management.

6.2.7 Correlating HRO principles with incident impact on customer

In Figure 37 it was aimed to correlate the incident impact on customers with observed HRO principles during the management of incidents. A marginal, positive relationship was identified although it was hypothesised that a high incident impact negatively correlates with the scores for observed HRO principles. It was initially assumed that low observance of HRO principles would have an adverse impact on customers, *i.e.* prolonging the incident or aggravating the hazard exposure of the population.

It was then stipulated that the impact on customers would have to consider the potential incident impact, *i.e.* a measure for incident impact reduction was required to evaluate the effectiveness of HRO principles and in Figure 38 it was demonstrated how the reduction of incident impact correlates with observed HRO principles. Here, it could be concluded that the observance of HRO principles has a positive effect on reducing the impact on customers.

6.3 High reliability principles for risk-based asset management

In chapter 4, the objective was to identify learning opportunities from incident analyses to enhance risk assessments that are subsequently used for asset investment and maintenance decision making in asset management. In chapter 2, a large proportion of incidents were associated to asset failures which, in turn, define the technical reliability of the water supply system and in this section, the management of technical reliability and learning opportunities to enhance risk assessments relating to technical reliability are further discussed.

In practice, many water utilities are nowadays embarking on an explicit trade-off between investment cost and risk for asset investment and maintenance decision making (MacGillivray *et al.*, 2006). In Appendix 1 it was demonstrated that - similar to capital, labour and natural resources -, risk can be allocated an incremental unit and a price or cost based on risk assessments and evaluation. In substitutional production functions the input factors can be substituted (Bonart and Peters, 1997) with units of risk. This mathematical derivation underpins the optimal outcome of cost benefit analysis for investment decision making as long as all risk including social costs through externalities are accounted for.

In the Regional Water Utility, it was found that the asset management function is concerned with the provision of the infrastructure which enables the operations function to provide safe and reliable drinking water. It was found that the organisation does not necessarily require ‘state of the art’ equipment but rather considers the assessed reduction of risk and its monetary evaluation alongside capital investment requirements in the decision making process. The organisation aims to maximise capital spending efficiency to a point where the monetary value of risk reduction balances cash requirements for investment.

The assessed reduction of risk has to consider the compliance of technology outputs with the ever increasing standards of water quality parameters which corresponds to the lack of control over raw water quality sourced in a catchment. Such technology has potential to increase the technical complexity of a water supply system.

HROs have been described to maintain existing technology at exceptionally high standards and there is zero tolerance of defective, substandard or malfunctioning equipment (Roberts, 1990b). In the Regional Water Utility, maintenance decision making takes a more differentiating view on capital maintenance which is in line with the 'Common Maintenance Framework' (UK Water Industry Research Limited, 2002) building on economic principles described above. Maintenance decisions are increasingly based on risk assessments and a trade-off between cost of maintenance and perceived, monetary value of risk reduction (cost benefit analysis). This process heavily relies on accurate and consistent risk assessments. The risk assessment procedure has been implemented in a top down approach and requires asset managers and asset engineers to report and file risks bottom up from asset level to the Strategic Asset Management Department. An information system was designed to log risks on a risk database. The database is semi-structured to guide the risk assessor in providing accurate and consistent risk assessments. The database also houses risk data derived from risk evaluation models based on quantitative risk assessments via statistical analysis designed to evaluate failure probabilities and impacts Yet, the process relies on the competency, skills and experience of asset managers and asset engineers to identify and evaluate risks accurately. Similarly, the design of quantitative risk assessment models depends on the availability of failure data and competency in designing these models. Deviations from accurate and consistent risks reported on the risk database are sought out with quality assurance procedures to ensure effective allocation of cash. The aforementioned risk training programme was also launched to enhance the capability of risk assessors to identify and assess risks.

6.3.1 Learning from incidents to enhance risk assessments

In this thesis, further opportunities were investigated to learn from failure with a view to enhance risk assessments. The collection of incident data in the incident database represents a collective memory for failures and incidents. It was stipulated that the incident history of the Regional Water Utility could help to anticipate future problems in enhanced asset risk assessments.

The Regional Water Utility identifies risks at component level. From a theoretical viewpoint, the maximum possible number of risk assessments based on the current risk assessment framework used in the Regional Water Utility was calculated in Table 54. This was compared to the actual number of risk assessments currently filed on the risk database and it was found that the numbers significantly deviate. By comparing risk assessments per asset type it was found that smaller, less complex assets with a small number of components are generally overrepresented with risk assessments, whereas water treatment works with substantially more components are underrepresented (Table 55). From an economic viewpoint (cost benefit analysis), the ratio of risk assessments per component should be equal for all assets.

Risk assessments were then compared to past incidents to compare the frequency or probability, causes, effects and customer impacts of past failures with perceived future risks. It was found that these parameters often significantly deviated from another representing a discrepancy in the perception of risk compared to the reality of actual incidents. Unless the supply and demand patterns, the operating environment and the actual risk profile of assets have significantly changed, the parameters for long-term physical assets should not be significantly different between risks and incidents. The only exception arises for the introduction of new technologies. For instance, the introduction of IT systems for enhanced monitoring, control has led to an increase of unprecedented incidents, and learning from failure is only possible in the short-term since new technologies will supersede older versions of monitoring and control equipment and systems. It was sought to explain this phenomenon with the influence of psychological and sociological perception of risk as opposed to strict (economic) rationality.

It was further sought to explain why risk assessments can deviate from another and it was aimed to uncover how risk assessors perceive risk. In a small experiment, a number of staff were given a case study to assess risk for an asset. It was found that the risk assessors returned risk assessments that significantly deviated from the average. Three main factors were identified for this phenomenon: firstly, risk assessors may have incentives to over-estimate risk. They can arise from their (risk averse) concern for public health but also from incentives the organisation has in place to honour good performance or stigmatise poor asset performance. Secondly, a lack of understanding of ‘the risk concept’ can lead to under-representing risks. Thirdly, the time element of filing risk assessments may lead to insufficient risk assessments available for decision making. This is particularly applicable for large asset systems with significantly many components and interacting subsystems.

In a further attempt to improve the consistency of risk assessment data, it was argued that highly structured risk assessment templates and procedures are required to assess asset risks. Based on the incident review methodology adapted to identify the causes, effects and impacts of incidents (Appendix 3.3.1), a highly structured risk assessment template was developed that closely resembles the unfolding of incidents (Appendix 5.2). Since operators commonly understand how incidents unfold, it was thought that the new system enhances the artificial concept of probability and consequence assessment by prompting the risk assessor to think through an incident scenario in a decision tree structure.

The new risk assessment template significantly deviates from the current business process used in the Regional Water Utility. It also requires significantly more detail and, hence, prolongs the risk assessment process for individual risk assessors. This is a critical factor since the existing process was criticised by interviewees for the amount of detailed analysis required for populating risk assessments. Nevertheless, it provides some distinct advantages compared to the current risk assessment process in that it reduces the heuristic ambiguity of 'risk' into tangible resemblance of true incidents that are considered with a probability of occurrence.

6.4 The price of risk and incidents

In Chapter 5, the objective was to investigate the prevalence of incidents from a financial and customer perspective on the 'price' of risk and the benefit arising for customers to reduce the frequency or probability of incidents.

It was previously discussed that the water sector is increasingly embarking on the explicit trade-off between cost and risk. In cost benefit analyses, the relationship between units of risk and assets needs to consider the price or cost for risk and assets. Assuming the need to maximise benefit (or profit) the optimal equilibrium between risk and assets is governed by their respective 'market' prices or costs. The determination of the risk price may consider the direct cost of incidents to the utility but also the 'social' cost (Hughes and Ferrett, 2003) for the affected population. Alternatively, the incremental unit of risk and their 'market price' can also take the form of opportunity cost that a water utility customer is willing to pay in order for a risk event not to occur

(UK Water Industry Research Limited, 2002). The 'Common Maintenance Framework' (UK Water Industry Research Limited, 2002) proposes an assessment of the risk price to be a reflection of customer benefit. It was found that the Regional Water Utility conducted customer service studies to inquire their perceived benefit of risk reduction. These evaluations are used for asset investment and maintenance planning. Based on the latter principle, it was demonstrated how the Regional Water Utility define the rate of technical substitution between risk and assets that is governed by the negative ratio of their production input factor prices (Bonart and Peters, 1997).

A substantial amount of risk assessments are used in the Regional Water Utility that assess the probability of an impact from incidents, yet, little funding is available to reduce those risks. In a number of case studies (Chapter 5), it was found that the benefit of reducing the probability of incidents had been assessed previous to the occurrence of an incident. Due to the low cost benefit ratio, these investments were not carried out. As a consequence, these incidents were accepted by the Regional Water Utility as the best possible customer interest since reducing the risks *i.e.* the probability of incidents was not deemed to be in the interest of customers.

Once the incident occurred the water utility mobilises its resources to reduce the impact of incidents and to re-instate normal operations. For this purpose, the Regional Water Utility maintains an incident control centre to manage incidents reactively.

From a regulatory viewpoint, only a limited number of incidents led to prosecution and fines for water utilities (Table 65). From a theoretical perspective, it was argued that low fines discourage water utilities to reduce the frequency and impact of incidents on customers, since these fines are a factor to consider in the price of risk. If the price of risk would be higher by increasing the fines imposed on water utilities, the cost benefit equilibrium would shift towards more investment and maintenance spending. This, in turn, would require an increase in the water price to finance asset investment and maintenance, unless other sources of finance are obtained.

In the current regulatory regime, it was found that shareholders in stock-market listed water companies enjoy near risk free returns on their investment (Figure 54) while their customers are exposed to frequent incidents from their water supply system.

6.5 Are water utilities high reliability organisations?

This thesis set out to investigate High Reliability Theory in the context of water utilities. Technical and organisational reliability define the overall reliability of the organisation in pursuit of its organisational and societal objectives. It was found that the Regional Water Utility pursues two main objectives: Firstly, the provision of a safe and reliable drinking water supplies for customers in line with 'level of service' objectives set by the regulator and, secondly, shareholder value in investment, operations and maintenance decisions. It was found that this conflict of interest between financial returns on investment and public health concern is most evident in the asset management function. Here, the decision making processes consider the public health objective, public wealth objective ('willingness to pay') and the shareholder perspective. These conflicting objectives can be reduced to an asset risk trade-off model for investment and maintenance decision making. In this model, risks and risk reductions are assessed as monetary evaluation, *i.e.* risk units, the price of risk and the cost of asset investment and maintenance.

With respect to HRO, the following model in Figure 56 was conceptualised. It represents a matrix to classify organisations according to their technical and organisational reliability.

Traditional HRT consider a HRO to be technically and organisationally highly reliable. The evidence found in this research project does not consider water utilities to be technically highly reliable. It was found, however, that the reactive incident management organisation can be considered to be a high reliability function within the organisation. In this thesis, it was argued that many HRO principles were readily observable during incident management in the Regional Water Utility and the organisation excels in reactively responding to incidents. However, this was not observable consistently for all incidents investigated. In a number of case studies and incidents, the lack of one or more HRO principles during the management of incidents contributed to a prolonged incident duration or hazard exposure. A high reliability function – such as incident management – requires consistency in high reliability performance. On the other hand, the organisation has processes in place to review and learn from failure and deficiencies in the incident management response are sought out in incident review meetings. In considering the model below, the Regional Water Utility is a medium reliability organisation based on medium to low technical reliability and medium to high organisational reliability in reactive incident management.

Figure 56 also provides an economic perspective: In the Regional Water Utility, reactive asset maintenance and incident management are often considered to have a higher benefit cost ratio than pro-actively preventing incidents to occur. Again, technical and organisational reliability are, to some degree, substitutional. The reduction of incidents based on investments in technical reliability requires substantial investment and maintenance spending, whereas the comparative overheads for maintaining an incident management infrastructure are marginal in comparison.

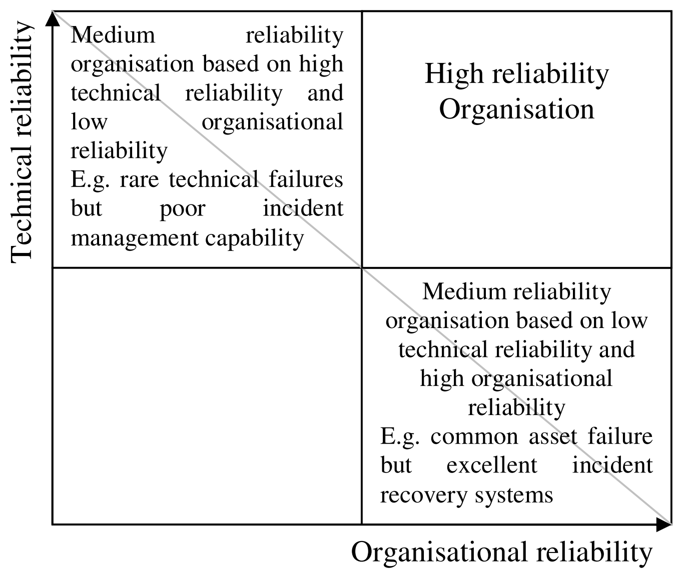

Figure 56 The trade-off between technical and organisational reliability

In the outset of this thesis it is hypothesised that the "*principles of HRO facilitate a) organisational resilience under trying conditions and b) learning from failure to enhance the safety and reliability of drinking water supply*".

In Figure 38 it was demonstrated that the principles of HRO facilitate organisational resilience under trying conditions. It was shown that a positive correlation between incident impact reduction and increased observation of HRO principles exist. Therefore, the hypothesis is accepted. Considering type II error, the result is not significant.

In Chapter 5, it was demonstrated that the principles of HRO facilitate learning from failure to enhance the safety and reliability of drinking water supply. It was found that incident documentation and analysis can be effectively used to enhance risk assessments. These enhanced risk assessments could be subsequently used in asset investment and maintenance decision making. The hypothesis is accepted. Considering the type II error, the result is not significant.

7 Conclusions

In conclusion, the observations and the studies conducted in the Regional Water Utility and other organisations suggest that many of the explored HRO characteristics contribute to reduce the public health impact of incidents and can also help a water utility to anticipate future risks and enhance their assessment.

From a methodological perspective, HRO theory was specifically investigated under "*trying conditions*" (Weick, 1987) and the effects of HRO principles as a means of generating organisational resilience during incident situations were carefully studied. For this purpose, "*the short periods of stress*" (World Health Organisation, 2004) that define incidents were characterised in an assessment of incident frequencies, cause and effect relationships and impact on customers.

- From the study of incidents, it is concluded that incidents frequently occur in the Regional Water Utility and water utilities in England and Wales.
- The investigated incidents commonly unfolded under diverse cause and effect relationships.
- The investigated incidents could be attributed to asset, process and human factor related causes.
- In a number of incidents more than one cause was identified that contributed to the unfolding of incidents.

The study of incidents was followed by an investigation of the benefit of HRO principles in incident management. Here, the incident impacts on customers and impact reductions were correlated with observation of high reliability principles under trying conditions.

- It is concluded that many HRO principles were readily observable in the incident management capability of the Regional Water Utility.
- A significant proportion of HRO principles are deemed cost beneficial in contributing to the safety and reliability of drinking water supply.
- HRO principles contribute to a reduction of the incident impact on customers.

A specific HRO principle is the ability to learn from failure and, in this thesis, opportunities were sought and identified to learn from incident analyses to enhance risk assessments that are subsequently used for asset investment and maintenance decision making in asset management.

- From the investigation into incident analysis and reviews it is concluded that the emphasis on technical failure and human error emphasises the need for operators to comply with standard operating procedures. These constitute normative and coercive pressures on staff to act in the interest of the organisation.
- It is concluded that incident documentation and analysis provides a mechanism to learn from failures and incidents.
- From the comparison of risk data with incident data it is concluded that discrepancies arise that may be explained with the psychological and sociological perception of risk rather than rational explanations.
- Statistical analysis of incidents provides an opportunity to enhance and further structure risk assessments and can help organisations to prioritise risk assessment programmes.

This thesis investigated the prevalence of incidents from a financial and customer perspective on the ‘price’ of risk and the benefit arising for customers to reduce the frequency or probability of incidents.

- It is concluded that the price of risk can explain why incidents occur since a low price of risk in cost benefit analyses leads to lower investment and maintenance in water supply assets.

A limited number of recommendations are formulated for how water utilities should make use of the research results obtained in this research project.

Firstly, the comparative analysis of incidents may provide a tool for water industry regulators to monitor the frequency and impact of incidents on customers beyond the current level of service indicators used in England and Wales.

From a regulatory perspective, the monitoring of frequency, exposure to hazard types and failure modes, the size of populations exposed to hazards or failures and the duration of exposure may provide effective performance monitoring criteria for

benchmarking effective risk management. Beyond the monitoring of operational performance of water utility, this methodology may also be used to strengthen their assessment of capital investment and maintenance by considering the costs of incidents and future risks. This cost evaluation should consider the direct consequential cost of incidents to water utilities, customer expectations and public interests whilst identifying the opportunity cost of enhanced investments and maintenance that reduce the cost of reactive incident management.
The analyses of incidents in Chapter 2 may provide the basis for further strengthening failure reporting and analysis with a view to enhance the analysis of future risk as described in Chapter 4. In particular, the clear definition of failure modes, causes, effects and impact of incidents may enhance the practicality of failure analysis as a feasible methodology to anticipate future risks.

Secondly, the HRO principles investigated in Chapter 3 may provide useful benchmarking criteria to evaluate the effectiveness of incident management interventions. Following an incident, these criteria may be used to evaluate the organisational effeciveness in managing the incident and may help water utilities to strengthen the organisational design for effective incident management capabilities. Water utilities may also want to consider these HRO principles for the management of interagency - and stakeholder relationships. To this end, it is recommended that water utilities evaluate these principles for interagency relationships concerning coordinated incident management but also for wider water utility relationships with agencies e.g. for capital investment and maintenance decision making.

8 Suggestions for further work

This study has predominantly concentrated on one water utility and as such is not representative for the entire water sector. It was reasoned that "*unlike pure sciences, in which theories are assessed by how much empirical activity they provoke, the insights of safety scientists and safety practitioners are ultimately judged by the extend to which their practical application leads to safer systems*" (Reason, 2000b). In reflecting on Reason's (2000b) quote, not the average water utility was of interest in this study but the ones who were thought to exceed their peer group in the provision of safe and reliable drinking water. In that sense, the selection of participants and the Regional Water Utility represent a non-random selection of "*extreme samples*" *i.e.* experts in their field and organisations with advanced risk management capabilities (Schnell *et al.*, 1995). In this project, it was sought to enhance risk assessment capabilities in one organisation that is already considered to be advanced in its approach to risk assessment and management. Hence, the study of excellence justified the use of limited contributors and the study of one Regional Water Utility, if that study reflects 'best practice' insights and learning opportunities for other water utilities.

The ideas, concepts, models and methodologies in this thesis were previously publicly communicated and this thesis provides a channel for other water utilities to compare their systems, processes and operational philosophy to this case study. From an academic perspective, it is suggested to further investigate HRO principles and risk management practice in other water utilities. These studies should focus on the role of the incident review meeting and the psychological and sociological pressures that may bias the quality of incident review data. A further research need also arises for investigating the transition of organisations that aim to implement HRO principles and enhanced risk management capabilities in their organisations.

A further research idea arose from the review of financial risk: In chapter 5, the financial evaluation of risk was introduced. It was found that financial risk in the Capital Asset Pricing Model (CAPM) is evaluated as the retrospective measure of cash flow volatility in the past 60 months. An equity beta factor is calculated that is used to derive an interest rate for the valuation of assets or businesses. In capital valuation, the net present value of future cash flows is calculated to derive its current value with an interest rate reflecting retrospective risk. Two methodological problems arise: firstly, it is assumed that the retrospective risk factor beta is representative for future risk. In reality, a high beta asset will be evaluated at a high interest rate even if future risks, *i.e.* volatility in future cash flows, are perceived to be lower. This could arise through enhanced risk management. Secondly, as a consequence, rapidly diminishing discount factors are used to evaluate future profits. This emphasises cash flows in the near future to be more relevant for the overall value of the business than cash flows further in the future. On the other hand, a low beta asset is evaluates future profit expectations at a low interest rate even if that asset faces high future risks. The discount factor used to evaluate future profits diminishes at a lower rate than a high interest discount rate. As a consequence, a low risk asset has a longer investment horizon than a high risk asset and, therefore, a high beta asset requires shorter term risk management capability than a low beta asset. In this proposed project, a different methodology to asset evaluation is to be investigated: Rather than using a retrospective asset beta derived interest rate, future cash flows are evaluated at a risk-free interest rate and risks that are perceived to affect an asset in the future are discounted as a future cash flow. This methodology would fully integrate risk assessment and management into the valuation of asset and places a greater emphasis on consistency and accuracy of risk assessments and risk evaluation.

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APPENDICES

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Equations

1 Appendix - Asset risk trade-off model

The following model, adapted from Bonart and Peters (1997), is a general mathematical model to facilitate the internalisation of risk in asset investment decision making.

A water utility uses technologies to transform input factors into outputs. The three main input factors are commonly known as capital, labour and natural resources. The management process considers which production factors to use, how to combine these production factors and the prices for production factors as well as the market prices for the output.

Similar to capital, labour and natural resources, it is assumed that risk can be allocated an incremental unit and a market price. Increasingly, risk assessments are used in the water sector to assess the inherent risk units of water supply systems (Deere *et al.*, 2001) and commercial or monetary evaluation methods are used to derive the cost of risk (Lifton and Smeaton, 2003; Lifton, 2005; Abell, 2005). Based on this development, 'risk', i.e. the probability of adverse effects, is assumed the fourth production input factor i_1 besides labour, capital and natural resources.

In this paper formalises the relationship between units of risk, their market value and the substitution of risk with risk reduction measures.

A production function describes the quantitative correlation between production input factors and outputs (Bonart and Peters, 1997). Production functions can be distinguished in two different groups. Firstly, substitutional production functions and secondly, linear – limitational production functions (Bonart and Peters, 1997). In substitutional production functions the input factors can be substituted within a reasonable area of the function, whereas in limitational production functions the input factors are set at a particular ratio (Bonart and Peters, 1997). Substitutional production functions allow the substitution of production input factors without an effect on the overall output (Bonart and Peters, 1997). In analogy, risk can be substituted by investing in assets that are designed to reduce the exposure to health hazard. The Cobb-Douglas function is such a production function (Bonart and Peters, 1997). In Equation 1, it takes the form:

$$o(i_1, i_2) = a * i_1^{\alpha} * i_2^{(1-\alpha)}$$

with

o = output

i = production input factor

$0 \leq \alpha \leq 1$

Equation 1 Cobb-Douglas-production function

Figure 1 shows a projection of iso-quantitative outputs, for Equation 1. For the purpose of this figure, the input factors capital, labour and natural resources were aggregated in i_2.

The axes of this figure represent unit values for risk and combined unit values for capital, labour and natural resource that produce a quantity of equal output. Each point on a graph represents equal output in units drinking water and theoretically demonstrates the substitutional character of the two production input factors to achieve constant unit output.

It is important to note that only the combination of input factors provides an output, hence a full substitution of one input factor is not defined in this function. This is, e.g., reflected in the idea that a residual risk in a water supply system cannot be reduced to zero.

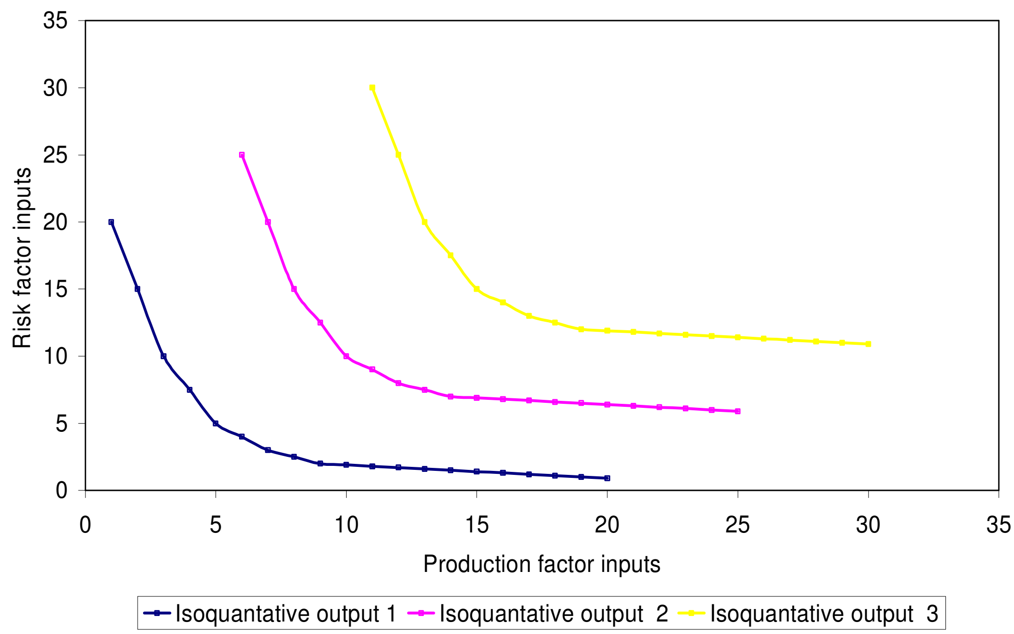

Figure 1 Horizontal projection of equal output in production based on substitution of production input factors

Figure 2 is a vertical projection of a substitutional production function describing the correlation of a constant production input factor i_1 (risk units) and a variable production input factor i_2 (labour, capital and natural resources units) in relation to the output (Bonart and Peters, 1997).

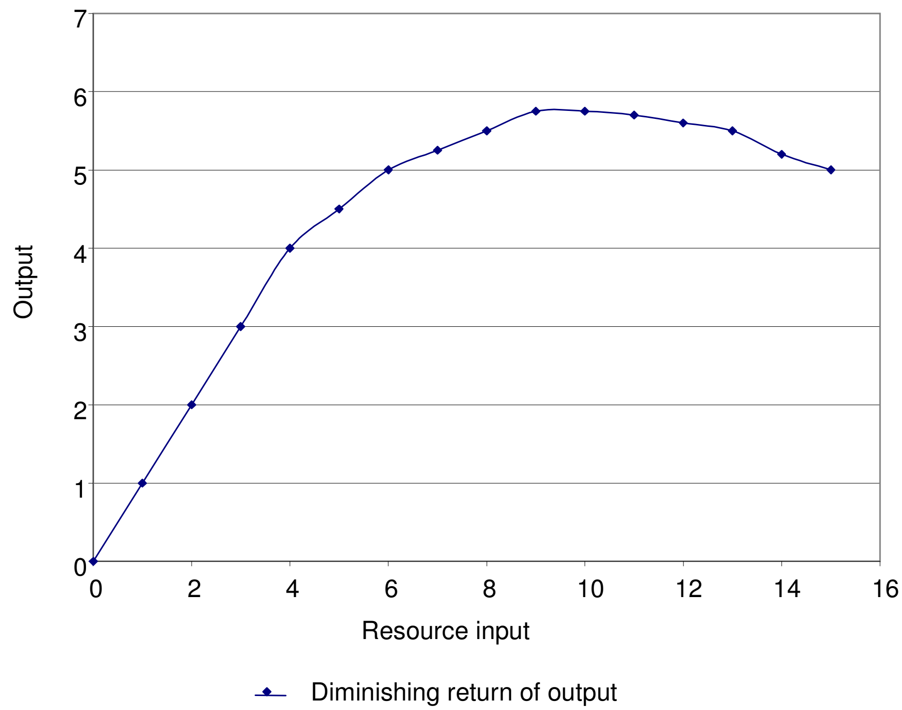

Figure 2 Vertical projection of substitutional production function, adapted from (Bonart and Peters, 1997)

Figure 2 demonstrates the productivity of one input factor in relation to outputs and measures the change in output for an infinitesimal change of one variable production input factor i_2 at a constant production input factor i_1. Figure 2 illustrates the principle of diminishing marginal returns and increasing the variable input will eventually result in diminishing outputs. The productivity ratio is a differential equation for a variable production input factor i_2, a constant i_1 and output. This is shown in Equation 2

$$o'_{i_2} = \frac{\delta o}{\delta i_2}$$

Equation 2 Differential equation for productivity with one variable production input factor

The optimal combination of input factors depends on both factor productivities. Therefore, Equation 3 takes the form

$$do(i_1, i_2) = o'_{r_1}(i_{1,} i_2) * di_1 + o'_{i_2}(i_2; i_1) * di_2$$

Equation 3 Total differential equation for productivity with two variables production input factors

For the optimal equilibrium, Equation 3 equals zero and the iso-quants shown in Figure 1 can be derived that demonstrate the substitutional character of Equation 1 for a constant output. The rate of substitution is defined in Equation 4

$$\frac{di_2}{di_1} \text{ at } o = const$$

Equation 4 Rate of technical substitution

From re-arranging Equation 3 it can be demonstrated that the rate of substitution is the negative, reciprocal ratio of productivities for the variable production input factors. This is shown in Equation 5

$$\frac{di_2}{di_1} = -\frac{o'_{i_1}(i_{1,}i_2)}{o'_{i_2}(i_2, i_1)} \text{ at } o = const$$

Equation 5 Rates of substitution in relation to production input factor productivities

Economic decisions in a firm are based on the overriding aim to maximise wealth for shareholders and owners. (In a water utility, the owner can be a public authority representing public interest.) In a free market, this is a function of turnover, i.e. market price times the production output minus costs. Equation 6 is the basis for decision making and determines the magnitude of production output in relation to the unit price for production input factors

$$P(i_1, i_2) = p_o * o(i_{1,}i_2) - (p_{i_1} * i_1 + p_{i_2} * i_2)$$

with

P = profit

p = market price

Equation 6 Primary economic function for decision making in production

To maximize wealth, the differential equation for i_1 and i_2 in Equation 6 equal zero and take the form of Equation 7

$$P_{i_1}^{'} = p_o * o_{i_1}^{'}(i_1, i_2) - (p_{i_1})$$

$$P_{i_2}^{'} = p_o * o_{i_2}^{'}(i_2, i_1) - (p_{i_2})$$

Equation 7 Differential equations to maximise wealth

Equation 7 is the productivity of production input factor i_1 and i_2 taking into account the market price for services provided and the cost for unit input factors, i.e. price for unit risk and capital, labour and natural resource unit prices, respectively. Therefore, Equation 7 can be rewritten to Equation 8:

$$o_{i_1}^{'} = \frac{p_{i_1}}{p_o} \text{ and } o_{i_2}^{'} = \frac{p_{i_2}}{p_o}$$

Equation 8 Productivity relation to output price and production input factor prices

With Equation 5 describing the rate of technical substitution to be the negative, reciprocal ratio of productivities for the variable production input factors, we can re-write Equation 8 to

$$\frac{o_{i_1}^{'}}{o_{i_2}^{'}} = \frac{p_{i_1}}{p_{i_2}}$$

Equation 9 Ratio of production input factor productivities in relation to ratio of production input factor prices

Equation 9 and Equation 5 are based on the ratio of productivities of production input factors and aggregate to

$$\frac{di_2}{di_1} = -\frac{p_{i_1}}{p_{i_2}}$$

Equation 10 Relation between the rate of technical substitution and ratio of production input factor prices

Equation 10 describes the rate of technical substitution to be the negative ratio of the production input factor prices (Bonart and Peters, 1997). It demonstrates that the optimal rate of substitution for production input factors is directly dependant on their factor prices (Bonart and Peters, 1997). This equation explains the need to optimize the production process whenever factor prices change so that a maximum level of wealth or benefit is being created (Bonart and Peters, 1997).

Figure 3 is an example for the technical substitution of risk with assets that are designed to reduce the health effects from hazards in drinking water supply. In this model, the increasing provision of water treatment capability reduces public health risks or the exposure to water-related hazards.

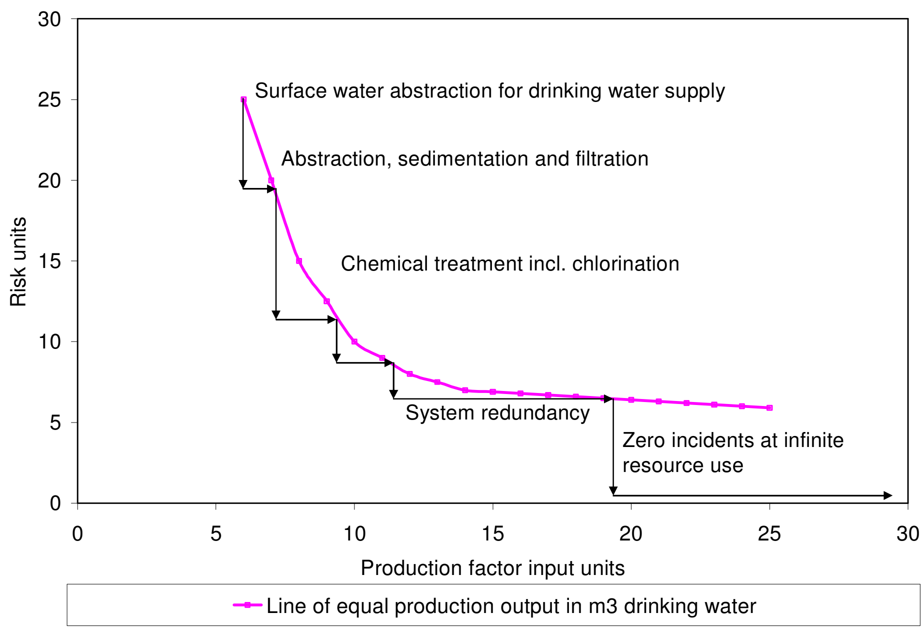

Figure 3 Example for technical substitution of risks with assets aimed at reducing the health exposure to hazards in a drinking water supply

However, Figure 3 does not consider the cost of assets or the cost of risk to derive the optimal, technical rate of substitution between assets and risk. Whereas the cost of physical assets, labour and natural resources are commonly obtainable on markets, the derivation of the cost of risk is more complex. It depends on multiple factors such as the risk model used to derive the units of risk. In Deere *et al.* (2001) this is function of the dose response to hazards, the size of the population affected by hazards and the duration of hazard exposure. Evaluating the 'price' of risk can use several approaches that often depend on the type of organisation. An unregulated, private company that pursues the objective to maximise shareholder value would only consider its direct, consequential cost. These include all legal, economic and financial costs arising from adversities. From a public perspective, further costs can arise that are known as externalities (Endres, 1994), i.e. moral or social 'costs' that are not accounted for in the production function of a private company. These costs often represent non-monetary costs or costs that are less tangible, e.g. loss of life, reduced life expectancy, loss of earnings due to illness, reduced economic growth, costs for the National Health Service etc.. In other words, internalising these externalities in the production function may have additional benefits for society as a whole or individual groups. One of the reasons why the public sector is often seen to operate inefficiently is because they often have a wider understanding of benefits arising from their decision-making that considers social costs. An investment schemes that is financially not viable may have the additional advantage of reducing unemployment or stimulating economic growth.

Another model to evaluate the 'price' of risk evaluates '*willingness of customers to pay'* for benefits arising from measures to reduce risks or the likelihood of an incident to occur (UK Water Industry Research Limited, 2002). It is based on economic valuations with stated preference techniques (Bateman *et al.*, 2002). Here, the 'price' of risk takes the form of opportunity cost that a water utility customer is willing to pay to reduce risk or the likelihood of an incident to occur (UK Water Industry Research Limited, 2002; Bateman *et al.*, 2002).

Using risk units and the 'price' of risk in investment decision-making is a form of cost benefit analysis. Here, the benefit arises through risk reduction that is balanced with the cost of investment and maintenance in assets.

2 Appendix - The asset management process

The asset management process

The asset management process is a multiple step process.

The key steps of the asset management process are:

- Setting operational objectives for assets
- Definition of risk & risk identification
- Data from asset performance, statistical data, reliability data
- Acceptability criteria for public health risks, Health, Safety & Welfare, access, lifting & maintenance
- Risk assessment & prioritisation
- Specification of water safety criteria based on public health risk assessment
- Engineering specification, e.g. technical reliability
- Design specification for data flow, monitoring & control
- Design of incident detection and response procedure
- Normal & abnormal operating procedures

A conceptual process flow model is shown below.

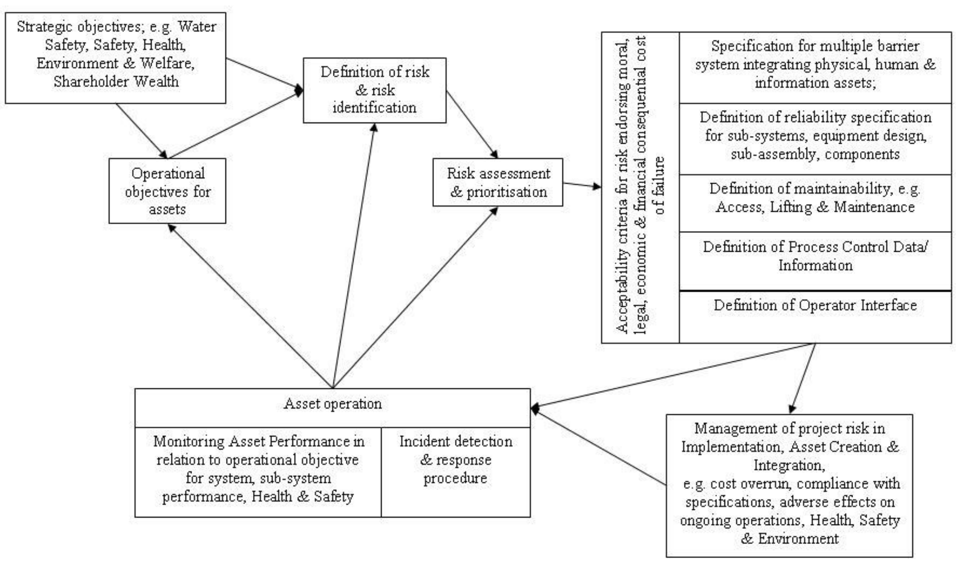

Figure 4 The asset management process

The Context of an effective water safety strategy has been identified and summarised from the water safety literature, engineering standards, regulatory expectations and industry practice (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003) (DVGW). The DVGW, in particular, has designed an audit-based water safety management system (TSM) (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003) reflecting international understanding of best practice in utility management to achieve water safety. TSM does not fully match the requirements of a Water Safety Plan with respect to risk assessments. Therefore, additional criteria from the New Zealand framework for risk management plans (Ministry of Health, 2005a) with specific respect to risk assessments were introduced.

Setting operational objectives for physical assets (British Standard Institution, 2003)

GOAL

The organisation identifies the required performance and reliability of assets and evaluates their failure in terms of impact on public health, Safety, Health, Environment, Welfare of employees.

INPUT

Strategic objectives for the organisation

Data from asset performance monitoring

OUTPUT

Assessment criteria to identify risks in relation to strategic and operational objectives

Clear vision and mission statements communicated to utility operations and functions in water utility

DESCRIPTION

The operational objectives identify the scope for asset management. From the organisational objectives, risks can be defined, identified and assessed.

General aspects of utility management and decision-making

Organisational structure (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The organisation receives regular and up-to-date information relevant to the water sector.
- The organisation maintains an organisational plan (organogram) mentioning functional units and the names of their directing managers.
- The competencies, duties and responsibilities of functional units and their directing managers are defined and documented.
- The allocation of staff and responsibilities to functional units is unambiguous with a clear reporting structure.
- The organisational plan includes all employees.
- The organisation plan highlights authorised personnel to obtain legal and regulatory permissions.
- One functional unit is responsible for customer care and public communication.

Functional descriptions and definition of duties and responsibilities (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The functions of organisational units are described and highlight the main areas of duty and responsibility.
- The interfaces between functional units are defined and described?
- The functional description for management staff provides details on duties, authorisations and area of responsibility. They are provided to management staff.

- Functional managers are provided with a description of competencies, responsibility, reporting structure to superiors and subordinates.

Rules of delegation (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- Delegated powers and acting responsibilities for functional managers and directors are defined and made available to staff.
- Delegated powers and acting responsibilities are documented in the organisational plan.

Economic control (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- A long-term strategy to ensure the safety of drinking water resources, abstraction, treatment and distribution is defined.
- Criteria for economic viability for individual capital investments are defined.
- Criteria are defined to determine capital investment needs and their financing.
- The organisation defines processes and responsibilities for billing, accounting and financial controlling.
- The organisation has a defined system to maintain and administrate insurance cover.

Qualifications of personnel/ CPD (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The responsible managers in functional units are sufficiently qualified. Their qualification is stated in the organisational plan and known across the organisation.
- The organisation maintains documented requirements on qualifications and relevant experience for functional and task orientated employment positions.
- The documented requirements on qualifications and relevant experience are defined and adhered to in the recruitment process or the process of promoting staff.
- Qualifications of staff are kept on record and updated.
- Functional and task orientated CPD and training are systematically derived according to the needs of the functional unit.
- Regulatory requirements for training are planned, executed on the planned date and documented. The documentation includes the content of the training course and attending employees.
- Employees are given the opportunity to contribute to the planning of CDP and staff training.

<u>Definition of risk & risk identification (hazard assessment and risk characterisation) (World Health Organisation, 2004)</u>

<u>GOAL</u>

The organisation gains clarity of scope to manage risks. The definition and identification of risk focuses the attention of management towards assessment and control of risks.

<u>INPUT</u>

Definition of operational objectives from which the definition of risk is derived.

Asset performance data

Monitoring in normal operation

Incident detection and response procedure

OUTPUT

The output of this process is a risk register in relation to the organisational objective. The subsequent assessment benches the risk against acceptability criteria and prioritises all risks.

DESCRIPTION

The definition of risk comprises of adverse events or significant deviations from normal operations (failure event) and likelihood. The risk definition names and describes the relationship of “failures” from event as a top down approach from strategic level to operations level. The identification of susceptibility to failure events is a process that is informed by the definition of risk, asset performance data and operational objectives for assets in a bottom up approach from operations level to strategic level.

Risk assessment (hazard assessment and risk characterisation (World Health Organisation, 2004))

GOAL

The organisation identifies the level of system reliability in a water supply system via the assessment of risks using the previous definition and identification of risks.

The process of risk assessment considers probabilities, return periods or frequencies and the consequences of risk. Ideally, the consequences of risk are measures with a common denominator as unit risk (Deere *et al.*, 2001).

INPUT

Definition and identified risk

Acceptability criteria for risk

OUTPUT

Assessment of risks in comparison to overall risks in the organisation

Prioritisation of risks

Information to focus management activity, risk control and investment strategy

DESCRIPTION

The assessment process determines the level of safety built into a water supply system

General

- The assessment considers causes for public health risks, preventative measures, checking the preventative measures and corrective actions. Probability and consequence are assessed as rare, unlikely, possible, likely, almost certain and insignificant, minor, moderate, major and catastrophic, respectively (Ministry of Health, 2005a).
- The assessment considers demographic change and age of population with respect to demand for water when assessing supply systems (Winkler, 2006).

Hazard analysis/ risk assessment Catchment

Surface and groundwater

- The organisation carries out a public health hazard analysis and risk assessment for source water (surface and groundwater) to assess receiving discharges or leachate from a contaminated site, discharges from domestic or industrial processes (direct or indirect), discharges from mining operations, leachate from landfill sites, waste originally discharged to land, spillages or leakage from storage or use of hazardous substances, septic tank discharges, run-off from urban or sealed surfaces, material from surface impoundments, treated effluent or untreated effluent from ponds, waste disposal in wells and bores, leakage of contaminants from abandoned or decommissioned wells, faecal matter from livestock or feral animals, agrichemicals, contaminants washed into source water during irrigation, sediments and agrichemical from forestry activity, fertilisers during application, geothermal contaminants, mineral deposits, intruding saline water and potential of experiencing algae bloom. (Ministry of Health, 2002b)

Hazard analysis/ risk assessment Abstraction

Boreholes and Wells

- The organisation carries out a public health hazard analysis and risk assessment for boreholes and wells to assess potential for not enough source water available for abstraction, contamination of bore/well during construction, ingress of contaminated water into the bore/well from shallower depths, ingress of contaminated water getting into the bore/well from the surface, contamination of the aquifer and too little water can be drawn from the bore/well to meet demand. (Ministry of Health, 2001f)

Groundwater abstraction – Springs

- The organisation carries out a public health hazard analysis and risk assessment for spring source water, in particular assessing availability of source water for abstraction, contamination of the spring box, contamination of the aquifer, too little source water to be drawn from the spring resulting in low pressures and potential sucking in contaminants (Ministry of Health, 2001g).

Surface water abstraction

- The organisation carries out a public health hazard analysis and risk assessment for the surface water abstraction from lakes and reservoirs, in particular assessing availability of source water for abstraction, raw water quality too poor for treatment, contamination of the lake or reservoir and factors contributing to flows too little water to be drawn from intake to meet demand resulting in low pressures and potential for suction of contaminant into the source(Ministry of Health, 2001j).

River, Streams and Infiltration Galleries

- The organisation carries out a public health hazard analysis and risk assessment for the application of source abstraction from rivers streams and infiltration galleries, in particular assessing availability of source water for abstraction, raw water quality too poor for treatment, contamination of the river or stream, water quality not improved by infiltration gallery, infiltration gallery producing insufficient flows, abstraction flows from the intake do not meet demand. (Ministry of Health, 2001k)

Hazard analysis/ risk assessment Water Treatment processes

Design of treatment plant

- The organisation carries out a public health hazard analysis and risk assessment for the design of water treatment plants, in particular assessing the potential of a treatment plant unable to produce water of satisfactory quality or sufficient flows. (Ministry of Health, 2001u)

Operation of transmission, bore and process pumps

- The organisation carries out a public health hazard analysis and risk assessment for the operation of transmission, bore and process pumps, in particular assessing changes in pressures from the bore and the potential to suck contaminants into the water, changes in pressure (Transient pressures) from transmission pumps and the potential to suck contaminants into the water and incorrect chemical dosing leading to poor treatment performance. (Ministry of Health, 2002d)

Water Transmission

- The organisation carries out a public health hazard analysis and risk assessment for water transmission, in particular assessing contamination entering into trunk mains, sediment containing contaminants being stirred up, contamination gets into open channel conduits and break pressure tanks.(Ministry of Health, 2001x)

Destratification

- The organisation carries out a public health hazard analysis and risk assessment for the application of destratification techniques in lakes and reservoirs, in particular assessing poor mixing of the water body leading to algae blooms, raw water unsuitable for treatment and difficult treatment control because of variability in raw water quality. (Ministry of Health, 2001h)

Application of algaecides

- The organisation carries out a public health hazard analysis and risk assessment for the application of algaecides, in particular assessing events where too much algaecides are added to the water, algaecides dosing cannot reduce very high algae population and the formation of disinfection by-products when barley straw is used as an algaecide. (Ministry of Health, 2002a)

Pre-oxidation

- The organisation carries out a public health hazard analysis and risk assessment for the application of pre-oxidation, in particular assessing oxidant doses too low or too high and the excessive formation of oxidant by-products (Ministry of Health, 2005b)

Waste-Liquor Reintroduction

- The organisation carries out a public health hazard analysis and risk assessment for the re-introduction of waste-liquor re-introduction, in particular assessing re-introduction of previously removed contaminants and loss of process control. (Ministry of Health, 2001i)

pH adjustment

- The organisation carries out a public health hazard analysis and risk assessment of pH adjustment, in particular too high pH resulting in poor disinfection with chlorine, pH levels to low dissolving heavy metals and germs introduced during aeration. (Ministry of Health, 2001t)

Coagulation, Flocculation and Sedimentation

- The organisation carries out a public health hazard analysis and risk assessment for the application of coagulation, flocculation and sedimentation processes, in particular assessing particles not being removed, natural organic matter not being removed and treatment chemicals carried into distribution system. (Ministry of Health, 2001o)

Direct Filtration

- The organisation carries out a public health hazard analysis and risk assessment for the application of direct filtration processes, in particular assessing particles not being removed, natural organic matter not being removed and treatment chemical carried into the distribution system. (Ministry of Health, 2001p)

Slow sand filtration

- The organisation carries out a public health hazard analysis and risk assessment for the application of rapid sand filtration, in particular assessing particles not being removed and natural organic matter not being removed. (Ministry of Health, 2001z)

Rapid Sand filtration

- The organisation carries out a public health hazard analysis and risk assessment for the application of rapid sand filtration, in particular assessing particles not being removed, natural organic matter not being removed and treatment chemicals carried into the distribution system. (Ministry of Health, 2001y)

Application of cartridge filtration

- The organisation carries out a public health hazard analysis and risk assessment for the application of cartridge filtration units, in particular assessing particle removal below 2-3 µm in size (Cryptosporidium ocysts), removal of target chemical contaminants and growth of germs in the filter. (Ministry of Health, 2001l)

Membrane filtration

- The organisation carries out a public health hazard analysis and risk assessment for the application of membrane filtration units, in particular assessing membranes not performing to specifications e.g. relating to Cryptosporidium ocyst removal, membrane failure and membrane cleaning chemicals present in water. (Ministry of Health, 2001r)

Removal of iron and manganese

- The organisation carries out a public health hazard analysis and risk assessment for the application of iron and manganese removal processes, in particular assessing not all manganese removed in oxidation or ion exchange, oxidant doses too high, germs introduced during aeration and build-up of germs in the resin bed. (Ministry of Health, 2002c)

Softening

- The organisation carries out a public health hazard analysis and risk assessment for the application of softening processes in ion exchange units, in particular assessing build-up of germs in the resin bed (Ministry of Health, 2002e).

Trace organics removal (Granulated Activated Carbon (GAC))

- The organisation carries out a public health hazard analysis and risk assessment for the application of trace organics removal, in particular assessing effects of too little or no powdered activated carbon dosed, inability of GAC to remove all trace organic compounds and growth of germs in the GAC bed (Ministry of Health, 2001v).

Chlorination

- The organisation carries out a public health hazard analysis and risk assessment for the application of chlorination, in particular assessing not enough free available chlorine, too much free available chlorine and excessive formation of chlorination by-products (Ministry of Health, 2001m).

Chlorine Dioxide

- The organisation carries out a public health hazard analysis and risk assessment for the application of chlorine dioxide, in particular assessing the chlorine dioxide concentration too low or too high and excessive formation of by-products from chlorine dioxide application. (Ministry of Health, 2001n)

Ozone disinfection

- The organisation carries out a public health hazard analysis and risk assessment for the application of ozone disinfection, in particular assessing ozone concentrations too low and excessive formation of ozonation by-products (Ministry of Health, 2001s).

UV irradiation

- The organisation carries out a public health hazard analysis and risk assessment for the application of UV irradiation, in particular assessing too low UV doses and re-infection and germ revival (Ministry of Health, 2001w).

Fluoridation

- The organisation carries out a public health hazard analysis and risk assessment for the application of fluoridation, in particular assessing fluoride concentrations greater than required for dental protection. (Ministry of Health , 2001q)

Hazard analysis/ risk assessment Drinking water storage

Post treatment storage

- The organisation carries out a public health hazard analysis and risk assessment for post treatment storage, in particular assessing excessive demand over supply as this reduces the pressure and may allow re-contamination of drinking water, introduction of contamination material into service reservoir, development and re-suspension of sediment within reservoir and chlorine contact time. (Ministry of Health, 2001c)

Hazard analysis/ risk assessment Drinking water distribution

Distribution operation and maintenance

- The organisation carries out a public health hazard analysis and risk assessment for normal operation and maintenance of distribution networks, in particular assessing the introduction of contaminating materials, re-suspension of contaminants in sediments, development of sediment or biofilms and failure to maintain sufficient water pressures.(Ministry of Health, 2001b)

Backflow prevention

- The organisation carries out a public health hazard analysis and risk assessment for backflow prevention, in particular assessing water pressures in the distribution system in relation to supplied premises and requirements for backflow prevention devices (Ministry of Health, 2001a).

System pressure

- The organisation carries out a public health hazard analysis and risk assessment for maintaining adequate system pressures in the distribution network, in particular assessing the introduction of contamination from pressure fluctuation and re-suspension of sediments or biofilm within the mains by pressure fluctuations. (Ministry of Health, 2001d)

Hazard Analysis/Risk Assessment

Monitoring water quality from catchment to tap

- The organisation carries out a public health hazard analysis and risk assessment for monitoring water quality from catchment to tap, in particular assessing water quality data used for supply management. (Ministry of Health, 2001e)

Acceptability criteria and specification for public health risk control, physical asset reliability, access lifting and maintenance, Health & Safety, Welfare and Environment, in relation to physical assets operation (Define monitoring and control measures) (World Health Organisation, 2004)

GOAL

The organisation defines the acceptability of risks in order to assess the need to control risks and identify acceptable controls for risks. These are the benchmarks during risk assessment and reliability of systems design.

With risk acceptability criteria, the organisation has the ability to convert (public health) risk assessments into physical asset specifications. These asset specifications determine systems reliability for physical assets.

INPUT

Definition of risk

Risk assessment

OUTPUT

Acceptability criteria for risk

Specifications for acceptable levels of risk in physical assets

Ability to design solutions for multiple barriers to control risk to acceptable standard whilst optimising strategic business objectives

DESCRIPTION

The acceptability of a risk reflects societal values (moral, economic and financial cost). Acceptability criteria for risks are the benchmark in risk assessments but also establish a specification for the design of a multiple barrier system to control risks to acceptable standards. The reliability of a system is ultimately specified for the interaction between assets, equipment and component with performance criteria that are subject to a risk assessment.

Documentation of Specifications (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- Codes of practice, design standards and specifications are kept up to date and are readily available.
- Acts of parliament and specific regulations are kept up to date and are readily available.
- Changes to acts of parliament, regulations, codes of practices, design standards, specifications are assessed and disseminated to functional units within the organisation.
- Functional units have access to any information above customised to their needs and level of detail required.

Specification for watershed/aquifer protection

Surface and groundwater

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2002b).

Specification of water abstraction facilities (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The organisation has defined criteria for the exploration of water resources that consider the known, natural environment. The definition contains criteria for source protection, flow and quantitative criteria, riparian competition for water resources.
- The choice of service providers commissioned to explore water resources for the organisation considers their qualifications, expertise and compliance with technical specifications.

Boreholes and Wells

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2001f).

Groundwater abstraction – Springs

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2001g).

Surface water abstraction

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2001j).

River, Streams and Infiltration Galleries

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2001k)

Specification of water treatment facilities (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The organisation has defined criteria for the planning of water treatment facilities.
- The defined specifications aim to achieve legislative and regulatory requirements for safe drinking water.
- In addition to compliance with legislative and regulatory requirements for safe drinking water, specifications reflect best practice in the design of water treatment processes based on water sector experience (e.g. turbidity, iron, manganese).
- The organisation maintains an asset register of water treatment works which operate processes critical to public health, i.e. where process failure has an impact on public health.
- The organisation maintains an asset register of water treatment works where microbiologically contaminated raw water is processes and disinfected. The organisation ensures that no public health impact can arise from these plants.
- Wastes from treatment processes have specified routes of disposal (e.g. recycling, disposal, discharge) which reflects legislative and regulatory requirements.
- Disinfection products and processes are specified.

Design of treatment plant

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2001u)

Operation of transmission, bore and process pumps

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2002d)

Water Transmission

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures.(Ministry of Health, 2001x)

Destratification

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2001h)

Application of algaecides

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2002a)

Pre-oxidation

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2005b)

Waste-Liquor Reintroduction

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2001i)

pH adjustment

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2001t)

Coagulation, Flocculation and Sedimentation

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2001o)

Direct Filtration

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2001p)

Slow sand filtration

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2001z)

Rapid Sand filtration

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2001y)

Application of cartridge filtration

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2001l)

Membrane filtration

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2001r)

Removal of iron and manganese

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2002c)

Softening

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2002e).

Trace organics removal (Granulated Activated Carbon (GAC))

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2001v).

Chlorination

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2001m).

Chlorine Dioxide

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2001n)

Ozone disinfection

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2001s).

UV irradiation

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2001w).

Fluoridation

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health , 2001q)

Specification of water storage facilities (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The organisation has defined criteria for the planning of water storage facilities.
- The organisation has defined criteria for the usage of materials approved for water storage facilities.
- Cement-based plant components that are in direct contact with drinking water have specified material properties.
- Cleaning agents and process are specified.

Post treatment storage

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2001c)

Specification of water distribution facilities (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The organisation has defined criteria for the planning of water distribution mains and networks.
- The organisation has defined criteria to distinguish between pipe work repair and replacement. A process is in place to assess the results from pipe inspections that systematically considers criteria of increased leakage frequencies.
- The organisation has defined criteria for consultants and contractors to plan and design water distribution mains and networks (Contract specifications).
- Plant components which are in direct contact with drinking water have specified material properties (cement based, metals)
- The welding processes are defined and specify criteria for the qualification and experience of welders.
- The procedure of tying-in pipe work to existing mains & networks and disinfection is specified.
- Setting out procedures are defined and specified.
- A pressure test for new pipe work is specified.
- A commissioning procedure incl. water quality testing for new pipe work is specified.
- The organisation defines criteria for $CaCO_3$ solubility.

- The organisation defines specifications for pipe materials.

Distribution operation and maintenance

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures(Ministry of Health, 2001b)

Backflow prevention

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2001a).

System pressure

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures. (Ministry of Health, 2001d)

Quality monitoring and assurance (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The location, water quality parameters and intervals for water quality sampling is specified.
- Water quality sampling for distribution networks is specified for regular intervals but also during maintenance and cleaning procedures.
- The analysis of water quality samples is executed in accredited laboratories where personnel is trained, qualified and accredited. The accredited laboratory operates a quality assurance system.
- The laboratory is accredited under ISO 17025.
- The laboratory immediately reports exceeding water quality parameters. A robust system of communication is in place.

Monitoring water quality from catchment to tap

- Based on the risk assessment, the organisation has specifications and specified procedures for control (preventative) measures (Ministry of Health, 2001e)

Management of materials (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- A system is in place that defines responsibilities and interfaces for the technical specifications and the selection of materials and equipment that is used for plant design and work procedures.
- Minimal requirements for materials are specified, monitored and controlled.
- Minimal requirements for stocking of material are specified for incident and emergency responses.
- Minimal stocking levels for materials are controlled and monitored.
- The storage of materials complies with manufacturers' recommendations and specifications.

<u>Design definition of process control data, information (Define monitoring and control measures) and definition of operator interface (Standard Operating Procedure) (Supporting programmes) (World Health Organisation, 2004)</u>

<u>GOAL</u>

The organisation has the ability to monitor (operational) performance risks within a designed system architecture of operational data and clear operating definitions at operations level. The operator interface enables the ability of clear decision making during normal operations and highlights abnormal operating conditions.

The operational interface for operators is designed for optimal operability, access lifting and maintenance.

<u>INPUT</u>

Design objectives for asset

<u>OUTPUT</u>

Design specification for project implementation, asset creation & integration

<u>DESCRIPTION</u>

The data strategy facilitates data and information required for optimal operation of physical assets.

The definition of the operator interface drives the optimal design of assets to be operable, accessible and maintainable. It defines clear operating procedures for routine tasks and facilitates adequate ability to intervene during emergencies. Standard operating procedures and emergency responses are clearly set out in the operations & maintenance (O&M) manual.

<u>Project Implementation, Asset creation & integration (design, construction and commissioning) (Supporting programmes (World Health Organisation, 2004))</u>

<u>GOAL</u>

The organisation has the ability to effectively integrate new asset projects. The integration considers design, construction, commissioning and handover to operations.

The integration process effectively manages risks to existing operations but also future risks from the asset being created.

<u>INPUT</u>

Acceptability criteria for risk

Specifications for assets

<u>OUTPUT</u>

Operational assets that comply with risk based specifications for public health protection, acceptable risk in HSE, designed for operability, access, lifting and maintenance

<u>DESCRIPTION</u>

The creation and integration of new assets into the existing infrastructure entails the processes are design, construction and commissioning. The new asset requires the “translation” of specifications, design rationale and scope into an operable asset. Process controls are required to ensure that specified reliability of the system is built into the infrastructure, i.e. performance requirements are met in the subsequent operation of the asset. Furthermore, the asset creation process has to manage risks to existing asset operations.

Planning of water abstraction facilities (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The pre-selection process for exploration of water resources uses an expert peer review to determine the feasibility.
- The criteria for planning water abstraction plants are defined and documented.
- The criteria for planning water abstraction plants comply with legislative, regulatory requirements and codes of practices (e.g. well head protection against floods, water ingress from ducting, etc).
- Constraints from the licensing and regulatory authorities during design and construction of water abstraction plants are adhered to and complied with.

Construction of water abstraction plants (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The organisation has defined criteria for the choice of consultants and contractors to build water abstraction plants.
- The monitoring and supervision of construction activities is ensured.
- The monitoring and supervision of construction activities is documented (e.g. daily log).
- Constraints from planning and regulatory authorities are monitored for compliance.
- The handover procedure for the plant is defined, documented and kept on record for the duration of the asset life.

Capital maintenance and decommissioning of water abstraction plant (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The responsibilities for maintenance within the organisation are defined.
- The maintenance of water abstraction plant is conducted by competent personnel, consultant or contractor
- The condition of plant is monitored and documented.
- The responsibilities for decommissioning within the organisation are defined.
- The decommissioning of water abstraction plant is conducted by competent personnel, consultant or contractor

Planning of water treatment works (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The criteria for planning water abstraction plants are defined and documented.
- The criteria for planning water abstraction plants comply with legislative, regulatory requirements and codes of practices.
- Constraints from the licensing and regulatory authorities during design and construction of water abstraction plants are adhered to and complied with.

Construction of water treatment works (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The organisation has defined criteria for the choice of consultants and contractors to build water treatment plants.
- The monitoring and supervision of construction activities is ensured.
- The monitoring and supervision of construction activities is documented (e.g. daily log).
- Constraints from planning and regulatory authorities are monitored for compliance.
- The handover procedure for the plant is defined and in compliance with strategic objectives and specifications. The handover procedure is documented and kept on record for the duration of the asset life.

Capital maintenance and decommissioning of water treatment works

- The responsibilities for maintenance within the organisation are defined.
- The maintenance of water treatment plant is conducted by competent personnel, consultant or contractor
- The condition of plant is monitored and documented.
- The responsibilities for decommissioning within the organisation are defined.
- The decommissioning of water treatment plant is conducted by competent personnel, consultant or contractor

Planning of water storage facilities (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The criteria for planning water abstraction plants are defined and documented.
- The criteria for planning water abstraction plants comply with legislative, regulatory requirements and codes of practices.
- Constraints from the licensing and regulatory authorities during design and construction of water storage facilities are adhered to and complied with.

Construction of water storage facilities (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The organisation has defined criteria for the choice of consultants and contractors to build water storage facilities.
- The monitoring and supervision of construction activities is ensured.
- The monitoring and supervision of construction activities is documented (e.g. daily log).
- Constraints from planning and regulatory authorities are monitored for compliance.
- The usage of materials is compliant with specifications.
- The handover procedure for the plant is defined and in compliance with strategic objectives and specifications. The handover procedure is documented and kept on record for the duration of the asset life.

Capital maintenance and decommissioning of water storage facilities

- The responsibilities for maintenance within the organisation are defined.
- The maintenance of water storage facilities is conducted by competent personnel, consultant or contractor

- The condition of plant is monitored and documented.
- The responsibilities for decommissioning within the organisation are defined.
- The decommissioning of water storage facilities is conducted by competent personnel, consultant or contractor

Planning of water distribution facilities (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The criteria for planning water abstraction plants are defined and documented.
- The criteria for planning water abstraction plants comply with legislative, regulatory requirements and codes of practices.
- The planning and design from external consultants and contractors is monitored against specifications.
- Permission to access private land, highways and footpaths is applied for prior to construction to commence.

Construction and maintenance of water distribution facilities (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The organisation has defined criteria for the choice of consultants and contractors to build water storage facilities.
- External consultant or contractors are sufficiently ensured against third party liabilities.
- The usage of materials is compliant with specifications.
- The welding processes and welder qualifications from internal or external contractors are monitored and documented.
- The usage of ground rockets ensures adequate safety distances to other underground services.
- The monitoring and supervision of construction activities is ensured. Enhanced monitoring and supervision is ensured for newly employed contractors.
- The monitoring and supervision of construction activities is documented (e.g. daily log).
- Constraints from planning and regulatory authorities are monitored for compliance.
- The compliance with procedures for tying-in and disinfecting new pipe work is monitored.
- The responsibilities and co-operation for tying-in pipe work affecting different organisational units, contractors and third parties in defined and documented.
- The setting out for pipe work is compliant with specifications.
- During commissioning of pipe work a pressure test is executed and documented.
- Construction activities, in particular relating to safety relevant materials, equipment and components clearly marked and documented.
- Prior to handover to operations, pipe work is sufficiently flushed and disinfected. After flushing and disinfection, a water sample is tested for E. Coli and other microbiological indicators.
- The results for water sample testing are documented.
- The commissioning process completes with a commissioning certificate signed by authorised and present personnel.

Normal operation/ Asset performance monitoring (Define monitoring of control measures) (World Health Organisation, 2004)

GOAL

The organisation is able to operate its assets effectively and reliably.

The organisation is competent to make effective decisions in maintenance and improvement of assets.

INPUT

Operational asset from asset creation

Definition of process control data and operator interface

Data from normal operation

Data from incident detection and emergency procedure

OUTPUT

Safe operational asset

Data analysis of asset performance

Information for risk assessments and acceptability criteria

Recommendations for operational objectives for system

DESCRIPTION

Operating assets in the water sector takes up the longest time period in the lifecycle of an asset. Throughout the operational lifetime, the system is prone to technical and human error. Reducing human error but also technical error is our concern.

The monitoring of asset performance facilitates the planning of asset maintenance and operational improvements. The monitoring builds on operational data from asset operations enhanced with data, information and knowledge on asset condition.

Operations management (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The organisation maintains a central control centre. The organisation of the control centre is defined and documented.
- Roles and responsibilities in the control centre are defined and documented.
- Control centre staff are qualified and provided with information, training, instructions and supervision.
- Control centre staff is regularly trained. Training is documented.
- The availability of the central control centre is always maintained (, i.e. within/without working normal working hours).

Delegation of responsibility (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- Operators are specifically nominated to operate plant and equipment. Nominations are documented.
- The organisation nominates personnel for specific functions regulated by legislation, regulatory requirements and union representation. (E.g. health and safety, water quality monitoring, reservoir engineers)
- The nomination of personnel for specific function contains a documented description of roles and responsibilities.

- The nomination of personnel for specific functions relating to plant safety is provided for all functional units.
- The organisation has access to specialists for occupational health and safety.
- The organisation has access to specific medical consultation.
- The organisation reviews the need for nominating personnel dedicated to waste management and implements a nomination where required.
- The organisation nominates personnel responsible for transportation of hazardous materials.
- The organisation nominates personnel responsible for emission control.
- The organisation nominates personnel responsible for incident detection and emergency response.
- The organisation nominates personnel responsible for data protection.
- The organisation nominates personnel responsible for waste management.
- The organisation nominates personnel responsible for watershed and aquifer protection.
- The organisation nominates personnel responsible for radiation control.
- The organisation nominates personnel responsible the control of working with asbestos.

Work procedures (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The organisation provides work procedures, procedures describing duties and responsibilities, process procedures, operating procedures, Operations- and Maintenance Manual.
- The organisation provides an overview on relevant and applicable procedures.
- Staff is furnished only with recent and most up-to-date procedures.
- The roles and responsibilities for writing, dissemination, making public and maintain procedures is clearly defined.
- The processes for handling, changing, maintaining up-to date and dissemination of Operations- and Maintenance Manuals is clearly defined.
- The organisation operates a version control for O&M manuals.
- The compliance with procedures and the O&M manual is supervised. Supervision is documented.

Watershed/aquifer protection zones (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- Working in watershed/aquifer protection zones ensures adequate protection for the water body and avoids adverse impact on raw water quality.
- The organization ensures that regulatory requirements relating to water protection zones are complied with and adhered to.
- The reporting of activities with potential adverse impact on water quality to regulatory authorities is defined.
- Discharges of wastewater from water treatment processes are compliant with regulatory requirements and have the necessary discharge consent.
- Hazardous substances are controlled to avoid pollution of watercourses.

Surface and groundwater

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2002b).

Operations and maintenance of water abstraction plant (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

Operation

- The responsibilities for operations within the organisation are defined.
- The abstraction flows in relation to the hydraulic conditions are well understood and documented.
- The risk of contamination has been assessed and is documented.
- The catchment area around the water abstraction plant is a water protection zone based on regulatory authority or decree.
- The catchment area is regularly inspected in order to identify changes that can have an impact on drinking water quality. The inspection is documented.
- The water levels in an aquifer are monitored and documented (in line with abstraction licensing conditions and constraints).
- The usage of the catchment area for hazardous plant, activities and occurrences which could adversely impact on drinking water resources is documented.
- The quality of raw water in the abstraction plant and in the catchment is regularly monitored (with a monitoring program). The intervals for sampling are defined.
- The raw water quality samples are analysed, documented and retained for future decision-making.
- The intervals for visual and functional inspection of water quality sampling and monitoring are defined.
- *Maintenance*
- The responsibilities for maintenance within the organisation are defined.
- The maintenance of water abstraction plant is conducted by competent personnel, consultant or contractor
- The condition of plant is monitored and documented.
- The intervals for inspection (e.g. functional assessment, regeneration, operational testing) and maintenance are defined and execution documented.

Boreholes and Wells

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2001f).

Groundwater abstraction – Springs

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2001g).

Surface water abstraction

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2001j).

River, Streams and Infiltration Galleries

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2001k)

Operation and maintenance of water treatment works (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The responsibilities for operations within the organisation are defined.
- The responsibilities for maintenance within the organisation are defined.
- The maintenance of water abstraction plant is conducted by competent personnel, consultant or contractor
- The condition of plant is monitored and documented.
- The intervals for inspection (e.g. functional assessment, regeneration, operational testing) and maintenance are defined in the O&M manual and its execution documented.
- Wastes from treatment processes are recycled, disposed, or discharged according to legislative and regulatory requirements.
- Disinfection products and processes are specified and their compliance with required specifications is monitored
- The quality assurance monitoring of disinfection products is defined and carried out by competent personnel.
- The concentration of water quality parameters, in particular additives (e.g. disinfection products, water treatment chemicals), are monitored and documented.
- The usage of new or infrequent additives is communicated to the public/customers prior to commencement of operation.
- The usage of all regular water treatment additives is annually communicated to the public/customers.
- Weekly consumption of water treatment additives is monitored and documented.
- The disinfection residual for specified disinfection products is monitored at least daily, if not continuously, and documented.
- The effective concentration of water treatment additives other than disinfection products is monitored, aggregated to weekly consumption and documented.
- An operational logbook is used to record operational data. The logbook is filed for 6 years.

Operation of transmission, bore and process pumps

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2002d)

Water Transmission

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures.(Ministry of Health, 2001x)

Destratification

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2001h)

Application of algaecides

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2002a)

Pre-oxidation

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2005b)

Waste-Liquor Reintroduction

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2001i)

pH adjustment

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2001t)

Coagulation, Flocculation and Sedimentation

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2001o)

Direct Filtration

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2001p)

Slow sand filtration

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2001z)

Rapid Sand filtration

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2001y)

Application of cartridge filtration

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2001l)

Membrane filtration

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2001r)

Removal of iron and manganese

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2002c)

Softening

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2002e).

Trace organics removal (Granulated Activated Carbon (GAC))

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2001v).

Chlorination

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2001m).

Chlorine Dioxide

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2001n)

Ozone disinfection

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2001s).

UV irradiation

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2001w).

Fluoridation

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health , 2001q)

Operation and maintenance of water storage facilities (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The responsibilities for operations within the organisation are defined.
- The responsibilities for maintenance within the organisation are defined.
- The maintenance of water storage facilities is conducted by competent personnel, consultant or contractor
- The intervals for inspection (e.g. functional assessment, cleaning, and operational testing) and maintenance are defined in the O&M manual and its execution documented.
- An operational logbook is used to record operational data. The logbook is filed for 6 years.
- The usage of cleaning agents and processes is compliant with specifications.
- Wastes from cleaning processes are disposed off (recycled, disposed, discharged) in compliance with legislative and regulatory requirements

Post treatment storage

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2001c)

Operation and maintenance of water distribution facilities (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The responsibilities for operations within the organisation are defined.
- The responsibilities for maintenance within the organisation are defined.
- The underground pipe work inspection requires the walking off the route. Pipe work inspection is documented.
- Above ground pipe work is inspected and documented.
- The repair of leakages imminently repaired.
- Pipe fittings are regularly inspected. Street furniture is inspected.
- Roles, responsibilities and processes for the inspection of hydrants are defined and inspections executed at regular intervals.
- A residual of disinfectant for drinking water can be maintained in the distribution network at all times.
- The inflows of drinking water from different water treatment sources maintain the specification for $CaCO_3$ solubility.
- Maintenance of pipe work ensures the compliance with pipe material specifications.

Distribution operation and maintenance

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2001b)

Backflow prevention

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2001a).

System pressure

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2001d)

Electo-technical assets, Remote supervisory control and data acquisition, wireless communication (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The organisation defines roles and responsibilities for the operation of electrical assets, including remote supervisory control and data acquisition units, in particular with respect to regulatory requirements.
- Electrical assets are monitored for performance and maintained by competent personnel.
- Remote supervisory control and data acquisition, wireless communication and communication units are regularly monitored for performance and maintained to ensure availability.

Monitoring equipment (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The organisation defines roles and responsibilities to monitor the performance of monitoring (e.g. pressure gauges, water quality instruments) equipment.
- The organisation ensures that monitoring equipment is monitored for performance, calibrated and adjusted.

- The organisation defines processes to monitor the performance of monitoring equipment. The processes are documented.

Monitoring water quality from catchment to tap

- Based on the risk assessment, the normal operation has defined management procedures to check and monitor control (preventative) measures (Ministry of Health, 2001e).

Asset documentation (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The organisation keeps and maintains an asset register that contains planning and layout drawings, design drawings, survey charts and information on services (e.g. gas, water, electricity. The information on the asset register highlight adherence to codes of practice, normative standards and regulatory requirements.
- The organisation keeps and maintains copies of the asset register in a safe location protected from the elements (e.g. water, fire, etc.).
- Asset register information is updated and reflects new infrastructure and modifications.
- The organisation uses survey maps and plans when setting out new infrastructure. Personnel is qualified (e.g. surveyors) to set out new infrastructure. New information is kept and maintained on record and is reflected on the asset register.
- Layout and detailed design drawings are inspected for accuracy, completeness and plausibility.
- The organisation has a system in place to keep on record, maintain and disseminate information on services (e.g. water mains, electricity, and gas) to third parties, i.e. construction firms, regulators.
- The organisation provides information to third parties for any work carried out in the vicinity of underground services.
- The provision and receipt for information to third parties on underground services is documented.
- Construction firms commissioned to undertake groundworks for municipalities, public authorities and developers (e.g. road construction) are made aware of the duty to request information on underground services from utilities.
- The documentation of assets for water abstraction, treatment, storage and distribution of drinking water includes layout & detail design drawings for wells, artesian and monitoring wells, schematics, licences, commissioning and handover documents, test certificates and amendments to the original design. Documents are complete, updated and designed for ease of reading and understanding.
- The documentation of raw water abstraction includes abstraction licenses, maps and regulatory approval of water protection zones. Documents are complete, updated and designed for ease of reading and understanding.
- The documentation for distribution networks includes layout &detail design drawings, lists of construction materials, welding protocols, test and commissioning certificates. Documents are complete, updated and designed for ease of reading and understanding.
- All documentation of assets is readily available for incident and emergency response.

- The organisation keeps and maintains copies of the asset documentation in a safe location protected from the elements (e.g. water, fire, etc.).

Safe systems at work (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- Work procedures are assessed for risks; the assessment is documented.
- The organisation forms an occupational health and safety council that meets on a regular basis.
- The occupational health and safety council meetings are documented and actions for implementation are monitored.
- Responsibilities for occupational health and safety are delegated to management staff of functional units. The delegation of responsibilities is documented.
- Personal protective equipment is provided for staff.
- Special personal protective equipment for enclosed and confined areas (e.g. gas monitors, harnesses) and staff working alone is provided to staff where necessary.
- A system is in place for replacement and maintenance of personal protective equipment.
- The use of personal protective equipment is monitored and supervised.
- Safe working procedures are formulated for safety critical tasks.

First aid (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- First aiders are trained and available to all functional units.
- Continuous first aid training is provided to staff according to regulatory requirements.
- First aid kit is readily available and their location specified, documented and displayed.
- First aid kit is checked on a regular basis and the usage controlled and restocked or replaced.
- The reporting procedures for accidents are defined and contact details are updated.

Fire safety (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- Appropriate fire extinguishers are provided in sufficient quantities.
- The location for fire extinguishers is clearly indicated and displayed with fluorescent signs.
- Fire extinguishers, fire detection monitors and automated fire extinguishing equipment is maintained according to specifications and regulatory requirements. Maintenance intervals are recorded and documented.
- Staff receive training for the use of fire extinguishers.
- Emergency escape routes are kept clear and are clearly marked and displayed.

Security (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- Access to site and equipment is controlled for authorised personnel only.

Hazardous materials (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The organisation maintains a register/database of hazardous materials.
- The organisation maintains chemical safety data sheets for all hazardous materials.
- The use of hazardous materials is documented and work procedures are defined.
- Regular staff training is provided for the use of hazardous materials. Training is documented.
- A system is in place to introduce new hazardous materials. The process is defined and compliance monitored and supervised.

- A system is in place for the safe transportation of hazardous materials. The systems consider specifications for the vehicle, loading requirements and transport documentation.

Waste management (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- Waste disposal routes are defined and documented. The certificates of disposal are maintained.
- Processing wastes from the treatment processes are disposed according to legislation, regulation and codes of practices. Documentation of disposal is maintained.

Plant safety (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- Assets, equipment and components deemed for inspection according to regulatory requirements are centrally recorded, inspected and maintained. Inspection and maintenance is documented.
- The responsibilities for inspection and maintenance are defined.
- The methods of inspection and maintenance and intervals or dates for inspection and maintenance are defined, recorded and monitored.
- Equipment for inspection and maintenance is available and accessible.
- Equipment and plant containing hazardous materials are bunded and contained.

Third parties (e.g. contractors, temporary staff) (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- Third parties adhere to work procedures defined by the organisation.
- Third party employees receive relevant information, training, instruction and supervision, in particular relating to aspects of plant safety and risks to operations. Provision of information, training, instruction and supervision is documented.
- The selection process for third parties considers criteria of qualification and previous experience.
- Contract specifications detail the roles and responsibilities, in particular relating to specifications of plant safety and work procedures.
- Where appropriate, external health and safety coordinators are appointed to manage third parties. The selection criteria for health and safety coordinators consider their qualification and experience.
- Where third parties are employed to work on public highways, the selection process ensures that traffic management is provided and supervised by a competent person.
- The performance of third parties in relation to compliance with safety requirements and specifications is monitored, documented, audited and reviewed.

Training (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- Training and CPD are provided and documented for call-out staff operators and maintenance staff.

Control of radon (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The organisation ensures the compliance with regulatory requirements for the exposure of personnel and plant with radon gas.

Welding (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The organisation has nominated a qualified supervisor for welding operations (metallic and non-metallic).Welding operatives are supervised by a nominated supervisor and receive regular training. Training and supervision are documented.

Quality monitoring and assurance (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The roles and responsibilities for quality assurance, mandatory reporting and investigation procedures for water quality incidents is defined and documented.
- The specifications for water quality monitoring and assurance are adhered to.
- Records of water quality analysis are kept on file for sufficient long time periods.
- Monitoring equipment for the control of water treatment processes are regularly calibrated and checked.
- Operational logbooks document activities and execution of procedures. Logbooks are retained for sufficiently long time periods.

Incident detection and response procedure (Prepare management procedures) (World Health Organisation, 2004)

GOAL

The organisation has the ability to respond to abnormal operating conditions of its assets.

We are interested how each level of the organisation responds to abnormal operating conditions. In particular relating to novel risks and well understood risks.

INPUT

Definition of operator interface

OUTPUT

Minimising the risk to organisational objectives

Reliability in an emergency response

DESCRIPTION

The organisation is competent to respond to incidents. Incidents are detected, evaluated, and a response is initiated. The response procedure is a risk-assessed procedure with varying levels of process definition.

Incident detection and emergency response (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- A reporting and information process is in place to communicate exceeding water quality parameters to regulating authorities and the public/customers.
- Immediate actions following exceeding water quality parameters are defined and co-ordinated with regulatory authorities.
- Personnel is nominated to develop and maintain action plans for exceeding water quality parameters.
- The organisation has a centralised data collection point to report damaged or failed equipment.

Exceeding water quality parameters (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- Personnel is nominated to develop action plans responding to exceeding water quality parameters.
- Reporting and communication channels to regulating authorities and the public/customer are maintained.
- Actions plans are immediately initiated after incoming reports of exceeding water quality parameters.

Incident management (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The control centre has immediate access to a catalogue of questions and procedures for incoming reports on incidents.
- The control centre has immediate access to all operational documentation (e.g. instructions, emergency response plans, telephone directories, incident report forms)
- The process of managing an incident is documented from initial report to re-instatement of safe operation.
- The control centre provides behavioural guidance for incident reporters.
- The control centre has access to communication facilities to initiate an emergency response from standby staff or contractors.
- The organisation of incident/emergency provides work procedures for commonly re-occurring incidents.

Incident management (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The organisation has defined the staff who manage the re-instatement of plant and networks.
- In emergencies, a competent manager is available to direct staff in order to control risks and to communicate with authorities.

Emergency response teams (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- The organisation of emergency response is defined and documented.
- The design of emergency response organisation is adequately sized in relation to the water supply area and likely incidents/emergencies. The location of emergency response teams considers the response time from initiation to presence at site.
- The planning for emergency response evaluates local and safety related factors, e.g. access roads, weight and height restrictions.
- Emergencies are grouped according to levels of severity. The level of severity determines response times and communication and reporting routes.
- The emergency response team/unit has access to communication links to other emergency services and civil protection units.
- For high severity emergencies a communications and reporting chain to senior management and regulatory authorities is established.
- The process of emergency response is documented so that incident/accident investigation can easily re-capitulate the sequence of events.

- Emergencies and incidents are analysed for root causes in order to define correction and preventative measures.
- The effectiveness of corrective and preventative measures is assessed and evaluated.
- The planning for emergency response considers contracts with other utilities or service providers to support efforts of emergency response.
- The emergency response team has access to asset documentation.
- The emergency response team has information, training, instruction and supervision to utilise the asset documentation for the needs of emergency response.
- The emergency response teams have access to asset documentation in their vehicles.
- Asset documentation for emergency response teams is up-to-date.
- The vehicles of emergency response teams contain all tool, equipment and materials to contain the hazard and re-instate the plant.
- An index of tools, equipment and materials for emergency response vehicles provides information on the capability of the emergency response team or unit.
- The emergency response team/unit has access to required materials.
- Response times from initiation to presence on site are documented.
- The hygienic requirements of the emergency response team and their equipment are controlled, in particular when shared with other utilities or wastewater functions.
- The process of emergency response initiates quick containment of a hazard and aims to reduce other related hazards to occur.
- Emergency response planning is negotiated with all stakeholders and the documentation of the emergency plans is communicated and readily available to all stakeholders.
- The reporting and external communication chains and emergency response procedures for high severity incidents, e.g. natural disasters, war and sabotage, are defined and established.
- The emergency response for imminent danger/hazard is defined and established.
- The emergency response for actual/acute dangers/hazard is defined and established.
- The organisation ensures that emergency response procedures are imminently initiated from all stakeholders.

Pipe work repair (Deutsche Vereinigung des Gas- und Wasserfaches e.V. 2003)

- During repair of pipe work, the condition of the pipe work is assessed (aggressive soil, corrosion, condition of coating) and documented.

Corrective action: Watershed/Aquifer protection/Surface and groundwater

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme (Ministry of Health, 2002b).

Corrective actions: Abstraction

Boreholes and Wells

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme (Ministry of Health, 2001f)

Groundwater abstraction – Springs

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme (Ministry of Health, 2001g).

Surface water abstraction

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme (Ministry of Health, 2001j).

River, Streams and Infiltration Galleries

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme (Ministry of Health, 2001k)

Corrective actions: Water Treatment processes

Design of treatment plant

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme (Ministry of Health, 2001u)

Operation of transmission, bore and process pumps

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme (Ministry of Health, 2002d)

Water Transmission

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme(Ministry of Health, 2001x)

Destratification

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme (Ministry of Health, 2001h)

Application of algaecides

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme (Ministry of Health, 2002a)

Pre-oxidation

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme (Ministry of Health, 2005b)

Waste-Liquor Reintroduction

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme (Ministry of Health, 2001i)

pH adjustment

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme (Ministry of Health, 2001t)

Coagulation, Flocculation and Sedimentation

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme (Ministry of Health, 2001o)

Direct Filtration

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme (Ministry of Health, 2001p)

Slow sand filtration

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme (Ministry of Health, 2001z)

Rapid Sand filtration

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme (Ministry of Health, 2001y)

Application of cartridge filtration

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme (Ministry of Health, 2001l)

Membrane filtration

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme (Ministry of Health, 2001r)

Removal of iron and manganese

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme (Ministry of Health, 2002c)

Softening

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme (Ministry of Health, 2002e).

Trace organics removal (Granulated Activated Carbon (GAC))

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme (Ministry of Health, 2001v).

Chlorination

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme (Ministry of Health, 2001m).

Chlorine Dioxide

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme (Ministry of Health, 2001n)

Ozone disinfection

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme (Ministry of Health, 2001s).

UV irradiation

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme(Ministry of Health, 2001w).

Fluoridation

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme. (Ministry of Health , 2001q)

Corrective actions: Drinking water storage

Post treatment storage

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme (Ministry of Health, 2001c)

Corrective actions: Drinking water distribution

Distribution operation and maintenance

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme.(Ministry of Health, 2001b)

Backflow prevention

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme (Ministry of Health, 2001a).

System pressure

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme. (Ministry of Health, 2001d)

Corrective action: Monitoring water quality from catchment to tap

- Based on the risk assessment and reliable information on water quality, the organisation responds to failures of control (preventative) measures with a corrective action programme. (Ministry of Health, 2001e)

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3 Appendix – Incident analysis

3.1 Case studies

In the assessment of the 145 incidents between 2004 and 2006, a number of case studies were identified that reflect the "*trying conditions*" (Weick, 1987) for the organisation during incidents. These case studies reflect the diversity of asset involved during incidents but also reflect on the incident management response required to reduce the impact on customers and re-instate normal operations.

Reducing incident narratives into statistical data simplifies and reduces the complexity of incident data to be more tangible and accessible. In previous analyses, it was demonstrated that the impact of incidents can even be expressed in numerical values. Here, it is aimed to demonstrate that incidents are complex and often uncertain events that require a competent approach to incident management. Although simplification and reducing complex causalities may be beneficial to learn lessons from incidents, a need was identified to present a number of case studies to demonstrate the diversity, complexity and uncertainty of circumstances under which incidents arise. These case studies - although only a selection and therefore not representative for all incidents - indicate the challenges for effective incident management. Foremost, these case studies demonstrate the need for a systematic approach to decision-making, communication and organisational flexibility for a speedy identification of incident causes and effect, effective reduction of the incident impact and the re-instating of a normal and safe water supply.

In the following case studies the diversity, multicausality and interdependence prevailing during some incidents is demonstrated.

3.1.1 Chlorination failure

This case study demonstrates

- how easy a construction activity on a site can unfold into an incident,
- the rapid detection of an incident situation in the control centre,
- the lack of a fail-safe chlorination system that could have led to unchlorinated drinking water to be passed into distribution, and
- the effectiveness in the incident management response that was adopted to reduce the impact of the incident.

Summary of Incident

An interruption to chlorination at the Water Treatment works for around 2 hours occurred on Tuesday. At that time, contractors were working on the inlet meters on the outlet tank. When digging, the contractor did not come across any warning tape or sand that is used to identify a power cable further below. As no warning was visible, the contractor continued and hit the power cable that caused a power failure to site.

The site logbook identifies the sequence of events:

09:45 approx – Contractor hit the power cable

09:45 1st alarm of power failure in the regional control centre

09:45 to 10:15 – Confirmation of control room actions and contractor confirmation of damage
10:48 Operator arrived on site – cleared low alarms for final chlorine and resets chlorination system
11:25 Operator tested treated water on service reservoir inlet and confirms low chlorine residual
11:30 Operator tested treated water on service reservoir outlet and confirms low chlorine residual
12:55 Operator notified Water Quality Department of power failure
13:35 Operator had discussions with line management regarding the need to slug dose the service reservoir
13:45 Operator commenced slug dosing
Later on it was concluded that the 'normal level of chlorination' had been achieved for drinking water supplied to customers. This was due to the remaining residual of free chlorine in the service reservoir, the slug dosing procedure and the speedy intervention by the operator.

What went well?

- Contractor's knowledge of the correct contact details
- Co-ordinator role facilitating communication between the control centre, the water quality department and field operatives
- Operations manager and site staff remained in constant communication throughout

What can be improved?

- Correct terminology of assets to be used in site documentation
- Contactibility of staff via mobile

Lessons learnt and recommendations arising

- The plant's fail safe system for chlorine needs to be reviewed and adjusted to the minimum time
- Chlorine monitors need to be put on SCADA
- Installation of uninterrupted power supply is required

3.1.2 Power and subsequent chlorination failure

This case study demonstrates

- the vulnerability of water supply systems to external power supplies,
- the reliance of the water utility on customers to report incidents,
- the slow incident response due to other incidents unfolding simultaneously,
- the secondary incident due to a lack of manpower for monitor the performance of an emergency power supply system, and
- the impact of "overstretched" human resources required to manage an incident.

Summary of Event

This Water treatment works takes water from an adit and receives chlorination and phosphate dosing. It directly supplies a number of villages and scattered properties the vicinity. A total population of 250 are supplied directly. The water treatment works also contributes to the supply of a larger village via a Service Reservoir. This population is estimated at around 1100.

Following a power failure affecting the water treatment works there was a failure of the direct supply for up to 10 hours and a failure of chlorination for 3 hours. Boil advice was given to 113 properties on the direct supply. The service reservoir was slug dosed and disinfection was not regarded as being compromised. There was some intermittent discolouration at customer's taps which was probably due to disturbance of sediment in the contact tank at the works. Turbidity in water leaving the WTW was greater than 1 FTU. The PCV of 4 FTU was also breached at customer's taps. Three samples failed the Mn standard.

Causes and impact of the event

A power failure at around 05:00 on Saturday resulted in an automatic works shutdown. This fail safe procedure involves the inlet valve closing but the treated water in the contact water tank continuing into supply**.** The contact water tank eventually ran dry and the supply failed to some properties. The first no water complaint was received at 16:00 on Saturday and there were 11 others up to 16:00 on Sunday. At 15:00 on Sunday a generator was installed and treatment re-started. The level of water in the contact water tank was close to zero at the time. At 21:00 on Sunday the generator failed as it had run out of fuel. The chlorination ceased but on this occasion, probably because the Uninterruptable Power Supply had become exhausted, the works inlet did not shut down and untreated water passed into the contact water tank and then into supply. The works was shut down at 24:00 on Sunday by manually closing the outlet and inlet valves.

Bottled water was delivered to the area in the early hours of Monday morning. The Service Reservoir was slug dosed with chlorine at around 00:30 on Monday morning. Leaflets advising customers to boil water were distributed before the water supply was restored on Monday 10 January. Leaflets advising customers to boil water were distributed by 16:00 on Monday and the outlet valve then opened and water allowed to pass into supply.

Mains power was re-instated at around 06:00 on Monday and the works re-started. The boil order was lifted after two consecutive sets of bacteriological samples were clear of faecal indicators on Thursday.

This incident took place against a background of numerous power failures across a very wide area affecting water production and supply. Personnel were severely stretched and there were delays in responding to alarms. Furthermore, there were interruptions in the supply of data because of the power problems.

3.1.3 Specification for Chlorination systems

It is a policy in the Regional Water Utility, where possible, to automatically shutdown a treatment works upon disinfection failure or divert to waste.
The Policy states that: -
"*All water treatment works should failsafe following failure of disinfection to minimize the risk of non disinfected water entering supply*."
The Drinking Water Inspectorate hold the view that a disinfection system may also be failsafe if there are full back up systems that take over dosing following failure of the duty system.
The following specifications are used to audit chlorination systems on all water treatment works and facilities were chlorination is required.

Failsafe specification for chlorination systems
Specification 1.General Failsafe
A site is classed as non-compliant if there is no failsafe facility.
I.e. neither:

- An Auto Shutdown in a fail-safe manner
- An Auto Shutdown/divert to waste.
- A fully replicated disinfection system.

If either of these systems are present then the site will be considered compliant providing the installation meets the criteria listed below for that system.

Specification 2. Auto Shutdown Systems
Auto Shutdown Systems are classed as non-compliant if they do not comply with the following:

- Plant and equipment is provided to prevent improperly disinfected water from entering the supply system preferably prior to the contact tank.
- The shutdown operation (I.e. close on power failure) is installed with no flow validation.
- The shutdown panel is protected with a dedicated UPS.
- The shutdown panel outputs are failsafe on power failure.
- Are triggered by illegal chlorine residuals at appropriate points to prevent improperly disinfected water from entering supply.
- Shutdown is triggered by power failure
- Shutdown is triggered by triple validation failure.
- Shutdown is triggered by sample failure.

Specification 3. Replicated Gravity Feed Sites and Power Supplies
A site is classed as non-compliant if it has a gravity feed system and has no alternative/emergency power provision.
When an alternative/emergency power supply is present, it must:

- Auto start and auto switch.
- Support the entire disinfection system.
- If it is a second feed then it must be fed from a separate sub station.

Specification 4. Control Systems
Control systems will be classed as non-compliant unless they comply with the following basic philosophy:

- Samples are representative of water passing the sample point.
- Sample lines are non-metallic and have a residence time of no greater than 6 minutes.
- Sample lines are dedicated to Chlorine residual analysers.
- Sample lines are monitored by the appropriate instrumentation. (E.g. Flow and pressure switches or both)
- Samples are buffered using the appropriate buffer.
- Chlorine Control points are monitored by triple validated Chlorine residual analysers.
- Critical instrumentation and control equipment is protected by dedicated UPS.

Specification 5. Flow Measurement.
Flow meters used on chlorination control systems will be classed as non-compliant unless:

- They are magnetic flow meters.
- The flow signal is validated using a separate device.

Specification 6. Telemetry Alarms.
The telemetry alarms for the Chlorine residual signals shall be considered non-compliant unless:

- For single chlorine instruments the analogue and the digital high and low alarms are hard wired to telemetry.
- For triple validated systems the triple validated analogue signal and a triple validation failure digital alarm are hard wired to telemetry
- Alarms have appropriate priorities and dead bands.

3.1.4 Power failure

This case study demonstrates

- the vulnerability of water supply systems to external power suppliers and their services,
- the increasing reliance on pumped systems as opposed to gravity-fed water supply and distribution system,
- the technology issues for the installation of un-interrupted power supply, and
- the need for effective communication during the incident.

Summary of incident
A power failure at a water pumping station in a distribution network caused widespread loss of supply. It is currently believed to have been due to a short duration power loss. Initially, the on-site generator failed to start. Even after manually starting the generator, the pumps would not power up and hence no water entered the adjacent Water Tower. Hence, supplies were lost from approx 08:00. The pumps were restarted by approx 09:15 and supplies restored within the next 2 hours. Following restoration there were a

significant number of contacts logged for milky/air, fortunately very few for discolouration.

Cause and effect of incident

The logbook indicates the sequence of events:

08:08 First Low Pressure contact from customer received

08:18 First No Water contact from customer received

08:27 Operator is onsite at water pumping station and is having problems with the incoming power - electrician is booked and on his way. Requests support from Regional Electricity Company. He has the generator started but cannot get it to drive the pumps.

08:40 Electricians are on site and have reset the trip switch but they are still not able to get the pumps to recognise and run on generator power.

08:45 Call centre informs the Incident manager of 100 of customer contacts

08:46 Press Office is going to get the news on the local radio stations

08:54 The fire brigade have been called to site because of all the smoke from the generator onsite.

09:14 Operator and electrician have three pumps running and the system is charging up now starting with the tower. There are a number of things wrong:-

1. Generator didn't start on auto when the power blipped and tripped the incomer, this was reset by the AMBS technician which
2. When it was started on hand it does not drive the pumps.
3. Trips switches have to be manually reset before the pumps can receive power from the generator.

09:17 Press officer has just done a live interview with the local radio station and it is going onto the regional BBC website

09:45 Supplies starting to recover.

09:48 Checked with regional electricity company. Job not allocated yet and reference number quoted has been cancelled. Incident manager re-raised it, escalated it and formally complained regarding response. Electricity company will ring back with new timescale in ten minutes.

10:44 Water quality sampling officer requests details of depressurised areas, as he is on site now to take samples. DM advises of locations.

10:52 Incident manager contacts regional electricity company to request onsite time for their engineer just in case the info above was meant to close the contact down. Advised that they were struggling to find an engineer to attend and that they didn't have a fault on their systems. Incident manager advised the regional electricity company that assistance was urgently required onsite to meet with electricians and asset management staff to discuss both the security of current supply and the risks in switching back to the live incomer. Although supplies had been restored, the water supply system was still very susceptible to failure and the incident manager was unwilling to come off of the generator until we were sure this was the best option. They promised to send their engineer as soon as he is free.

11:45 Incident manager faxes Consumer Council for Water with details although this does not breach the major customer impact for greater than 4 hours criteria.

12:19 Operator advises that everything is back on mains power following a site meeting with all involved including the engineer from the regional electricity company. Everything is set in auto, however, there will need to be an interim procedure in place to

advise anyone attending site about the requirements for running the pumps on the generator.
It turned out that there was a short duration incoming power failure followed by a spike when it came back. This tripped the main circuit breaker (which was reset early on in this incident). In hindsight, it became apparent that the generator was linked to the wrong phase of the incoming mains and so didn't recognise the failure and didn't start on auto. Once the generator was started, the pump control panel was still seeing incoming mains even though the panel tripped and so didn't accept the power from the generator until both, the generator and the pump, control panels were switched onto hand and forced to run.
Effectively, 10,953 customers lost supplies for period approaching 2 hours. Following restoration, no water quality contacts were received from customers.

Issues arising and further required investigations

- Power breaker trip was not visible or indicated
- Why didn't the PLC recognise power status and take necessary actions?
- Investigate why pumps can't be run in hand and auto with current PLC configuration
- Investigate training provision and onsite guidance for managing failure scenarios.

What went well?

- Response, attitude and speed of those involved was excellent
- Communication was good from those involved.
- Communication with the media

3.1.5 Uninterruptable Power Supply failure

This case study demonstrates

- the vulnerability of water supply systems to external power suppliers and their services, and
- the technology issues for the installation of un-interruptable power supply.

Summary of incident

A power failure affected the site on day 1. The generator started but did not power the site. The service partner electrician was called out but could not rectify the fault. The generator service partner was subsequently called out. The fault was traced to the local generator controller. A temporary fix was installed to allow the generator to power the works.
However, after 8 hours outage and a burst in distribution, the service reservoir got as low as 7% but recovered quickly when the works was restarted and changes had been made in distribution.

3.1.6 Telemetry failure

This case study demonstrates

- the technology issues arising from remote-controlled water supply systems,
- the need for fail-safe monitoring, control and telemetry systems, and
- the need for personnel to check water supply systems on-site.

Summary of incident

At 07:30hrs on Tuesday, the Process Engineer attended the Water treatment works as part of his regular visiting programme. He found that the works was shut-down and that the Treated Water Reservoir was too low to allow the High Lift pumps to operate. At a similar time, the regional control centre received a Low Alarm for the nearby water tower. The SCADA system at the Water treatment works seems to have lost connection to regional control centre at 03:49hrs on Monday and the works shut down at 14:15hrs on the same day. No alarms from the water treatment works were received post 03:49hrs on Monday.

The control of the adjacent water pumping station was altered to put more water into system and hence the level in water tower was stabilised. In addition, the transfer flow from another water treatment works was increased to stabilise the water level in the regional service reservoir.

The WTW was restarted and after intensive water quality checks, the works was returned into service at 14:45hrs on Tuesday.

3.1.7 Simultaneous failure types

This case study demonstrates

- the adverse legacy of poor maintenance on existing assets causing two seemingly independent failures simultaneously,
- the non-availability of resources to contain the impact of the incident, and
- the conflicting objectives to notify customers of the incident.

Summary of Incident

At approx 19:20 on Day 1 a large number of no water contacts were received in the regional control centre. An investigator was sent to the Service reservoir in the affected area to investigate, as there was no burst reported. The local control panel was checked and the service reservoir No.2 was found to be empty - No.1 was out of service at the time. Technicians had been working on the auto control from the feed pumps of the service reservoir earlier in the day due to problems the previous evening with maintaining res levels.

On investigation, it was found that the local control panel level readings for service reservoir No.2 were found to have been inhibited ca. **3 ½ years ago**; the pump control was working on the level signal from service reservoir No.1 and hence was not starting up automatically as it was out of service.

The following day 2, the regulatory combined sample (feeding from no.2) was reported to having failed with a count of 35 E. coli. The probable cause of contamination was

ingress due to faulty seals around the four hatch assemblies. According to site records, the failed regulatory sample was taken at 08:15 on Day 1, i.e. PRIOR to the reservoir running empty. Subsequently, on day 2, the tank was taken out of service for super-chlorination and cleaning. However, at 10:20, operator 1 advises that there is no chorus available as the delivery due yesterday has been quarantined.
10:48 The water quality manager is advising the incident manager of the potential need to issue a boil notice for the 3500 properties. Decision is postponed to await the first results of last night's samples. They are expected for mid-afternoon. Incident manager agrees to pre-warn the Communication team about a potential letter drop.
10:55 Operator 1 called to find out where we are with the delivery of chlorus. He advises it has been wrongly labelled and cannot be released until it has been relabelled - they are expecting this to happen sometime in the morning.
11:02 Operator 2 and 3 advised of the increased requirement to dose to 1ppm. They advise they have nothing to carry the chlorus in and will go first to another site to pick up some bottles then go to another site to decant the required volume before attending the incident site.
11:06 The reservoir cleaning team currently is currently at another site and are finishing up and making their way to the incident site to clean No. 1 today. This will then be filled (or part-filled) slug dosed and put into supply so that No. 2 can be isolated and cleaned.
13:50 Incident manager calls Customer Communication Department regarding the need to issue a boil notice to 3500 customers if current action does not go to plan.
14:03 Service reservoir No.2 is chlorinated.

The SRE was chlorinated to 1 mg/l and this water drawn through the system to superchlorinate the associated water mains. The water pumping station was then started to feed supply direct via a pressure sustaining valve, and, therefore by-passing the service reservoir.
However, problems occurred during the cleaning of the reservoir: A pump got stuck in the outlet main.
19:20 Incident manager decides that boil orders are definitely not required
Eventually, the pumps were started in hand and supplied that area; all supplies being restored by approx 20:45. Overall, potentially 1000 properties were affected by the loss of supply due to the "quick fix" solution of rigging the level control for the reservoir and one customer reported discoloured water. The response to the E. coli failure was inadequate.

What went well?
Response from technicians to rectify loss of supply.
Precautionary sampling.
Response of cleaning team.

What went less well?
Mobilisation of mobile chlorination (due to comms & enabling issues)
Hesitation and failure to order a boil notice out of fear from bad press and regulatory ramifications.

3.1.8 Process failure

This case study demonstrates

- the impact of poorly maintained systems on the treatment process,
- insufficient design of systems having an adverse impact during an incident,
- the lack of visible indication of systems not operating,
- the lack of resources to manage the incident (e.g. discharge consents to divert drinking water to waste), and
- the extended duration of incidents due to a lack of speedy repair of failed assets

Summary of incident

Prior to Day 1, turbidity problems had been experienced at this water treatment works which were believed to originate from within the treatment process that treats raw water of reasonably poor quality. On the first day of the incident, a high turbidity spike led to a series of cleaning and maintenance schedules in logical sequence. These attempts failed to reduce the turbidity. It was then recognised that the speed of the stirrers on the primary and secondary flocculators were not the same. The Primary stirrer was running as specified, the Secondary was running too quickly and breaking up the previously formed floc. It was found the speed of the secondary stirrers could not be changed due to a wear issue. It was therefore decided to switch off the secondary stirrers on floc tanks. This was due to high turbidity off the floatation units onto first stage filters that were passing high turbidity into drinking water supply to customers. Following the stopping of the stirrers, the turbidity going onto first stage filters reduced from nine to 3ftu. An order was raised for the secondary stirrer mechanism to be fixed and notice was attached to the relevant SCADA screen stating that the secondary stirrers should not be switched on.

Historical telemetry records show that clarified turbidity was since increasing slowly and by Day 3 increased to similar values as experienced on Day 1. This trend continued until mid morning on the 24th Day when the secondary stirrers were switched back on after repair. In the interim period, a significant amount of work was carried out to improve the turbidity levels by adjustments to the process and dosing. Efforts to reduce turbidity by these improvements or by increased filter washing were seriously hampered by the dirty wash water capacity and restrictions on discharge to waste. On Day 20, a short-lived turbidity spike triggered an alarm and response that indicated it was short lived and that acceptable turbidity levels had since resumed. On Day 22, a further significant spike caused an alarm that led to attendance at site, taking of samples and fitting of Crypto monitoring equipment. On the Day 24, further analysis and examination of trends was conducted and discussions were held between water quality science and process engineer that resulted in the secondary stirrers being brought back into operation. A significant turbidity spike occurred immediately after the stirrers had been switched on. By lunchtime, these spikes had turned into a serious turbidity issue through the works and a decision was taken to shut the works down rather than place treated water storage in jeopardy. In the following 18 hours, significant work went on to return the works into service and by Day 25 a flow of 15tcmd was restored to supply. Throughout the whole period, turbidity was also being addressed by manual instigation of filter washing which may account for the return to normal levels after some of the spikes.

Cause and effect of incident
An essential secondary stirrer failed and was not repaired for over 24 days despite ongoing water quality problems and a perceived, elevated Cryptosporidium risk.
The poor process performance was aggravated by the duty compressor of the DAF showing running when in fact it was not. The pressure control on the compressor was faulty and contributed to poor process performance. The DAF nozzles also seemed inadequate to inject highly air charged water to the DAF tank.
With respect to incident management performance, the current discharge to waste arrangement on the WTW site are limited with the effect that poor quality drinking water output from the works cannot be discharged appropriately. Water can only pass on into supply or the water treatment works needs shutting down.

Effect on customers
Repeated supply of drinking water with elevated and spikes in turbidity to customers.
A number of discolouration contacts immediately downstream of the WTW.

3.1.9 Susceptible customers

This case study demonstrates

- the major impact a human error can have,
- the lack of understanding of customer needs,
- the disproportionate effort to recover a failed system in relation to the ease of causing a failure, and
- the full-scale escalation procedure and incident management capability of the water utility.

Summary of incident
At approximately 12:15 on Day 1, the supply to a District Hospital was inadvertently interrupted during rehab work of water mains by a contractor. Although the supply was made available again after 30 minutes the hospital management decided to isolate the hospital supply from the distribution system until clear bacti sample results were obtained. Bottled water was immediately supplied by the contractor and tankering and sampling arrangements put in place. The Chief Executive of the Regional Health Trust was contacted in response to the concerns regarding this interruption and the previous history of issues with the hospital. A press statement was prepared and the water utility assisted the hospital with tankering and bottled water. A significant part of the hospital was effectively closed because of the isolation, including the Critical Care Unit, the kitchens, the renal unit, the sterilisation unit as well as a number of wards. A sampling programme was agreed with the hospital although the water utility maintained that water quality had not been compromised and the hospital's actions were overly cautious – a view shared by the DWI.
Tankering and bottled water supplies continued during Day 2 and close contact and consultation was maintained with hospital staff and Health Trust management. Clear bacti sample results were obtained on the evening of Day 2. The water utility worked for the hospital in precautionary cleaning and disinfection of the hospitals storage tanks prior to the hospital restoring mains supplies early morning on Day 3.

Cause and effect of the problem

Work was being carried out to install a branch on the water main. The contractor closed a valve on the network, which should have been left opened. Supply to the hospital was cut off until the valving operation was reversed to it normal operating position. Despite reassurance that water quality had not been compromised, the hospital's "procedures" require supply to be shut down until water is proven bacteriologically sound.

The timeline of the incidents reflects the challenges the water utility faced to re-instate normal operations.

Day 1

12:26 Received a call from the Hospital who reported no water at the hospital.
Contractor is carrying out mains renewal nearby but do not think they have caused this. Decision is taken to supply bottled water to the hospital by the contractor as a precaution.
The Hospital is concerned about allowing water back into the hospital when supplies return; they require a clear bacti samples similar to the situation at another Hospital in the previous week.

12:44 The water utility receives confirmation of contractor that they have operated a valve that may have affected the hosp supply; Incident manager instructs them to reverse the valving ASAP. The view is that the supply may not have actually gone off, just low pressure to the hospital as a result.

12:55 Water pressure is back on at the hospital.

13:00 Hospital takes the decision to isolate their supply

13:02 Hospital has confirmed all supplies were lost, not just low pressure.

13:30 CEO of Health Trust is not at all happy about the loss of supply and request a call back. Decision is taken that a high-level contact from the water utility is needed to respond to her.
At this time, the cause of problem is finally established.

14:15 High-level contact from the water utility is not currently available – there is a board meeting in progress.

14:27 Hospital will have to cancel operations and clear the renal unit until normal supplies are restored. The hospital has called the fire service to fill the boiler tanks to stop them running dry.

In the meanwhile, alternative water supply is arranged.

15:24 Call from an operator: Whilst there are concerns regarding the quality of the hose pipes delivered to site to be used to provide alternative supplies, the hospital have now indicated they are not willing to accept any water from a hose and wish for a tank to tank transfer.

15.57 Incident Vehicle going to site. Delegated incident manager is going to the hospital to support staff on site and to respond to media queries.

18:05 Operator arrives on site with 'new unused food grade bagging (hose pipe)'.

18:30 Chlorination and swabbing of bagging complete - water should be entering header tanks within 15 mins.

22:00 Operator had an accident where he fell into an excavation (the banking collapsed).

22:15 DWI informed.

Day 2

00:58 The 2 tractor units are remaining on site as if the tankers are left in situ full they will sink into the tarmac car park over night. One driver is now on sleep time and the other is available to operate the units overnight.

02:20 Water quality sampling at hospital. Unfortunately, the fire hydrants on site are in poor condition so there was a lot of work to do prior to taking the samples

07:00 Meeting arranged with Hospital about their procedures and criteria to bring the water back into use.

09:30 Confirmation of the first water quality samples: All samples are clear from bacteriological contamination

10:30 Further samples taken from hydrant. If supplies switched on following on-site meeting later this morning, further samples from within the hospital are required

10:50 10 portaloos arrive to site.

13:40 Laboratory confirm that all further samples are clear from bacteriological contamination. Further sample results will be available at 21:00.

15:55 Photographer is on his way from Evening News. Senior management would therefore like the operation to appear as inconspicuous as possible.
To this end, as few people as possible should be on site.

16:17 Confirmation that the photographer had been on site and some of the hospital staff had almost posed for photos.

21:28 Water quality sample results have been accepted by the Infection Control Nurse.

21:45 Site is cleaned up

22:02 Discussion on health and safety implications of cleaning team working very long hours. Contingencies made for stopping job if necessary, continuing tankering\bottled water and finding accommodation for resting the team.

Day 3

00:05 Health and safety concerns are discussed for cleaning team who clean and disinfect onsite water storage tanks - they have been at work since 07:00 yesterday morning. Arrangements for accommodation and alternative transport discussed.

00:37 Cleaning gang are currently working on the group on six tanks in the first building - the team are confident that the job is very straightforward and are looking to complete the job in one operation. The biggest delay is the standing time for chlorine disinfection.

04:05 Cleaning of tank is still going well; they are currently draining the last of the six tanks at this location. There are no drain valves so each tank needs to be pumped out before cleaning and after chlorination - this is slowing things up a bit. The tanks are being tested by the hospital engineer and so far chlorine residuals have been satisfactory.
The team are OK so far regarding tiredness; none of them wants to stay over.
Arrangements are made for some rest prior to travelling back. When the last two tanks are being cleaned, there will be the chance for each team of two to get a couple of hours rest.

06:47 Tankers are moved off site.

08:15 It is anticipated the last two tanks will be complete by 10:00.

11:43 All the tanks on site have been cleaned and all RWU personnel and equipment have left site.

What went well?
Efforts of all teams involved in incident management.
Communications between Press Office and incident team
Timely deployment of incident support vehicle

What could be improved?
Use of specific plans for the hospital
Communications around bottled water delivery
Contactability of senior managers during incidents
Appropriate use of senior managers in incident management
Personal logging of actions
Coordination of communications on site
The Hospital had an internal procedure for loss of supply incidents that the water utility was unaware. Do any other customers have internal restart procedures that the water utility needs to be aware of?

3.1.10 Incident escalation procedures

This case study demonstrates
- the rapid escalation of technical issues resulting in an incident,
- the need for fail-safe systems to avoid high risk process failures, and
- the need for staff to operate existing incident escalation procedures.

Summary of incident
This incident commenced with polymer transfer pump No. 2 failing on the evening of Day 1 that resulted in no polymer being transferred to the day holding tank for several hours. Ultimately, the day holding tank emptied as coagulation and clarification continued but clarification was eventually lost with the polymer holding tank running dry. A manual changeover from batching tank No2 to batching tank No1 (and in turn polymer transfer from pump No2 to pump No1) did not take place until the operator arrived on site several hours after the loss of the transfer pump.
Loss of the polymer dosing resulted in clarification being lost and the clarified water turbidity was elevated almost instantly to levels in excess of 10FTU. This had the knock-on effect to latter stage of purification such that post filter combined turbidity was elevated to levels in excess of 3FTU (both were off the scale of instrument's range) and therefore final water turbidity elevated to a peak of levels in excess of 8FTU.
Water during this period continued to be supplied to Distribution.
This continued for several hours before this was brought back under control with the re-instatement of polymer dosing but it took longer for the turbidity of the water currently in the process and in the final water tank to be brought back under the acceptable levels and PCV. The water in the final water tank was not back under PCV until much later in the morning of Day 2.

A regulatory sample taken early morning on Day 2 showing that the final water turbidity was measured as 1.4FTU. This sample was in breach of the 1.0FTU PCV level. However, no customer contacts during the 24-hour period following the incident were recorded.
The incident manager was not made aware of the situation and events until informed by the line manager of the operator on site. No escalation of the events had taken place. The incident escalation and management procedure was not followed.
Service reservoirs were slug-dosed with chlorine during Day 2 and no cryptosporidium occysts were measured in either the final water outlet sample.
In conclusion, it appears that on several occasions, the following of the appropriate procedures did not take place and this resulted in the lack of opportunity to get others involved to approve and verify the actions taken.
Following this incident, it was recommended that

- An early warning system is required for inlet turbidity whereby an appropriate trigger level is established to alert the incident manager of a serious risk to treatment
- An auto-shutdown facility should be installed for excessive levels of turbidity on the raw water inlet.
- the need for training of individuals in quality management systems, incident escalation and decision procedures and the understanding of on-site process operation must be reviewed.

3.1.11 Catastrophic consequences of asset failures

This case study demonstrates

- the catastrophic consequences of high hazard asset failures,
- the multiple impacts of incidents.

Summary of incident
Between Day 1 and Day 3, an estimated 2,000 kg of 96% concentrated sulphuric acid leaked from an acid injection apparatus at the raw water inlet of a WTW causing a build up of sulphuric acid in the dosing chamber. This chamber is fitted with a submersible pump designed to keep the chamber free of rainwater. The pump removed the leaking acid from the chamber and pumped it to sewer where it travelled to the nearby wastewater treatment works on site and killed all the biological function of the works as well as damaging interstage transfer pipework. In addition, the acid escaped from the chamber drain pipe and then flowed into a local drain to nature reserve. The Acid pollution to the watercourse is believed to be contained at this point with some vegetation damage.
On the morning of the 2nd August, two employees attended the Wastewater treatment works and came into contact with the fumes from the acid. This alerted staff of the incident and from there it was escalated, the source of the acid repaired and the flow stopped. The two employees were precautionally checked out at a local hospital and were discharged safe and well. The works and watercourse had a significant concentration and quantity of acid removed.

3.1.12 Failure of standby systems

This case study demonstrates
- the common cause failure due to poor condition of assets, and
- the effective, temporary measures adopted to avoid the impact of the incident on customers.

Summary of incident
Problems were encountered with both booster pumps at a Water Tower that it feeds a whole area containing 1700 properties. Pump No. 1 stopped working on Friday evening and was not able to be repaired on site. It was therefore removed for repair. Pump No. 2 was nursed along with much attention from staff, but unfortunately, that stopped working in the early hours of Sunday morning. A combination of contingency measures were deployed to maintain supplies, these were:
- Use of an Angus Fire Pump to put water into the DMA served by the tower, from an adjacent DMA.
- Rezoning from an additional adjacent DMA to further reduce demand on the tower.
- Installation of a pump removed from another water pumping station

This was the more permanent solution, which was only made possible by the first two incident mitigation measures to “buy” some time.
The tower reached a low level of 8% on Saturday morning and 15% on Sunday afternoon. However, supplies were not lost to any customers.

3.1.13 Failure of standby systems

This case study demonstrates
- the common cause failure due to poor design of assets, and
- the long-term risk from asset failures.

Summary of incident
In the evening of Day 1 a 450mm main burst. Unfortunately, this main was laid close to the edge of a quarry and a bend had "blown" into the quarry causing a landslide leaving the main suspended over 35m above the ground. The alternative main to continue supply is only one metre away from the burst main and therefore unsafe to use. The affected area has been re-zoned onto water from another water supply source.
As the mains permanent repair solution will be a very lengthy process, 8,000 properties are at medium risk of loosing their supply until the repair work is complete.

3.1.14 Design error

This case study demonstrates

- the impact of design flaws on safe operation of water supply systems.

Summary of incident

The dosing of Monosodium Phosphate at a WTW into a main - that had been shut down since Day 1 - continued in proportion to a flow signal from another water main that was controlling the dose. When the main was re-commissioned on Day 4, a slug of the chemical, estimated to be around 1 tonne, was pumped towards a Service Reservoir. This was detected later the same evening.

An incident team was established in the control centre and in the Field. The senior scientist was consulted and extensive sampling initiated to determine the extent of the contamination. The slug was contained in the water mains section between two service reservoirs, before it reached any customers. A flushing programme for these mains was devised and implemented for one of the mains on Day 5. There was a serious risk of this water, with a high concentration of the chemical, being supplied customers.

3.1.15 3rd party access to water supply systems

This case study demonstrates

- the vulnerability of drinking water distribution system to third party access.

Summary of incident

At approximately 18.00hrs on Day 1 a cluster of discoloured water contact were noted in one area. These quickly spread in the village and were followed by a more rapid and extensive spread downstream of the village. By 21.00hrs, there were over 30 complaints recorded and the DWI was notified. Extensive flushing was carried out until midnight. Samples were also taken. At 7.40 hrs on Day 2, further customer contacts were received and further investigation, flushing and sampling was undertaken. On the morning of the Day 3, a tanker was caught filling from a hydrant with a 2" standpipe. The driver denied being in the area in previous days but his Company is investigating.

The excessive flows from the standpipe are deemed the most likely cause to having re-suspended deposits in the water mains.

3.1.16 Impact on public assets

This case study demonstrates

- the potential impact of burst water mains on 3rd party assets, and
- the challenges in identifying an incident site, in particular involving below ground assets.

Summary of incident

Customers in a particular area have been suffering poor pressure problems over the last two days. Despite intensive efforts from Field operations, no burst could be located until late yesterday afternoon. The area was rezoned and everyone now has an improved supply

A repair was planned for last night but the actual site of the leak could not be located. Today a fracture on the 12" main running down a main has been discovered. Unfortunately, this leak has scoured a **significant, bus-sized cavern** under the road that will necessitate the closure of at least two lanes of the outbound carriageway. The road is a main arterial commuter route into a major city and hence the closure will cause significant traffic congestion. It is hoped that the road can be re-opened by the weekend but we await confirmation from the Highways Department of the full extent of road repair that will be required.

3.2 Further detailed data analysis

3.2.1 Incidents in England and Wales between 2004 and 2006

3.2.1.1 Chi Square analysis of asset type and asset life cycle phase

Root causes to incidents					
For incident root causes, does a relationship exist between the categories of asset classes and asset life cycle phases?					
H0= In the distribution of most probable incident root causes asset type and asset life cycle are randomly distributed					
H1= In the distribution of most probable incident root causes asset type and asset life cycle are not randomly distributed.					
SL	0.05				
SL	0.001				
Observation based on 92 incident case studies in 2005					
	Catchment	**WTW**	**SR**	**Distribution**	**Sum**
Design	6	18	8	3	**35**
Operations	6	19	11	22	**58**
Maintenance	0	10	6	50	**66**
Sum	**12.00**	**47.00**	**25.00**	**75.00**	**159.00**
Expected values					
	Catchment	**WTW**	**SR**	**Distribution**	**Sum**
Design	2.64	10.35	5.50	16.51	**35**
Operations	4.38	17.14	9.12	27.36	**58**
Maintenance	4.98	19.51	10.38	31.13	**66**
Sum	**12**	**47**	**25**	**75**	**159**
Chi Squared					
	Catchment	**WTW**	**SR**	**Distribution**	**Sum X2**
Design	4.27	5.66	1.13	11.05	
Operations	0.60	0.20	0.39	1.05	
Maintenance	4.98	4.64	1.85	11.44	
Sum	**9.85**	**10.50**	**3.37**	**23.54**	**47.26**
Degrees of freedom		6			

X2 (Chi square table)		12.59	for SL	0.05	
47.26 > 12.59					
H0 is rejected at a SL of 5%					
There exists a dependency between asset type and asset life cycle phase to explain root causes to incidents.					
Variations between expected distribution of root causes to failure and actual distribution of failure root causes is sizeable.					
Degrees of freedom		6			
X2 (Chi square table)		22.46	for SL	0.001	
47.26 > 22.46					
H0 is rejected at a SL of 0.1%					
There exists a dependency between asset type and asset life cycle phase to explain root causes to incidents.					
Variations between expected distribution of root causes to failure and actual distribution of failure root causes is sizeable.					

Table 1 Chi square testing for incident occurrence in asset type - asset life cycle matrix

3.2.1.2 Incidents in England and Wales

Drinking Water Incidents 2004							Hazard score	Hazard score	Hazard score	
							0.33	0.33	0.33	
Date	Company	Duration in hrs	Days	Population	Hazard description	Hazard categories	P	H	D	**Sum**
01/01/2004	Yorkshire	72	3.00	10000	high turbidity	Chemical present above guidelines	4	8	16	**9.24**
05/01/2004	United Utilities	24	1.00	3600	Discoloured water	Aesthetics problems and above guidelines	2	32	8	**13.86**
06/01/2004	United Utilities	72	3.00	20500	Discoloured water	Aesthetics problems and above guidelines	8	32	16	**18.48**
08/01/2004	United Utilities	72	3.00	17000	Discoloured water	Aesthetics problems and above guidelines	8	32	16	**18.48**
13/01/2004	Three Valleys	5	0.21	2200	Discoloured water	Aesthetics problems and above guidelines	2	32	2	**11.88**
16/01/2004	Southern	12	0.50	100000	Contamination of water	Potential unwholesome, potential low health effect	32	16	4	**17.16**
18/01/2004	dwr cymru	576	24.00	77500	aesthetics (algae in raw water_)	Aesthetics problems and above guidelines	32	32	125	**62.37**
21/01/2004	South East	48	2.00	0	High turbidity and possible microbiological contamination	Potential biological pathogens present	2	6	16	**7.92**
23/01/2004	Thames	24	1.00	7300	Discoloured water	Aesthetics problems and above guidelines	2	32	8	**13.86**
25/01/2004	Southern	24	1.00	197000	high chlorine in water	Chemical present above guidelines	64	8	8	**26.4**
29/01/2004	Severn Trent	48	2.00	12500	loss of supply	loss of supply	4	16	16	**11.88**
03/02/2004	dwr cymru	24	1.00	12600	potential for contamination	Potential biological pathogens present	4	6	8	**5.94**
03/02/2004	United Utilities	12	0.50	28500	high ph	Chemical present above guidelines	8	8	4	**6.6**
03/02/2004	Northumbrian	72	3.00	22600	Discoloured water	Aesthetics problems and above guidelines	8	32	16	**18.48**
03/02/2004	dwr cymru	504	21.00	12900	high turbidity	Chemical present above guidelines	4	8	125	**45.21**
10/02/2004	dwr cymru	24	1.00	2000	Discoloured water	Aesthetics problems and above guidelines	2	32	8	**13.86**
11/02/2004	Yorkshire	7	0.29	700	Discoloured water	Aesthetics problems and above guidelines	2	32	2	**11.88**
20/02/2004	Wessex	24	1.00	2000	Discoloured water	Aesthetics problems and above guidelines	2	32	8	**13.86**
10/03/2004	Northumbrian	48	2.00	3500	Discoloured water	Aesthetics problems and above guidelines	2	32	16	**16.5**
15/03/2004	dwr cymru	72	3.00	2000	Discoloured water	Aesthetics problems and above guidelines	2	32	16	**16.5**
16/03/2004	United Utilities	48	2.00	5000	Discoloured water	Aesthetics problems and above guidelines	2	32	16	**16.5**

19/03/2004	United Utilities	24	1.00	21000	Discoloured water	Aesthetics problems and above guidelines	8	32	8	**15.84**
01/04/2004	Yorkshire	48	2.00	7500	Discoloured water	Aesthetics problems and above guidelines	2	32	16	**16.5**
05/04/2004	Northumbrian	48	2.00	540	Contamination of water	Potential biological pathogens present, health effects envisaged	2	48	16	**21.78**
16/04/2004	Wessex	24	1.00	500	Discoloured water	Aesthetics problems and above guidelines	2	32	8	**13.86**
16/04/2004	Yorkshire	48	2.00	4000	Aesthetics	Aesthetics problems and above guidelines	2	32	16	**16.5**
20/04/2004	Northumbrian	72	3.00	33200	Disinfection failure	Potential biological pathogens present, health effects envisaged	16	48	16	**26.4**
24/04/2004	Northumbrian	72	3.00	370	plant failure with potential contamination	Potential biological pathogens present, health effects envisaged	2	48	16	**21.78**
04/05/2004	Three Valleys	96	4.00	15	Wholesomeness concern	Potential unwholesome, potential low health effect	2	16	32	**16.5**
10/05/2004	Yorkshire	168	7.00	620	Microbiological contamination in distribution	Biological pathogens present	2	8	32	**13.86**
12/05/2004	dwr cymru	72	3.00	100000	Discoloured water	Aesthetics problems and above guidelines	32	32	16	**26.4**
15/05/2004	Thames	30	1.25	145000	Discoloured water	Aesthetics problems and above guidelines	64	32	8	**34.32**
17/05/2004	Southern	0	0.00	0	Potential contamination from raw water	Potential unwholesome, potential medium health effect	2	64	2	**22.44**
18/05/2004	Three Valleys	24	1.00	626000	low chlorine	Potential biological pathogens present	250	6	8	**87.12**
18/05/2004	United Utilities	168	7.00	673000	Discoloured water	Aesthetics problems and above guidelines	250	32	32	**103.62**
24/05/2004	Southern	72	3.00	150	potential contamination	Potential unwholesome, potential medium health effect	2	64	16	**27.06**
28/05/2004	Yorkshire	6	0.25	17	Disinfection failure	Potential biological pathogens present	2	6	2	**3.3**
29/05/2004	Yorkshire	72	3.00	50000	Discoloured water	Aesthetics problems and above guidelines	16	32	16	**21.12**
03/06/2004	Yorkshire	96	4.00	175	Microbiological contamination in distribution	Biological pathogens present, health effects envisaged	2	64	32	**32.34**
06/06/2004	Northumbrian	72	3.00	67500	Discoloured water	Aesthetics problems and above guidelines	32	32	16	**26.4**
06/06/2004	Sutton east surrey	48	2.00	20	Microbiological contamination in distribution	Biological pathogens present, health effects envisaged	2	64	16	**27.06**
10/06/2004	Southwest	312	13.00	115	Microbiological contamination in distribution	Biological pathogens present, health effects envisaged	2	64	64	**42.9**
13/06/2004	Essex and Suffolk	0	0.00		Plant failure affecting disinfection	Potential Biological pathogens present		6		**1.98**
13/06/2004	Northumbrian	48	2.00	4500	Discoloured water	Aesthetics problems and above guidelines	2	32	16	**16.5**
14/06/2004	Portsmouth	7	0.29	1500	Discoloured water	Aesthetics problems and above guidelines	2	32	2	**11.88**
14/06/2004	Yorkshire	72	3.00	13700	Discoloured water	Aesthetics problems and above guidelines	4	32	16	**17.16**

14/06/2004	dwr cymru	168	7.00	130000	Discoloured water	Aesthetics problems and above guidelines	64	32	32	**42.24**
30/06/2004	Essex and Suffolk	72	3.00	250	Loss of supply and potential contamination	Potential biological pathogens present, health effects envisaged	2	48	16	**21.78**
02/07/2004	Wessex	72	3.00	78000	Microbiological contamination in distribution	Biological pathogens present	32	8	16	**18.48**
14/07/2004	United Utilities	24	1.00	6700	Discoloured water	Aesthetics problems and above guidelines	2	32	8	**13.86**
18/07/2004	Northumbrian	24	1.00	5000	Discoloured water	Aesthetics problems and above guidelines	2	32	8	**13.86**
24/07/2004	United Utilities	24	1.00	29300	Disinfection failure	Potential biological pathogens present	8	6	8	**7.26**
25/07/2004	Northumbrian	72	3.00	73000	Discoloured water	Aesthetics problems and above guidelines	32	32	16	**26.4**
29/07/2004	Yorkshire	24	1.00	87500	Discoloured water	Aesthetics problems and above guidelines	32	32	8	**23.76**
30/07/2004	Yorkshire	144	6.00	6	Microbiological contamination in distribution	Biological pathogens present, health effects envisaged	2	64	32	**32.34**
05/08/2004	Bristol	48	2.00	60000	Discoloured water	Aesthetics problems and above guidelines	16	32	16	**21.12**
07/08/2004	Northumbrian	72	3.00	200	Microbiological contamination in distribution	Biological pathogens present, health effects envisaged	2	64	16	**27.06**
14/08/2004	Yorkshire	168	7.00	25	Contamination of water	Potential biological pathogens present, health effects envisaged	2	48	32	**27.06**
16/08/2004	Bristol	96	4.00	18900	Microbiological contamination in distribution	Biological pathogens present	8	8	32	**15.84**
19/08/2004	dwr cymru	288	12.00	5600	high colour	Chemical present above guidelines	2	8	64	**24.42**
21/08/2004	United Utilities	72	3.00	6200	Microbiological contamination in distribution	Biological pathogens present	2	8	16	**8.58**
21/08/2004	Yorkshire	96	4.00	320	Discoloured water	Aesthetics problems and above guidelines	2	32	32	**21.78**
21/08/2004	United Utilities	48	2.00	2500	Microbiological contamination in distribution	Biological pathogens present, health effects envisaged	2	64	16	**27.06**
28/08/2004	United Utilities	96	4.00	6300	Discoloured water	Aesthetics problems and above guidelines	2	32	32	**21.78**
31/08/2004	South East	24	1.00	0	No sample for crypto taken		2		8	**3.3**
31/08/2004	dwr cymru	120	5.00	3200	Microbiological contamination in distribution	Biological pathogens present, health effects envisaged	2	64	32	**32.34**
09/09/2004	United Utilities	96	4.00	12300	Discoloured water	Aesthetics problems and above guidelines	4	32	32	**22.44**
13/09/2004	dwr cymru	72	3.00	32500	Microbiological contamination in distribution	Biological pathogens present, health effects envisaged	16	64	16	**31.68**
15/09/2004	Yorkshire	12	0.50	5000	Discoloured water	Aesthetics problems and above guidelines	2	32	4	**12.54**
17/09/2004	Thames	168	7.00	11600	Microbiological contamination in distribution	Biological pathogens present	4	8	32	**14.52**
17/09/2004	Essex and Suffolk	4	0.17	460	Discoloured water	Aesthetics problems and above guidelines	2	32	2	**11.88**

25/09/2004	Yorkshire	96	4.00	41400	Discoloured water	Aesthetics problems and above guidelines	16	32	32	**26.4**
01/10/2004	Severn Trent	48	2.00	82000	Discoloured water	Aesthetics problems and above guidelines	32	32	16	**26.4**
04/10/2004	United Utilities	48	2.00	25000	Discoloured water	Aesthetics problems and above guidelines	8	32	16	**18.48**
07/10/2004	Bristol	48	2.00	9200	Discoloured water	Aesthetics problems and above guidelines	4	32	16	**17.16**
08/10/2004	Northumbrian	72	3.00	5300	Discoloured water	Aesthetics problems and above guidelines	2	32	16	**16.5**
15/10/2004	United Utilities	72	3.00	12800	Discoloured water	Aesthetics problems and above guidelines	4	32	16	**17.16**
21/10/2004	Northumbrian	504	21.00	22	Potential contamination (boil water notice)	Potential biological pathogens present, health effects envisaged	2	48	125	**57.75**
25/10/2004	Three Valleys	168	7.00	20	Microbiological contamination in distribution	biological pathogens present	2	8	32	**13.86**
25/10/2004	Severn Trent	28	1.17	164000	Microbiological contamination in distribution	Biological pathogens present	64	8	8	**26.4**
02/11/2004	South Staffordshire	15	0.63	19000	Discoloured water	Aesthetics problems and above guidelines	8	32	4	**14.52**
04/11/2004	dwr cymru	192	8.00	13300	Microbiological contamination in distribution	Biological pathogens present	4	8	64	**25.08**
08/11/2004	Bournemouth West Hampshire	1	0.04	0	Plant failure affecting disinfection	Potential Biological pathogens present	2	6	2	**3.3**
24/11/2004	Anglian	72	3.00	5	Microbiological contamination in distribution	Biological pathogens present	2	8	16	**8.58**
28/11/2004	Essex and Suffolk	24	1.00	1000	Potential contamination (boil water notice)	Potential biological pathogens present, health effects envisaged	2	48	8	**19.14**
07/12/2004	Yorkshire	48	2.00	100000	Discoloured water	Aesthetics problems and above guidelines	32	32	16	**26.4**
08/12/2004	Yorkshire	48	2.00	10000	Discoloured water	Aesthetics problems and above guidelines	4	32	16	**17.16**
09/12/2004	Sutton east surrey	24	1.00	10	high ph and odour	Chemical present above guidelines	2	8	8	**5.94**
14/12/2004	Yorkshire	10	0.42	30000	Discoloured water	Aesthetics problems and above guidelines	16	32	2	**16.5**
Average		**80.15**		**38372.05**			**15.34**	**30.20**	**20.63**	**21.59**
SD		**101.79**		**101868.36**			**39.01**	**17.25**	**23.44**	**15.47**
SE		**10.79**		**10798.02**			**4.13**	**1.83**	**2.48**	**1.64**
CI 95 min		**59.00**		**17207.92**			**7.24**	**26.62**	**15.75**	**18.38**
CI 95 max		**101.29**		**59536.17**			**23.44**	**33.79**	**25.50**	**24.80**

Table 2 Drinking Water Quality incidents 2004

Drinking Water Incidents 2005									Hazard score	Hazard score	Hazard score	
									0.333	0.333	0.333	
Date	Company	Duration in hrs	Days	Population	Hazard'	Boil notice/ Not to drink	Hazard categories	Unfit/ Breach of regulation	P	H	D	**Sum**
01/01/2005	southern	840	35.00	42500	Water quality failure / Pesticide	NA	Chemical present above guidelines	Breach	16	8	250	**91.24**
06/01/2005	United Utilities	24	1.00	96000	Water quality failure	NA	Potential unwholesome, potential low health effect	NA	32	8	8	**15.98**
07/01/2005	Thames	5	0.21	33181	Loss of supply, then disinfection failure	NA	loss of supply	NA	16	64	2	**27.31**
08/01/2005	Yorkshire	240	10.00	15035	Discoloured water	NA	Aesthetics problems and above guidelines	NA	8	32	64	**34.63**
09/01/2005	Yorkshire	8	0.33	17000	Discoloured water	Boil notice	Aesthetics problems and above guidelines	NA	8	32	2	**13.99**
09/01/2005	Yorkshire	8	0.33	17000	Discoloured water	NA	Aesthetics problems and above guidelines	NA	8	32	2	**13.99**
09/01/2005	Northumbrian	144	6.00	14903	Supply failure	NA	Potential biological pathogens present, health effects envisaged	NA	4	48	32	**27.97**
10/01/2005	Yorkshire	96	4.00	250	Disinfection failure	Boil notice	Potential biological pathogens present, health effects envisaged	Unfit/ Breach	2	48	32	**27.31**
12/01/2005	United Utilities	0	0.00	0	Sampling failure	NA		Breach	2		2	**1.33**
08/02/2005	Severn Trent	120	5.00	193980	Discoloured water	NA	Aesthetics problems and above guidelines	NA	64	32	32	**42.62**
09/02/2005	Northumbrian	24	1.00	19347	Discoloured water	NA	Aesthetics problems and above guidelines	NA	8	32	8	**15.98**
26/02/2005	United Utilities	48	2.00	52500	Discoloured water	NA	Aesthetics problems and above guidelines	NA	16	32	16	**21.31**
09/03/2005	Three Valleys	48	2.00	10	Aesthetics	NA	Aesthetics problems and above guidelines	Unfit	2	32	16	**16.65**
17/03/2005	Bristol	18	0.75	237	Discoloured water	NA	Aesthetics problems and above guidelines	NA	2	32	4	**12.65**
19/03/2005	Three Valleys	432	18.00	75	Aesthetics	NA	Chemical present above guidelines, health effects envisaged	Unfit/Breach	2	32	125	**52.95**
22/03/2005	United	12	0.50	23265	Discoloured water	NA	Aesthetics problems and above	NA	8	32	4	**14.65**

	Utilities						guidelines					
30/03/2005	Northumbrian	27	1.13	60248	Discoloured water	NA	Aesthetics problems and above guidelines	Potential unfit/Breach	16	32	8	**18.65**
31/03/2005	southern	3	0.13	0	Disinfection failure	NA	Potential biological pathogens present	Breach	2	6	2	**3.33**
13/04/2005	South Staffordshire	24	1.00	20000	Discoloured water	NA	Aesthetics problems and above guidelines	Breach	8	32	8	**15.98**
14/04/2005	Severn Trent	23	0.96	31000	Discoloured water	NA	Aesthetics problems and above guidelines	NA	16	32	4	**17.32**
26/04/2005	United Utilities	48	2.00	40000	Discoloured water	NA	Aesthetics problems and above guidelines	NA	16	32	16	**21.31**
26/04/2005	Essex and Suffolk	48	2.00	300000	Aesthetics	NA	Aesthetics problems and above guidelines	NA	125	32	16	**57.61**
29/04/2005	Folkestone Dover	144	6.00	25	Disinfection failure, boil notice	Boil notice	Potential biological pathogens present, health effects envisaged	NA	2	48	32	**27.31**
06/05/2005	Three Valleys	1512	63.00	68912	Water quality failure / Pesticide	NA	Chemical present above guidelines, health effects envisaged	Breach	32	32	500	**187.81**
11/05/2005	dwr cymru	48	2.00	8000	Discoloured water	NA	Aesthetics problems and above guidelines	Breach	4	32	16	**17.32**
12/05/2005	Thames	3360	140.00	9775	Discoloured water	NA	Aesthetics problems and above guidelines	NA	4	32	1000	**344.99**
20/05/2005	United Utilities	48	2.00	32000	Discoloured water	NA	Aesthetics problems and above guidelines	NA	16	32	16	**21.31**
25/05/2005	Yorkshire	30	1.25	4540	Discoloured water	NA	Aesthetics problems and above guidelines	NA	2	32	8	**13.99**
26/05/2005	United Utilities	24	1.00	20783	Discoloured water	NA	Aesthetics problems and above guidelines	NA	8	32	8	**15.98**
27/05/2005	Northumbrian	13	0.54	4994	Discoloured water	NA	Aesthetics problems and above guidelines	NA	2	32	4	**12.65**
03/06/2005	Wessex	168	7.00	12000	Microbiological contamination in distribution	NA	Biological pathogens present	Breach	4	8	32	**14.65**
03/06/2005	Anglian	48	2.00	10250	Discoloured water	NA	Aesthetics problems and above guidelines	NA	4	32	16	**17.32**
06/06/2005	Anglian	20	0.83	937	Discoloured water	NA	Aesthetics problems and above guidelines	NA	2	32	4	**12.65**
07/06/2005	Severn Trent	48	2.00	76	Discoloured water	NA	Aesthetics problems and above guidelines	NA	2	32	16	**16.65**
07/06/2005	Northumbrian	48	2.00	11952	Discoloured water	NA	Aesthetics problems and above guidelines	NA	4	32	16	**17.32**

10/06/2005	United Utilities	6	0.25	32500	Discoloured water	NA	Aesthetics problems and above guidelines	NA	16	32	2	**16.65**
14/06/2005	Severn Trent	72	3.00	7	Contamination of water, not to drink notice	Not to drink	Potential biological pathogens present, health effects envisaged	NA	2	48	16	**21.98**
21/06/2005	South East	48	2.00	250	Discoloured water	NA	Aesthetics problems and above guidelines	NA	2	32	16	**16.65**
24/06/2005	Severn Trent	50	2.08	465	Disinfection failure	NA	Potential biological pathogens present	Breach	2	6	16	**7.99**
29/06/2005	United Utilities	216	9.00	18832	Discoloured water	NA	Aesthetics problems and above guidelines	NA	8	32	64	**34.63**
06/07/2005	United Utilities	24	1.00	21548	Discoloured water	NA	Aesthetics problems and above guidelines	NA	8	32	8	**15.98**
07/07/2005	South East	144	6.00	200	Microbiological contamination in distribution	NA	Biological pathogens present, health effects envisaged	Unfit/ Breach	2	64	32	**32.63**
08/07/2005	southern	72	3.00	725	Microbiological contamination in distribution	Boil notice	Biological pathogens present, health effects envisaged	NA	2	64	16	**27.31**
18/07/2005	southern	48	2.00	146627	Water quality failure	NA	Chemical present above guidelines	NA	64	8	16	**29.30**
22/07/2005	Thames	120	5.00	87	Aesthetics	NA	Aesthetics problems and above guidelines	NA	2	32	32	**21.98**
27/07/2005	Anglian	0.5	0.02	16411	Loss chlorination	NA	Potential biological pathogens present	NA	8	6	2	**5.33**
28/07/2005	United Utilities	10	0.42		Disinfection failure	NA	Potential biological pathogens present	NA		6	2	**2.66**
29/07/2005	United Utilities	13	0.54	5000	Discoloured water	NA	Aesthetics problems and above guidelines	NA	2	32	4	**12.65**
01/08/2005	dwr cymru	672	28.00	125000	Aesthetics	NA	Aesthetics problems and above guidelines	NA	64	32	125	**73.59**
09/08/2005	South Staffordshire	9	0.38	7400	Discoloured water	NA	Aesthetics problems and above guidelines	NA	2	32	2	**11.99**
16/08/2005	Thames	96	4.00	350	Aesthetics	NA	Aesthetics problems and above guidelines	NA	2	32	32	**21.98**
17/08/2005	Anglian	72	3.00	5000	Microbiological contamination in distribution	NA	Biological pathogens present	NA	2	8	16	**8.66**
20/08/2005	Essex and Suffolk	96	4.00	30	Microbiological contamination in distribution	Boil notice	Biological pathogens present	NA	2	8	32	**13.99**
20/08/2005	southern	2	0.08	15200	Loss of supply, then discoloration	NA	Aesthetics problems and above guidelines	NA	8	32	2	**13.99**

23/08/2005	Severn Trent	24	1.00	67905	Microbiological contamination in distribution	NA	Biological pathogens present	NA	32	8	8	**15.98**
24/08/2005	Anglian	120	5.00	162	Microbiological contamination in distribution	Boil notice	Biological pathogens present, health effects envisaged	NA	2	64	32	**32.63**
26/08/2005	Thames	48	2.00	6500	Loss of supply	NA	loss of supply	NA	2	16	16	**11.32**
26/08/2005	Northumbrian	11	0.46	6792	Discoloured water	NA	Aesthetics problems and above guidelines	NA	2	32	2	**11.99**
26/08/2005	Yorkshire	96	4.00	190	Microbiological contamination in distribution, boil notice	Boil notice	Biological pathogens present, health effects envisaged	NA	2	64	32	**32.63**
31/08/2005	United Utilities	96	4.00	50000	Discoloured water	NA	Aesthetics problems and above guidelines	NA	16	32	32	**26.64**
05/09/2005	Severn Trent	1344	56.00	870000	Microbiological contamination in distribution	NA	Biological pathogens present	NA	250	8	250	**169.16**
09/09/2005	Northumbrian	48	2.00	43	high turbidity and potential ingress	Boil notice	Chemical present above guidelines, health effects envisaged	NA	2	32	16	**16.65**
10/09/2005	Anglian	168	7.00	470	Microbiological contamination in distribution	Boil notice	Biological pathogens present, health effects envisaged	NA	2	64	32	**32.63**
12/09/2005	Wessex	120	5.00	500	Microbiological contamination in distribution	NA	Biological pathogens present	NA	2	8	32	**13.99**
12/09/2005	Yorkshire	432	18.00	75	Microbiological contamination in distribution, do not drink	NA	Biological pathogens present, health effects envisaged	NA	2	64	125	**63.60**
19/09/2005	dwr cymru	72	3.00	2000	Microbiological contamination in distribution	NA	Biological pathogens present	NA	2	8	16	**8.66**
22/09/2005	Wessex	1176	49.00	34000	Water quality failure, aesthetics, algae bloom in res,	NA	Aesthetics problems and above guidelines	Potential unfit	16	32	250	**99.23**
03/10/2005	Portsmouth	0	0.00	0	Cryptosporidium detected in population	Boil notice	Potential biological pathogens present, health effects envisaged	NA	2	48	2	**17.32**
05/10/2005	Severn Trent	16	0.67	8422	Disinfection failure	NA	Potential biological pathogens present	NA	4	6	4	**4.66**
05/10/2005	Northumbrian	72	3.00	93070	Discoloured water	NA	Aesthetics problems and above guidelines	NA	32	32	16	**26.64**

08/10/2005	Yorkshire	12	0.50	6700	Discoloured water	NA	Aesthetics problems and above guidelines	NA	2	32	4	**12.65**
10/10/2005	dwr cymru	168	7.00	12000	Discoloured water	NA	Aesthetics problems and above guidelines	Breach	4	32	32	**22.64**
17/10/2005	Sutton east surrey	72	3.00	0	Microbiological contamination in distribution	NA	Biological pathogens present	NA	2	8	16	**8.66**
04/11/2005	dwr cymru	2016	84.00	70000	Cryptosporidium detected in population	Boil notice	Biological pathogens present, health effects envisaged	NA	32	64	500	**198.47**
08/11/2005	Northumbrian	96	4.00	67500	Discoloured water	NA	Aesthetics problems and above guidelines	NA	32	32	32	**31.97**
10/11/2005	dwr cymru	1008	42.00	2	Microbiological contamination in distribution	Boil notice	Biological pathogens present, health effects envisaged	NA	2	64	250	**105.23**
11/11/2005	dwr cymru	120	5.00	28000	Discoloured water	NA	Aesthetics problems and above guidelines	NA	8	32	32	**23.98**
14/11/2005	dwr cymru	96	4.00	180	Microbiological contamination in distribution	NA	Biological pathogens present	NA	2	8	32	**13.99**
15/11/2005	Wessex	48	2.00	5	Precautionary measure	Boil notice	Potential biological pathogens present, health effects envisaged	Potential unfit	2	48	16	**21.98**
17/11/2005	United Utilities	8	0.33	200	Aesthetics	Not to drink	Aesthetics problems and above guidelines	NA	2	32	2	**11.99**
18/11/2005	Yorkshire	12	0.50	250	Water quality failure	NA	Potential unwholesome, potential low health effect	NA	2	8	4	**4.66**
22/11/2005	Severn Trent	144	6.00	1250	Discoloured water	NA	Aesthetics problems and above guidelines	NA	2	32	32	**21.98**
24/11/2005	Sutton east surrey	25	1.04	3750	Discoloured water	NA	Aesthetics problems and above guidelines	NA	2	32	8	**13.99**
02/12/2005	Anglian	144	6.00	625	Microbiological contamination in distribution	NA	Biological pathogens present	NA	2	8	32	**13.99**
09/12/2005	Sutton east surrey	15	0.63	2030	Discoloured water	NA	Aesthetics problems and above guidelines	NA	2	32	4	**12.65**
12/12/2005	Severn Trent	24	1.00	8542	Microbiological contamination in distribution	NA	Biological pathogens present	NA	4	8	8	**6.66**
14/12/2005	southern	8	0.33	10500	Loss of supply, then disinfection failure	NA	Potential biological pathogens present	NA	4	6	2	**4.00**

15/12/2005	Three Valleys	216	9.00	4750	Water quality failure, chemical, process failure	NA	Chemical present above guidelines	NA	2	8	64	**24.64**
16/12/2005	United Utilities	5	0.21	12500	Discoloured water	NA	Aesthetics problems and above guidelines	NA	4	32	2	**12.65**
16/12/2005	Severn Trent	24	1.00	35250	Discoloured water	NA	Aesthetics problems and above guidelines	NA	16	32	8	**18.65**
17/12/2005	Wessex	24	1.00	34000	Water quality failure, pesticide	NA	Chemical present above guidelines	NA	16	8	8	**10.66**
20/12/2005	Essex and Suffolk	72	3.00	52	Microbiological contamination in distribution	Boil notice	Biological pathogens present, health effects envisaged	NA	2	64	16	**27.31**
23/12/2005	Severn Trent	72	3.00	324000	Microbiological contamination in distribution	NA	Biological pathogens present	NA	125	8	16	**49.62**
Average		**191.33**		**36071.98**					**14.20**	**29.96**	**50.98**	**31.52**
SD		**472.44**		**103239.75**					**32.79**	**16.93**	**131.66**	**47.60**
SE		**48.99**	**0.00**	**10705.46**					**3.40**	**1.76**	**13.65**	**4.94**
CI 95 min		**95.31**	**0.00**	**15089.27**					**7.53**	**26.52**	**24.22**	**21.85**
CI 95 max		**287.35**	**0.00**	**57054.69**					**20.86**	**33.40**	**77.74**	**41.20**

Table 3 Drinking Water Quality incidents 2005

Drinking Water incidents 2006								Hazard score	Hazard score	Hazard score	
								0.333	0.333	0.333	
Date	Company	Duration in hrs	Days	Population	Hazard'	Boil notice/ Not to drink	Hazard categories	P	H	D	**Sum**
29/12/05	Severn Trent	72	3.00	215,415	Microbiological contamination in distribution		Biological pathogens present	125	8	16	**49.62**
09/01/06	Tendring	312	13.00	52,493	Water quality failure		Chemicals present above guidelines	16	8	64	**29.30**
10/01/06	Anglian	312	13.00	132,826	Water quality failure		Chemicals present above guidelines	64	8	64	**45.29**
15/01/06	Anglian	24	1.00	5,655	Discolouration		Aesthetics above guidelines	2	32	4	**12.65**
23/01/06	Dwr Cymru	72	3.00	11,000	Loss of supply, then discoloration		Aesthetics above guidelines	4	32	16	**17.32**
27/01/06	United Utilities	12	0.50	457,500	plant failure with potential contamination		Aesthetics above guidelines	125	32	2	**52.95**
31/01/06	Yorkshire	96	4.00	10,000	Water quality failure, chemical, process failure		Chemicals present above guidelines	4	8	16	**9.32**
06/02/06	South West	144	6.00	6,250	taste and odour		Aesthetics above guidelines	2	32	32	**21.98**
07/02/06	Southern	14	0.58	130,400	Plant failure affecting disinfection		Chemicals present above guidelines	64	8	4	**25.31**
16/02/06	Dwr Cymru	48	2.00	1,069	Discolouration		Aesthetics above guidelines	2	32	8	**13.99**
17/02/06	Wessex	24	1.00	3,150	Discolouration		Aesthetics above guidelines	2	32	4	**12.65**
13/03/06	Wessex	18	0.75	500	Discolouration		Aesthetics above guidelines	2	32	4	**12.65**
17/03/06	Southern	9	0.38	0	Plant failure affecting disinfection		Potential biological pathogens present	2	6	2	**3.33**
19/03/06	Severn Trent	24	1.00	142	plant failure with potential contamination	Boil notice	Potential biological pathogens present	2	6	4	**4.00**
28/03/06	Yorkshire	5	0.21	13,597	Discolouration		Aesthetics above guidelines	4	32	2	**12.65**
02/04/06	Dwr Cymru	48	2.00	5,941	Discolouration		Aesthetics above guidelines	2	32	8	**13.99**
07/04/06	Northumbrian	48	2.00	5,702	Discolouration		Aesthetics above guidelines	2	32	8	**13.99**
12/04/06	Dwr Cymru	24	1.00	23,000	Discolouration		Aesthetics above guidelines	8	32	4	**14.65**
13/04/06	Southern	12	0.50	2,000	Loss of supply		Loss of supply	2	16	2	**6.66**
21/04/06	Dwr Cymru	72	3.00	100,000	Water quality failure, chemical, process failure		Chemicals present above guidelines	32	8	16	**18.65**
23/04/06	Cambridge	24	1.00	30,000	Discolouration		Aesthetics above guidelines	8	32	4	**14.65**
04/05/06	South East	48	2.00	30,919	Discolouration		Aesthetics above guidelines	16	32	8	**18.65**
05/05/06	South West	48	2.00	1,000	Water quality failure	Not to drink	Chemicals present above guidelines, health effects envisaged	2	32	8	**13.99**
18/05/06	Yorkshire	24	1.00	78,000	Discolouration		Aesthetics above guidelines	32	32	4	**22.64**

19/05/06	Severn Trent	120	5.00	10	Microbiological contamination in distribution		Biological pathogens present	2	8	32	**13.99**
22/05/06	United Utilities	4	0.17	282	Disinfection failure		Potential biological pathogens present	2	6	2	**3.33**
23/05/06	Severn Trent	20	0.83	5290	Loss of supply		Loss of supply	2	16	4	**7.33**
26/05/06	Anglian	4200	175.00	30	Contamination of water, not to drink notice	Not to drink	Chemicals present above guidelines, health effects envisaged	2	32	1000	**344.32**
05/06/06	Yorkshire	33600	1400.00	3	taste and odour		Aesthetics above guidelines	2	32	1000	**344.32**
05/06/06	Three Valleys	4	0.17	1,250	Plant failure affecting disinfection		Potential biological pathogens present	2	6	2	**3.33**
06/06/06	Northumbrian	20	0.83	2,500	Discolouration		Aesthetics above guidelines	2	32	4	**12.65**
08/06/06	Southern	24	1.00	100,300	Water quality failure, pesticide		Chemicals present above guidelines	32	8	4	**14.65**
11/06/06	Yorkshire	44	1.83	6,250	Discolouration		Aesthetics above guidelines	2	32	8	**13.99**
15/06/06	Wessex	22	0.92	3,865	Discolouration		Aesthetics above guidelines	2	32	4	**12.65**
17/06/06	Yorkshire	144	6.00	193	Microbiological contamination in distribution		Biological pathogens present	2	8	32	**13.99**
23/06/06	United Utilities	8	0.33	32,500	Discolouration		Aesthetics above guidelines	16	32	2	**16.65**
30/06/06	Bournemouth West Hampshire	48	2.00	25	Microbiological contamination in distribution	Boil notice	Biological pathogens present, health effects envisaged	2	64	8	**24.64**
03/07/06	Severn Trent	10	0.42	20,000	Loss of supply		Loss of supply	8	16	2	**8.66**
03/07/06	Severn Trent	1.5	0.06	1,370,000	Disinfection failure		Potential biological pathogens present	500	6	2	**169.16**
04/07/06	Yorkshire	11	0.46	6,747	Discolouration		Aesthetics above guidelines	2	32	2	**11.99**
12/07/06	Dwr Cymru	48	2.00	20,000	Discolouration		Aesthetics above guidelines	8	32	8	**15.98**
16/07/06	Dwr Cymru	48	2.00	27,000	Water quality failure, chemical, process failure		Chemicals present above guidelines	8	8	8	**7.99**
18/07/06	South West	5	0.21	57,500	Disinfection failure		Potential biological pathogens present	16	6	2	**7.99**
25/07/06	South Staffordshire	12	0.50	20,000	Discolouration		Aesthetics above guidelines	8	32	2	**13.99**
27/07/06	Severn Trent	24	1.00	51,000	Disinfection failure		Potential biological pathogens present	16	6	4	**8.66**
30/07/06	Essex and Suffolk	96	4.00	43	Contamination of water, not to drink notice	Boil notice	Potential biological pathogens present, health effects envisaged	2	48	16	**21.98**
31/07/06	Anglian	360	15.00	33	Potential contamination (boil water notice)	Boil notice	Potential biological pathogens present, health effects envisaged	2	48	64	**37.96**
03/08/06	South West	12	0.50	5	Disinfection failure		Chemicals present above guidelines, health effects envisaged	2	32	2	**11.99**
04/08/06	Sutton East Surrey	840	35.00	275	Microbiological contamination in distribution	Boil notice	Biological pathogens present, health effects envisaged	2	64	250	**105.23**
06/08/06	South West	48	2.00	175	Microbiological contamination in distribution	Boil notice	Biological pathogens present, health effects envisaged	2	64	8	**24.64**

09/08/06	Northumbrian	72	3.00	10,647	Discolouration		Aesthetics above guidelines	4	32	16	**17.32**
11/08/06	United Utilities	840	35.00	85,569	taste and odour		Aesthetics above guidelines	32	32	250	**104.56**
11/08/06	South East	3	0.13	11,684	Discolouration		Aesthetics above guidelines	4	32	2	**12.65**
11/08/06	Thames	816	34.00	3	taste and odour		Aesthetics above guidelines	2	32	250	**94.57**
16/08/06	Yorkshire	24	1.00	93,000	Plant failure affecting disinfection		Chemicals present above guidelines	32	8	4	**14.65**
17/08/06	United Utilities	168	7.00	4,503	plant failure with potential contamination		Potential biological pathogens present	2	6	32	**13.32**
18/08/06	Wessex	168	7.00	13,600	aesthetics (algae in raw water_)		Aesthetics above guidelines	4	32	32	**22.64**
19/08/06	Severn Trent	48	2.00	6,000	Loss of supply		Loss of supply	2	16	8	**8.66**
24/08/06	Anglian	48	2.00	4,835	Microbiological contamination in distribution		Biological pathogens present	2	8	8	**5.99**
24/08/06	Folkestone	528	22.00	11,995	Discolouration		Aesthetics above guidelines	4	32	125	**53.61**
26/08/06	Yorkshire	12	0.50	62,500	Disinfection failure		Potential biological pathogens present	32	6	2	**13.32**
06/09/06	United Utilities	9	0.38	575	Disinfection failure		Potential biological pathogens present	2	6	2	**3.33**
06/09/06	Dwr Cymru	48	2.00	10,000	Microbiological contamination in distribution		Biological pathogens present	4	8	8	**6.66**
15/09/06	Thames	48	2.00	14,000	Discolouration		Aesthetics above guidelines	4	32	8	**14.65**
23/09/06	Anglian	288	12.00	150	Microbiological contamination in distribution		Biological pathogens present	2	8	64	**24.64**
25/09/06	Wessex	96	4.00	5	Microbiological contamination in distribution	Boil notice	Biological pathogens present, health effects envisaged	2	64	16	**27.31**
28/09/06	Three Valleys	5712	238.00	88	Discolouration		Aesthetics above guidelines	2	32	1000	**344.32**
28/09/06	Sutton East Surrey	96	4.00	10	Microbiological contamination in distribution	Boil notice	Biological pathogens present, health effects envisaged	2	64	16	**27.31**
02/10/06	Anglian	840	35.00	8	Aesthetics		Aesthetics above guidelines	2	32	250	**94.57**
03/10/06	Three Valleys	96	4.00	150	Microbiological contamination in distribution	Boil notice	Biological pathogens present, health effects envisaged	2	64	16	**27.31**
07/10/06	United Utilities	72	3.00	103	Microbiological contamination in distribution		Biological pathogens present	2	8	16	**8.66**
09/10/06	Northumbrian	72	3.00	23	Microbiological contamination in distribution	Boil notice	Biological pathogens present, health effects envisaged	2	64	16	**27.31**
09/10/06	Three Valleys	48	2.00	120,000	Water quality failure, chemical, process failure		Chemicals present above guidelines	32	8	8	**15.98**
12/10/06	Dwr Cymru	72	3.00	8	Microbiological contamination in distribution		Biological pathogens present	2	8	16	**8.66**
14/10/06	Dwr Cymru	48	2.00	50,000	Discolouration		Aesthetics above guidelines	16	32	8	**18.65**
15/10/06	Severn Trent	9	0.38	44,623	Discolouration		Aesthetics above guidelines	16	32	2	**16.65**
15/10/06	Three Valleys	288	12.00	200	Microbiological contamination in distribution		Biological pathogens present	2	8	64	**24.64**
26/10/06	Southern	768	32.00	150,000	taste and odour		Aesthetics above guidelines	64	32	125	**73.59**
31/10/06	United Utilities	2856	119.00	110,323	taste and odour		Aesthetics above guidelines	32	32	500	**187.81**

01/11/06	South East	7	0.29	12,500	Discolouration		Aesthetics above guidelines	4	32	2	**12.65**
05/11/06	Yorkshire	2	0.08	210,000	Disinfection failure		Potential biological pathogens present	125	6	2	**44.29**
13/11/06	Thames	0	0.00	0	Plant failure affecting disinfection		Chemicals present above guidelines	2	8	2	**4.00**
19/11/06	United Utilities	36	1.50	33,695	Loss of supply		Loss of supply	16	16	8	**13.32**
20/11/06	Mid Kent	6	0.25	30,000	Discolouration		Aesthetics above guidelines	8	32	2	**13.99**
24/11/06	Northumbrian	24	1.00	3,000	Discolouration		Aesthetics above guidelines	2	32	4	**12.65**
29/11/06	Anglian	96	4.00	6,000	Discolouration		Aesthetics above guidelines	2	32	16	**16.65**
29/11/06	Three Valleys	0	0.00	8	Discolouration		Aesthetics above guidelines	2	32	2	**11.99**
01/12/06	Dwr Cymru	24	1.00	3	Microbiological contamination in distribution	Boil notice	Biological pathogens present, health effects envisaged	2	64	4	**23.31**
04/12/06	Dwr Cymru	24	1.00	3	Microbiological contamination in distribution	Boil notice	Biological pathogens present, health effects envisaged	2	64	4	**23.31**
08/12/06	South East	48	2.00	0	Microbiological contamination in distribution		Potential biological pathogens present	2	6	8	**5.33**
09/12/06	Thames	360	15.00	175	taste and odour		Aesthetics above guidelines	2	32	64	**32.63**
11/12/06	United Utilities	24	1.00	1,600	Discolouration		Aesthetics above guidelines	2	32	4	**12.65**
12/12/06	Dwr Cymru	13	0.54	100,000	Water quality failure, chemical, process failure		Chemicals present above guidelines	32	8	4	**14.65**
19/12/06	Severn Trent	0	0.00	85,000	Microbiological contamination in distribution		Biological pathogens present	32	8	2	**13.99**
20/12/06	Dwr Cymru	24	1.00	8,000	Discolouration		Aesthetics above guidelines	4	32	4	**13.32**
22/12/06	Southern	6	0.25	14,607	Loss of supply		Loss of supply	4	16	2	**7.33**
31/12/06	Colderton district	48	2.00	1,500	Disinfection failure	Not to drink	Chemicals present above guidelines, health effects envisaged	2	32	8	**13.99**
Average		**579.82**	**24.16**	**44871.42**				**17.78**	**25.90**	**59.61**	**34.40**
SD		**3475.06**	**144.79**	**149689.42**				**55.12**	**17.04**	**183.18**	**63.32**
SE		**352.84**	**14.70**	**15198.66**				**5.60**	**1.73**	**18.60**	**6.43**
CI 95 min		**-111.75**	**-4.66**	**15082.05**				**6.81**	**22.51**	**23.15**	**21.79**
CI 95 max		**1271.38**	**52.97**	**74660.79**				**28.75**	**29.29**	**96.06**	**47.00**

Table 4 Drinking Water quality incidents 2006

3.2.1.3 Incidents in England and Wales according to hazard type

2004	**Aesthetics**					**Biological pathogens present**					**Biological pathogens present, health effects**			
Number	P	H	D	Sum		P	H	D	Sum		P	H	D	Sum
1	2	32	8	13.86		2	8	32	**13.86**		2	64	32	**32.34**
2	8	32	16	18.48		32	8	16	**18.48**		2	64	16	**27.06**
3	8	32	16	18.48		8	8	32	**15.84**		2	64	64	**42.9**
4	2	32	2	11.88		2	8	16	**8.58**		2	64	32	**32.34**
5	32	32	125	62.37		4	8	32	**14.52**		2	64	16	**27.06**
6	2	32	8	13.86		2	8	32	**13.86**		2	64	16	**27.06**
7	8	32	16	18.48		64	8	8	**26.4**		2	64	32	**32.34**
8	2	32	8	13.86		4	8	64	**25.08**		16	64	16	**31.68**
9	2	32	2	11.88		2	8	16	**8.58**		2	48	16	**21.78**
10	2	32	8	13.86		2	6	16	**7.92**		16	48	16	**26.4**
11	2	32	16	16.5		4	6	8	**5.94**		2	48	16	**21.78**
12	2	32	16	16.5		250	6	8	**87.12**		2	48	16	**21.78**
13	2	32	16	16.5		2	6	2	**3.3**		2	48	32	**27.06**
14	8	32	8	15.84			6		**1.98**		2	48	125	**57.75**
15	2	32	16	16.5		8	6	8	**7.26**		2	48	8	**19.14**
16	2	32	8	13.86		2	6	2	**3.3**					
17	2	32	16	16.5										
18	32	32	16	26.4										
19	64	32	8	34.32										
20	250	32	32	103.62										
21	16	32	16	21.12										
22	32	32	16	26.4										
23	2	32	16	16.5										
24	2	32	2	11.88										
25	4	32	16	17.16										
26	64	32	32	42.24										
27	2	32	8	13.86										

28	2	32	8	13.86										
29	32	32	16	26.4										
30	32	32	8	23.76										
31	16	32	16	21.12										
32	2	32	32	21.78										
33	2	32	32	21.78										
34	4	32	32	22.44										
35	2	32	4	12.54										
36	2	32	2	11.88										
37	16	32	32	26.4										
38	32	32	16	26.4										
39	8	32	16	18.48										
40	4	32	16	17.16										
41	2	32	16	16.5										
42	4	32	16	17.16										
43	8	32	4	14.52										
44	32	32	16	26.4										
45	4	32	16	17.16										
46	16	32	2	16.5										
Average	**16.87**	**32.00**	**16.67**	**21.63**		**25.87**	**7.13**	**19.47**	**16.38**		**3.87**	**56.53**	**30.20**	**29.90**
SD	**38.40**	**0.00**	**18.44**	**15.21**		**64.25**	**1.02**	**16.47**	**20.23**		**4.93**	**8.26**	**29.58**	**9.72**
SE	**5.66**	**0.00**	**2.72**	**2.24**		**16.06**	**0.26**	**4.12**	**5.06**		**1.27**	**2.13**	**7.64**	**2.51**
CI 95 min	**5.77**	**32.00**	**11.34**	**17.23**		**-5.61**	**6.62**	**11.40**	**6.47**		**1.37**	**52.35**	**15.23**	**24.98**
CI 95 max	**27.97**	**32.00**	**22.00**	**26.02**		**57.35**	**7.63**	**27.53**	**26.29**		**6.36**	**60.71**	**45.17**	**34.82**
N0				**46**					**16**					**15**

Table 5 Drinking water incidents for 2004 by hazard category (selection)

2005	Aesthetics					Biological pathogens present					Biological pathogens present, health effects			
Number	P	H	D	Sum		P	H	D	Sum		P	H	D	Sum
1	8	32	64	34.632		4	8	32	14.652		2	64	32	32.634
2	8	32	2	13.986		2	8	16	8.658		2	64	16	27.306
3	8	32	2	13.986		2	8	32	13.986		2	64	32	32.634
4	64	32	32	42.624		32	8	8	15.984		2	64	32	32.634
5	8	32	8	15.984		250	8	250	169.164		2	64	32	32.634
6	16	32	16	21.312		2	8	32	13.986		2	64	125	63.603
7	2	32	16	16.65		2	8	16	8.658		32	64	500	198.468
8	2	32	4	12.654		2	8	16	8.658		2	64	250	105.228
9	8	32	4	14.652		2	8	32	13.986		2	64	16	27.306
10	16	32	8	18.648		2	8	32	13.986		4	48	32	27.972
11	8	32	8	15.984		4	8	8	6.66		2	48	32	27.306
12	16	32	4	17.316		125	8	16	49.617		2	48	32	27.306
13	16	32	16	21.312		2	6	2	3.33		2	48	16	21.978
14	125	32	16	57.609		2	6	16	7.992		2	48	2	17.316
15	4	32	16	17.316		8	6	2	5.328		2	48	16	21.978
16	4	32	1000	344.988			6	2	2.664					
17	16	32	16	21.312		4	6	4	4.662					
18	2	32	8	13.986		4	6	2	3.996					
19	8	32	8	15.984										
20	2	32	4	12.654										
21	4	32	16	17.316										
22	2	32	4	12.654										
23	2	32	16	16.65										
24	4	32	16	17.316										
25	16	32	2	16.65										
26	2	32	16	16.65										
27	8	32	64	34.632										

28	8	32	8	15.984										
29	2	32	32	21.978										
30	2	32	4	12.654										
31	64	32	125	73.593										
32	2	32	2	11.988										
33	2	32	32	21.978										
34	8	32	2	13.986										
35	2	32	2	11.988										
36	16	32	32	26.64										
37	16	32	250	99.234										
38	32	32	16	26.64										
39	2	32	4	12.654										
40	4	32	32	22.644										
41	32	32	32	31.968										
42	8	32	32	23.976										
43	2	32	2	11.988										
44	2	32	32	21.978										
45	2	32	8	13.986										
46	2	32	4	12.654										
47	4	32	2	12.654										
48	16	32	8	18.648										
Average	**12.65**	**32.00**	**42.65**	**29.07**		**26.41**	**7.33**	**28.78**	**20.33**		**4.13**	**57.60**	**77.67**	**46.42**
SD	**21.32**	**0.00**	**146.64**	**49.33**		**64.93**	**0.97**	**56.44**	**38.58**		**7.73**	**8.11**	**132.51**	**47.42**
SE	**3.08**	**0.00**	**21.17**	**7.12**		**15.30**	**0.23**	**13.30**	**9.09**		**1.99**	**2.09**	**34.21**	**12.24**
CI 95 min	**6.61**	**32.00**	**1.16**	**15.11**		**-3.58**	**6.89**	**2.70**	**2.51**		**0.22**	**53.49**	**10.61**	**22.42**
CI 95 max	**18.68**	**32.00**	**84.13**	**43.02**		**56.41**	**7.78**	**54.85**	**38.16**		**8.04**	**61.71**	**144.73**	**70.42**
N0				**48**					**18**					**15**

Table 6 Drinking water quality incident in 2005 by hazard category (selection)

2006	**Aesthetics**					**Biological pathogens present**					**Biological pathogens present, health effects**			
Number	P	H	D	Sum		P	H	D	Sum		P	H	D	Sum
1	2	32	4	12.654		125	8	16	49.617		2	64	8	24.642
2	4	32	16	17.316		2	8	32	13.986		2	64	250	105.228
3	125	32	2	52.947		2	8	32	13.986		2	64	8	24.642
4	2	32	32	21.978		2	8	8	5.994		2	64	16	27.306
5	2	32	8	13.986		4	8	8	6.66		2	64	16	27.306
6	2	32	4	12.654		2	8	64	24.642		2	64	16	27.306
7	2	32	4	12.654		2	8	16	8.658		2	64	16	27.306
8	4	32	2	12.654		2	8	16	8.658		2	64	4	23.31
9	2	32	8	13.986		2	8	64	24.642		2	64	4	23.31
10	2	32	8	13.986		32	8	2	13.986		2	48	16	21.978
11	8	32	4	14.652		2	6	2	3.33		2	48	64	37.962
12	8	32	4	14.652		2	6	4	3.996					
13	16	32	8	18.648		2	6	2	3.33					
14	32	32	4	22.644		2	6	2	3.33					
15	2	32	1000	344.322		500	6	2	169.164					
16	2	32	4	12.654		16	6	2	7.992					
17	2	32	8	13.986		16	6	4	8.658					
18	2	32	4	12.654		2	6	32	13.32					
19	16	32	2	16.65		32	6	2	13.32					
20	2	32	2	11.988		2	6	2	3.33					
21	8	32	8	15.984		125	6	2	44.289					
22	8	32	2	13.986		2	6	8	5.328					
23	4	32	16	17.316										
24	32	32	250	104.562										
25	4	32	2	12.654										
26	2	32	250	94.572										
27	4	32	32	22.644										
28	4	32	125	53.613										

29	4	32	8	14.652										
30	2	32	1000	344.322										
31	2	32	250	94.572										
32	16	32	8	18.648										
33	16	32	2	16.65										
34	64	32	125	73.593										
35	32	32	500	187.812										
36	4	32	2	12.654										
37	8	32	2	13.986										
38	2	32	4	12.654										
39	2	32	16	16.65										
40	2	32	2	11.988										
41	2	32	64	32.634										
42	2	32	4	12.654										
43	4	32	4	13.32										
Average	**10.81**	**32.00**	**88.47**	**43.72**		**39.91**	**6.91**	**14.64**	**20.46**		**2.00**	**61.09**	**38.00**	**33.66**
SD	**21.45**	**0.00**	**225.72**	**75.43**		**108.86**	**1.02**	**19.00**	**35.48**		**0.00**	**6.47**	**72.22**	**24.12**
SE	**3.27**	**0.00**	**34.42**	**11.50**		**23.21**	**0.22**	**4.05**	**7.57**		**0.00**	**1.95**	**21.77**	**7.27**
CI 95 min	**4.40**	**32.00**	**21.00**	**21.17**		**-5.58**	**6.48**	**6.70**	**5.64**		**2.00**	**57.27**	**-4.68**	**19.41**
CI 95 max	**17.23**	**32.00**	**155.93**	**66.26**		**85.40**	**7.34**	**22.57**	**35.29**		**2.00**	**64.92**	**80.68**	**47.91**
N0				**43**					**22**					**11**

Table 7 Drinking Water Quality incidents in 2006 by hazard category (selection)

Significance testing										**H0: X1 - X2 = 0**			**X1: (F*H) for 2004**				**Legend**	
										H1: X1 - X2 <>0			**X2: (F*H) for 2005**				**F**	**Frequency of occurrence**
										SL: 5%							**H**	**Average incident impact per hazard category**
2004					**2005**													
	F	**H**	**SE**			**F**	**H**	**SE**		**mean X1 - mean X2**	**Variance X1-X2**	**SE**	**CI 95% min**	**CI 95% max**	**H0**	**SL**		**Comment**
Aesthetics	46	21.63	2.24		Aesthetics	48	29.07	7.12		-400.32	55.72	7.46	-14.63	14.63	Reject	0.05	X2>>X1	**Higher impact in 2005**
Biological pathogens present	16	16.38	5.06		Biological pathogens present	18	20.33	9.09		-103.95	108.27	10.41	-20.39	20.39	Reject	0.05	X2>>X1	**Higher impact in 2005**
Biological pathogens present, health effects	15	29.90	2.51		Biological pathogens present, health effects	15	46.42	12.24		-247.83	156.19	12.50	-24.50	24.50	Reject	0.05	X2>>X1	**Higher impact in 2005**
Chemical present above guidelines	6	19.64	6.29		Chemical present above guidelines	4	38.96	17.87		-38.03	359.01	18.95	-37.14	37.14	Reject	0.05	X2>>X1	**Higher impact in 2005**
					Chemical present, health effects	3	85.80	52.07		-257.41	2711.25	52.07	-102.06	102.06	Reject	0.05	X2>>X1	**Higher impact in 2005**
Potential unwholesome medium health effect	2	24.75	2.31		Unwholesome	2	10.32	5.66		28.85	37.38	6.11	-11.98	11.98	Reject	0.05	X1>>X2	**Lower impact in 2005**
Potential Unwholesome, low health effect	2	16.83	0.33			0.00	0.00	0.00		33.66	0.11	0.33	-0.65	0.65	Reject	0.05	X1>>X2	**Lower impact in 2005**
Loss of supply	1	11.88	0.00		Loss of supply	2	19.31	7.99		-26.75	63.87	7.99	-15.66	15.66	Reject	0.05	X2>>X1	**Higher impact in 2005**

Table 8 Significance test for incidents in 2004 and 2005 by hazard categories

Significance testing										**H0: X1 - X2 = 0**			**X1: (F*H) for 2005**				**Legend**	
										H1: X1 - X2 <>0			**X2: (F*H) for 2006**				**F**	**Frequency of occurrence**
										SL: 5%							**H**	**Average incident impact per hazard category**
2005					**2006**													
	F	**H**	**SE**			**F**	**H**	**SE**		**mean X1 - mean X2**	**Variance X1-X2**	**SE**	**CI 95% min**	**CI 95% max**	**H0**	**SL**		**Comment**
Aesthetics	48	29.07	7.12		Aesthetics	43	43.72	11.50		-484.52	183.01	13.53	-26.52	26.52	Reject	0.05	X2>>X1	**Higher impact in 2006**
Biological pathogens present	18	20.33	9.09		Biological pathogens present	22	20.46	7.57		-84.25	139.93	11.83	-23.19	23.19	Reject	0.05	X2>>X1	**Higher impact in 2006**
Biological pathogens present, health effects	15	46.42	12.24		Biological pathogens present, health effects	11	33.66	7.27		326.01	202.75	14.24	-27.91	27.91	Reject	0.05	X1>>X2	**Lower impact in 2006**
Chemical present above guidelines	4	38.96	17.87		Chemical present above guidelines	11	18.16	3.48		-43.96	331.54	18.21	-35.69	35.69	Reject	0.05	X2>>X1	**Higher impact in 2006**
Chemical present, health effects	3	85.80	52.07		Chemical present, health effects	4	96.07	82.75		-126.87	9559.12	97.77	- 191.63	191.63	Accept	0.05	X2 = X1	**Equal impact**
Unwholesome	2	10.32	5.66							20.65	32.05	5.66	-11.10	11.10	Reject	0.05	X1>>X2	**Lower impact in 2006**
Loss of supply	2	19.31	7.99		Loss of supply	6	8.66	0.99		-13.32	64.85	8.05	-15.78	15.78	Accept	0.05	X2 = X1	**Equal impact**

Table 9 Significance test for incidents in 2005 and 2006 by hazard category

Significance testing										**H0: X1 - X2 = 0**			**X1: (F*H) for 2004**				**Legend**	
										H1: X1 - X2 <>0			**X2: (F*H) for 2006**				**F**	**Frequency of occurrence**
										SL: 5%							**H**	**Average incident impact per hazard category**
2004					**2006**													
	F	**H**	**SE**			**F**	**H**	**SE**		**mean X1 - mean X2**	**Variance X1-X2**	**SE**	**CI 95% min**	**CI 95% max**	**H0**	**SL**		**Comment**
Aesthetics	46	21.63	2.24		Aesthetics	43	43.72	11.50		-884.84	137.35	11.72	-22.97	22.97	Reject	0.05	X2>>X1	**Higher impact in 2006**
Biological pathogens present	16	16.38	5.06		Biological pathogens present	22	20.46	7.57		-188.20	82.80	9.10	-17.83	17.83	Reject	0.05	X2>>X1	**Higher impact in 2006**
Biological pathogens present, health effects	15	29.90	2.51		Biological pathogens present, health effects	11	33.66	7.27		78.17	59.17	7.69	-15.08	15.08	Reject	0.05	X1>>X2	**Lower impact in 2006**
Chemical present above guidelines	6	19.64	6.29		Chemical present above guidelines	11	18.16	3.48		-81.99	51.75	7.19	-14.10	14.10	Reject	0.05	X2>>X1	**Higher impact in 2006**
					Chemical present, health effects	4	96.07	82.75		-384.28	6847.87	82.75	- 162.19	162.19	Reject	0.05	X2>>X1	**Higher impact in 2006**
Potential unwholesome medium health effect	2	24.75	2.31							49.50	5.34	2.31	-4.53	4.53	Reject	0.05	X1>>X2	**Lower impact in 2006**
Potential Unwholesome, low health effect	2	16.83	0.33							33.66	0.11	0.33	-0.65	0.65	Reject	0.05	X1>>X2	**Lower impact in 2006**
Loss of supply	1	11.88	0.00		Loss of supply	6	8.66	0.99		-40.07	0.98	0.99	-1.94	1.94	Reject	0.05	X2>>X1	**Higher impact in 2006**

Table 10 Significance test for incidents in 2004 and 2006 by hazard category

3.2.1.4 Comparison of incidents at regional level with national incidents

			Scaled down national frequency of incident occurrence according to number of population served by water utility (F)				
2004	**Frequency of occurrence in England and Wales**	**Average incident impact**	**F Thames**	**F Severn Trent**	**F United Utilities**	**F Yorkshire**	**F Anglian**
Aesthetics	46.00	21.63	7.19	6.47	6.18	4.18	3.62
Biological pathogens present	16.00	16.38	2.50	2.25	2.15	1.45	1.26
Biological pathogens present, health effects	15.00	29.90	2.34	2.11	2.02	1.36	1.18
Chemical present above guidelines	6.00	19.64	0.94	0.84	0.81	0.55	0.47
Potential unwholesome medium health effect	2.00	24.75	0.31	0.28	0.27	0.18	0.16
Potential Unwholesome, low health effect	2.00	16.83	0.31	0.28	0.27	0.18	0.16
Loss of supply	1.00	11.88	0.16	0.14	0.13	0.09	0.08

Table 11 Scaled down national frequency of incident occurrence according to number of population served by water utilities in 2004

			Scaled down national frequency of incident occurrence according to number of population served by water utility (F)				
2005	**Frequency of occurrence in England and Wales**	**Average incident impact**	**F Thames**	**F Severn Trent**	**F United Utilities**	**F Yorkshire**	**F Anglian**
Aesthetics	48.00	29.07	7.39	6.61	6.18	4.19	3.76
Biological pathogens present	18.00	20.33	2.77	2.48	2.32	1.57	1.41
Biological pathogens present, health effects	15.00	46.42	2.31	2.07	1.93	1.31	1.18
Chemical present above guidelines	4.00	38.96	0.62	0.55	0.51	0.35	0.31
Chemical present, health effects	3.00	85.80	0.46	0.41	0.39	0.26	0.24
Unwholesome	2.00	10.32	0.31	0.28	0.26	0.17	0.16
Loss of supply	2.00	19.31	0.31	0.28	0.26	0.17	0.16

Table 12 Scaled down national frequency of incident occurrence according to number of population served by water utility in 2005

			Scaled down national frequency of incident occurrence according to number of population served by water utility (F)				
2006	**Frequency of occurrence in England and Wales**	**Average incident impact**	**F Thames**	**F Severn Trent**	**F United Utilities**	**F Yorkshire**	**F Anglian**
Aesthetics	43.00	43.72	6.62	5.93	5.53	3.76	3.41
Biological pathogens present	22.00	20.46	3.39	3.03	2.83	1.92	1.74
Biological pathogens present, health effects	11.00	33.66	1.69	1.52	1.42	0.96	0.87
Chemical present above guidelines	11.00	18.16	1.69	1.52	1.42	0.96	0.87
Chemical present, health effects	4.00	96.07	0.62	0.55	0.51	0.35	0.32
Loss of supply	6.00	8.66	0.92	0.83	0.77	0.52	0.48

Table 13 Scaled down national frequency of incident occurrence according to number of population served by water utility in 2006

2004	Aesthetics					Biological pathogens present					Biological pathogens present, health effects					Chemical present above guidelines			
	P	**H**	**D**	**Sum**		**P**	**H**	**D**	**Sum**		**P**	**H**	**D**	**Sum**		**P**	**H**	**D**	**Sum**
1.00	2.00	32.00	2.00	11.88		2.00	8.00	32.00	13.86		2.00	64.00	32.00	32.34		4.00	8.00	16.00	9.24
2.00	2.00	32.00	16.00	16.50		2.00	6.00	2.00	3.30		2.00	64.00	32.00	32.34					
3.00	2.00	32.00	16.00	16.50							2.00	48.00	32.00	27.06					
4.00	16.00	32.00	16.00	21.12															
5.00	4.00	32.00	16.00	17.16															
6.00	32.00	32.00	8.00	23.76															
7.00	2.00	32.00	32.00	21.78															
8.00	2.00	32.00	4.00	12.54															
9.00	16.00	32.00	32.00	26.40															
10.00	32.00	32.00	16.00	26.40															
11.00	4.00	32.00	16.00	17.16															
12.00	16.00	32.00	2.00	16.50															
Average	**10.83**	**32.00**	**14.67**	**18.98**		**2.00**	**7.00**	**17.00**	**8.58**		**2.00**	**58.67**	**32.00**	**30.58**		**4.00**	**8.00**	**16.00**	**9.24**
SD	**11.52**	**0.00**	**9.96**	**4.88**		**0.00**	**1.41**	**21.21**	**7.47**		**0.00**	**9.24**	**0.00**	**3.05**		**0.00**	**0.00**	**0.00**	**0.00**
SE	**3.33**	**0.00**	**2.87**	**1.41**		**0.00**	**1.00**	**15.00**	**5.28**		**0.00**	**5.33**	**0.00**	**1.76**		**0.00**	**0.00**	**0.00**	**0.00**
CI 95 min	**4.32**	**32.00**	**9.03**	**16.21**		**2.00**	**5.04**	**-12.40**	**-1.77**		**2.00**	**48.21**	**32.00**	**27.13**		**4.00**	**8.00**	**16.00**	**9.24**
CI 95 max	**17.35**	**32.00**	**20.30**	**21.74**		**2.00**	**8.96**	**46.40**	**18.93**		**2.00**	**69.12**	**32.00**	**34.03**		**4.00**	**8.00**	**16.00**	**9.24**
N0				**12.00**					**2.00**					**3.00**					**1.00**

Table 14 Regional Water Utility drinking water quality incidents grouped by hazard category in 2004

2005	Aesthetics					Biological pathogens present, health effects					Unwholesome			
	P	H	D	Sum		P	H	D	Sum		P	H	D	Sum
1.00	8.00	32.00	64.00	34.63		2.00	64.00	32.00	32.63		2.00	8.00	4.00	4.66
2.00	8.00	32.00	2.00	13.99		2.00	64.00	125.00	63.60					
3.00	8.00	32.00	2.00	13.99		2.00	48.00	32.00	27.31					
4.00	2.00	32.00	8.00	13.99										
5.00	2.00	32.00	4.00	12.65										
Average	**5.60**	**32.00**	**16.00**	**17.85**		**2.00**	**58.67**	**63.00**	**41.18**		**2.00**	**8.00**	**4.00**	**4.66**
SD	**3.29**	**0.00**	**26.94**	**9.40**		**0.00**	**9.24**	**53.69**	**19.60**		**0.00**	**0.00**	**0.00**	**0.00**
SE	**1.47**	**0.00**	**12.05**	**4.20**		**0.00**	**5.33**	**31.00**	**11.32**		**0.00**	**0.00**	**0.00**	**0.00**
CI 95 min	**2.72**	**32.00**	**-7.62**	**9.61**		**2.00**	**48.21**	**2.24**	**19.00**		**2.00**	**8.00**	**4.00**	**4.66**
CI 95 max	**8.48**	**32.00**	**39.62**	**26.09**		**2.00**	**69.12**	**123.76**	**63.36**		**2.00**	**8.00**	**4.00**	**4.66**
N0				**5.00**					**3.00**					**1.00**

Table 15 Regional Water Utility drinking water quality incidents grouped by hazard category in 2005

2006	Aesthetics					Biological pathogens present					Chemicals present above guidelines			
	P	**H**	**D**	**Sum**		**P**	**H**	**D**	**Sum**		**P**	**H**	**D**	**Sum**
1.00	4.00	32.00	2.00	12.65		2.00	8.00	32.00	13.99		4.00	8.00	16.00	9.32
2.00	32.00	32.00	4.00	22.64		32.00	6.00	2.00	13.32		32.00	8.00	4.00	14.65
3.00	2.00	32.00	1000.00	344.32		125.00	6.00	2.00	44.29					
4.00	2.00	32.00	8.00	13.99										
5.00	2.00	32.00	2.00	11.99										
Average	**8.40**	**32.00**	**203.20**	**81.12**		**53.00**	**6.67**	**12.00**	**23.87**		**18.00**	**8.00**	**10.00**	**11.99**
SD	**13.22**	**0.00**	**445.43**	**147.20**		**64.13**	**1.15**	**17.32**	**17.69**		**19.80**	**0.00**	**8.49**	**3.77**
SE	**5.91**	**0.00**	**199.20**	**65.83**		**37.03**	**0.67**	**10.00**	**10.21**		**14.00**	**0.00**	**6.00**	**2.66**
CI 95 min	**-3.19**	**32.00**	**-187.24**	**-47.91**		**-19.57**	**5.36**	**-7.60**	**3.85**		**-9.44**	**8.00**	**-1.76**	**6.77**
CI 95 max	**19.99**	**32.00**	**593.64**	**210.14**		**125.57**	**7.97**	**31.60**	**43.88**		**45.44**	**8.00**	**21.76**	**17.21**
N0				**5.00**					**3.00**					**2.00**

Table 16 Regional Water Utility drinking water quality incidents grouped by hazard category in 2006

									H0: RWU H*RWU F = SN H*SN F							
2004	**Baseline (National standard (SN) for RWU**				**Regional Water Utility (RWU) Incident Impact**				**H1: RWUH*RWU F<>SN H*SN F**							
Hazard category	SN F	SN H	SE		RWU F	RWU H	SE		**mean**	Var	SE	**CI 95% min**	**CI 95% max**	**H0**	**SL in %**	**Result**
Aesthetics	4.18	21.63	2.24		12.00	18.98	1.41		**137.29**	7.02	2.65	**-5.19**	**5.19**	**Reject**	**0.05**	**RWU do worse than SN**
Biological pathogens present	1.45	16.38	5.06		2.00	8.58	5.28		**-6.65**	53.45	7.31	**-14.33**	**14.33**	**Accept**	**0.05**	
Biological pathogens present, health effects	1.36	29.90	2.51		3.00	30.58	1.76		**50.99**	9.40	3.07	**-6.01**	**6.01**	**Reject**	**0.05**	**RWU do worse than SN**
Chemical present above guidelines	0.55	19.64	6.29		1.00	9.24	0.00		**-1.47**	39.61	6.29	**-12.34**	**12.34**	**Accept**	**0.05**	
Potential unwholesome medium health effect	0.18	24.75	2.31						**-4.50**	5.34	2.31	**-4.53**	**4.53**	**Accept**	**0.05**	
Potential Unwholesome, low health effect	0.18	16.83	0.33						**-3.06**	0.11	0.33	**-0.65**	**0.65**	**Reject**	**0.05**	**RWU do better than SN**
Loss of supply	0.09	11.88	0.00						**-1.08**	0.00	0.00	**0.00**	**0.00**	**Accept**	**0.05**	
Note																
SN F is the national frequency for this category incident scaled down with the percentage of customers served by this utility.																
Legend																
SN	National standard															
RWU	Regional Water Utility															
F	Frequency															
H	Hazard Impact factor for respective category															
SE	Standard error															
CI	Confidence Interval 95%															

Table 17 Significance test comparing incidents in Regional Water Utility against incidents in England and Wales in 2004

									H0: RWU H*RWU F = SN H*SN F							
2005	**Baseline (National standard (SN) for RWU**				**Regional Water Utility (RWU) Incident Impact**				**H1: RWUH*RWU F<>SN H*SN F**							
Hazard category	SN F	SN H	SE		RWU F	RWU H	SE		**mean**	Var	SE	**CI 95% min**	**CI 95% max**	**H0**	**SL in %**	**Result**
Aesthetics	4.19	29.07	7.12		5.00	17.85	4.20		**-32.69**	68.37	8.27	**-16.21**	**16.21**	**Reject**	**0.05**	**RWU do better than SN**
Biological pathogens present	1.57	20.33	9.09						**-31.98**	82.70	9.09	**-17.82**	**17.82**	**Reject**	**0.05**	**RWU do better than SN**
Biological pathogens present, health effects	1.31	46.42	12.24		3.00	41.18	11.32		**62.69**	277.94	16.67	**-32.68**	**32.68**	**Reject**	**0.05**	**RWU do worse than SN**
Chemical present above guidelines	0.35	38.96	17.87		0.00	0.00			**-13.62**	319.40	17.87	**-35.03**	**35.03**	**Accept**	**0.05**	
Chemical present, health effects	0.26	85.80	52.07		0.00	0.00			**-22.49**	2711.25	52.07	**-102.06**	**102.06**	**Accept**	**0.05**	
Unwholesome	0.17	10.32	5.66		1.00	4.66	0.00		**2.86**	32.05	5.66	**-11.10**	**11.10**	**Accept**	**0.05**	
Loss of supply	0.17	19.31	7.99						**-3.38**	63.87	7.99	**-15.66**	**15.66**	**Accept**	**0.05**	
Note																
SN F is the national frequency for this category incident scaled down with the percentage of customers served by this utility.																
Legend																
SN	National standard															
RWU	Regional Water Utility															
F	Frequency															
H	Hazard Impact factor for respective category															
SE	Standard error															
CI	Confidence Interval 95%															

Table 18 Significance tests comparing incidents in Regional Water Utility against incidents in England and Wales in 2005

									H0: RWU H*RWU F = SN H*SN F							
2006	**Baseline (National standard (SN) for RWU**				**Regional Water Utility (RWU) Incident Impact**				**H1: RWUH*RWU F<>SN H*SN F**							
Hazard category	**SN F**	**SN H**	**SE**		**RWU F**	**RWU H**	**SE**		**mean**	**Var**	**SE**	**CI 95% min**	**CI 95% max**	**H0**	**SL in %**	**Result**
Aesthetics	3.76	43.72	11.50		5.00	81.12	65.83		**241.32**	4465.74	66.83	**-130.98**	**130.98**	**Reject**	**0.05**	**RWU do worse than SN**
Biological pathogens present	1.92	20.46	7.57		3.00	23.87	10.21		**32.25**	161.55	12.71	**-24.91**	**24.91**	**Reject**	**0.05**	**RWU do worse than SN**
Biological pathogens present, health effects	0.96	33.66	7.27						**-32.36**	52.87	7.27	**-14.25**	**14.25**	**Reject**	**0.05**	**RWU do better than SN**
Chemical present above guidelines	0.96	18.16	3.48		2.00	11.99	2.66		**6.52**	19.23	4.39	**-8.60**	**8.60**	**Accept**	**0.05**	
Chemical present, health effects	0.35	96.07	82.75						**-33.58**	6847.87	82.75	**-162.19**	**162.19**	**Accept**	**0.05**	
Loss of supply	0.52	8.66	0.99						**-4.54**	0.98	0.99	**-1.94**	**1.94**	**Reject**	**0.05**	**RWU do better than SN**
Note																
SN F is the national frequency for this category incident scaled down with the percentage of customers served by this utility.																
Legend																
SN	National standard															
RWU	Regional Water Utility															
F	Frequency															
H	Hazard Impact factor for respective category															
SE	Standard error															
CI	Confidence Interval 95%															

Table 19 Significance test comparing incidents in Regional Water Utility against incidents in England and Wales in 2006

3.2.2 Incidents in the Regional Water Utility

3.2.2.1 Cause and effect relationships

Cause Effect	Aesthetics above guidelines	Biological pathogens present	Biological pathogens present, health effects envisaged	Chemicals present above guidelines	Chemicals present above guidelines, health effects envisaged	Loss of supply	Potential biological pathogens present	Potential biological pathogens present, health effects envisaged	**Sum**
3rd party incl. illegal connection	9	0			1	5		2	**17**
Adverse weather	1	0		1				1	**3**
Asset contamination	2	0	6		1		2	4	**15**
Asset damage	1	0				1		2	**4**
Asset failure	8	0		10		14	1	1	**34**
Burst main	35	2	2	1		79	2	4	**125**
Chlorination failure	0	0					18		**18**
Design failure	1	0							**1**
High Demand	2	0							**2**
IT, M&C, Telemetry fail	0	1				8			**9**
Maintenance work	26	2	7	1		8		1	**45**
Operational intervention	17	0		1		4			**22**
Power failure	4	0		2		13	1	1	**21**
Treatment failure	5	1		5					**11**
Raw Water quality	10	4	2				2		**18**
Sum	**121**	**10**	**17**	**21**	**2**	**132**	**26**	**16**	**345**

Table 20 Primary cause and effect matrix for incidents with impact on safety and reliability of drinking water for customers

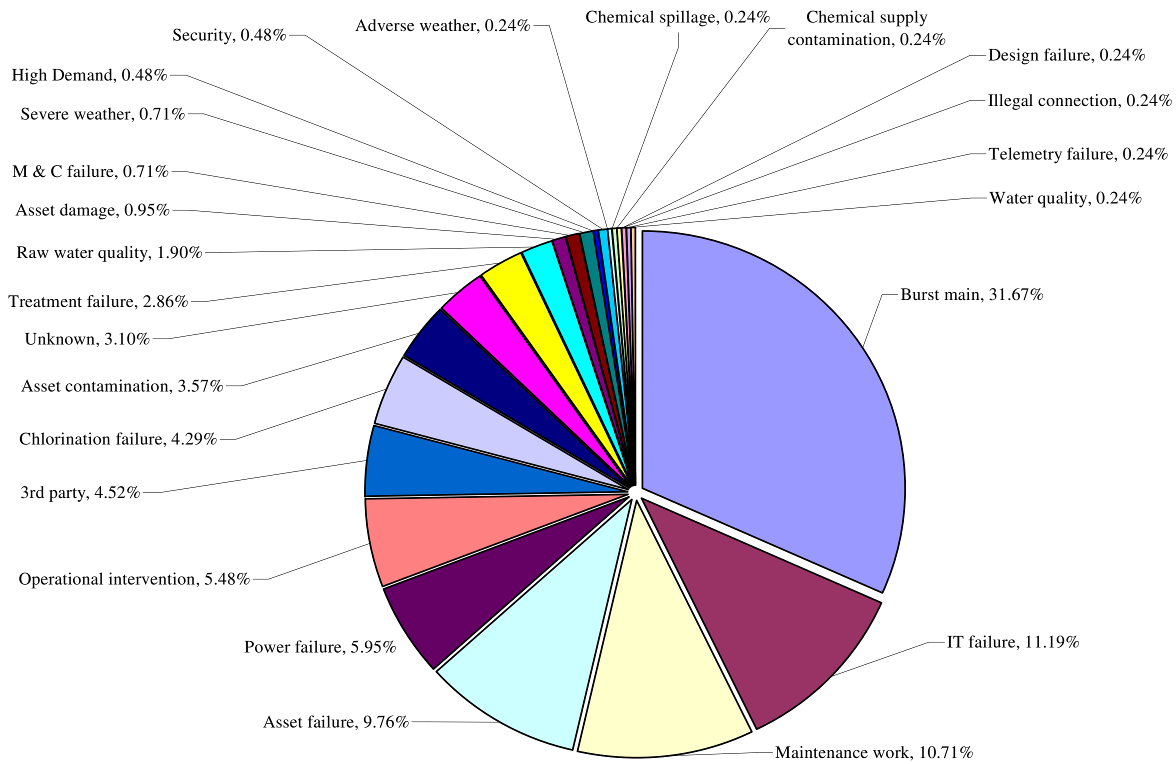

Figure 5 Primary incident causes between 1997 and 2006 in the Regional Water Utility

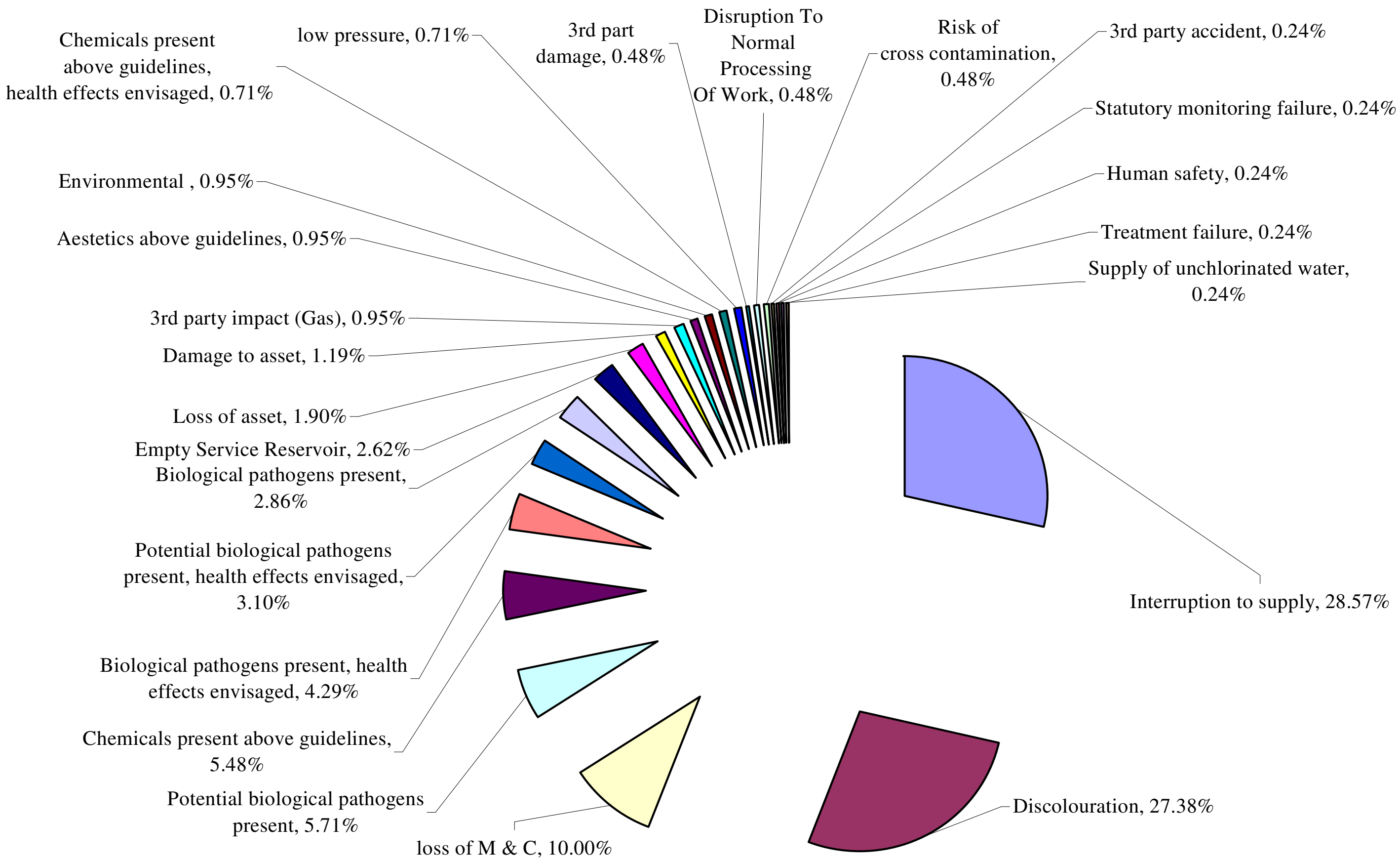

Figure 6 Primary incident effects between 1997 and 2006 in the Regional Water Utility

In the following section, the annual distribution of incident causes are presented. The rationale of this analysis is to identify patterns for specific primary incident causes over the years between 1997 and 2006. In the following figures the annual number for primary incident causes are shown which led to an incident. The figures are grouped in themes.

In Figure 7, the number of primary incident causes for IT failure, power failure and monitoring, control & telemetry failure that caused an incident is plotted for the years between 1997 and 2006.

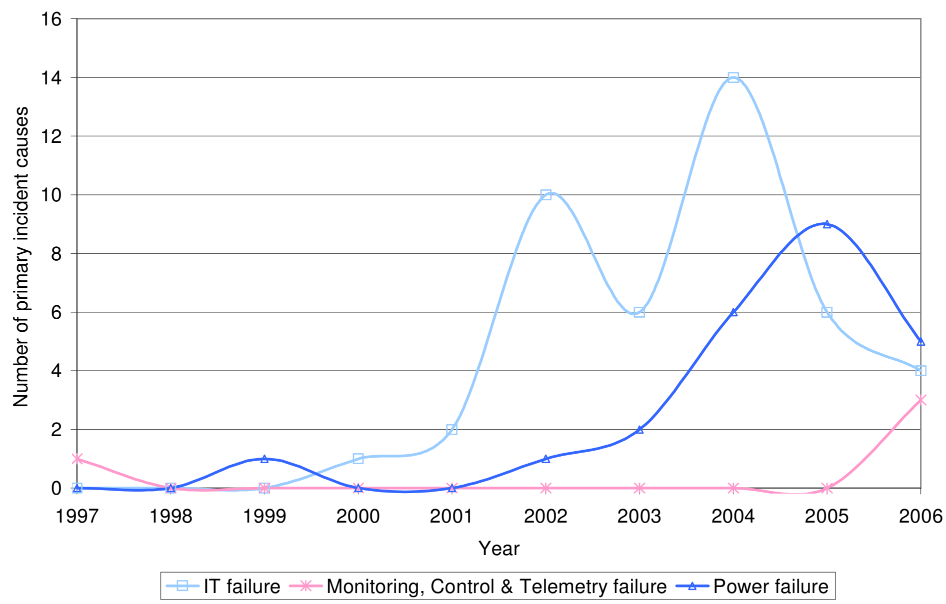

Figure 7 IT, power, monitoring, control and telemetry failures between 1997 and 2006

With respect to IT failure, a significant trend can be observed of increasing numbers of incidents between 1999 and 2005. This can be attributed to an increasing use of IT to manage business processes in the organisation. Since 2004, the number of IT related incidents reduces from 14 to four in 2006. According to one reporter, the "teething problems of introducing new technologies were initially having a huge impact on the business but have now been ironed out". Similarly, the number of power failures with the effect of an incident has significantly increased since 2001 to 2005. On enquiry, a number of factors were reported to explain this trend: Firstly, the supply of electricity by the electricity company is seen as less reliable nowadays than it was a few years ago. One reporter suggested that severe weather events have contributed to the overall reduction in the reliability of electrical supply. Secondly, according to one asset manager, the water utility has increased its use of water pumping stations in favour over water towers and reduced its capacity of gravity-fed water supply systems. In his view, increasing numbers of power-supply dependent water pumping stations correlates with the increasing number of incidents due to power supply failures. This trend is, however, overshadowed by investments in un-interruptible power supply systems. The organisation has increased its investments in un-interruptible power supply based on risk assessments and reliability studies from the power supply company.

In 2006, three incidents were specifically attributed to failures of monitoring and control equipment. This represents a significant increase compared to previous years. Similarly, to the use of IT, a trend can be observed in the organisation for increased use of monitoring and control equipment. This is related to an operational philosophy that requires all water treatment works to be operated from a regional operations and control centre without an operator on-site. This operational philosophy can also be observed for other assets owned by the water utility.

In Figure 8 incident causes are shown which relate to asset failures. The incident causes are classed as asset failures denoting failure of assets, equipment and components other than burst mains and failure of chlorination asset, equipment and components. Due to the high rate of occurrence, burst mains form a distinct group. Similarly, the failure of chlorination was recorded separably. The remaining category “Asset damage” denotes a severe impact on an asset that limited the ability to provide a service. In Figure 8, the number of primary incident causes for asset failures, burst mains, chlorination asset failure and asset damage is plotted for the years between 1997 and 2006.

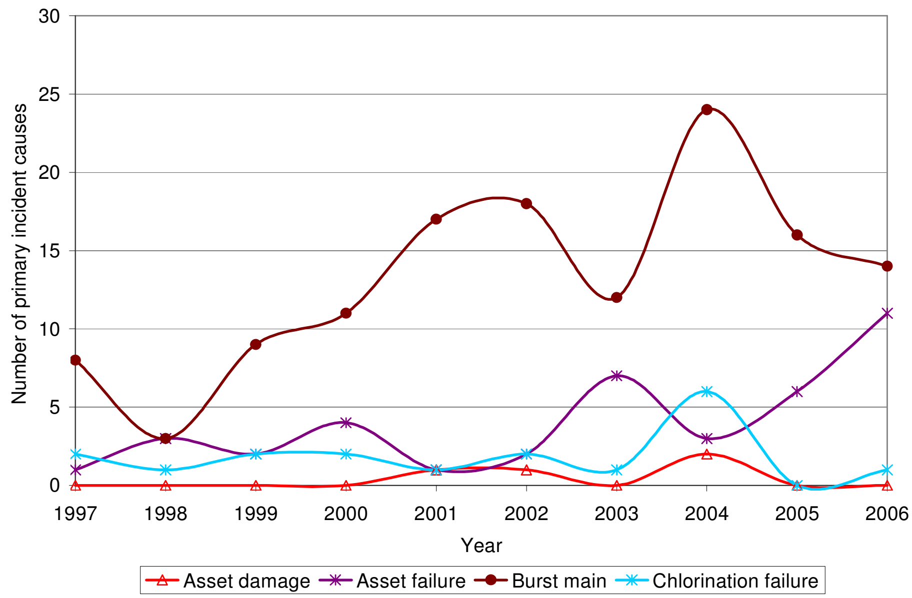

Figure 8 Asset damage, asset failure, burst mains and chlorination equipment failure between 1997 and 2006

The return period for incidents causes relating to burst mains can be represented as annual mean time between failures. In Figure 9, the annual mean time between burst main incidents is shown.

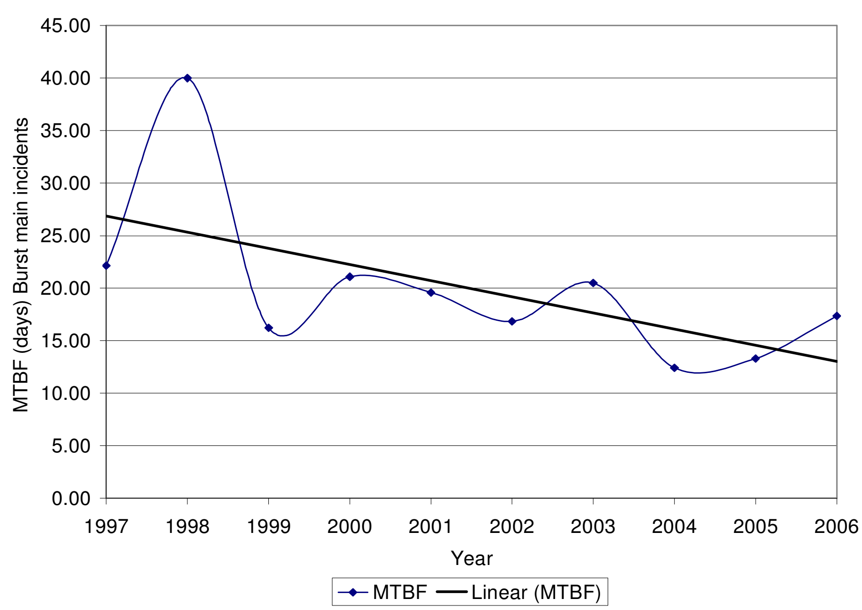

Figure 9 Mean time between failure in days for burst water mains causing an incident

A notable trend can be identified of increasing numbers of burst mains to cause an incident. This trend peaked in 2004 at 24 incidents and, since, the number of burst main incidents reduced to 14 in 2006. According to one reporter, the reduction of burst main incidents coincides with targeted mains refurbishment and replacement programmes.
A trend of increasing asset failures can also be identified. Throughout the 10 years, on average four asset failures per led to an incident. Since 2004, the number of asset failures increased to 6 and 11 for the years 2005 and 2006, respectively.
Failure of chlorination assets, equipment and components resulting in an incident averages at 1.8 failures per year. In 2004, the frequency of chlorination asset and equipment failure peaked at six incidents per year. Since then, the number has reduced to zero and one incident in the years 2004 and 2005, respectively. In a later section of this chapter, a case study will further investigate incidents surrounding the failure of chlorination assets and policies and strategies to reduce their risk.

In Figure 10 incident causes are shown which relate to operational activities on assets. The incident causes are classed as incidents that occurred during maintenance work and due to an operational intervention by utility staff. In addition, the figure shows incidents caused by chemical spillages on site. The figure shows the number of incidents causes in these categories leading to an incident in the years 1997 to 2006.

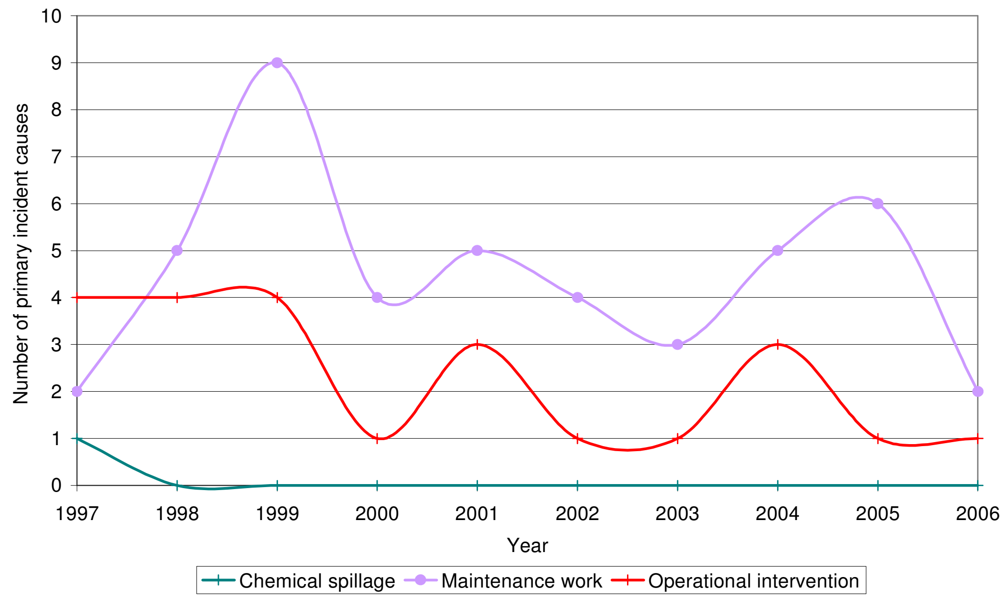

Figure 10 Incidents relating to operational activities on assets between 1997 and 2006

On average 4.5 incidents per year occur during maintenance work on assets. Although a trend can be identified of reducing numbers of incident causes in this category, the main observation suggests some form of periodical increase and decline of incidents in this category. 1999 and 2005 represent peaks in the number of incidents occurring. It appears that this periodical trend coincides with capital investment and maintenance spending during the subsequent asset management programmes (AMP). According to one asset manager, 1999 and 2004 are the final years of asset management programmes in which, historically, a considerable amount of investment and maintenance projects are implemented. These implementation phases are “busy” periods with many scheduled construction activities being carried out on or near water utility assets.

It appears that operational interventions resulting in an incident has a similar periodic pattern, which almost corresponds with incidents due to maintenance work on assets. There may be a correlation to increased construction activity. However, there was no data available to suggest this hypothesis. Providing evidence for this hypothesis would require an assessment of overall operational activity, in particular interventions into the water supply system, as a baseline to compare operational interventions causing an incident. The assessment would further require a measure for construction related activity on or near water supply system assets.

In Figure 11, incident causes are shown which are related to external factors to the organisation. They are impact from third parties on the utilities assets, breaches of site security, illegal connections onto the distribution network and contamination of chemicals from suppliers. The figure shows the number of incidents causes in these categories leading to an incident in the years 1997 to 2006. No significant trends can be identified other than the volatility of third party impacts leading to no and three incidents per year.

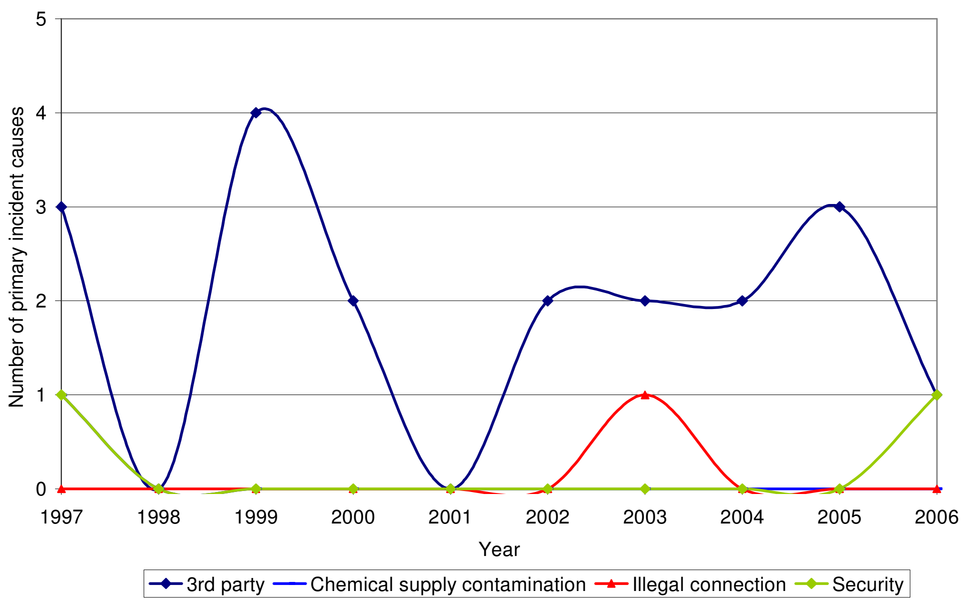

Figure 11 3rd party impact on water utility assets and operations between 1997 and 2006

In Figure 12, incident causes relating to the resilience of treatment process in context of their operating environment are shown. The categories include adverse weather, raw water quality, treatment process failure and asset contamination. The figure shows the number of incidents causes in these categories leading to an incident in the years 1997 to 2006.

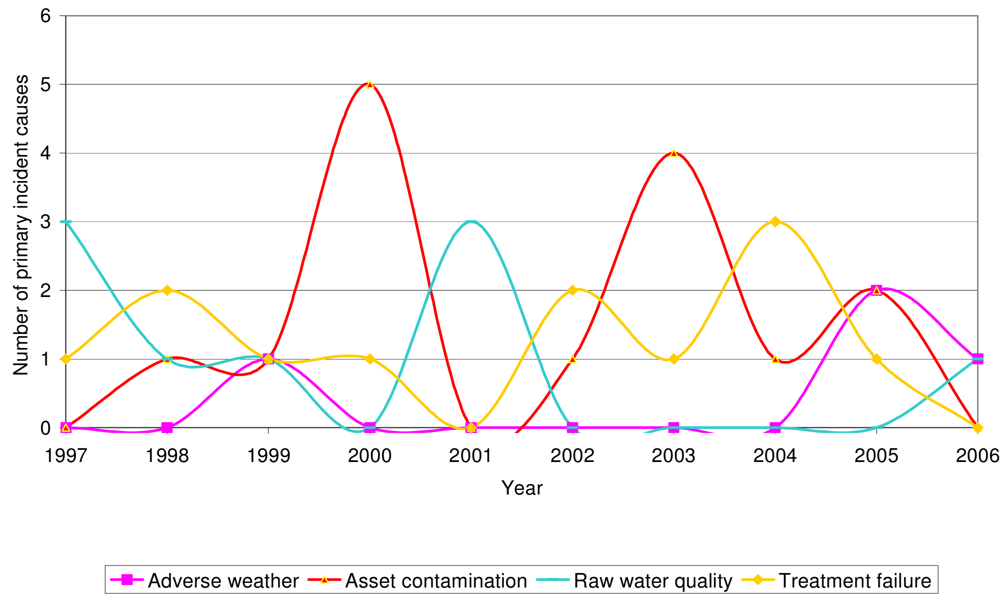

Figure 12 Process related incident causes between 1997 and 2006

Two distinct trends can be identified. Firstly, treatment process failures significantly increased between 2001 and 2004 and, since, reduced below the 10 year average of 1.2 incidents per year. Secondly, the trend of incidents that were primarily attributed to poor raw water quality has significantly reduced over the 10 years.

The number of incidents attributed to asset contamination can only be characterised as volatile with significant peaks in 2000 and 2003. The majority of these incidents relate to asset contaminations during planned and unplanned repair of leaking distribution network assets that were characterised as ingress of groundwater or sewage.

The primary causes of failure can be related to the impact assessment of failure. In the following analysis, the primary causes to incidents with a significantly low impact on customers are compared to the primary incident causes with a significantly high impact. For this purpose, a confidence interval at 95% for the incident impacts between 1997 and 2006 was constructed. Based on this confidence interval, those incidents were selected with significantly low and significantly high incident impacts. The primary causes leading to an incident in both categories were recorded in a histogram. This is presented in Table 21.

Primary incident causes	Incident impact < CI 95% min	Percentage of incidents	Incident impact > CI 95 max	Percentage of incidents
3rd party	4	2.47%	11	7.43%
Asset contamination	3	1.85%	12	8.11%
Asset damage	2	1.23%	2	1.35%
Asset failure	17	10.49%	10	6.76%
Burst main	79	48.77%	41	27.70%
Chemical supply contamination		0.00%	1	0.68%
Chlorination failure	12	7.41%	1	0.68%
Design failure		0.00%	1	0.68%
High Demand	1	0.62%	1	0.68%
Illegal connection		0.00%	1	0.68%
IT failure	6	3.70%		0.00%
M & C failure	1	0.62%	1	0.68%
Maintenance work	10	6.17%	31	20.95%
Operational intervention	5	3.09%	16	10.81%
Power failure	10	6.17%	6	4.05%
Raw water quality	4	2.47%	4	2.70%
Security		0.00%		0.00%
Severe weather	1	0.62%	3	2.03%
Telemetry failure	1	0.62%		0.00%
Treatment failure	3	1.85%		0.00%
Unknown	3	1.85%	6	4.05%
Total	**162**	**100.00%**	**148**	**100.00%**

Table 21Histogram of primary incident causes for significantly high and low incident impacts on customers for incidents between 1997 and 2006

The majority of incidents with a significantly low impact on customers can be identified as ‘burst mains (48.77%)’, ‘asset failure (10.49%)’, ‘chlorination failure (7.41%)’, ‘maintenance work (6.17%)’ and ‘power failure (6.17%)’. On the other hand, the majority of incidents with a significantly high impact on customers can be identified as ‘burst main (27.70%)’, ‘maintenance work (20.95%)’, ‘operational intervention (10.81%), ‘asset contamination (8.11%), ‘3rd party impact (7.43%)’ and ‘asset failure (7.67%).

In both groups, ‘burst mains’ constitute the largest number of incident causes. A distinct difference can be identified, in particular relating to the increased number of high

incident impacts due to maintenance works and operational intervention. On the other hand, chlorination systems failures constitute significantly low incident impact types.
A graphic representation of this histogram is presented in Figure 13 and Figure 14.

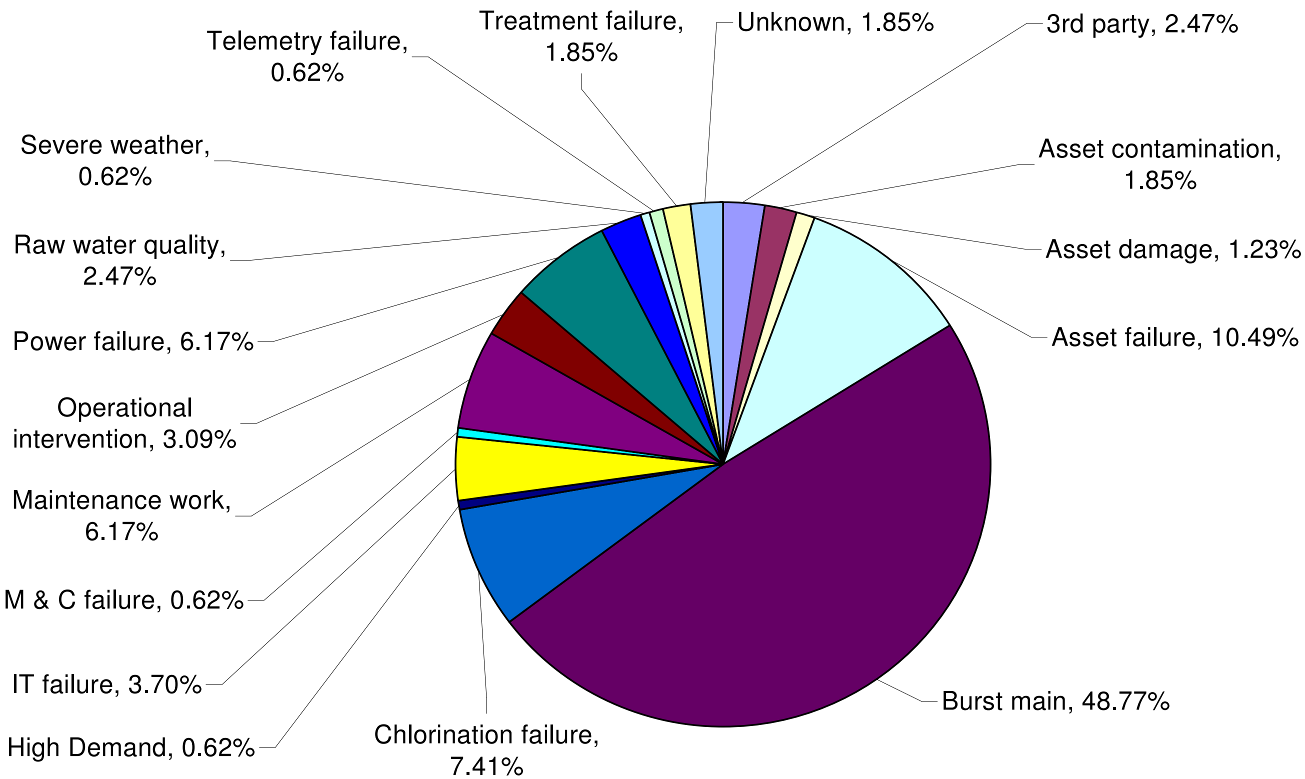

Figure 13 Primary causes for incidents with a significantly low impact on customers (1997-2006)

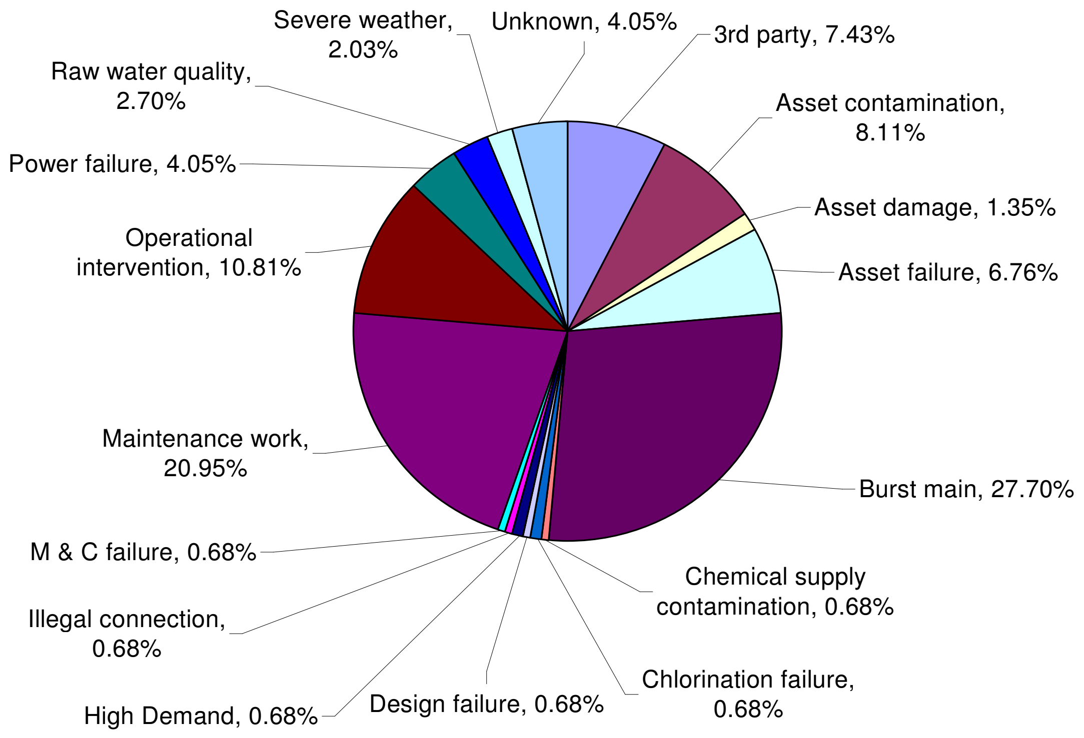

Figure 14 Primary causes for incidents with a significantly high impact on customers (1997-2006)

3.2.2.2 Chi Square analysis of asset type and asset life cycle phase

For incident root causes, does a relationship exist between the categories of asset classes and asset life cycle phases?					
H0= In the distribution of most probable incident root causes asset type and asset life cycle are randomly distributed					
H1= In the distribution of most probable incident root causes asset type and asset life cycle are not randomly distributed					
SL	0.05				
SL	0.001				
Observation based on RWU incidents between 1997 and 2006					
	Catchment	**WTW**	**SR**	**Distribution**	**Sum**
Design	2	38	4	24	**68**
Construction	0	1	2	54	**57**
Operations	2	14	8	33	**57**
Maintenance	0	18	4	165	**187**
Sum	**4**	**71**	**18**	**276**	**369**
Expected values					
	Catchment	**WTW**	**SR**	**Distribution**	**Sum**
Design	0.74	13.08	3.32	50.86	**68.00**
Construction	0.62	10.97	2.78	42.63	**57.00**
Operations	0.62	10.97	2.78	42.63	**57.00**
Maintenance	2.03	35.98	9.12	139.87	**187.00**
Sum	**4.00**	**71.00**	**18.00**	**276.00**	**369.00**

Chi Squared					
	Catchment	**WTW**	**SR**	**Distribution**	**Sum X2**
Design	2.16	47.45	0.14	14.19	
Construction	0.62	9.06	0.22	3.03	
Operations	3.09	0.84	9.80	2.18	
Maintenance	2.03	8.99	2.88	4.52	
Sum	**7.90**	**66.33**	**13.03**	**23.91**	**111.17**
Degrees of freedom		9			
X2 (Chi square table)		16.92	for SL	0.05	
111.17 > 16.92					
H0 is rejected at a SL of 5%					
There exists a dependency between asset type and asset life cycle phase to explain root causes to incidents.					
Variations between expected distribution of root causes to failure and actual distribution of failure root causes is sizeable.					
Degrees of freedom		9			
X2 (Chi square table)		27.88	for SL	0.001	
111.17 > 27.88					
H0 is rejected at a SL of 0.1%					
There exists a dependency between asset type and asset life cycle phase to explain root causes to incidents.					

Table 22 Chi Square testing for independence between asset types and asset life cycle

3.2.2.3 Incident impact for incidents in the Regional Water Utility

				Hazard score	Hazard score	Hazard score	
				0.333	0.333	0.333	
Date of Incident	Population (actual affected)	Duration (hr)	Hazard category	P	H	D	Sum
01/01/2004	100	24	Loss of supply	2	16	8	8.658
25/01/2004	1100	12	Loss of supply	2	16	4	7.326
25/01/2004	7600	12	Aesthetics above guidelines	4	32	4	13.32
10/02/2004	8595	9	Aesthetics above guidelines	4	32	2	12.654
10/02/2004	1400	8	Aesthetics above guidelines	2	32	2	11.988
17/02/2004	22	10	Loss of supply	2	16	2	6.66
03/03/2004	3000	27	Loss of supply	2	16	8	8.658
19/03/2004	2574	4	Loss of supply	2	16	2	6.66
19/03/2004	2574	4	Aesthetics above guidelines	2	32	2	11.988
31/03/2004	4129	3	Aesthetics above guidelines	2	32	2	11.988
01/04/2004	2776	48	Aesthetics above guidelines	2	32	16	16.65
09/04/2004	1697	48	Aesthetics above guidelines	2	32	16	16.65
16/04/2004	200	48	Loss of supply	2	16	16	11.322
16/04/2004	200	48	Aesthetics above guidelines	2	32	16	16.65
20/04/2004	0	1	Potential biological pathogens present	2	6	2	3.33
24/04/2004	2530	2	Aesthetics above guidelines	2	32	2	11.988
11/05/2004	250	48	Biological pathogens present, health effects envisaged	2	64	16	27.306
16/05/2004	0	1	Chemicals present above guidelines	2	8	2	3.996
19/05/2004	600	12	Loss of supply	2	16	4	7.326

28/05/2004	0	8	Potential biological pathogens present	2	6	2	3.33
02/06/2004	1900	24	Loss of supply	2	16	8	8.658
03/06/2004	75	72	Biological pathogens present, health effects envisaged	2	64	16	27.306
08/06/2004	4226	3	Aesthetics above guidelines	2	32	2	11.988
13/06/2004	86	16	Loss of supply	2	16	4	7.326
14/06/2004	5200	8	Aesthetics above guidelines	2	32	2	11.988
20/07/2004	6000	11	Loss of supply	2	16	2	6.66
27/07/2004	975	6	Loss of supply	2	16	2	6.66
29/07/2004	5000	4	Chemicals present above guidelines	2	8	2	3.996
30/07/2004	4	8	Biological pathogens present, health effects envisaged	2	64	2	22.644
05/08/2004	85	8	Potential biological pathogens present, health effects envisaged	2	48	2	17.316
07/08/2004	80	10	Loss of supply	2	16	2	6.66
13/08/2004	0	1	Potential biological pathogens present	2	6	2	3.33
14/08/2004	10	48	Biological pathogens present, health effects envisaged	2	64	16	27.306
20/08/2004	3207	6	Aesthetics above guidelines	2	32	2	11.988
22/08/2004	4661	8	Aesthetics above guidelines	2	32	2	11.988
27/08/2004	500	25	Loss of supply	2	16	8	8.658
03/09/2004	213	15	Aesthetics above guidelines	2	32	4	12.654
07/09/2004	0	8	Chemicals present above guidelines	2	8	2	3.996
15/09/2004	985	2	Aesthetics above guidelines	2	32	2	11.988
18/09/2004	2800	24	Aesthetics above guidelines	2	32	8	13.986
25/09/2004	30000	11	Loss of supply	16	16	2	11.322
25/09/2004	30000	11	Aesthetics above guidelines	16	32	2	16.65
28/09/2004	1079	5	Loss of supply	2	16	2	6.66
28/09/2004	1079	5	Aesthetics above guidelines	2	32	2	11.988
01/10/2004	246	12	Loss of supply	2	16	4	7.326
16/10/2004	1430	12	Loss of supply	2	16	4	7.326
27/10/2004	300	6	Loss of supply	2	16	2	6.66
11/11/2004	1402	6	Loss of supply	2	16	2	6.66
20/11/2004	500	6	Loss of supply	2	16	2	6.66
01/12/2004	3500	8	Loss of supply	2	16	2	6.66

07/12/2004	11669	24	Aesthetics above guidelines	4	32	8	14.652
18/12/2004	7743	24	Aesthetics above guidelines	4	32	8	14.652
23/12/2004	20	6	Loss of supply	2	16	2	6.66
30/12/2004	974	8	Loss of supply	2	16	2	6.66
Average	**3061.037**	**15.33333333**		**2.666667**	**25.07407**	**4.851852**	**10.85333**
SD	**5913.346**	**15.84714723**		**2.691706**	**14.66976**	**4.783649**	**5.819917**
SE	**804.7045**	**2.156523589**		**0.366295**	**1.996302**	**0.650972**	**0.79199**
CI 95% min	**1483.816**	**11.1065471**		**1.948729**	**21.16132**	**3.575946**	**9.301032**
CI 95% max	**4638.258**	**19.56011957**		**3.384605**	**28.98683**	**6.127757**	**12.40563**

Table 23 Incident impact in 2004

				Hazard score	Hazard score	Hazard score	
				0.333	0.333	0.333	
Date of Incident	Population (actual affected)	Duration (hr)	Hazard category	P	H	D	Sum
01/01/2005	500	10	Loss of supply	2	16	2	6.66
08/01/2005	6014	4	Aesthetics above guidelines	2	32	2	11.988
08/01/2005	4679000	48	Loss of supply	500	16	16	177.156
09/01/2005	6852	2	Aesthetics above guidelines	2	32	2	11.988
10/01/2005	122	3	Potential biological pathogens present, health effects envisaged	2	48	2	17.316
10/01/2005	122	3	Loss of supply	2	16	2	6.66
18/01/2005	250	8	Aesthetics above guidelines	2	32	2	11.988
19/01/2005	10	8	Chemicals present above guidelines	2	8	2	3.996
03/03/2005	100	12	Loss of supply	2	16	4	7.326
10/03/2005	4150	6	Loss of supply	2	16	2	6.66
16/03/2005	80	15	Loss of supply	2	16	4	7.326
18/03/2005	10000	24	Loss of supply	4	16	8	9.324
18/03/2005	10000	24	Aesthetics above guidelines	4	32	8	14.652
05/04/2005	0	8	Chemicals present above guidelines	2	8	2	3.996
25/04/2005	6	8	Potential biological pathogens present, health effects envisaged	2	48	2	17.316
05/05/2005	28	8	Potential biological pathogens present, health effects envisaged	2	48	2	17.316
23/05/2005	5300	24	Loss of supply	2	16	8	8.658
23/05/2005	5300	24	Aesthetics above guidelines	2	32	8	13.986
24/05/2005	1800	6	Aesthetics above guidelines	2	32	2	11.988
25/05/2005	2590	8	Loss of supply	2	16	2	6.66
17/06/2005	6	8	Biological pathogens present, health effects envisaged	2	64	2	22.644
19/06/2005	15278	8	Aesthetics above guidelines	8	32	2	13.986
20/06/2005	21	8	Potential biological pathogens present, health effects envisaged	2	48	2	17.316
29/06/2005	100	8	Potential biological pathogens present, health effects envisaged	2	48	2	17.316
12/07/2005	700	8	Aesthetics above guidelines	2	32	2	11.988
16/07/2005	1200	6	Loss of supply	2	16	2	6.66

05/08/2005	2	8	Biological pathogens present	2	8	2	3.996
25/08/2005	76	48	Biological pathogens present, health effects envisaged	2	64	16	27.306
06/09/2005	600	24	Aesthetics above guidelines	2	32	8	13.986
12/09/2005	67	8	Biological pathogens present, health effects envisaged	2	64	2	22.644
17/09/2005	2100	48	Biological pathogens present	2	8	16	8.658
20/09/2005	26	6	Loss of supply	2	16	2	6.66
08/10/2005	7000	5	Aesthetics above guidelines	2	32	2	11.988
18/10/2005	1	0.5	Loss of supply	2	16	2	6.66
26/10/2005	3500	8	Loss of supply	2	16	2	6.66
17/11/2005	0	3	Potential biological pathogens present	2	6	2	3.33
17/11/2005	0	4	Chemicals present above guidelines	2	8	2	3.996
18/11/2005	97	11	Loss of supply	2	16	2	6.66
28/11/2005	2700	12	Aesthetics above guidelines	2	32	4	12.654
28/11/2005	500	12	Loss of supply	2	16	4	7.326
11/12/2005	0	8	Chemicals present above guidelines	2	8	2	3.996
22/12/2005	0	4	Chemicals present above guidelines	2	8	2	3.996
30/12/2005	1600	6	Loss of supply	2	16	2	6.66
Average	**110879.02**	**11.97**		**13.81**	**25.63**	**3.86**	**14.42**
SD	**713226.58**	**11.71**		**75.91**	**16.48**	**3.89**	**26.04**
SE	**108766.03**	**1.79**		**11.58**	**2.51**	**0.59**	**3.97**
CI 95% min	**-102302.40**	**8.47**		**-8.88**	**20.70**	**2.70**	**6.64**
CI 95% max	**324060.45**	**15.46**		**36.50**	**30.55**	**5.02**	**22.20**

Table 24 Incident impact for 2005

				Hazard score	Hazard score	Hazard score	
				0.333	0.333	0.333	
Date of Incident	Population (actual affected)	Duration (hr)	Hazard category	P	H	D	Sum
04/01/2006	0	24	Chemicals present above guidelines	2	8	8	5.994
17/01/2006	0	8	Chemicals present above guidelines	2	8	2	3.996
29/01/2006	3832	48	Chemicals present above guidelines	2	8	16	8.658
05/02/2006	15150	2.5	Loss of supply	8	16	2	8.658
05/02/2006	9453	2.5	Aesthetics above guidelines	4	32	2	12.654
10/02/2006	8000	4	Loss of supply	4	16	2	7.326
25/02/2006	7	8	Loss of supply	2	16	2	6.66
28/02/2006	1300	8	Aesthetics above guidelines	2	32	2	11.988
14/03/2006	175	8	Loss of supply	2	16	2	6.66
28/03/2006	5439	8	Aesthetics above guidelines	2	32	2	11.988
01/04/2006	2685	6	Aesthetics above guidelines	2	32	2	11.988
21/04/2006	420	10	Loss of supply	2	16	2	6.66
14/05/2006	10	8	Loss of supply	2	16	2	6.66
14/05/2006	2500	6	Aesthetics above guidelines	2	32	2	11.988
22/05/2006	0	6	Chemicals present above guidelines	2	8	2	3.996
30/05/2006	0	12	Loss of supply	2	16	4	7.326
04/06/2006	7500	6	Loss of supply	4	16	2	7.326
09/06/2006	80	6	Loss of supply	2	16	2	6.66
11/06/2006	340	8	Loss of supply	2	16	2	6.66
13/06/2006	300	8	Loss of supply	2	16	2	6.66
17/06/2006	9700	6	Aesthetics above guidelines	4	32	2	12.654
17/06/2006	50	8	Biological pathogens present	2	8	2	3.996
16/07/2006	250	6	Loss of supply	2	16	2	6.66
18/07/2006	500	18	Loss of supply	2	16	4	7.326
18/07/2006	7000	24	Aesthetics above guidelines	2	32	8	13.986
06/08/2006	400	8	Loss of supply	2	16	2	6.66

10/08/2006	80	8	Potential biological pathogens present, health effects envisaged	2	48	2	17.316
14/08/2006	60000	48	Chemicals present above guidelines	32	8	16	18.648
25/08/2006	24500	12	Potential biological pathogens present	8	6	4	5.994
03/09/2006	6	8	Chemicals present above guidelines	2	8	2	3.996
06/09/2006	1248	8	Loss of supply	2	16	2	6.66
16/09/2006	1300	8	Biological pathogens present	2	8	2	3.996
20/09/2006	37000	4	Loss of supply	16	16	2	11.322
24/09/2006	37600	1	Loss of supply	16	16	2	11.322
10/10/2006	1000	8	Loss of supply	2	16	2	6.66
02/12/2006	70	18	Loss of supply	2	16	4	7.326
Average	**6608.19**	**10.83**		**4.17**	**17.94**	**3.33**	**8.47**
SD	**13155.93**	**10.46**		**5.88**	**9.70**	**3.45**	**3.66**
SE	**2192.65**	**1.74**		**0.98**	**1.62**	**0.57**	**0.61**
CI 95% min	**2310.59**	**7.42**		**2.25**	**14.78**	**2.21**	**7.28**
CI 95% max	**10905.80**	**14.25**		**6.09**	**21.11**	**4.46**	**9.67**

Table 25 Incident impact in 2006

	Aesthetics				Biological pathogens present				Biological pathogens present, health effects				Chemical present above guidelines				Chemical present above guidelines, health effects				Loss of supply			
No	P	H	D	Sum	P	H	D	Sum	P	H	D	Sum	P	H	D	Sum	P	H	D	Sum	P	H	D	Sum
1.00	4	32	4	13.32	2	6	2	3.33	2	64	16	27.306	2	8	2	3.996					2	16	8	8.658
2.00	4	32	2	12.654	2	6	2	3.33	2	64	16	27.306	2	8	2	3.996					2	16	4	7.326
3.00	2	32	2	11.988	2	6	2	3.33	2	64	2	22.644	2	8	2	3.996					2	16	2	6.66
4.00	2	32	2	11.988					2	64	16	27.306									2	16	8	8.658
5.00	2	32	2	11.988					2	48	2	17.316									2	16	2	6.66
6.00	2	32	16	16.65																	2	16	16	11.322
7.00	2	32	16	16.65																	2	16	4	7.326
8.00	2	32	16	16.65																	2	16	8	8.658
9.00	2	32	2	11.988																	2	16	4	7.326
10.00	2	32	2	11.988																	2	16	2	6.66
11.00	2	32	2	11.988																	2	16	2	6.66
12.00	2	32	2	11.988																	2	16	2	6.66
13.00	2	32	2	11.988																	2	16	8	8.658
14.00	2	32	4	12.654																	16	16	2	11.322
15.00	2	32	2	11.988																	2	16	2	6.66
16.00	2	32	8	13.986																	2	16	4	7.326
17.00	16	32	2	16.65																	2	16	4	7.326
18.00	2	32	2	11.988																	2	16	2	6.66
19.00	4	32	8	14.652																	2	16	2	6.66
20.00	4	32	8	14.652																	2	16	2	6.66
21.00																					2	16	2	6.66
22.00																					2	16	2	6.66
23.00																					2	16	2	6.66
Average	**3.10**	**32.00**	**5.20**	**13.42**	**2.00**	**6.00**	**2.00**	**3.33**	**2.00**	**60.80**	**10.40**	**24.38**	**2.00**	**8.00**	**2.00**	**4.00**	**0.00**	**0.00**	**0.00**	**0.00**	**2.61**	**16.00**	**4.09**	**7.56**
SE	**0.70**	**0.00**	**1.15**	**0.42**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**3.20**	**3.43**	**1.98**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.61**	**0.00**	**0.72**	**0.29**
CI 95% min	**1.72**	**32.00**	**2.95**	**12.60**	**2.00**	**6.00**	**2.00**	**3.33**	**2.00**	**54.53**	**3.68**	**20.49**	**2.00**	**8.00**	**2.00**	**4.00**	**0.00**	**0.00**	**0.00**	**0.00**	**1.42**	**16.00**	**2.68**	**6.99**
CI 95% max	**4.48**	**32.00**	**7.45**	**14.24**	**2.00**	**6.00**	**2.00**	**3.33**	**2.00**	**67.07**	**17.12**	**28.26**	**2.00**	**8.00**	**2.00**	**4.00**	**0.00**	**0.00**	**0.00**	**0.00**	**3.80**	**16.00**	**5.49**	**8.13**

Table 26 Incident impact by hazard categories in 2004

	Aesthetics				Biological pathogens present				Biological pathogens present, health effects				Chemical present above guidelines				Chemical present above guidelines, health effects				Loss of supply			
No	**P**	**H**	**D**	**Sum**	**P**	**H**	**D**	**Sum**	**P**	**H**	**D**	**Sum**	**P**	**H**	**D**	**Sum**	**P**	**H**	**D**	**Sum**	**P**	**H**	**D**	**Sum**
1.00	2.00	32.00	2.00	11.99	2.00	8.00	2.00	4.00	2.00	64.00	2.00	22.64	2.00	8.00	2.00	4.00					2.00	16.00	2.00	6.66
2.00	2.00	32.00	2.00	11.99	2.00	8.00	16.00	8.66	2.00	64.00	16.00	27.31	2.00	8.00	2.00	4.00					500.00	16.00	16.00	177.16
3.00	2.00	32.00	2.00	11.99	2.00	6.00	2.00	3.33	2.00	64.00	2.00	22.64	2.00	8.00	2.00	4.00					2.00	16.00	2.00	6.66
4.00	4.00	32.00	8.00	14.65					2.00	48.00	2.00	17.32	2.00	8.00	2.00	4.00					2.00	16.00	4.00	7.33
5.00	2.00	32.00	8.00	13.99					2.00	48.00	2.00	17.32	2.00	8.00	2.00	4.00					2.00	16.00	2.00	6.66
6.00	2.00	32.00	2.00	11.99					2.00	48.00	2.00	17.32									2.00	16.00	4.00	7.33
7.00	8.00	32.00	2.00	13.99					2.00	48.00	2.00	17.32									4.00	16.00	8.00	9.32
8.00	2.00	32.00	2.00	11.99					2.00	48.00	2.00	17.32									2.00	16.00	8.00	8.66
9.00	2.00	32.00	8.00	13.99																	2.00	16.00	2.00	6.66
10.00	2.00	32.00	2.00	11.99																	2.00	16.00	2.00	6.66
11.00	2.00	32.00	4.00	12.65																	2.00	16.00	2.00	6.66
12.00																					2.00	16.00	2.00	6.66
13.00																					2.00	16.00	2.00	6.66
14.00																					2.00	16.00	2.00	6.66
15.00																					2.00	16.00	4.00	7.33
16.00																					2.00	16.00	2.00	6.66
Count	**11.00**	**11.00**	**11.00**	**11.00**	**3.00**	**3.00**	**3.00**	**3.00**	**8.00**	**8.00**	**8.00**	**8.00**	**5.00**	**5.00**	**5.00**	**5.00**	**0.00**	**0.00**	**0.00**	**0.00**	**16.00**	**16.00**	**16.00**	**16.00**
Average	**2.73**	**32.00**	**3.82**	**12.84**	**2.00**	**7.33**	**6.67**	**5.33**	**2.00**	**54.00**	**3.75**	**19.90**	**2.00**	**8.00**	**2.00**	**4.00**	**0.00**	**0.00**	**0.00**	**0.00**	**33.25**	**16.00**	**4.00**	**17.73**
SD	**1.85**	**0.00**	**2.75**	**1.08**	**0.00**	**1.15**	**8.08**	**2.90**	**0.00**	**8.28**	**4.95**	**3.84**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**124.47**	**0.00**	**3.79**	**42.52**
SE	**0.56**	**0.00**	**0.83**	**0.32**	**0.00**	**0.67**	**4.67**	**1.68**	**0.00**	**2.93**	**1.75**	**1.36**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**31.12**	**0.00**	**0.95**	**10.63**
CI 95% min	**1.63**	**32.00**	**2.19**	**12.20**	**2.00**	**6.03**	**-2.48**	**2.04**	**2.00**	**48.26**	**0.32**	**17.23**	**2.00**	**8.00**	**2.00**	**4.00**	**0.00**	**0.00**	**0.00**	**0.00**	**-27.74**	**16.00**	**2.14**	**-3.10**
CI 95% max	**3.82**	**32.00**	**5.44**	**13.47**	**2.00**	**8.64**	**15.81**	**8.61**	**2.00**	**59.74**	**7.18**	**22.56**	**2.00**	**8.00**	**2.00**	**4.00**	**0.00**	**0.00**	**0.00**	**0.00**	**94.24**	**16.00**	**5.86**	**38.57**

Table 27 Incident impact by hazard type in 2005

	Aesthetics					Biological pathogens present					Biological pathogens present, health effects					Chemical present above guidelines					Loss of supply			
No	**P**	**H**	**D**	**Sum**		**P**	**H**	**D**	**Sum**		**P**	**H**	**D**	**Sum**		**P**	**H**	**D**	**Sum**		**P**	**H**	**D**	**Sum**
1.00	4.00	32.00	2.00	12.65		2.00	8.00	2.00	4.00		2.00	48.00	2.00	17.32		2.00	8.00	8.00	5.99		8.00	16.00	2.00	8.66
2.00	2.00	32.00	2.00	11.99		2.00	8.00	2.00	4.00							2.00	8.00	2.00	4.00		4.00	16.00	2.00	7.33
3.00	2.00	32.00	2.00	11.99		8.00	6.00	4.00	5.99							2.00	8.00	16.00	8.66		2.00	16.00	2.00	6.66
4.00	2.00	32.00	2.00	11.99												2.00	8.00	2.00	4.00		2.00	16.00	2.00	6.66
5.00	2.00	32.00	2.00	11.99												32.00	8.00	16.00	18.65		2.00	16.00	2.00	6.66
6.00	4.00	32.00	2.00	12.65												2.00	8.00	2.00	4.00		2.00	16.00	2.00	6.66
7.00	2.00	32.00	8.00	13.99																	2.00	16.00	4.00	7.33
8.00																					4.00	16.00	2.00	7.33
9.00																					2.00	16.00	2.00	6.66
10.00																					2.00	16.00	2.00	6.66
11.00																					2.00	16.00	2.00	6.66
12.00																					2.00	16.00	2.00	6.66
13.00																					2.00	16.00	4.00	7.33
14.00																					2.00	16.00	2.00	6.66
15.00																					2.00	16.00	2.00	6.66
16.00																					16.00	16.00	2.00	11.32
17.00																					16.00	16.00	2.00	11.32
18.00																					2.00	16.00	2.00	6.66
19.00																					2.00	16.00	4.00	7.33
20.00																								
Count	**7.00**	**7.00**	**7.00**	**7.00**		**3.00**	**3.00**	**3.00**	**3.00**		**1.00**	**1.00**	**1.00**	**1.00**		**6.00**	**6.00**	**6.00**	**6.00**		**19.00**	**19.00**	**19.00**	**19.00**
Av	**2.57**	**32.00**	**2.86**	**12.46**		**4.00**	**7.33**	**2.67**	**4.66**		**2.00**	**48.00**	**2.00**	**17.32**		**7.00**	**8.00**	**7.67**	**7.55**		**4.00**	**16.00**	**2.32**	**7.43**
SD	**0.98**	**0.00**	**2.27**	**0.74**		**3.46**	**1.15**	**1.15**	**1.15**		**0.00**	**0.00**	**0.00**	**0.00**		**12.25**	**0.00**	**6.86**	**5.74**		**4.47**	**0.00**	**0.75**	**1.46**
SE	**0.37**	**0.00**	**0.86**	**0.28**		**2.00**	**0.67**	**0.67**	**0.67**		**0.00**	**0.00**	**0.00**	**0.00**		**5.00**	**0.00**	**2.80**	**2.34**		**1.03**	**0.00**	**0.17**	**0.33**
CI 95% min	**1.85**	**32.00**	**1.18**	**11.91**		**0.08**	**6.03**	**1.36**	**3.36**		**2.00**	**48.00**	**2.00**	**17.32**		**-2.80**	**8.00**	**2.18**	**2.96**		**1.99**	**16.00**	**1.98**	**6.77**
CI 95% max	**3.29**	**32.00**	**4.54**	**13.01**		**7.92**	**8.64**	**3.97**	**5.97**		**2.00**	**48.00**	**2.00**	**17.32**		**16.80**	**8.00**	**13.16**	**12.14**		**6.01**	**16.00**	**2.65**	**8.09**

Table 28 Incident impact by hazard category in 2006

In the following tables, significance tests compare the incident impact in specified hazard categories for subsequent years.

								Significance testing						Legend		
								H0: X1 - X2 = 0			X1	1997.00			F	
								H1: X1 - X2 <>0			X2	1998.00			H	
Year				Year				SL: 5%								
1997.00				1998.00												
	F	H	SE		F	H	SE	mean X1 - mean X2	Variance X1-X2	SE	CI 95% min	CI 95% max	H0	SL		Comment
Aesthetics	5.00	17.58	2.43	Aesthetics	8.00	12.40	0.18	-11.32	5.96	2.44	-4.78	4.78	Reject	0.05	X2>>X1	Increase of impact compared to previous year
Biological pathogens present	2.00	24.81	20.15	Biological pathogens present	2.00	4.00	0.67	41.63	406.33	20.16	-39.51	39.51	Reject	0.05	X1>>X2	Reduced impact compared to previous year
Biological pathogens present, health effects	4.00	33.30	3.83	Biological pathogens present, health effects	3.00	28.19	4.44	48.62	34.35	5.86	-11.49	11.49	Reject	0.05	X1>>X2	Reduced impact compared to previous year
Chemical present above guidelines	1.00	4.00	0.00	Chemical present above guidelines	0.00	0.00	0.00	4.00	0.00	0.00	0.00	0.00	Reject	0.05	X1>>X2	Reduced impact compared to previous year
Chemical present above guidelines, health effects	0.00	0.00	0.00	Chemical present above guidelines, health effects	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Accept	0.05	X2 = X1	Equal impact
Loss of supply	11.00	8.78	0.57	Loss of supply	2.00	6.99	0.33	82.58	0.43	0.66	-1.29	1.29	Reject	0.05	X1>>X2	Reduced impact compared to previous year

								Significance testing								
								H0: X1 - X2 = 0			X1	1998.00				
								H1: X1 - X2 <>0			X2	1999.00				
Year				Year				SL: 5%								
1998.00				1999.00												
	F	H	SE		F	H	SE	mean X1 - mean X2	Variance X1-X2	SE	CI 95% min	CI 95% max	H0	SL		Comment
Aesthetics	8.00	12.40	0.18	Aesthetics	22.00	13.99	0.96	-208.46	0.95	0.97	-1.91	1.91	Reject	0.05	X2>>X1	Increase of impact compared to previous year
Biological pathogens present	2.00	4.00	0.67	Biological pathogens present	4.00	4.33	0.58	-9.32	0.78	0.88	-1.73	1.73	Reject	0.05	X2>>X1	Increase of impact compared to previous year
Biological pathogens present, health effects	3.00	28.19	4.44	Biological pathogens present, health effects	2.00	25.97	6.66	32.63	64.07	8.00	-15.69	15.69	Reject	0.05	X1>>X2	Reduced impact compared to previous year
Chemical present above guidelines	0.00	0.00	0.00	Chemical present above guidelines	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Accept	0.05	X2 = X1	Equal impact
Chemical present above guidelines, health effects	0.00	0.00	0.00	Chemical present above guidelines, health effects	1.00	13.99	0.00	-13.99	0.00	0.00	0.00	0.00	Reject	0.05	X2>>X1	Increase of impact compared to previous year
Loss of supply	2.00	6.99	0.33	Loss of supply	11.00	7.27	0.23	-65.93	0.16	0.40	-0.79	0.79	Reject	0.05	X2>>X1	Increase of impact compared to previous year

								Significance testing								
								H0: X1 - X2 = 0			X1	1999.00				
								H1: X1 - X2 <>0			X2	2000.00				
Year				Year				SL: 5%								
1999.00				2000.00												
	F	H	SE		F	H	SE	mean X1 - mean X2	Variance X1-X2	SE	CI 95% min	CI 95% max	H0	SL		Comment
Aesthetics	22.00	13.99	0.96	Aesthetics	16.00	13.24	0.48	95.90	1.15	1.07	-2.10	2.10	Reject	0.05	X1>>X2	Reduced impact compared to previous year
Biological pathogens present	4.00	4.33	0.58	Biological pathogens present	4.00	7.16	2.44	-11.32	6.27	2.50	-4.91	4.91	Reject	0.05	X2>>X1	Increase of impact compared to previous year
Biological pathogens present, health effects	2.00	25.97	6.66	Biological pathogens present, health effects	2.00	25.97	1.33	0.00	46.13	6.79	-13.31	13.31	Accept	0.05	X2 = X1	Equal impact
Chemical present above guidelines	0.00	0.00	0.00	Chemical present above guidelines	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Accept	0.05	X2 = X1	Equal impact
Chemical present above guidelines, health effects	1.00	13.99	0.00	Chemical present above guidelines, health effects	0.00	0.00	0.00	13.99	0.00	0.00	0.00	0.00	Reject	0.05	X1>>X2	Reduced impact compared to previous year
Loss of supply	11.00	7.27	0.23	Loss of supply	12.00	7.49	0.39	-9.99	0.20	0.45	-0.88	0.88	Reject	0.05	X2>>X1	Increase of impact compared to previous year

								Significance testing								
								H0: X1 - X2 = 0			X1	2000.00				
								H1: X1 - X2 <>0			X2	2001.00				
Year				Year				SL: 5%								
2000.00				2001.00												
	F	H	SE		F	H	SE	mean X1 - mean X2	Variance X1-X2	SE	CI 95% min	CI 95% max	H0	SL		Comment
Aesthetics	16.00	13.24	0.48	Aesthetics	9.00	12.58	0.21	98.57	0.27	0.52	-1.03	1.03	Reject	0.05	X1>>X2	Reduced impact compared to previous year
Biological pathogens present	4.00	7.16	2.44	Biological pathogens present	4.00	4.66	1.33	9.99	7.72	2.78	-5.44	5.44	Reject	0.05	X1>>X2	Reduced impact compared to previous year
Biological pathogens present, health effects	2.00	25.97	1.33	Biological pathogens present, health effects	2.00	22.31	0.33	7.33	1.89	1.37	-2.69	2.69	Reject	0.05	X1>>X2	Reduced impact compared to previous year
Chemical present above guidelines	0.00	0.00	0.00	Chemical present above guidelines	1.00	5.99	0.00	-5.99	0.00	0.00	0.00	0.00	Reject	0.05	X2>>X1	Increase of impact compared to previous year
Chemical present above guidelines, health effects	0.00	0.00	0.00	Chemical present above guidelines, health effects	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Accept	0.05	X2 = X1	Equal impact
Loss of supply	12.00	7.49	0.39	Loss of supply	13.00	8.86	1.55	-25.31	2.54	1.60	-3.13	3.13	Reject	0.05	X2>>X1	Increase of impact compared to previous year

									Significance testing							
									H0: X1 - X2 = 0		X1	2001.00				
									H1: X1 - X2 <>0		X2	2002.00				
Year				Year				SL: 5%								
2001.00				2002.00												
	F	H	SE		F	H	SE	mean X1 - mean X2	Variance X1-X2	SE	CI 95% min	CI 95% max	H0	SL		Comment
Aesthetics	9.00	12.58	0.21	Aesthetics	17.00	13.91	0.74	-123.21	0.59	0.77	-1.50	1.50	Reject	0.05	X2>>X1	Increase of impact compared to previous year
Biological pathogens present	4.00	4.66	1.33	Biological pathogens present	4.00	5.33	0.94	-2.66	2.66	1.63	-3.20	3.20	Accept	0.05	X2 = X1	Equal impact
Biological pathogens present, health effects	2.00	22.31	0.33	Biological pathogens present, health effects	1.00	17.32	0.00	27.31	0.11	0.33	-0.65	0.65	Reject	0.05	X1>>X2	Reduced impact compared to previous year
Chemical present above guidelines	1.00	5.99	0.00	Chemical present above guidelines	0.00	0.00	0.00	5.99	0.00	0.00	0.00	0.00	Reject	0.05	X1>>X2	Reduced impact compared to previous year
Chemical present above guidelines, health effects	0.00	0.00	0.00	Chemical present above guidelines, health effects	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Accept	0.05	X2 = X1	Equal impact
Loss of supply	13.00	8.86	1.55	Loss of supply	9.00	8.58	0.79	37.96	3.02	1.74	-3.40	3.40	Reject	0.05	X1>>X2	Reduced impact compared to previous year

								Significance testing								
								H0: X1 - X2 = 0			X1	2002.00				
								H1: X1 - X2 <>0			X2	2003.00				
Year				Year				SL: 5%								
2002.00				2003.00												
	F	H	SE		F	H	SE	mean X1 - mean X2	Variance X1-X2	SE	CI 95% min	CI 95% max	H0	SL		Comment
Aesthetics	17.00	13.91	0.74	Aesthetics	16.00	12.65	0.30	33.97	0.64	0.80	-1.56	1.56	Reject	0.05	X1>>X2	Reduced impact compared to previous year
Biological pathogens present	4.00	5.33	0.94	Biological pathogens present	0.00	0.00	0.00	21.31	0.89	0.94	-1.85	1.85	Reject	0.05	X1>>X2	Reduced impact compared to previous year
Biological pathogens present, health effects	1.00	17.32	0.00	Biological pathogens present, health effects	5.00	20.11	0.97	-83.25	0.95	0.97	-1.91	1.91	Reject	0.05	X2>>X1	Increase of impact compared to previous year
Chemical present above guidelines	0.00	0.00	0.00	Chemical present above guidelines	1.00	4.00	0.00	-4.00	0.00	0.00	0.00	0.00	Reject	0.05	X2>>X1	Increase of impact compared to previous year
Chemical present above guidelines, health effects	0.00	0.00	0.00	Chemical present above guidelines, health effects	1.00	11.99	0.00	-11.99	0.00	0.00	0.00	0.00	Reject	0.05	X2>>X1	Increase of impact compared to previous year
Loss of supply	9.00	8.58	0.79	Loss of supply	9.00	7.62	0.51	8.66	0.88	0.94	-1.84	1.84	Reject	0.05	X1>>X2	Reduced impact compared to previous year

								Significance testing								
								H0: X1 - X2 = 0			X1	2003.00				
								H1: X1 - X2 <>0			X2	2004.00				
Year				Year				SL: 5%								
2003.00				2004.00												
	F	H	SE		F	H	SE	mean X1 - mean X2	Variance X1-X2	SE	CI 95% min	CI 95% max	H0	SL		Comment
Aesthetics	16.00	12.65	0.30	Aesthetics	20.00	13.42	0.42	-65.93	0.27	0.52	-1.01	1.01	Reject	0.05	X2>>X1	Increase of impact compared to previous year
Biological pathogens present	0.00	0.00	0.00	Biological pathogens present	3.00	3.33	0.00	-9.99	0.00	0.00	0.00	0.00	Reject	0.05	X2>>X1	Increase of impact compared to previous year
Biological pathogens present, health effects	5.00	20.11	0.97	Biological pathogens present, health effects	5.00	24.38	1.98	-21.31	4.88	2.21	-4.33	4.33	Reject	0.05	X2>>X1	Increase of impact compared to previous year
Chemical present above guidelines	1.00	4.00	0.00	Chemical present above guidelines	3.00	4.00	0.00	-7.99	0.00	0.00	0.00	0.00	Reject	0.05	X2>>X1	Increase of impact compared to previous year
Chemical present above guidelines, health effects	1.00	11.99	0.00	Chemical present above guidelines, health effects	0.00	0.00	0.00	11.99	0.00	0.00	0.00	0.00	Reject	0.05	X1>>X2	Reduced impact compared to previous year
Loss of supply	9.00	7.62	0.51	Loss of supply	23.00	7.56	0.29	-105.23	0.35	0.59	-1.15	1.15	Reject	0.05	X2>>X1	Increase of impact compared to previous year

								Significance testing								
								H0: X1 - X2 = 0			X1	2004.00				
								H1: X1 - X2 <>0			X2	2005.00				
Year				Year				SL: 5%								
2004.00				2005.00												
	F	H	SE		F	H	SE	mean X1 - mean X2	Variance X1-X2	SE	CI 95% min	CI 95% max	H0	SL		Comment
Aesthetics	20.00	13.42	0.42	Aesthetics	11.00	12.84	0.32	127.21	0.28	0.53	-1.04	1.04	Reject	0.05	X1>>X2	Reduced impact compared to previous year
Biological pathogens present	3.00	3.33	0.00	Biological pathogens present	3.00	5.33	1.68	-5.99	2.81	1.68	-3.29	3.29	Reject	0.05	X2>>X1	Increase of impact compared to previous year
Biological pathogens present, health effects	5.00	24.38	1.98	Biological pathogens present, health effects	8.00	19.90	1.36	-37.30	5.77	2.40	-4.71	4.71	Reject	0.05	X2>>X1	Increase of impact compared to previous year
Chemical present above guidelines	3.00	4.00	0.00	Chemical present above guidelines	5.00	4.00	0.00	-7.99	0.00	0.00	0.00	0.00	Reject	0.05	X2>>X1	Increase of impact compared to previous year
Chemical present above guidelines, health effects	0.00	0.00	0.00	Chemical present above guidelines, health effects	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Accept	0.05	X2 = X1	Equal impact
Loss of supply	23.00	7.56	0.29	Loss of supply	16.00	17.73	10.63	-109.89	113.08	10.63	-20.84	20.84	Reject	0.05	X2>>X1	Increase of impact compared to previous year

								Significance testing								
								H0: X1 - X2 = 0			X1	2005.00				
								H1: X1 - X2 <>0			X2	2006.00				
Year				Year				SL: 5%								
2005.00				2006.00												
	F	H	SE		F	H	SE	mean X1 - mean X2	Variance X1-X2	SE	CI 95% min	CI 95% max	H0	SL		Comment
Aesthetics	11.00	12.84	0.32	Aesthetics	7.00	12.46	0.28	53.95	0.18	0.43	-0.84	0.84	Reject	0.05	X1>>X2	Reduced impact compared to previous year
Biological pathogens present	3.00	5.33	1.68	Biological pathogens present	3.00	4.66	0.67	2.00	3.25	1.80	-3.53	3.53	Accept	0.05	X2 = X1	Equal impact
Biological pathogens present, health effects	8.00	19.90	1.36	Biological pathogens present, health effects	1.00	17.32	0.00	141.86	1.84	1.36	-2.66	2.66	Reject	0.05	X1>>X2	Reduced impact compared to previous year
Chemical present above guidelines	5.00	4.00	0.00	Chemical present above guidelines	6.00	7.55	2.34	-25.31	5.49	2.34	-4.59	4.59	Reject	0.05	X2>>X1	Increase of impact compared to previous year
Chemical present above guidelines, health effects	0.00	0.00	0.00	Chemical present above guidelines, health effects	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Accept	0.05	X2 = X1	Equal impact
Loss of supply	16.00	17.73	10.63	Loss of supply	19.00	7.43	0.33	142.52	113.11	10.64	-20.85	20.85	Reject	0.05	X1>>X2	Reduced impact compared to previous year

Table 29 significance testing for incident in hazard categories

The following tables summarise the impact of incidents on customers for subsequent years.

	Population (actual)	Duration in hrs	P Score	H Score	D Score	Incident impact on customers
1997						
Number of incidents	23.00	23.00	23.00	23.00	23.00	23.00
Average	23,867.52	41.09	11.09	26.78	10.61	16.14
SD	68,997.47	59.41	25.93	19.09	14.26	12.10
SE	14,386.97	12.39	5.41	3.98	2.97	2.52
CI 95 min	-4,330.94	16.81	0.49	18.98	4.78	11.20
CI 95 max	52,065.98	65.37	21.68	34.58	16.44	21.09
1998						
Number of incidents	15.00	15.00	15.00	15.00	15.00	15.00
Average	2,323.47	26.67	2.27	31.87	7.07	13.72
SD	3,851.84	39.85	0.70	17.05	10.25	8.63
SE	994.54	10.29	0.18	4.40	2.65	2.23
CI 95 min	374.17	6.50	1.91	23.24	1.88	9.35
CI 95 max	4,272.76	46.83	2.62	40.49	12.25	18.09
1999						
Number of incidents	40.00	40.00	40.00	40.00	40.00	40.00
Average	7,694.85	14.00	4.45	26.30	4.60	11.77
SD	20,096.58	17.13	9.99	11.66	5.68	6.17
SE	3,177.55	2.71	1.58	1.84	0.90	0.98
CI 95 min	1,466.86	8.69	1.35	22.69	2.84	9.86
CI 95 max	13,922.84	19.31	7.55	29.91	6.36	13.68
2000						
Number of incidents	34.00	34.00	34.00	34.00	34.00	34.00
Average	5,231.06	18.44	3.06	25.24	5.47	11.24
SD	7,668.90	20.64	2.75	13.67	6.25	5.17
SE	1,315.20	3.54	0.47	2.34	1.07	0.89
CI 95 min	2,653.26	11.50	2.13	20.64	3.37	9.50
CI 95 max	7,808.86	25.38	3.98	29.83	7.57	12.98
2001						
Number of incidents	29.00	29.00	29.00	29.00	29.00	29.00
Average	1,898.17	21.86	2.14	22.14	6.55	10.27
SD	2,641.73	36.11	0.52	13.32	11.67	5.69
SE	490.56	6.71	0.10	2.47	2.17	1.06
CI 95 min	936.68	8.72	1.95	17.29	2.30	8.20
CI 95 max	2,859.66	35.01	2.33	26.99	10.80	12.34

Table 30 Summary of annual incident impacts

	Population (actual)	Duration in hrs	P Score	H Score	D Score	Incident impact on customers
2002						
Number of incidents	31.00	31.00	31.00	31.00	31.00	31.00
Average	8,381.26	17.03	4.32	24.52	5.29	11.36
SD	19,140.03	16.30	6.33	10.84	4.69	4.34
SE	3,437.65	2.93	1.14	1.95	0.84	0.78
CI 95 min	1,643.46	11.29	2.10	20.70	3.64	9.84
CI 95 max	15,119.05	22.77	6.55	28.33	6.94	12.89
2003						
Number of incidents	32.00	32.00	32.00	32.00	32.00	32.00
Average	3,575.91	13.41	2.63	29.75	4.00	12.11
SD	6,462.20	11.69	2.51	12.40	3.73	4.52
SE	1,142.37	2.07	0.44	2.19	0.66	0.80
CI 95 min	1,336.87	9.36	1.75	25.45	2.71	10.55
CI 95 max	5,814.94	17.46	3.50	34.05	5.29	13.68
2004						
Number of incidents	54.00	54.00	54.00	54.00	54.00	54.00
Average	3,061.04	15.33	2.67	25.07	4.85	10.85
SD	5,913.35	15.85	2.69	14.67	4.78	5.82
SE	804.70	2.16	0.37	2.00	0.65	0.79
CI 95 min	1,483.82	11.11	1.95	21.16	3.58	9.30
CI 95 max	4,638.26	19.56	3.38	28.99	6.13	12.41
2005						
Number of incidents	43.00	43.00	43.00	43.00	43.00	43.00
Average	110,879.02	11.97	13.81	25.63	3.86	14.42
SD	713,226.58	11.71	75.91	16.48	3.89	26.04
SE	108,766.03	1.79	11.58	2.51	0.59	3.97
CI 95 min	-102,302.40	8.47	-8.88	20.70	2.70	6.64
CI 95 max	324,060.45	15.46	36.50	30.55	5.02	22.20
2006						
Number of incidents	36.00	36.00	36.00	36.00	36.00	36.00
Average	6,608.19	10.83	4.17	17.94	3.33	8.47
SD	13,155.93	10.46	5.88	9.70	3.45	3.66
SE	2,192.65	1.74	0.98	1.62	0.57	0.61
CI 95 min	2,310.59	7.42	2.25	14.78	2.21	7.28
CI 95 max	10,905.80	14.25	6.09	21.11	4.46	9.67

Table 31 Summary of annual incident impacts

The following tables summarise the significance tests that compares the incident impact on customers for subsequent years (1997 -2006).

Significance testing	**H0: X1 - X2 = 0**	**SL: 5%**		**X1: 1997**		
	H1: X1 - X2 <>0			**X2: 1998**		
	Population	**Duration in hrs**	**P Score**	**H Score**	**D Score**	**Incident impact on customers**
mean X1 - mean X2	21,544.06	14.42	8.82	-5.08	3.54	2.42
Variance X1-X2	207,973,949.64	259.29	29.27	35.21	15.85	11.34
SE	14,421.30	16.10	5.41	5.93	3.98	3.37
CI 95% min	-28,265.75	-31.56	-10.60	-11.63	-7.80	-6.60
CI 95% max	28,265.75	31.56	10.60	11.63	7.80	6.60
H0	**Accept**	**Accept**	**Accept**	**Accept**	**Accept**	**Accept**
SL	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**
	X2 = X1	**X2 = X1**	**X2 = X1**	**X2 = X1**	**X2 = X1**	**X2 = X1**
Significance testing	**H0: X1 - X2 = 0**	**SL: 5%**		**X1: 1998**		
	H1: X1 - X2 <>0			**X2: 1999**		
	Population	**Duration in hrs**	**P Score**	**H Score**	**D Score**	**Incident impact on customers**
mean X1 - mean X2	-5,371.38	12.67	-2.18	5.57	2.47	1.95
Variance X1-X2	11,085,921.80	113.18	2.53	22.77	7.81	5.92
SE	3,329.55	10.64	1.59	4.77	2.79	2.43
CI 95% min	-6,525.92	-20.85	-3.12	-9.35	-5.48	-4.77
CI 95% max	6,525.92	20.85	3.12	9.35	5.48	4.77
H0	**Accept**	**Accept**	**Accept**	**Accept**	**Accept**	**Accept**
SL	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**
	X2 = X1	**X2 = X1**	**X2 = X1**	**X2 = X1**	**X2 = X1**	**X2 = X1**
Significance testing	**H0: X1 - X2 = 0**	**SL: 5%**		**X1: 1999**		
	H1: X1 - X2 <>0			**X2: 2000**		
	Population	**Duration in hrs**	**P Score**	**H Score**	**D Score**	**Incident impact on customers**
mean X1 - mean X2	2,463.79	-4.44	1.39	1.06	-0.87	0.53
Variance X1-X2	11,826,576.33	19.87	2.72	8.90	1.96	1.74
SE	3,438.98	4.46	1.65	2.98	1.40	1.32
CI 95% min	-6,740.40	-8.74	-3.23	-5.85	-2.74	-2.58
CI 95% max	6,740.40	8.74	3.23	5.85	2.74	2.58
H0	**Accept**	**Accept**	**Accept**	**Accept**	**Accept**	**Accept**
SL	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**
	X2 = X1	**X2 = X1**	**X2 = X1**	**X2 = X1**	**X2 = X1**	**X2 = X1**

Significance testing	**H0: X1 - X2 = 0**	**SL: 5%**		**X1: 2000**		
	H1: X1 - X2 <>0			**X2: 2001**		
	Population	**Duration in hrs**	**P Score**	**H Score**	**D Score**	**Incident impact on customers**
mean X1 - mean X2	3,332.89	-3.42	0.92	3.10	-1.08	0.98
Variance X1-X2	1,970,409.98	57.51	0.23	11.61	5.85	1.90
SE	1,403.71	7.58	0.48	3.41	2.42	1.38
CI 95% min	-2,751.28	-14.86	-0.94	-6.68	-4.74	-2.70
CI 95% max	2,751.28	14.86	0.94	6.68	4.74	2.70
H0	**Reject**	**Accept**	**Accept**	**Accept**	**Accept**	**Accept**
SL	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**
	X2 << X1	**X2 = X1**	**X2 = X1**	**X2 = X1**	**X2 = X1**	**X2 = X1**

Significance testing	**H0: X1 - X2 = 0**	**SL: 5%**		**X1: 2001**		
	H1: X1 - X2 <>0			**X2: 2002**		
	Population	**Duration in hrs**	**P Score**	**H Score**	**D Score**	**Incident impact on customers**
mean X1 - mean X2	-6,483.09	4.83	-2.18	-2.38	1.26	-1.10
Variance X1-X2	12,058,087.94	53.54	1.30	9.91	5.41	1.72
SE	3,472.48	7.32	1.14	3.15	2.33	1.31
CI 95% min	-6,806.05	-14.34	-2.24	-6.17	-4.56	-2.57
CI 95% max	6,806.05	14.34	2.24	6.17	4.56	2.57
H0	**Accept**	**Accept**	**Accept**	**Accept**	**Accept**	**Accept**
SL	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**
	X2 = X1	**X2 = X1**	**X2 = X1**	**X2 = X1**	**X2 = X1**	**X2 = X1**
Significance testing	**H0: X1 - X2 = 0**	**SL: 5%**		**X1: 2002**		
	H1: X1 - X2 <>0			**X2: 2003**		
	Population	**Duration in hrs**	**P Score**	**H Score**	**D Score**	**Incident impact on customers**
mean X1 - mean X2	4,805.35	3.63	1.70	-5.23	1.29	-0.75
Variance X1-X2	13,122,441.63	12.84	1.49	8.60	1.15	1.24
SE	3,622.49	3.58	1.22	2.93	1.07	1.12
CI 95% min	-7,100.08	-7.02	-2.39	-5.75	-2.10	-2.19
CI 95% max	7,100.08	7.02	2.39	5.75	2.10	2.19
H0	**Accept**		**Accept**	**Accept**	**Accept**	**Accept**
SL	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**
	X2 = X1		**X2 = X1**	**X2 = X1**	**X2 = X1**	**X2 = X1**

Significance testing	**H0: X1 - X2 = 0**	**SL: 5%**		**X1: 2003**		
	H1: X1 - X2 <>0			**X2: 2004**		
	Population	**Duration in hrs**	**P Score**	**H Score**	**D Score**	**Incident impact on customers**
mean X1 - mean X2	514.87	-1.93	-0.04	4.68	-0.85	1.26
Variance X1-X2	1,952,549.25	8.92	0.33	8.79	0.86	1.26
SE	1,397.34	2.99	0.58	2.96	0.93	1.12
CI 95% min	-2,738.78	-5.85	-1.13	-5.81	-1.82	-2.20
CI 95% max	2,738.78	5.85	1.13	5.81	1.82	2.20
H0	**Accept**	**Accept**	**Accept**	**Accept**	**Accept**	**Accept**
SL	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**
	X2 = X1	**X2 = X1**	**X2 = X1**	**X2 = X1**	**X2 = X1**	**X2 = X1**

Significance testing	**H0: X1 - X2 = 0**	**SL: 5%**		**X1: 2004**		
	H1: X1 - X2 <>0			**X2: 2005**		
	Population	**Duration in hrs**	**P Score**	**H Score**	**D Score**	**Incident impact on customers**
mean X1 - mean X2	-107,817.99	3.37	-11.15	-0.55	0.99	-3.57
Variance X1-X2	11,830,697,682.87	7.84	134.16	10.30	0.78	16.40
SE	108,769.01	2.80	11.58	3.21	0.88	4.05
CI 95% min	-213,187.26	-5.49	-22.70	-6.29	-1.73	-7.94
CI 95% max	213,187.26	5.49	22.70	6.29	1.73	7.94
H0	**Accept**	**Accept**	**Accept**	**Accept**	**Accept**	**Accept**
SL	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**
	X2 = X1	**X2 = X1**	**X2 = X1**	**X2 = X1**	**X2 = X1**	**X2 = X1**
Significance testing	**H0: X1 - X2 = 0**	**SL: 5%**		**X1: 2005**		
	H1: X1 - X2 <>0			**X2: 2006**		
	Population	**Duration in hrs**	**P Score**	**H Score**	**D Score**	**Incident impact on customers**
mean X1 - mean X2	104,270.83	1.13	9.65	7.68	0.53	5.95
Variance X1-X2	11,834,857,867.20	6.23	134.98	8.93	0.68	16.14
SE	108,788.13	2.50	11.62	2.99	0.83	4.02
CI 95% min	-213,224.74	-4.89	-22.77	-5.86	-1.62	-7.88
CI 95% max	213,224.74	4.89	22.77	5.86	1.62	7.88
H0	**Accept**	**Accept**	**Accept**	**Reject**	**Accept**	**Accept**
SL	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**
	X2 = X1	**X2 = X1**	**X2 = X1**	**X1>X2**	**X2 = X1**	**X2 = X1**

Significance testing	H0: X1 - X2 = 0	SL: 5%		X1: 1997		
	H1: X1 - X2 <>0			X2: 2006		
	Population	Duration in hrs	P Score	H Score	D Score	Incident impact on customers
mean X1 - mean X2	17,259.33	30.25	6.92	8.84	7.28	7.67
Variance X1-X2	211,792,574.08	156.49	30.20	18.45	9.17	6.74
SE	14,553.10	12.51	5.50	4.30	3.03	2.60
CI 95% min	-28,524.07	-24.52	-10.77	-8.42	-5.94	-5.09
CI 95% max	28,524.07	24.52	10.77	8.42	5.94	5.09
H0	Accept	Reject	Accept	Reject	Reject	Reject
SL	0.05	0.05	0.05	0.05	0.05	0.05
	X2 = X1	X1 >> X2	X2 = X1	X1 >> X2	X1 >> X2	X1 >> X2

Table 32 Significance testing for incident statistics between 1997 and 2006

3.2.2.4 Comparison of incidents in the Regional Water Utility with national incidents

RWU Incident database				**National Standard (DWI) customised to RWU (Frequency adjusted over Population)**				**Significance testing**								
								H0: X1 - X2 = 0			X1	RWU				
								H1: X1 - X2 <>0			X2	SN				
RWU Incident database								SL: 5%								
2004.00																
	F	H	SE		F	H	SE	mean X1 - mean X2	Variance X1-X2	SE	CI 95% min	CI 95% max	H0	SL		**Comment**
Aesthetics	20.00	13.42	0.42	Aesthetics	4.18	21.63	2.24	177.99	5.20	2.28	-4.47	4.47	Reject	0.05	X1 >> X2	**RWU do worse**
Biological pathogens present	3.00	3.33	0.00	Biological pathogens present	1.45	16.38	5.06	-13.82	25.57	5.06	-9.91	9.91	Reject	0.05	X2 >> X1	**RWU do better**
Biological pathogens present, health effects	5.00	24.38	1.98	Biological pathogens present, health effects	1.36	29.90	2.51	81.13	10.23	3.20	-6.27	6.27	Reject	0.05	X1 >> X2	**RWU do worse**
Chemical present above guidelines	3.00	4.00	0.00	Chemical present above guidelines	0.55	19.64	6.29	1.28	39.61	6.29	-12.34	12.34	Accept	0.05	X1 = X2	
Chemical present above guidelines, health effects	0.00	0.00	0.00					0.00	0.00	0.00	0.00	0.00	Accept	0.05	X1 = X2	
Loss of supply	23.00	7.56	0.29	Loss of supply	0.09	11.88	0.00	172.75	0.09	0.29	-0.57	0.57	Reject	0.05	X1 >> X2	**TW do worse**
				Potential unwholesome medium health effect	0.18	24.75	2.31	-4.50	5.34	2.31	-4.53	4.53	Accept	0.05	X1 = X2	
				Potential Unwholesome, low health effect	0.18	16.83	0.33	-3.06	0.11	0.33	-0.65	0.65	Reject	0.05	X2 >> X1	**RWU do better**

Table 33 Comparison of incident impact at regional level (Regional Water Utility) with national incident (DWI) for 2004

RWU Incident database				**National Standard (DWI) customised to RWU (Frequency adjusted over Population)**				**Significance testing**								
								H0: X1 - X2 = 0			X1	RWU				
								H1: X1 - X2 <>0			X2	SN				
RWU Incident database								SL: 5%								
2005.00																
	F	H	SE		F	H	SE	mean X1 - mean X2	Variance X1-X2	SE	CI 95% min	CI 95% max	H0	SL		**Comment**
Aesthetics	11.00	12.84	0.32	Aesthetics	4.19	29.07	7.12	19.26	50.80	7.13	-13.97	13.97	Reject	0.05	X1 >> X2	**RWU do worse**
Biological pathogens present	3.00	5.33	1.68	Biological pathogens present	1.57	20.33	9.09	-16.00	85.51	9.25	-18.12	18.12	Accept	0.05	X1 = X2	
Biological pathogens present, health effects	8.00	19.90	1.36	Biological pathogens present, health effects	1.31	46.42	12.24	98.33	151.73	12.32	-24.14	24.14	Reject	0.05	X1 >> X2	**RWU do worse**
Chemical present above guidelines	5.00	4.00	0.00	Chemical present above guidelines	0.35	38.96	17.87	6.36	319.40	17.87	-35.03	35.03	Accept	0.05	X1 = X2	
Chemical present above guidelines, health effects	0.00	0.00	0.00	Chemical present, health effects	0.26	85.80	52.07	-22.49	2711.25	52.07	-102.06	102.06	Accept	0.05	X1 = X2	
Loss of supply	16.00	17.73	10.63	Loss of supply	0.17	19.31	7.99	280.34	176.87	13.30	-26.07	26.07	Reject	0.05	X1 >> X2	**RWU do worse**
				Unwholesome	0.17	10.32	5.66	-1.80	32.05	5.66	-11.10	11.10	Accept	0.05	X1 = X2	

Table 34 Comparison of incident impact at regional level (Regional Water Utility) with national incidents (DWI) for 2005

RWU Incident database				**National Standard (DWI) customised to RWU (Frequency adjusted over Population)**				**Significance testing**								
								H0: X1 - X2 = 0			X1	RWU				
								H1: X1 - X2 <>0			X2	SN				
RWU Incident database								SL: 5%								
2006.00																
	F	H	SE		F	H	SE	mean X1 - mean X2	Variance X1-X2	SE	CI 95% min	CI 95% max	H0	SL		**Comment**
Aesthetics	7.00	12.46	0.28	Aesthetics	3.76	43.72	11.50	-77.02	132.40	11.51	-22.55	22.55	Reject	0.05	X2 >> X1	**RWU do better**
Biological pathogens present	3.00	4.66	0.67	Biological pathogens present	1.92	20.46	7.57	-25.36	57.67	7.59	-14.88	14.88	Reject	0.05	X2 >> X1	**RWU do better**
Biological pathogens present, health effects	1.00	17.32	0.00	Biological pathogens present, health effects	0.96	33.66	7.27	-15.04	52.87	7.27	-14.25	14.25	Reject	0.05	X2 >> X1	**RWU do better**
Chemical present above guidelines	6.00	7.55	2.34	Chemical present above guidelines	0.96	18.16	3.48	27.83	17.63	4.20	-8.23	8.23	Reject	0.05	X1 >> X2	**RWU do worse**
Chemical present above guidelines, health effects	0.00	0.00	0.00	Chemical present, health effects	0.35	96.07	82.75	-33.58	6847.87	82.75	-162.19	162.19	Accept	0.05	X1 = X2	
Loss of supply	19.00	7.43	0.33	Loss of supply	0.52	8.66	0.99	136.65	1.09	1.04	-2.04	2.04	Reject	0.05	X1 >> X2	**RWU do worse**

Table 35 Comparison of incident impacts at regional level (Regional Water Utility) with national incidents (DWI) for 2006

3.2.2.5 Comparison of incidents in the Regional Water Utility with incidents reported to the DWI

RWU Incident database				**RWU reported to DWI**				**Significance testing**								
								H0: X1 - X2 = 0			X1	RWU				
								H1: X1 - X2 <>0			X2	DWI				
								SL: 5%								
2004.00																
	F	H	SE		F	H	SE	mean X1 - mean X2	Variance X1-X2	SE	CI 95% min	CI 95% max	H0	SL		Comment
Aesthetics	20.00	13.42	0.42	Aesthetics	12.00	18.98	1.41	40.70	2.16	1.47	-2.88	2.88	Reject	0.05	X1 >> X2	The actual incident impact is higher than reported
Biological pathogens present	3.00	3.33	0.00	Biological pathogens present	2.00	8.58	5.28	-7.17	27.88	5.28	-10.35	10.35	Accept	0.05	X1 = X2	
Biological pathogens present, health effects	5.00	24.38	1.98	Biological pathogens present, health effects	3.00	30.58	1.76	30.14	7.03	2.65	-5.20	5.20	Reject	0.05	X1 >> X2	The actual incident impact is higher than reported
Chemical present above guidelines	3.00	4.00	0.00	Chemical present above guidelines	1.00	9.24	0.00	2.75	0.00	0.00	0.00	0.00	Reject	0.05	X1 >> X2	The actual incident impact is higher than reported
Chemical present above guidelines, health effects	0.00	0.00	0.00	Chemical present above guidelines, health effects	0.00	0.00		0.00	0.00	0.00	0.00	0.00	Accept	0.05	X1 = X2	
Loss of supply	23.00	7.56	0.29	Loss of supply				173.83	0.09	0.29	-0.57	0.57	Reject	0.05	X1 >> X2	The actual incident impact is higher than reported

Table 36 Comparison between actual and reported incidents in 2004

RWU Incident database				**RWU reported to DWI**				**Significance testing**								
								H0: X1 - X2 = 0			X1	RWU				
								H1: X1 - X2 <>0			X2	DWI				
								SL: 5%								
2005.00																
	F	H	SE		F	H	SE	mean X1 - mean X2	Variance X1-X2	SE	CI 95% min	CI 95% max	H0	SL		Comment
Aesthetics	11.00	12.84	0.32	Aesthetics	5.00	17.85	4.20	51.95	17.78	4.22	-8.26	8.26	Reject	0.05	X1 >> X2	The actual incident impact is higher than reported
Biological pathogens present	3.00	5.33	1.68					15.98	2.81	1.68	-3.29	3.29	Reject	0.05	X1 >> X2	The actual incident impact is higher than reported
Biological pathogens present, health effects	8.00	19.90	1.36	Biological pathogens present, health effects	3.00	41.18	11.32	35.63	129.90	11.40	-22.34	22.34	Reject	0.05	X1 >> X2	The actual incident impact is higher than reported
Chemical present above guidelines	5.00	4.00	0.00					19.98	0.00	0.00	0.00	0.00	Reject	0.05	X1 >> X2	The actual incident impact is higher than reported
Chemical present above guidelines, health effects	0.00	0.00	0.00					0.00	0.00	0.00	0.00	0.00	Accept	0.05	X1 = X2	
Loss of supply	16.00	17.73	10.63					283.72	113.00	10.63	-20.84	20.84	Reject	0.05	X1 >> X2	The actual incident impact is higher than reported
				Unwholesome	1.00	4.66	0.00	-4.66	0.00	0.00	0.00	0.00	Reject	0.05	X2 >> X1	The actual incident impact is lower than reported

Table 37 Comparison between actual and reported incidents in 2005

RWU Incident database				**RWU reported to DWI**				**Significance testing**								
								H0: X1 - X2 = 0			X1	RWU				
								H1: X1 - X2 <>0			X2	DWI				
								SL: 5%								
2006.00																
	F	H	SE		F	H	SE	mean X1 - mean X2	Variance X1-X2	SE	CI 95% min	CI 95% max	H0	SL		Comment
Aesthetics	7.00	12.46	0.28	Aesthetics	5.00	81.12	65.83	-318.35	4333.51	65.83	-129.03	129.03	Reject	0.05	X2 >> X1	The actual incident impact is lower than reported
Biological pathogens present	3.00	4.66	0.67	Biological pathogens present	3.00	23.87	10.21	-57.61	104.77	10.24	-20.06	20.06	Reject	0.05	X2 >> X1	The actual incident impact is lower than reported
Biological pathogens present, health effects	1.00	17.32	0.00					17.32	0.00	0.00	0.00	0.00	Reject	0.05	X1 >> X2	The actual incident impact is higher than reported
Chemical present above guidelines	6.00	7.55	2.34	Chemicals present above guidelines	2.00	11.99	2.66	21.31	12.59	3.55	-6.95	6.95	Reject	0.05	X1 >> X2	The actual incident impact is higher than reported
Chemical present above guidelines, health effects	0.00	0.00	0.00					0.00	0.00	0.00	0.00	0.00	Accept	0.05	X1 = X2	
Loss of supply	19.00	7.43	0.33					141.19	0.11	0.33	-0.66	0.66	Reject	0.05	X1 >> X2	The actual incident impact is higher than reported

Table 38 Comparison between actual and reported incidents in 2006

3.2.3 Correlating the capacity of assets with the incident impact on customers

In this analysis, the capacity of an asset that failed during an incident is correlated with the incident impact on customers. The capacity of the asset relates to the production rate of process facilities, the volume of storage facilities or the flow rate or diameter of water mains.

In a previous analysis, 324 incidents between 1997 and 2006 had an incident impact calculated using the methodology advanced by (Deere *et al.*, 2001). Out of these, 158 incidents identified the capacity of the asset that had failed during the incident. All these incidents were burst water or trunk mains for which the incident documentation identifies the diameter of the failed asset.

The design capacity of a water main is a function of the water main diameter and the designed velocity of flow. This is shown in Equation 11.

$$Q = \frac{\Pi}{4} d^2 * v$$

with

Q flow in $\frac{m^3}{s}$

Π Pie = 3.14159

d diameter in m

v velocity in $\frac{m}{s}$

Equation 11 Design rationale for water mains

According to one reporter it is common practice to design water mains with a self-cleansing velocity of at least v= 0.9 m/s. In the design of hydraulic systems, other aspects have to be taken into account (e.g. ordnance datum and the required headloss to reduce pressure for specific geographic locations). For calculating the capacity of water mains a velocity v = 1m/s is assumed.

In the following analyses the diameter and the capacity of the failed asset is correlated with the calculated incident impact factor. Diameter and asset capacity are also correlated with the duration of the incident and the size of the population affected during the incident.

In this analysis, the incident impact factors that had been calculated for the above incidents are used to identify any correlation with the capacity of the asset that failed and caused an incident.

In Figure 15 the diameter of failed water mains is correlated with the incident impact scores calculated for the incidents that arose through the water main failures. Although the correlation trend line with y=0.0019x+9.97 suggests a marginally positive correlation between the two factors, the coefficient of determination R^2=0.0068 is too low to explain the incident impact score as a function of water main diameters. It can be identified that the incident impact scores for identical water main diameters commonly range between an incident impact score of 5 and 25.

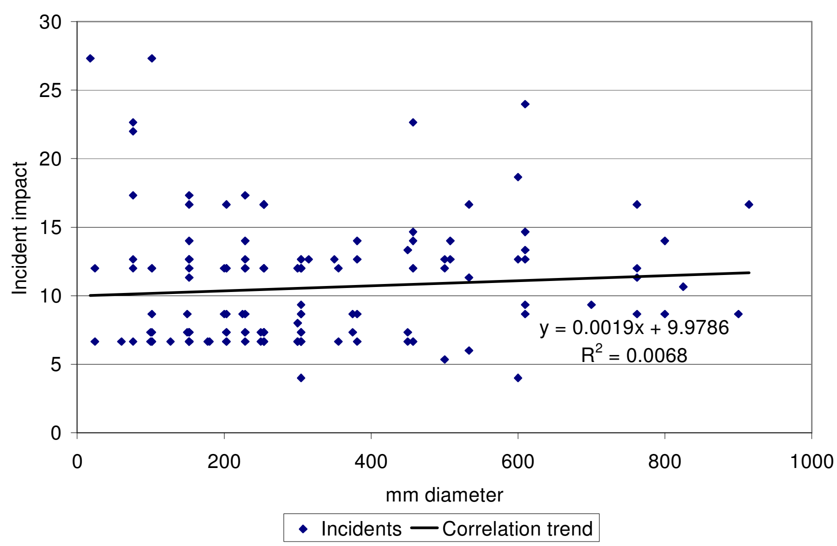

Figure 15 Correlating the incident impact and the diameter of water mains that caused the incident

Similarly, the incident impact score is correlated with the calculated flow rate of the asset that failed as a precursor for the incident impact. The calculated capacity of the water main uses the diameter and assumes a designed flow velocity of 1 m/s. In this Figure 16, the coefficient of determination R^2=0.0158 explains only 1.58% of the variation in the incident impact score as a function of the water main capacities. However, the gradient of the trend line with y=4.176x+10.123 suggests that an increase in the capacity of the water main marginally correlates with the consequential impact of its failure.

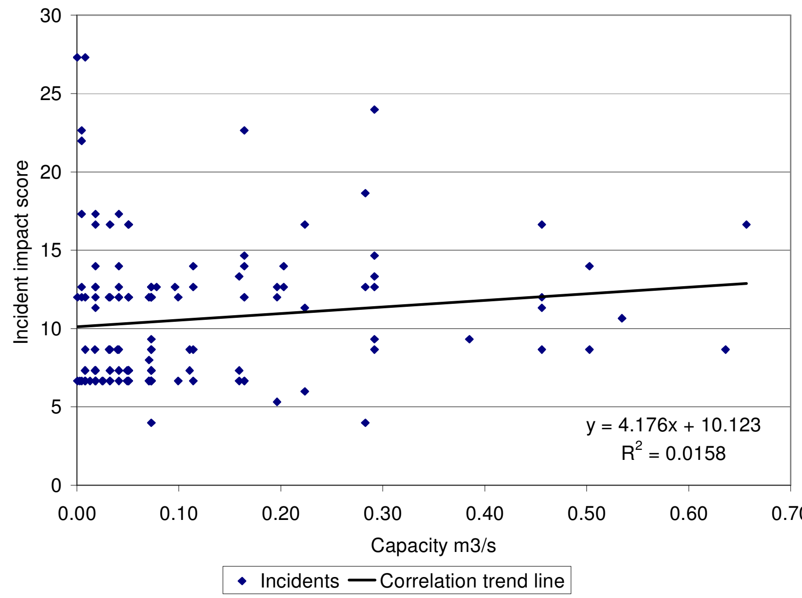

Figure 16 Correlating the incident impact with the assumed capacity of the water main that caused the incident

In the above analyses, the correlation between the diameter and capacity of water mains and the incident impact were investigated. In these analyses, the type of hazard exposure was not differentiated according to hazard categories, e.g. incidents affecting customers with aesthetical problems associated to the drinking water, loss of supply or pathogens present in the drinking water.

In the following Figure 17, the incident impact scores were calculated for specific hazard categories. The figure differentiates between incident impact scores for 'loss of supply', 'biological pathogens present', 'potential biological pathogens present' and 'aesthetics'. The incident impact scores for the respective hazard categories are correlated with the capacity of the water main that caused the incident.

Incident impacts relating to aesthetical unpleasing drinking water quality correlate positively with the capacity of the failed water main at a gradient of y=0.0781x + 12.651. The coefficient of determination of R^2=0.1324 explains 13.24% of the variation in incident impact as a function of the capacity.

Similarly, incident impacts relating to loss of supply correlate positively with the capacity of the failed water main at a gradient of y=0.0493x + 7.419. The coefficient of determination of R^2=0.0479 explains 4.79% of the variation in incident impact as a function of the capacity.

Interestingly, the presence of pathogens and the potential for the presence of pathogens in the drinking water for customers correlate negatively with the capacity of failed water mains. Incident impacts relating to pathogens present in the drinking water negatively correlate with the capacity of the failed water main at a gradient of $y=- 0.7834x + 19.295$. The coefficient of determination of R^2=0.4956 explains 49.56% of the variation in incident impact as a function of the capacity.

Similarly, incident impacts relating to the potential of pathogens present in the drinking water negatively correlate with the capacity of the failed water main at a gradient of $y= - 0.8882x + 18.831$. The coefficient of determination of R^2=0.767 explains 76.7% of the variation in incident impact as a function of the capacity.

This is an interesting finding because a positive trend between incident impact scores and the capacity of water supply system was anticipated. I.e., the larger the scale of water supplies systems, the larger the impact from an incident would be on customers.

In appears that the knowledge or anticipation of bacteriological contamination inverts this relationship. Following the initial symptoms of an incident, the water utility usually allocates resources to reduce the impact of the incident and to re-instate normal operations. It was hypothesised that the anticipation of potential pathogens present in the drinking water supply in combination with the knowledge of the capacity of the systems prioritises the incident management efforts so that bacteriological contamination on large scale water supply systems receive disproportionate measures to reduce the incident impact.

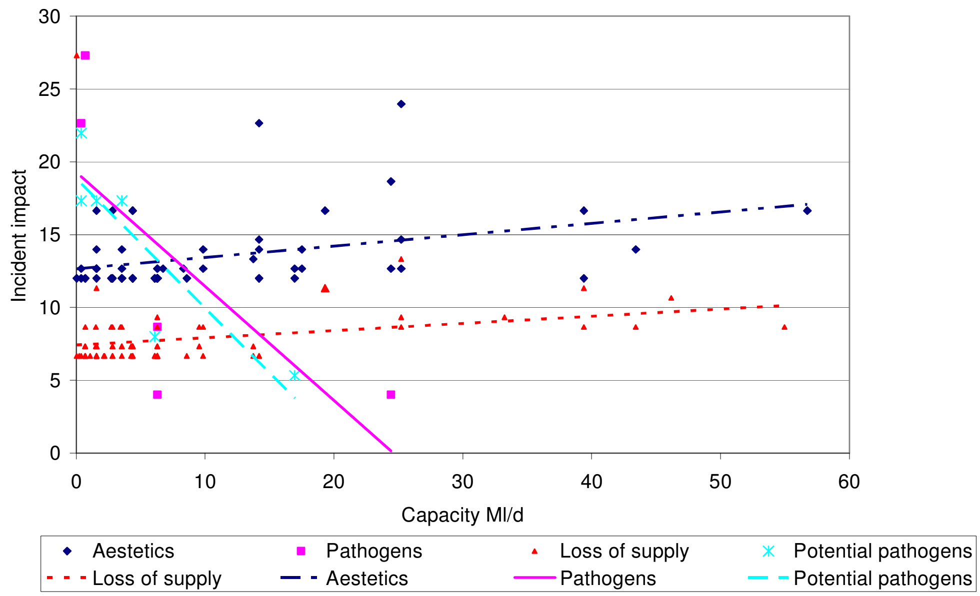

Figure 17 correlating the incident impact with the assumed capacity of water mains that caused the incident, by hazard categories

In the following Figure 18, the diameter of the failed water main is correlated with the actual size of population affected by the incident caused by its failure. A positive correlation with y=22.57x - 2034.8 suggests a positive, marginal correlation between the two factors. The coefficient of determination R^2=0.173 explains 17.3% of the variation in incident impact scores as a function of the capacity.

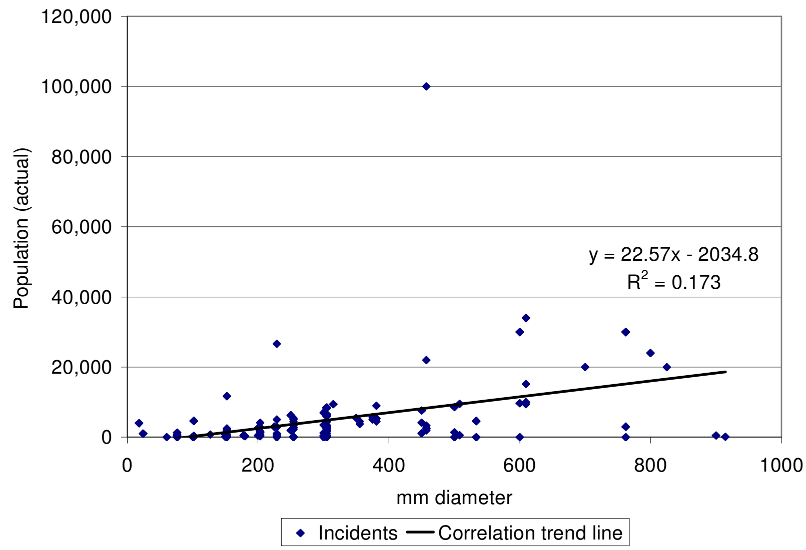

Figure 18 Correlating the size of population affected by incidents with the diameter of the water main that caused the incident

In Figure 19, a similar gradient for a best fit trend line is obtained in correlating the capacities of the failed water mains with the respective sizes of the affected population during the incidents. A positive trend between the water mains capacity and the size of affected population can be identified in the gradient of y=31339x. The coefficient of determination explains 15.49% of the variation in actual population size as a function of the water mains capacity.

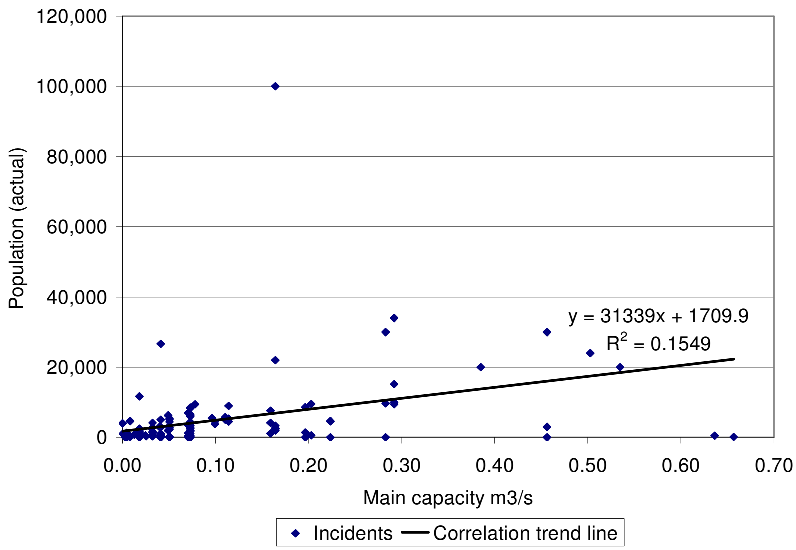

Figure 19 Correlating the size of population affected by an incident and the assumed capacity of the water main that caused the incident

In Figure 20, the diameter of failed water mains is correlated with the actual duration of the subsequent incidents. In this analysis, no correlation could be identified.

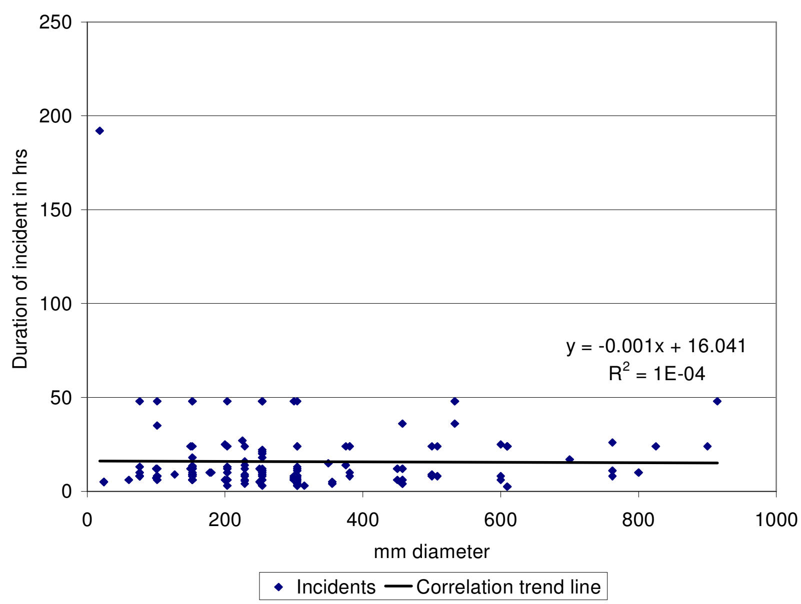

Figure 20 Correlating the duration of incidents with the diameter of the water mains that caused the incidents

In the above analysis, no conclusive evidence was found that the incident impact directly correlates with the capacity of the failed asset that caused the incident. Only limited evidence was found that a correlation between incident impact for specific hazard categories and the capacity of the failed asset that caused the incident exist. These results have to be seen in perspective of the governing multiple stages of an incident: Following an asset failure, the water utility directs resources towards reducing the impact on customers and to re-instate normal operations. It is stipulated that the incident management procedures significantly reduce the impact on customers and, therefore, overshadow the ultimate impact of incidents on customers.

3.3 Research tools

3.3.1 Incident assessment template

Incident Assessment Tool	Reference to selection menu
	In Table 40 and Table 41
At which installation type did the failure occur?	**1**
Asset reference	
At which process did the failure occur?	**2**
N/A	
At which element did the failure occur?	**22**
Asset reference	
At which component did the failure occur?	**3**
At which type of IT/IS asset did the failure occur?	**4**
Asset reference	
In which phase did the incident occur?	**24**
What happened (Symptom or effect)?	**5**
Why did it happen (cause of failure)?	**5**
Why did it happen (cause of failure)?	
Why did it happen?	**5**
What was the immediate incident response?	**41**
What happened next (Symptom or effect)?	
Why did it happen (cause of failure)?	**5**
What happened next?	**5**
Why did it happen (cause of failure)?	**5**
What was the response?	**41**
It can also be attributed to….	**7**
It can also be attributed to….	**7**
It can also be attributed to….	**7**
Did Human factor play a role in causing the failure?	**8**
Did any aspects of organisational culture contribute?	**9**
What type of probability assessment for the equipment was used?	10
Assessed probability/frequency of equipment to trip or failure per year?	
Exposure time or how long does it take to reset/repair/replace asset in days? Max repair time is the lower of the following : 365 or	
Did the component have immediate redundancy (e.g. duty standby)?	**11**
N/A	
N/A	
Assessed non-availability of element in days	
Assessed non-availability of element as percentage (probability)	
What was the assessed probability that other, alternative or parallel processes will compensate for the loss of one process?	**13**
Assessed non-availability of installation in days	
Assessed non-availability of installation as percentage (probability)	
Were there any installations between the failed installation and the customer which reduced the impact?	**15**
Not applicable, reset field to N/A	**16**
Not applicable, reset field to N/A	
Customer impact in days	
Assessed probability of customer impact	
Is the incident frequency/probability reflected in the risk assessment?	
Can you characterise the impact on customers?	**17**
Boil notice?	
How many people were affected?	**24**
How long in hrs?	
Can you characterise other impact on customers?	**17**
How many people were affected?	

How long in hrs?	
Can you characterise other impact on customers?	**17**
How many people were affected?	
How long in hrs?	
How was the failure of the component noticed?	**18**
What other method was used to mitigate against the impact (e.g. alternative plant, system)?	**20**
Incident impact	
Incident impact	
Incident impact	
Total incident impact	
Assessed risk score	
What type of management intervention might effectively reduce the risk?	
Did the incident management procedure provide guidance to assess the impact of the incident?	27
Did the incident management procedure provide guidance to reduce the impact of the incident?	27
Did the incident management procedure provide guidance to re-instate a safe system?	27
How would you rate the effectiveness of communication during the incident?	**28**
How would you rate the effectiveness of communication between operations and asset management?	28
How do you rate your decision making capacity during the incident?	**29**
How would you rate the ability of the organisation to adapt its organisational structure to the needs of an incident?	**30**
How would you rate the availability and use of system redundancy during an incident?	**31**
How would you rate the procedures to learning from this incident?	**30**
How would you rate your organisations ability to learn from this and other previous incidents to anticipate similar risks?	31
How would you rate the state of your assets?	32
How do you rate the ability of your organisation to manage infrastructure investment and maintenance effectively?	32
How would you rate the need for funding in order to invest in new assets and maintain/refurbish/replace existing assets?	32

Table 39 Detailed incident analysis questionnaire

24	5	1	2	22	4	3	18	7	8	9		10	11
Asset life cycle	What happened first?	Which physical asset type is the source of the incident?	Process group	Building	Was an IT/IS asset the source of the incident?	Can the incident be attributed to a specific component?	How was it notified?	The failure scenario can be attributed to ….	Did Human factor play a role in causing the incident?	Culture	Was this type of incident previously assessed for this type of risk?	Type of prob assess ment	Standby
Design Construction Commissioning Operation Pro-active maintenance Reactive maintenance Decommissioning	Asset failure Component failure Civil failure Water main failure Mechanical failure Electrical failure Treatment process failure Water quality failure ICA failure Power failure Scheduled repair work Out of commission Pollution Raw water quality Adverse weather Pollution 3rd party impact Fire Accident/injury 3rd party accident Ingress of contamination security failure Asset does not meet requirement to meet demand Asset does not meet water quality objectives Asset failed to deliver service/product Hydraulic effect Insufficient capacity Change in demand No water Main scouring Too much water Unfit for purpose Re-suspended solids Water quality deterioration Overflow Operational requirement IT failure N/A	Asset type Aquifer BH Catchment IRE River abstraction Raw water pumping station Raw water main/Aqueduct WTW WPS SRE Water tower Distribution system customer installation Power generation/power supply IT Infra Other supply sources Affected site was isolated N/A	Intake Sedimentation coagulation Flocculation DAF Primary filtration Secondary filtration Chlorination Chemical storage & treatment equipment N/A	Civil Water main Mechanical Electrical Process Environment Monitors control Chemicals IT Infra Power	Information assets Monitoring equipment Control equipment (e.g. MCC) SCADA PLC Telemetry IT architecture N/A	Component type N/A Dam Reservoir intake Reservoir embankment BH/River - Structure (Well/Bore) BH/River - Pump & motor BH/River - water main BH/River - valve BH/River - Flow meter BH/River - monitoring equipment BH/river - control equipment Environment Catchment - Structures Raw water trunk main Structure Inlet Screening Coagulation Flocculation Distribution - control equipment Pump & motor Valve water main monitoring equipment Control equipment Generator Bund Power supply WTW - Sedimentation WTW - Filtration WTW - Chem. Removal WTW - Contact tank WTW - Pump & motor WTW - Valve WTW - Flow meter WTW - Monitoring equipment WTW - control equipment Chemical storage Chemical dosing equipment Chemical dosing pumps Intermediate trunk main	customer contact 3rd party Contractor Member of public Operator Manager Emergency services PLC SCADA Laboratory results Anticipated impact Regulator	Material fatigue Corrosion Wear&Tear operating environment (climate, soil condition) 3 rd part impact Accidental damage to asset Unfit for purpose Lack of information Lack of maintenance Lack of standby Poor design Poor operational use Poor access Poor lifting facilities Poor maintainability Poor ability to isolate Poor SOP Poor work methods Poor planning Poor condition Age Inappropriate use Scheduled repair work Adverse weather Water hammer/Transient pressure Differential settlement Quality of chemicals Draught flooding Main scouring Contamination Asset does not meet requirement to meet demand Asset does not meet water quality objectives Asset failed to deliver service/product Poor capacity Solids deposition N/A	N/A Operator error lack of experience Lack of knowledge Lack of information Lack of training Lack of instructions Lack of supervision Poor planning Poor outage planning Poor design Unauthorised use Unanticipated effect	N/A Poor attitude Poor behaviour Carelessness Poor work processes Poor training Poor decision making Poor communication Acted in good faith Risk had to be taken Risk of experienced effect was considered	Unpredicted failure Predicted failure Predicted failure, but unanticipated impact Operate to fail policy Low risk Medium risk High risk Asset failure predicted but not impact on customer	Manual decision tree Weibull Network analysis	Duty only Duty/Standby Duty/Duty/Standby No redundancy Common cause failure N/A

Table 40 Multiple choice menu to characterise incidents

12	15	19	20	17	13	16	27	28	29	30	31	41
Redundancy	Other installations	Other installations	Other redundancy	Can you characterise the impact on customers?	Alternative processes	Customer impact	Guidance	Communication	Decision making	Org. Structure	Redundancy	
No redundancy Common cause failure VH H M L VL Failsafe	No other installations available WTW SRE Water tower WPS Distribution rezoning capability	No other installations available Aquifer BH Catchment IRE River abstraction Raw water pumping station Raw water main/Aqueduct WTW SRE Water tower Drinking water trunk main (>300mm) Water main (distribution) Power generation/power supply WPS	Water tankering Bottled water Overland main N/A	Biological pathogens present, Public health effect. Illness through drinking water Biological pathogens present, health effects envisaged, Boil order as risk of illness through drinking water Biological pathogens present, PCV failure leading to an undertaking Biological pathogens present, Trivial sample failure Potential biological pathogens present, health effects envisaged Potential biological pathogens present Chemicals present above guidelines, health effects envisaged, PCV failure leading to an undertaking Chemicals present above guidelines, Trivial sample failure Aesthetics above guidelines, >200ug/l Iron or DWI reportable incident. Highly discoloured, resembles beer or Guinness Aesthetics, >150 ug/l or notable events. Opaque and discoloured resembles weak milky tea. Aesthetics, 100-150ug/l Iron or minor events. Translucent and discoloured resembles orange juice or lager. Aesthetics, 50-100 ug/l Iron and no events. Particulate material visible in clear water Aesthetics, < 50ug/l Iron and no events - Slight discolouration noticed in customer bath, Compliance but customer complaint Loss of supply Potential contaminant ingress Pressure <15m pressure Pressure - No flow upstairs at peak demand period (<10m pressure) Pressure - No flow at peak demand period (<5m pressure) Accident (Staff) Accident (3rd party) Injury (Staff) Injury (3rd party) Pollution N/A	None available Asset failed Common cause failure VL L M H VH Yes, they operated effectively - no impact	A customer impact could not be avoided VL L M H VH customer impact was avoided Installation failed N/A	Not explicitly stated Appropriate Not required Yes but too high level Very detailed	Poor communication Areas of improvement were identified Effective communication Excellent communication	Good decision making Responsive to needs Bureaucratic decision making non-adaptive to situation Poor judgment Poor decision making	Adaptable to situation Inflexible Adequate considering the circumstances	Redundancy available Good use of redundancy No redundancy was available Redundancy could not avoid customer impact	Re-zoning Isolation Restart Flushing Manual operation Bypass Installation UPS Operate Standby Replace asset Repair Chlorination N/A

Table 41 Multiple choice menu to characterise incidents (Part 2)

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4 Appendix – Incident management

4.1 Case studies

4.1.1 Detection of faecal coliforms and clostridia in water supply

Date 11.05.04

Background

The Company's Contractor was carrying out mains rehabilitation in the area as part of ongoing Section 19 (Water Industries Act, 1991) work.

Work commenced on site on the Day 1 and the first intervention occurred on the Day 3. Between the Day 3 and the Day 48, 4.2 km of water mains were scraped and lined.

Water quality samples were taken as standard practice before each main was re-commissioned and customers are advised to boil all water used for drinking and food preparation during the 48 hours following restoration of supplies. Prior to the event, 48 bacteriological samples were taken by the Contractor between Day 3 and Day 48, all bar two of which were free from coliforms. Bowsers were provided to supply customers whilst their main was out of commission and were regularly sampled with all samples being free from coliforms.

The contractors have experienced minor vandalism during work in this area and the teams carrying out the rehabilitation regularly have had to deal with excavations being filled with debris by local residents overnight. Rain prior to the event lead to difficult working conditions with excavations containing standing water.

On Day 47, Rehabilitation work was ongoing in the area where the incident occurred.

Following completion of the relining work, samples were taken at the hydrants prior to restoration of supplies under the standard 48 hour precautionary boil water advice.

Both hydrant samples taken that day were reported as containing three *E.Coli* colonies per 100 ml. Further samples were taken at ten locations in the surrounding area including the upstream service reservoir and source water.

The results of the samples taken on Day 48 were reported with the repeat sample from the customers tap containing 1 *E.Coli* /100 ml. and 9 Clostridium perfringens/100 ml. Three of other ten investigatory samples also contained low counts of clostridia, but no coliforms. All construction on site was stopped and a chlorination and flushing programme was implemented. Further samples were then taken.

On Day 49, no faecal indicators were found in samples following the work carried out the previous day. However, a higher than expected chlorine demand was noted and the main was swabbed and chlorinated. The swabs used were sampled for clostridia.

The 48-hour precautionary boil advice ready in place was extended.

A larger area was also chlorinated and flushed as a precaution due to a risk of it being subject to reduced pressures or interruptions to supply due to valving required as part of the swabbing exercise and customers in a further 250 properties were also advised, as a precautionary measure to boil due to these risks.

On day 50, Clostridia were found in the swabs used the previous day.

The flushing and chlorination operations were widened to take account of the swab samples.

Clostridia was subsequently reported in two samples from the previous day and further flushing carried out at the extremities of the system.
Nine further samples were taken.
On day 51, all sample results were reported as satisfactory and the boil notice was lifted on the morning of Day 52.

Potential Causes of the Incident

There was no indication of contamination during the refurbishment itself, and procedures appear to have been followed, but the possibility of contamination of fittings stored on site cannot be eliminated. Two valves and a hydrant had been fitted. It was apparent from an inspection on Day 48 that such fittings were being stored on a stretch of recreational grass in advance of the work. These fittings were not being stored on pallets as required by company procedures. This therefore left them exposed and vulnerable to potential contamination. It is acknowledged by the Contractors that this practice contravenes water quality procedures on site and steps were immediately taken to ensure that this practice will not occur on site in the future.
The set of circumstances above is the only known deviation from company procedures; however, it should not be assumed that contamination of the fittings was the definitive cause of the incident. Whilst there is no evidence of any other possible cause, contamination during other piecing up activities cannot be eliminated and it should be noted that the excavation outside No.25 was left open for approximately one week prior to replacing the tee and could have contained bacteriologically contaminated material.
The ground conditions within the excavations were heavily saturated and although the standard 150 mm clearance between the base of the main and the bottom of the excavation was adhered to, it is possible that standing water within the excavation could have been transferred into the pipework whilst connections were made.
This additional potential cause of contamination has lead to a thorough review of site working practices, detailed in section 5. In addition, Interviews with Contractors operatives were undertaken and training reviewed from which it was concluded that all disinfection procedures had been followed.

Actions taken to prevent a recurrence.

At a meeting with the contractor, it was agreed and established that: company procedures required any fittings to be dispatched immediately before use and any limited on-site storage should be on pallets, and that there was general awareness of this and that appropriate training had been given. The contractor was strongly reminded of the importance of these procedures. Further meetings have taken place to establish why these procedures were being ignored and action considered.
The Company and its Contractor has established a working group to investigate the conditions surrounding this event and highlight any further potential sources of contamination. Outputs from this group will be fed back into the Company’s procedures to reduce the risk of future potential incidents.

The following actions have been reviewed and remedial action taken:
The policies and procedures in place for the storage and use of fittings were considered robust; however, these have been reviewed and reinforced throughout the Contractor’s organisation. Procedures will ensure that fittings delivered to site are sufficient for the

job, are delivered in shrink-wrap and are placed on palates. A store of fittings must not be maintained on site.
Training has been reviewed and refresher training given to all of the Contractors operational teams.
The Contractor is re-training the whole site workforce (200 operatives) using water quality training provided by the Company. Fifty percent of the gang involved in this event received re-training on Day 49 and the remainder received training on the Day 65.
The length of time that access pits remain open has been reviewed and recommendations to keep this to the absolute minimum possible have been made.
The partnership between the Company and its Contractor does not demand supervision of all work the work undertaken, but is reliant on an audit function provided by the Solution Assistants. Water Quality also provides training and an independent Audit role. It is intended that site audits will be reinforced and that Water Quality will closely monitor the effectiveness of these.

Assessment of Actions taken

In accordance with standing procedures, an extensive sampling exercise was immediately carried out following the reports of the initial failed samples.
An immediate decision to flush and chlorinate was taken and was this successful in preventing further coliform failures. Low levels of Clostridia were also subsequently reported increasing the concern that some faecal contamination may have occurred.
Chlorination of the main was carried out and this process indicated a chlorine demand within the main and a decision was taken to swab, flush and chlorinate.
The precautionary boil advice already extant in this area was extended and it was felt prudent to extend the advice to a further 250 properties which may be affected by reduced pressures generated because of the swabbing. The mitigation plans also included pulling chlorinated water throughout all of the area covered by the precautionary advice as a further safeguard. These plans were fully discussed with the Health Protection Agency and the Metropolitan Council.
Results from the twenty samples taken were all free from coliforms but two contained low levels of presumptive clostridia (one of which did not subsequently confirm).
Further flushing was undertaken and samples were taken throughout the area. All of these samples were satisfactory and free from Coliforms and Clostridia and following consultation with the HPA, the boil advice was lifted.
The company was possibly over cautious in extending both the period and area of boil advice; however, advice from the Health Protection Agency suggested that this was appropriate.
In conclusion, the incident management response was swift and aimed to minimise the public health impact of the directly affected population but also populations in surrounding areas. The decision to extent the boil notice and superchlorinate the water mains in the area was directly targeted to eliminate the hazard. Without these procedures, the impact of this incident could have been significantly worse and public health could have been jeopardised for a significantly large population.
A review of the incident leading to enforcement of existing procedures and re-training of contractor staff demonstrates the organisation’s willingness to learn from failure.

Actual impact: High
Potential impact: Significantly higher (high hazard, large population, extended duration)

Incident detection: Water quality sample with incubation period
Incident management response: Very effective
Incident impact reduction: Medium

4.1.2 Microbiological contamination following water mains rehabilitation

Date 14 08 04
Background
The 8” cast iron main was being scraped & lined with rapid setting poly-urethane (PU) resin in approximately 125m sections. Following completion of each section samples were taken and analysed for microbiological parameters. All samples had been free of indicator organisms. Following completion of the length of main, similarly clear results were obtained from the sample taken at the end of the lined section of 8” main. However on restoration of supplies one property reported no water. To resolve this problem the ferrule connecting the service to the main was dug-out, cleaned and re-connected. Because of this activity, and because the main had been de-pressurised, a sample was taken following restoration of supplies.
All appropriate precautions are believed to have been followed in carrying out this activity. Following re-connection of the ferrule a sample was taken from the hydrant; it is this sample which contained indicator organisms.
The samples taken were reported to contain significant numbers of E Coli and total coliforms. This was reported to the Water Quality Standby scientist who discussed the matter with the Duty Manager.
Discussions were held identifying options to protect customers as the 48hr precautionary advice to boil water would expire shortly. Sampling would be undertaken from properties supplied via the affected main. Boil notices are to be hand delivered to10 affected properties
Plans were developed to chlorinate the main to 20ppm; this will require the installation of fittings on the main to facilitate the injection of solution.
The DWI, Health Protection Agency and the City Council have been contacted.
The Duty Manager and Water Quality Scientist agreed that the Distribution Asset Manager would go to site and manage chlorination of the main as follows:-

- Vigorous flush of main to end hydrant
- Chlorinate and pull 20ppm to taps in property
- Take pressure off main and stand for one hour
- Flush again to clear chlorine solution from main
- Draw water in properties to obtain normal Chlorine levels
- Ensure customers know boil order is still in place

The samples obtained after chlorination were again confirmed to have failed with low numbers of coliforms & E Coli and it was requested that the main would be re-chlorinated. Two of four samples taken still contained low numbers of bacteria. The 4” main was re-chlorinated to 20mg/l up to customers taps.
The following day, one of seven Samples taken the previous day contained low numbers of bacteria. Further samples were taken from customers properties. These were

confirmed to be free of bacteria with the exception of one property that failed with E.coli. Subsequently it was established that this property had a DIY-installed, under-sink filtration unit that may explain why positive counts lingered.
Two days later, all samples taken the previous days were confirmed to be free of bacteria and the advice to Boil lifted by hand delivery of leaflets.

Cause
No confirmed cause of the contamination could be established; however, the digging out of the blocked ferrule is considered a possible explanation, although all appropriate precautions are stated to have been followed. It is possible that debris entered the main whilst de-pressurised to renew the ferrule.
The sampling hydrant was found to be in poor condition and leaking into a chamber full of debris.
Contamination of the lined main is considered unlikely as the post-lining sample was free from bacteria.
The extended nature of the detection of bacteria in the main is considered to be due to the poor condition of the main with pronounced tuberculation.

Assessment of Actions Taken
Once contamination had been confirmed in the main the company acted to protect public health by issue of Advice to Boil Water to affected properties; up to that time those properties were covered by the 48 precautionary advice to boil water issued as part of the mains rehabilitation process. The boil notice that was in place during the rehabilitation work of the main was a precautionary measure that anticipated the risk of microbiological contamination during the construction work.

The Company confirmed that no other properties served by the 8" main had been affected as a result of subsequent de-pressurisations.
Although it is probable that lining the main earlier would have shortened the period for which customers were affected, the Company had expected that flushing followed by chlorination would remove the contamination.
Customers were kept informed personally by a Public Health Scientist, and were provided with bottled water supplies for the duration of the event.
In conclusion, the incident management response was swift and aimed to minimise the public health impact of the directly affected population. The decision to extend the boil notice and superchlorinate the water mains in the area was directly targeted to eliminate the hazard. The incident management response was effective, although the first attempt to super-chlorinate the main failed to kill all microbiological contaminants and the procedure was repeated.
Although the cause of the incident could not be established, it is possible that the DIY-installation on a customer's premises masked the original microbiological contamination.
Without the effective incident management response, the impact of this incident could have been significantly worse and public health could have been jeopardised for the population supplied by the water supply system.

Actual impact: High
Potential impact: Significantly higher (high hazard, large population, extended duration)

Incident detection: Water quality sample with incubation period
Incident management response: Mostly effective
Incident impact reduction: Medium

4.1.3 Power failure leading to chlorination failure

Date 28/05/04

Background

A regional power failure caused plant failures at three Water Treatment Works. One of them (WTW 1) experienced the most severe problems leading to a failure of dosing systems. The failure of the normal dosing systems and "fail safe disinfection system" at this WTW resulted in the supply of unchlorinated water for approximately two hours.

05:38 Alarms received in control room.
  a) From WTW 1, dosing pump failure alarms for all of the major dosing systems.
  b) From WTW 2, final chlorine failure alarm.
  c) From WTW 3, power failure alarms

06:07 Plant Engineer (1) made aware of alarms at three Water Treatment works. Plant Engineer (1) will be visiting WTW 2 first.

06:35 Pre contact chlorine dose at WTW 1 at zero

07:00 Plant Engineer (1) passes chlorination dosing failure alarms to Plant Engineer (2).

07:40 Plant Engineer (2) on site at WTW 1

07:40 Final chlorine residual at WTW 1 at zero

08:05 Chlorination restarted and "fail safe" disinfection equipment started

08:35 Plant Engineer (2) reports that unchlorinated water has entered supply, 6 properties are supplied from trunk main feeding a service reservoir.

08:40 Water quality department informed immediately by Plant Engineer (2) to arrange sampling.

09:00 Plant Engineer (2) doses Service Reservoirs as required in the site manual.

09:15 Final chlorine residual still at zero

09:55 Final chlorine residual at 0.77 mg/l

11:15 Quality Assurance Scientist contacted DWI

11:40 Sampler notes that chlorine detected at customers' taps on direct feed properties.

Incident causes

The power supplier has confirmed that the power in the area was subject to brief interruption at 05:37. They note that the interruption was reset by their automatic systems but were unable to quantify its length.

Power failure at WTW 1 will have been experienced as either a total loss of power or a drop in voltage. The pump starters appear to have failed and had no auto recovery systems associated with them.

The emergency dosing pump failed to operate due to a fault condition arising from a manually initiated test-run of the dosing pump (following changing the chemical carboy). The fault condition that prevented auto-operation happened because the control

system saw the pump running but had not requested it to run. This conflict in logic prevented auto operation.
The battery-powered Emergency Dosing Pump is supposed to be automatically initiated when:

- Pre-Contact Tank chlorine residual falls below 0.3mg/l, for 15 minutes.
- A multi-cell Triple validation error occurs on the chlorine monitoring for the Pre-Contact Tank.
- Both Hypochlorite storage tanks (for the main site dosing) at low level.
- The pump operates for 5 minutes daily (to ensure availability, and to avoid possibility of pump air locking).

Assessment of action taken
Plant Engineer (1) assessed the initial notification of alarms correctly and attended the site at Richmond Water Treatment Works that appeared to have the most serious fault. On realising that he would be unable to attend [Name of] Water Treatment Works within a reasonable timescale, he contacted Plant Engineer (2). Plant Engineer (2) attended site promptly assessed the condition of the plant and re-set the systems, this appears to have been done within a reasonable timescale. Plant Engineer (2) has also gone on to dose the reservoir at as required within the ISO manual.
Unfortunately, the fault condition leading to the problems was not configured to raise an alarm on SCADA nor was it reset-able from SCADA. These have now been modified, and now both generate an alarm and can be reset from SCADA.

The previous distribution configuration for WTW 1 would not allow for the plant to auto-shutdown when chlorine failed as some properties were directly fed. This position will be reviewed in light of the new distribution configuration.
The incident will be used in scenario training exercises to indicate the difficulty in dealing with multiple events.

Actual impact: Low
Potential impact: Significantly higher

- High hazard due to treatment process,
- failure and potential for micro-bacteriological growth in distribution, and
- potentially large population.

Incident detection: Instant, multiple alarms on SCADA
Incident management response: Very effective, however lack of prioritisation for multiple failure scenarios; critical alarms not raised on SCADA but identified by proxy alarms.
Incident impact reduction: High

4.1.4 Coagulation failure leading to micro-biological contamination risk

Date 07 09 04

Background

The WTW uses a three stage process (dissolved air flotation followed by two stages of rapid gravity filtration) to treat upland raw water which flows to the works under gravity.

Incoming raw water to the WTW is dosed, at the primary flash mixer, with ferric sulphate and the coagulation pH is adjusted to set point automatically, if required, by the addition of lime. A facility to carbon dose exists should it be necessary.

Dosed raw water enters the flocculators via a splitter arrangement where the water is slowly stirred to encourage floc formation before passing into a bank of eight flotation units. Floated water is given a further dose of lime dose ahead of primary filtration through six rapid gravity filters.

Following filtration, the water is chlorinated ahead of the contact tank where it receives approximately 30-60 minutes contact time whereupon further lime is added for final pH control before second stage filtration. Water from the WTW supplies approximately 58,900 people.

A leak on the coagulant dosing system caused a reduction in coagulant flow which adversely affected the primary flotation treatment stage resulting in a slight deterioration in final water quality. Reduced coagulation efficiency could have resulted in incomplete disinfection and or the passage of cryptosporidium into supply, but all samples taken confirmed that this did not occur. Reduced coagulation efficiency may have resulted in incomplete treatment, but in the event there was little or no impact upon the quality of water at the customers' tap.

The coagulant dosing system including pipework is duplicated giving duty and standby operation and the lines are fitted with flow meters that are set to alarm on low coagulant flow and to change to standby operation on dose failure. At the time of the event, the works was receiving exceptionally poor quality raw water requiring coagulant dose rates well in excess of the "normal" 130 litres/hour

On arrival at site the Plant Engineer restored coagulant flow, increased the chlorine dose rate and arranged for a scientist to attend. Samples were taken from the works outlet for *Cryptosporidium* and *Giardia* analysis and sampling exercises were carried out within the distribution system.

Incident cause

The data from the SCADA has been interrogated and shows the following:

a) The coagulant flow begins to drop below the target flow of approximately 200 litres/hour and continues to fall reaching a minimum of 83 litres / hour two hours later prior to the Plant Engineer restoring flow. This minimum flow was insufficient to trigger the low flow alarm (set at 60 litres per hour) or the auto pump changeover.

b) The in-process turbidity monitors shows floated water turbidity beginning to deteriorate before rapidly increasing to trigger an alarm. Floated water turbidity peaks at around 16 NTU before falling rapidly on restoration of the coagulant flow. Turbidity at the outlet of the primary filters peaks with a maximum value of approximately 2.9

NTU. The effect on the final water is much less marked with a slow deterioration being observed with maximum values between 0.8 and 0.9 NTU being observed.
c) The in-process chlorine monitor data shows the second stage inlet controller being overridden, which allowed the Plant Engineer to increase the applied dose. This arrested the reduction in chlorine at the works outlet. As an additional precaution, the splitter box was also slug dosed with sodium hypochlorite, which can be seen as a peak on the final water chlorine trace. Chlorine levels leaving the service reservoir were unaffected.

All samples taken from the final water complied with the relevant PCVs, however, it is likely that the iron content of the water leaving the treatment works would have been in excess of 200 ug/l for a period during the final water turbidity peak and that this was “diluted out” in the distribution and service reservoir network. No discoloured water complaints were received from customers.

Actions to prevent re-occurrence
The setting of the low coagulant flow has been raised to 120 litres/hour in light of the current high coagulant demands being experienced.

Assessment of Actions taken
The Controller and Standby Plant Engineer responded promptly to the alarms such that the Plant Engineer was able to attend site and restore full coagulant dosing in around 1 hour of the initial alarm. Subsequent actions to wash filters and increase chlorine were appropriate in the circumstances.
Internal communication procedures were followed and all appropriate staff were made aware of the difficulties and the need for water quality sampling including analysis for cryptosporidium.

Actual impact: Low
Potential impact: Significantly higher

- High hazard due to treatment process failure,
- Potential carry over of Cryptosporidium oocycsts,
- Potential of zero free chlorine in distribution,
- potential for micro-bacteriological growth in distribution, and
- potentially large population.

Incident detection: Instant alarms on SCADA
Incident management response: Very effective, however, direct alarms not raised on SCADA but identified by proxy alarms.
Incident impact reduction: Very high

4.1.5 Micro-biological contamination during mains rehabilitation

Date 25 08 05
Background
As part of the progressive mains improvements in the area, the contractor had re-laid a 110m section of 4" main and commissioned it back into service under usual business procedures on Day 1. The subsequent water quality sample taken at that time was

reported on Day 2 to have failed. A second subsequent sample taken on Day 2 was also reported to have failed on Day 3.

Immediate action was taken on Day 3 to serve a Precautionary Boil Advice leaflet to 76 residential properties a school affected by the normal circulation supply area from this new main. A decision was taken to re-chlorinate the affected mains to 1.5 mg/l using the contractor's team of mains chlorinator experts; however, it was subsequently found that the main was subjected to residuals of chlorine at 3.0 mg/l instead of 1.5 mg/l as set on the chlorinator dosing unit, before it was flushed & re-sampled. The DWI and the water customer representative body were formally notified of the incident on Day 3.

Following two subsequent sets of clear bacti samples on Day 4 and Day 5, the customers were issued with Boil Advice Lifted leaflets, and the main was returned to normal operation.

Cause

The cause of the incident was not identified.

Actions taken to prevent re-occurrence

Not identified

Assessment of Action taken

This incident was identified through repeat water quality sample failures. On Day 3 of the incident, action was taken to super-chlorinate the water main. During super-chlorination, a wrong setting led to an excessive chlorination. Simultaneously on Day 3, a Boil Advice was issued to customers and the affected school.

In summary, the response to the initial water quality failure was slow and during the super-chlorination process, a failure occurred that led to excessive chlorine residual in the drinking water.

Actual impact: High
Potential impact: Insignificantly higher
Incident detection: Water quality sample with incubation period
Incident management response: Slow response
Incident impact reduction: Medium to low

4.1.6 Micro-biological contamination during mains rehabilitation

Date 17 06 05

Background

On Day 1 a burst occurred on a 3" Cast Iron Supply main. The burst was repaired during the evening using standard techniques. In line with normal procedure a sample was taken after reinstatement of the main. Results from this sample indicated both Coliform and faecal coliforms to be present. Clostridia were also reported. As a result a precautionary boil advice was placed on the 6 properties supplied by the main, whilst the additional steps of swabbing and super chlorinating the main were undertaken.

As a result of the swab becoming lodged in the main, temporary overland supplies were provided during the early hours on the Day 2 and customers fed via this route. This method of supply remains in place whilst the main is scraped and lined prior to reinstatement.

Samples were taken from properties supplied by this arrangement on Day 2 and Day 3 whilst still under precautionary boil advice.

The mains repair sample, which was taken from a Hydrant following its repair, contained 490 coliforms 90 Faecal Coliforms and 20 Clostridia. All investigatory and follow up samples taken from properties supplied by the main and from the bypass arrangement have been fully compliant and free from any indicator organisms with the exception of a single faecal streptococcus isolated from a follow up sample taken on Day 3 which was reported on Day 5.

This sample was from the first property supplied by one of the two bypass arrangements. All samples below this point and from the other properties on bypass were clear.

Incident cause

It is possible that the contamination arose during the repair of the main or - more likely – that the standpipe from which sample was taken was contaminated.

Given the level of contamination reported on the afternoon of Day 1, it was decided that precautionary boil water advice should be issued whilst remedial action was carried out.

Investigation has identified that the main is in poor condition and has had a recent history of bursts. Some of these may be attributable to third party activity as the mains location is on an active building site, where recent gas services connections have been also been made.

Assessment of actions taken

A precautionary boil advice was put on the properties supplied by the main, following the laboratory reporting the bacteriological results of the contractor's sample on Day 1.

Advice was initially provided verbally and confirmed by the delivery of notices. Bottled water was made available and supplied to the affected properties.

The main was swabbed with a swab soaked in a 1000 mg/l solution of chlorine and supplies isolated at the customers stop taps. It was intended that the main would then be super chlorinated to 50mg/l following and allowed to stand for 2 hours before being flushed and returned to supply under the existing precautionary boil advice. Sampling would then be undertaken and the boil advice lifted following satisfactory results in accordance with standard procedures.

In accordance with standard procedures, the boil water advice was lifted on the afternoon of Day 4 following receipt of satisfactory results from samples taken on the previous two days. It should be noted that the Company's procedures do not require that boil water advice be extended for a further 24 hours whilst the final faecal streptococci results are reported (provided that all other results are satisfactory).

Actual impact: High
Potential impact: Significantly higher
Incident detection: Water quality sample with incubation period

Incident management response: Good response
Incident impact reduction: High

4.1.7 Power failure leading to treatment failure

Date 17 11 2005
Background
Following a power dip, a large WTW suffered serious treatment problems, i.e. the coagulant dosing reduced and the chlorine dosing equipment failed. This resulted in the plant producing water that was not fully treated. It is estimated that unchlorinated water was entering the contact water tank for approx. 4 hours. The works could not be shut down on over SCADA and telemetry, therefore the Process Engineer had to attend site.
The DWI was notified and strategic service reservoirs in the area were slug dosed. Extensive water quality samples were also obtained. All samples were clear from microbiological contaminants in particular Cryptosporidium.
The extent of the incident management is best demonstrated with the logbook entries:
At 20:45 on Day 1, Engineer (1) rang in to report on the impact of a power cut.
The engineer (1) called in again around 21:30 to advise he had reset some system alarms. At 21:55, the Duty Manager was advised of a communications failure for the WTW. However, according to the service provider, there was no fault on the communication lines.
Engineer (2) called in at 22:09 reporting that he had managed correct Ferric dosing rate and reported that chlorine dosing seized at ca. 18:30. This was only identified after he arrived on site.
Informed by Engineer (3) that the power dip at the WTW has taken out the entire treatment process. Subsequently the WTW was shut down.
23.15 Duty manager called engineer (1) to ask for turbidity reading to be obtained from the service reservoir outlet and that the site reservoir is to be slug dosed.
Duty Manager called distribution managers to reduce water demand on the WTW
23.30 Duty Manager formulating plan to reduce demand on the WTW supply system
On day 2, 00.30, the initial slug dosing of the site service reservoir was completed
01.20 Decision made to restart plant, there is confidence that there will be good water quality as front end of the treatment process was kept going.
04.16 Water going back into contact water tank
05:30 Service reservoir slug dosed again
07:15 Service reservoir slug dosed again
08:00 Laboratory confirmed the grab samples of WTW were clear of Cryptosporidium.
During the day, a team worked on the times of Travel for the water from the WTW reaching distribution points and service reservoirs. This was so sampling times could be derived to check the water quality corresponding to the water leaving the WTW during the time of the problems.
17:45 Laboratory confirmed that the sample of the WTW obtained earlier today did not contain any Cryptosporidium.
20:05 Engineer (3) called Duty Manager with update on plan of action for tonight and tomorrow-

Engineer (4) will be doing the slug dosing with assistance from a team. Residuals to be raised by 0.2mg/l, Disinfection Manager is available for assistance with working out chloros volumes.
22:58 Confirmation received from laboratory that emergency bacti samples taken yesterday have passed.
On day 3, at 16:35, the laboratory confirmed that all distribution samples obtained yesterday had passed.
17:19 Laboratory confirmed all samples from yesterday had passed.
In total, the incident recovery phase lasted 44 hours – a long time considering that the incident was triggered by a power dip.

Action taken to prevent re-occurrence
This WTW should have a failsafe chlorination system and a shutdown system for critical alarms. For this specific site, it is to be investigated why this system was not fitted or did not operate.

Assessment of Action taken
Between the actual power failure that marks the initial incident moment and awareness of the incident, ca. 3 hours elapsed. During that time, the control centre was unaware that a large scale WTW was operating beyond their control. In effect, the treatment process collapsed that partially treated and un-chlorinated water passed into distribution. On awareness of a treatment process failure, the organisation excelled in effectively reducing the impact of the incident on customers. In the following 44 hours, a concerted programme of activities was implemented to reduce the impact of the incident and to re-instate normal operations.

Actual impact: Low
Potential impact: Significantly higher

- Use of systems redundancy significantly reduced the potential impact.

Incident detection: SCADA failure alarm, however critical alarms relating to this incident were not relayed to control centre due to communication line failure (common incident cause: power failure)
Incident management response: Excellent incident response as soon as the incident became known to the control centre
Incident impact reduction: High

4.1.8 Micro-biological contamination coinciding with mains repair

Date 05 08 2005
Background
Following the repair of a 12" burst main on Day 1 a sample was taken from a downstream hydrant after the mains return to service.
The sample subsequently failed with a count of 94 coliforms and 22 faecal coliforms. It was suspected that the failures related to the method of sampling but as a precaution, this leg of main was chlorinated.

During chlorination, it was evident that there was a variation in residuals obtained, at several locations it being higher than expected.
As such, it was decided to provide alternative supplies to the three properties connected to this main. This would allow sufficient time to flush and sample the main and allow a return to service after satisfactory bacteriological results.
All samples taken during the event were free from coliforms and other indicator organisms, although one sample taken on Day 3 from an end hydrant contained two Clostridia. This result is not considered to pose any risk to health. The main is a short length of 3” asbestos cement main feeding a single property at its start and an apparently disused cemetery at its end. Samples taken following flushing of this main on Day 4 was free from any indicator organisms.

Incident causes
The burst occurred at the location of a reinstated access pit. This had previously been used to gain access during earlier mains rehabilitation. The leak occurred on a dowel piece and was repaired using standard techniques.
The presence of bacteria in the burst main sample could indicate potential contamination of the main during repair, or, more likely of the standpipe by which the sample was taken.
It is possible that the initial hydrant sample was contaminated as it was taken, nevertheless, given the level of contamination reported, on the afternoon of Day 1 it was decided that precautionary flushing and chlorination should be undertaken.
Difficulties achieving target residual during chlorination were experienced. Samples taken indicated streaming and it is felt that the large size and flushing velocities may have resulted in improper mixing and streaming.
In the event, residuals were higher than anticipated 0.5 mg/l but will have served to further aid disinfection.
The cause of over-dosing with chlorine is still being investigated as the rig appears to be in good working order and is covered by a valid certificate.
The main was left isolated from the properties until the main had been flushed to background residuals and two days of satisfactory results had been obtained from hydrants on this main.
A further sample taken from an end Hydrant contained two Clostridia. The main feeding this is a short section of 3” AC main with no significant demand, and following this result, was flushed during the afternoon and resampled. The results were satisfactory with no detection of Clostridia. Because of the discovery that this is effectively little used, a review of its condition and future need is planned.

Actions taken to prevent re-occurrence
The burst had been repaired using standard techniques and there were no potential sources of contamination reported during the course of the repair. The main was fully chlorinated and disinfected as a precaution in light of the number of coliforms obtained and the presence of E Coli.

Assessment of action taken
Bottled water and alternative supplies were made available to the affected properties.

The main was isolated and chlorinated on Day 1. It was intended that the main would be chlorinated to 0.5mg/l and flushed, but difficulties in chlorination resulted in higher than expected residuals being obtained.
As a precaution the main was taken out of supply and customers supplied via temporary overland supplies and with bottled water whilst further flushing was undertaken and satisfactory bacteriological results were obtained.
Temporary bypass arrangements were removed on the Afternoon of Day 3 following two sets of satisfactory results being obtained.

Actual impact: Low
Potential impact: Insignificantly higher
Incident detection: Water quality sample with incubation period
Incident management response: standardised response
Incident impact reduction: Medium to low

4.1.9 Discolouration following trunk main failure

Date 17 06 06
Background
A burst on a 600mm diameter main led to an increase of velocity within the trunk main, and in turn disturbance of historic sediments in the trunk main network.

Incident cause
Failure of a 600mm water trunk main: The burst occurred on the 600mm main which forms part of the trunk main system. The burst deteriorated rapidly and proceeded to a significant failure of the main. At the time of the burst the main was operating from one service reservoir towards another service reservoir. As a result the rate of flow had significantly increased, and it became clear that an emergency repair would be required.
In order to isolate the burst one distribution management area was supplied in an alternative direction by opening a normally closed valve. The source of the discolouration was disturbance of historic sediments within the 600mm trunk main. The water quality samples data showed higher concentrations of aesthetic parameters fed from this section of trunk main.
Customer contacts for discolouration were received from nine distribution management areas. Customer contacts were received from distribution management areas at various points along the trunk main.
A number of other distribution management area from which no discolouration contacts have been received are also fed by the same section of the 600mm main. It seems likely the discolouration in the trunk main was of relatively short duration which was then drawn into a subset of the distribution management area fed from this section of the trunk main.
Four of the distribution management areas from which contacts were received have undergone rehabilitation within the last 10 years: at this time trunk main cleaning was not supported as part of the S19 Distribution Undertaking.

There was no significant difference in the number of discolouration contacts received between zones that have been rehabilitated and those which will be rehabilitated in the future.
The cause of the burst has been identified as external corrosion.

Assessment of action taken
Distribution management areas supplied via the damaged section of 600mm main were rezoned to maintain supplies from alternative sources, and the burst was isolated. The main was repaired using standard techniques.
Overall, the water utility acted in accordance with standard operating procedures to contain the incident. Communication, decision making and use of systems redundancy was effective. However, it was not anticipated that the water mains failure would rapidly deteriorate and, hence, aggravate the incident effect.
There has been only one previous failure of this main in the last five years. A similar failure on this water main occurred 4 years previous to this incident and was also due to external corrosion. This would not fail our normal criteria for mains replacement. However, options are investigated for an investigation into the condition of the main to better understand the risk of future failure occurring.

Actual impact: High
Potential impact: Insignificantly higher
Incident detection: Reported observation
Incident management response: Standardised response
Incident impact reduction: Medium to low

4.1.10 Flow meter failure leads to system out of control

Date 01 04 06
Background
A flow meter controlling a water pumping station 1 failed causing a major increase in flows to service reservoir 1. This in turn resulted in loss of supply to water pumping station 2 and these pumps tripped out on low suction pressure. A significant length of 24" main between service reservoir 2 and water pumping station 2 was depressurised. This main was recharged in around 30 minutes but the velocity changes were expected to have disturbed a large amount of mains deposits as this length of main has not been cleaned. Flushing and monitoring of water quality was started and bottled water was mobilised as a precaution.
Nine hours later, the first discoloration contact was logged followed by a rapid build up of contacts from three distribution management areas. Vulnerable customers were proactively contacted.
Flushing of the trunk main continued at water pumping station 2 and turbidity monitored; bottled water was deployed to the three affected distribution management areas. Flushing of the trunk main was successful in removing the discolouration and water pumping station 2 was put back into service to support levels in service reservoir 3 that was rapidly falling. It was decided that local flushing within the distribution

management areas would not be beneficial and customers reported that water was clear by mid-afternoon.
Notifications to external agencies were made 12 hours after the initial event.
Investigative samples were taken from the three distribution management areas and from the service reservoirs.

Cause of the incident
Failure of a flow meter causing failure of the gravity flow control.

Assessment of Action taken
During the management of the incident, a plan was devised and everyone who was involved adhered to this plan. The risk of discolouration was recognised early on during the incident and the organisation put measures in place to manage its impact. This led to an effective mitigation of discolouration as far as possible. Mobilisation of bottled water was swift and reached affected customers.
The interaction with vulnerable customers was effective.
Communication and decision making was effective.
The means of incident detection were criticised in hindsight: The telemetry information to support staff in diagnosis of water supply system faults did not indicate a flow meter failure and, hence, prolonged the incident management response or, even, preventative measures. It was felt that the reliability of site controls needed to be reviewed from the asset management department. In particular, the Maintenance record for the flow meter needed to be studied and an investigation launched into what caused the flowmeter failure.
Furthermore, a need to identify the source for discoloured water and an investigation into solutions to prevent future discolouration were identified.

Actual impact: High
Potential impact: Insignificantly higher
Incident detection: Indirect SCADA and telemetry reports of system abnormality
Incident management response: Good response
Incident impact reduction: Medium to low

4.1.11 Chlorination failure

Date 25 08 06
Background
Low level in the service water tank at the water treatment works led to the loss of motive water to all the chlorinators. This resulted in the loss of all chlorine dosing for approximately twelve hours. Over this period, chlorine levels in the contact water tank decayed slowly, eventually resulting in potentially un-disinfected water going into supply for 2 hours 40 minutes.

Cause

Motive Water Supply

Motive water is supplied to the chlorinators via a system of tanks.

Water from the works outlet main gravitates into the old service reservoir that is located outside the plant. The old service reservoir contains a 3" submersible pump that is controlled on high and low level probes in the service water tank and is used to transfer water when the tank level drops below the probe. At the time of the event, there was no analogue signal back to the SCADA giving actual level in the tank.

Water from the service water tank supplies 6 motive water chlorinator pumps and two service water pumps which in turn supply the lime makeup system, de-alkalisation plant for lime carrier water makeup and the activated carbon dosing plant makeup water. The duty and standby wash water pumps for washing the rapid gravity filters are also fed out of this tank.

The service water tank supplies the lime makeup system directly via the service water pumps. Carrier and flushing water however is supplied indirectly from this tank via a connection to the service water pump main via two booster pumps. As there have been historical problems with calcium precipitation in the dosing lines causing blockages, the carrier and flushing water is supplied via the de-alk plant where the water is de-alkalised by acidification to pH 4.5 with sulphuric acid, followed by air bubbling and de-gassing to remove bicarbonate alkalinity as free CO2. Under normal circumstances, the six lime dosing lines would automatically flush on a weekly basis on automatic duty pump changeover.

Prior to the incident the de-alkalisation plant had been out of service from 27th June to 21st August due to a problem which was eventually tracked down to the acid dosing flow-meter. As the de-alkalisation plant had been out of service for an extended period of time, blockage of the dosing lines was becoming an increasing problem. Manual flushing of all the lines had been done in the days leading up to the event in an attempt to improve the blockage situation.

On the evening of the 24th August, the standby process engineer was on site dealing with problems with the lime system and changed the duty on two of the lime pumps by pressing the emergency stops on both. This changed the duty and automatically set the now standby pumps to flush for the allotted period of time (1 hour). Due to a PLC software problem the lime pumps flushing did not automatically switch off as it should, which meant that all three standby dosing pumps were flushing overnight prior to the event. Further investigation highlighted that this situation only occurs when the emergency stops are used to change over the pump duties. It does not happen when the duties are rotated in the normal way by the SCADA.

With the absence of any flow measurement or level indication on either the old service reservoir, service water or de-alkalisation tanks and the absence of any filter washing around the time of the event, the reasonable assumption has been made that the loss of water in the service water tank was solely due to the constant flushing of the lime dosing lines instigated beforehand. This can be further corroborated by de-alkalisation plant sulphuric acid use that was double its normal level in the days leading up to the event indicating an elevated flow through the de-alkalisation plant

The dosing line flushing was stopped and there have been no further problems with the level in the service water tank since this time.

Failsafe Disinfection

Failsafe disinfection was provided at this Water treatment works in 2000 in the form of a system providing dual redundancy on contact tank and final water chlorinators, motive water pumps, and dosing pipe-work. Dual redundancy was the preferred option in providing failsafe at this time due to hydraulic concerns in shutting down the raw water mains in a controlled manner.

Dual redundancy was provided in all the dosing equipment and motive water pumps, but did not extent to the service water tanks from which the water was drawn. The Company considers this a reasonable approach to have adopted at the time. As the incident was caused by low level in the service water tank causing loss of motive water to the chlorinators, it is reasonable to suggest that the mode of failure could not have been anticipated

Alarm Handling in the control centre

In normal working hours, RTS alarms are acknowledged by the shift controllers at the ROCC who then pass the alarms verbally to the production coordinator for that area. He/she will then interrogate the SCADA via reachout and decide whether corrective action can be taken or if they need to call someone on site or to site if it is unmanned.

Out of working hours, on receipt of an RTS alarm the shift controller will interrogate the SCADA of the alarming site and decide if any corrective action can be taken. If there is any uncertainty about which course of action to take, the standby process engineer will be called.

Alarms that appear on the shift controllers' screens are magenta but turn yellow when they are "noted" by the controllers. At this point, the alarms are passed verbally to the production coordinator in working hours or to the standby process engineer if out of hours. If the alarm happens to clear before it is noted it will turn blue, but if it clears after it has been noted it turns green. Only alarms that have turned either blue or green are accepted by the controllers, who clear the alarm from the screen because the alarm state has already cleared. Once the alarm has been noted and passed verbally to the production coordinator, it will only be passed to the production coordinator or standby process engineer again if the alarm occurs again.

On the day of the event the systems controller passed a series of pH alarms to the production coordinator verbally. Although the alarm would have stayed on the screen, the shift controller was under the impression he had passed the alarm onto the production coordinator and that he was dealing with it. As a result, it was not specifically passed again.

Later on, the shift controller and production coordinator had a further conversation about alarms. According to the production coordinator, assumed the conversation was about pH alarms only as no mention was made of chlorine alarms. According to the shift controller, all alarms were passed to the production coordinator. It would appear on this occasion that there was a misunderstanding between the two regarding what type of alarms had been passed on. During this conversation, the production coordinator indicated that someone was on site dealing with the problems. 10 hours later, the production coordinator had a further conversation with the shift controller on leaving for home when he indicated that someone was still on site waiting for the pH's to settle following the problems with the lime system.

The contact water tank low free chlorine alarm and the total chlorine alarm came in at that time. The contact water tank low low free chlorine alarm came in two hours later.

The shift controller acknowledged the alarms but did not pass them on to anyone because they assumed that someone was still on site, as the production coordinator had indicated earlier. Both process engineers had actually left site at 16:15 without letting the shift controller know they had done so.

Alarm handling at the water treatment works

There are audible enunciator panels in various parts of the works, including the control room and lime areas, which sound a common alarm that does not differentiate between types of alarm. They do not give any visual indication as to the type of alarm, or indeed, what part of the process it is from. To differentiate, the process engineers must interrogate the SCADA in the control room to view what type of alarm has been raised.

On the day of the event, the local alarm was on reset all day due to the high number of pH and lime alarms caused by the problems with the lime system. As a result, there were no audible alarms on site for chlorination system failure, but there would have been a visual indication on certain SCADA pages.

The process engineers on site were dealing with a number of problems with the lime system and were working in the lime area for a substantial part of the day. The lime system is in an area remote from the control room and has no separate access to the SCADA or RTS. Whilst the process engineers viewed the SCADA in the control room on a number of occasions throughout the day, they were unaware of any problems with the chlorine system, so only viewed SCADA pages pertaining to the lime system.

Prior to leaving site at 16:15 the process engineers checked the SCADA pages pertaining to the lime system and ascertained that all was well. They did not check any pages pertaining to the chlorine system, as they had no reason to suspect there was any problem due to the lack of local alarms or telephone calls from the production coordinator to indicate this. They left site without speaking to the shift controller.

Communications

The WTW has no mobile phone signal on the telecommunications network used by the company therefore all communications with the site have to be via one dedicated landline. This can, and has caused difficulty in contacting the site on occasions in the past.

Actions taken to prevent a recurrence

Failsafe Shutdown

A site audit has been carried out on the current system and it has been decided that full failsafe shutdown should be installed. As a result, the scope of works has already been identified and full failsafe, with auto shutdown will be delivered during the remainder of this financial year.

Motive Water Supply

It is clear from the investigations that the loss of motive water to the chlorinators was caused by low level in the service water tank, which in turn was caused by constant flushing of the lime dosing lines leading up to the event.

The existing ultrasonic level detector in the service water tank which only gave start and stop signals for the 3" pump in the old service reservoir has now been cabled to give an analogue level signal which has been brought back to the SCADA for control purposes. This analogue signal will be used to inhibit filter washing and de-alkalisation plant

makeup on a predetermined low and low low level, and will generate a priority alarm should either of these conditions occur.
Feedback signals from the 3” transfer pump in the old service reservoir will be installed to demonstrate that the pump is actually working when called for, and the information will be displayed and alarmed on the SCADA.

Lime dosing system
Constant manual flushing of the lime dosing lines was stopped on the day following the incident when it became clear this was the cause. The PLC fault causing the pumps to constantly flush when the emergency stops are pressed is under investigation by an external contractor.
The problem does not occur when the pump duties are rotated in the normal manner via the changeover panel so the process engineers have been instructed not to use the emergency stops to shut off pumps and change duties until a solution is found.

Alarm Handling in the control centre
The verbal alarm handling procedure adopted between the shift and production controllers has now been modified and a written confirmation has been adopted. On receipt of the alarm, the shift controller copies the alarms into a proforma and two copies are printed. The alarms are subsequently signed for, and dated by, the production coordinator as proof of receipt. The shift controller and production coordinator keep separate copies of this receipt. The appropriate response to the alarm is, as before, determined by the production coordinator.
Process engineers in certain areas of Water Production have been trialling toughbook notebook computers for a number of months and the pilot has proved successful. As a result, rollout to all process engineers will take place. This system will include alarm-handling functionality and will give the benefit of wider visibility of alarms and the requirement for feedback response in the form of actions taken, and by whom.
The appearance of “pop ups” on the coordinators screen to alert them to anomalies on sites in their region of interest is also being investigated, and in future all coordinators workstations will have dual screens to allow easier visibility of alarms.

Alarm handling at the water treatment works
The SCADA has been modified so that a “Chlorine System Failure” banner is now displayed clearly on every SCADA page. This banner will highlight any problems associated with the chlorine dosing system or chlorine residual, irrespective of which page is being viewed.

Communications
Non-existent or poor mobile phone coverage at the site and a number of other sites have been identified and passed to the Company’s telecommunications department for investigation.

Assessment of Actions taken

A number of technical glitches, misunderstandings and poor communication between staff led to the extent of the incident. The availability of system redundancy reduced the incident impact on customers considerably: the chlorinated drinking water in the contact water tank was diluted by the unchlorinated water produced in the water treatment works.

Company staff responded promptly once the implications and extent of the chlorination failure were understood. The final chlorine dose was re-set via SCADA reach-out and the process engineer immediately attended site when it was found that the contact tank chlorine could not be reset. Once on site all the chlorine residuals in the works were re-established within a matter of minutes.

The contact water tank on site was slug dosed with sodium hypochlorite at the earliest opportunity to try to achieve a level of 1.0 mg/l free chlorine going into supply. The reservoir was further slug dosed 2 hours later when it became apparent that the chlorine residual on the outlet had dropped again and a 3rd slug dose was considered 1.5 hrs later. This was subsequently decided against, as the chlorine had stabilised at an appropriate residual by this time.

Time of travel calculations were used to asses the potential time of arrival of any possible poor quality water at key points along the system and the appropriate service reservoirs on the system were sampled and slug dosed with sodium hypochlorite at appropriate times over a 3-day period.

Water Quality samples were taken at the earliest opportunity with those on the treatment works and service reservoirs being taken on the night of the event and those in distribution as early as possible the following day owing to the late hour of sampling restricting access to customer properties. Sampling at fixed points other than customer properties was considered on the night of the event but only one property (an all night garage) was known to be open at this time of night.

Actual impact: Low
Potential impact: Medium
Incident detection: Direct SCADA and telemetry reports of system abnormality. These were ignored due to human error.
Incident management response: Poor response, however, in-built system redundancy reduced the incident considerably
Incident impact reduction: Medium to low

4.1.12 Coliforms in supply after water mains failure

Date 17 06 06

Background

The presence of a burst main was notified to the water utility and a job raised with the company's repair and maintenance contractor to effect a repair. The nature of the burst prevented an under pressure repair, and assistance in performing a shut-off was required. In total 77 properties downstream of the burst as well as 32 properties were shut off for a short period whilst the burst was repaired in line with standard procedure. The burst was not associated with the previous mains rehabilitation activity as this length of main was not included in the scheme.

Following the repair of a burst main low numbers of coliform bacteria were experienced at a number of properties on a road in the area. A number of actions, including flushing, chlorination, and swabbing were carried out over a period of days to restore normal water quality. DWI and other relevant bodies were notified.

Cause

Sampling at a hydrant following the repair of the burst main indicated the presence of coliform and *E. coli* bacteria. Further investigations at customer installations indicated the presence of coliform and *Clostridia* bacteria but no faecal indicator organisms.

The only Hydrant available to obtain a sample was subsequently found to be in a poor condition repair. However, this was the only representative location at which sample could be taken following the return of supplies.

A physical inspection of the hydrant further suggested that this was the cause of contamination of the post repair sample. The hydrant has now been replaced

It is possible that when the burst was isolated groundwater was drawn into the isolated section. It is believed actions taken to repair the burst mains, as well as chlorination, caused disturbance in sections of unlined cast iron main (this is backed by the findings of the camera investigation). This disturbance may have lead to the resuspension of historic sediments with the mains network.

The presence of a clear bacteriological sample from a neighbouring property indicated the source of the positive sample was likely to be related to domestic fittings and was supported by a positive swab result. A further sampling programme was undertaken on the failing property and neighbouring properties.

Following the event, the section of cast iron main (presumed to be asbestos cement), was replaced by 90mm HDPE. All coils used had certificates of sterilisation.

The members of the gang carrying out the main rehabilitation had undergone appropriate training in disinfection and the use of chlorine. The gang had been previously audited and have been further audited subsequent to the event. No issues have been found.

Assessment of action taken

The water utility responded swiftly to repair the reported water mains failure. Due to the nature of the water main, a repair under pressure could not be performed and the water main was depressurised.

On confirmation of positive bacteriological samples, flushing, chlorination and swabbing were carried out. Repeated sample failures were responded to by investigative work to trace the source of contamination. Corrective actions were instigated and a safe water supply was re-instated.

During this incident, normal operating procedures were used to manage the incident. On confirmation of sample failures, the organisation responded with appropriate measures. Communication between the incident control centre and site staff was effective. Decision making, relating to non-routine actions were problem focussed and significantly contributed to a speedy re-instatement of normal operating conditions.

Actual impact: Low
Potential impact: Significantly higher
Incident detection: Reported water mains failure and laboratory results
Incident management response: Effective response in line with standard operating procedures
Incident impact reduction: High

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4.2 HRO surveys

4.2.1 HRO survey with international contributors

Ref	Description	1) Observations in the organisations				2) Cost – beneficial to implement and maintain			
1) Aggregated number of observed HRO characteristics by all survey participants 2) Aggregated number of cost benefit evaluations for HRO characteristics by all survey participants		Strongly agree	Agree	Disagree	Strongly disagree	Positive cost benefit	Balanced cost benefit	Negative cost benefit	
Organisational culture of reliability									
A1	In my organisation, staff in operations have a strong sense for the primary mission of the organisation and share a common system of beliefs and perceptions.	5	6	2	0	8	3	0	
A2	In my organisation, the water supply system is continuously monitoring so that failure events are foreseen and understood.	2	9	1	0	8	4	0	
A3	In my organisation, our staff in operations have a highly developed understanding of their contribution to water safety and their role in the system.	3	8	1	0	7	5	0	
A4	In a water quality incident, our staff in operations act in a collaborative and collegiate manner and the group interaction can be described as collective intelligent interaction.	6	5	1	0	9	3	0	
A5	Our staff in operations are sensitive towards all events where water supply reliability is concerned. Staff know that a very small initial moment of inattention or misperception can lead to an escalation of failure which can result in a water quality incident.	5	6	1	0	7	5	0	
A6	All our employees take responsibility where problems are identified and immediate corrective action programmes are required.	1	7	4	0	3	8	1	
A7	Our staff in operations are obliged to report their mistakes without fear of punishment.	2	8	2	0	2	7	1	
A8	In our organisation, individual behaviours, which jeopardise the primary mission of reliability, are labelled as disgrace.	0	0	10	2	1	2	5	
A8a	Our senior management is committed to the reliability of the organisation. This is communicated to all levels in the organisation and demonstrated with investments in technology, processes and personnel.	2	10	0	0	7	6	0	
A9	In our organisation, individuals “monitor, advise, criticize and support” each other, in particular in situations where mistakes are more likely to occur.	1	5	6	0	3	4	2	
A10	In general, our staff are attentive, alert and act with care.	5	7	0	0	7	4	0	

Table 42 Combined results from 14 participants in the HRO survey

Ref.	Description	1) Observations in the organisations				2) Cost – beneficial to implement and maintain			
1) Aggregated number of observed HRO characteristics by all survey participants 2) Aggregated number of cost benefit evaluations for HRO characteristics by all survey participants		Strongly agree	Agree	Disagree	Strongly disagree	Positive cost benefit	Balanced cost benefit	Negative cost benefit	
Continuous learning and intensive training									
B1	In order to facilitate continuous learning and intensive training, our organisation constantly reviews their processes and ways of operating.	3	8	1	0	6	5	0	
B2	In preparation for a job, our staff in operations and maintenance staff receive training on the requirements of maintaining a safe system. These are embedded in formal rules, general guidelines and standardised frameworks.	2	8	5	0	6	5	1	
B3	Our staff in operations must adhere to standard operating procedures but also pro-actively identify potential sources of failure and actions to stop faults from escalating.	2	8	4	0	3	9	1	
X1	Our staff question procedures when in doubt about their appropriateness.	1	7	3	1	3	4	3	
X2	In unforeseen situations, staff in operations don't follow rules blindly, but negotiate the course of action in a collegial manner with more experienced staff and supervisors.	1	7	4	0	4	5	2	
X3	During a water quality incident, staff in operations establish an emergency response team for joint decision making in order to avoid overlooking complex circumstances.	7	4	1	0	6	5	1	
B4	All our staff maintain a commitment to continuous learning and seek the acquisition and improvement of skills.	0	7	4	1	3	6	1	
B5	In our organisation we learn from failures, near misses and mistakes by other utilities and use these as a means to study the failure susceptibility of the own organisation.	3	5	3	1	7	4	1	
B6	In our organisation, even minor errors and incidents provide a source for learning which are assessed through root cause analysis.	0	4	6	2	4	5	2	
B7	Our organisation develops a collective memory for failures, incidents and root causes for failure, which helps the organisation to anticipate future problems.	0	6	7	1	3	7	1	
B8	In our organisation, we share a sense that learning from trial and error is not feasible to understand our water supply system. For staff training, we use offline methods of learning which consist of realistic drills, simulations and exercises to replicate potential failure scenarios.	0	7	4	1	3	7	1	

Table 43 Combined results from 14 participants in the HRO survey (continued)

Ref.		1) Observations in the organisations				2) Cost – beneficial to implement and maintain			
1) Aggregated number of observed HRO characteristics by all survey participants **2) Aggregated number of cost benefit evaluations for HRO characteristics by all survey participants**		Strongly agree	Agree	Disagree	Strongly disagree	Positive cost benefit	Balanced cost benefit	Negative cost benefit	
Effective and varied patterns of communication									
C1	Our communication system makes our water supply system better understandable, predictable and controllable.	1	7	4	0	3	8	0	
C2	Our organisation operates in an information rich environment. All processes are measured and understood. Data are transparent and made available to all.	1	7	5	0	3	5	3	
C3	Our staff in operations are encouraged to share their experiences relating to the reliability of the system. Communication is designed as bottom up and top down to ensure rapid flow of information through the hierarchy of the system. Rapid dissemination of information helps the organisation to respond to water quality incidents with corrective action aiming to prevent the escalation of failure.	1	9	3	0	5	7	0	
X1	During a water quality incident, the response team maintains "closed loop" communication with all stakeholders within the organisation	1	7	6	0	5	5	2	
X2	During a water quality incident, the organisation maintains "closed loop" communication with the public, regulators and government authorities	1	7	3	0	3	6	2	
C4	In our organisation, communicating information shapes the 'big picture' of our organisational vision, mission and responsibility of individuals towards reliability.	1	6	5	0	5	7	0	
C5	Our organisation uses various channels to transmit different types data and information relating to monitoring and control of our assets (and ultimately water safety). Direct and complementary information enhance information reliability and provides a form of redundancy.	0	11	1	0	4	7	2	
C6	Multiple monitoring and control data from a variety of sources provide information density which allows individual signals to be scrutinised for fitting into the whole information pattern. Abnormal signals are treated as an indication for latent errors to unfold into failures.	0	8	5	1	4	4	3	
C7	In our organisation, interpersonal communications are formalised in a precise, unambiguous, impersonal and efficient structure, which denies individuals to communicate in their idiosyncratic communication style.	0	0	10	2	0	4	5	

Table 44 Combined results from 14 participants in the HRO survey (continued)

Ref.	Description	1) Observations in the organisations				2) Cost – beneficial to implement and maintain			
1) Aggregated number of observed HRO characteristics by all survey participants 2) Aggregated number of cost benefit evaluations for HRO characteristics by all survey participants		Strongly agree	Agree	Disagree	Strongly disagree	Positive cost benefit	Balanced cost benefit	Negative cost benefit	
Adaptable decision making dynamics and flexible organisational structures									
D1	Our organisation can only prevent outbreaks with a high level of centralisation, because low-level decision makers have insufficient understanding of the inter-relationship between their action and consequences on other elements of the water supply system. During an emergency, control has to be maintained highly centralised in order to maintain overview of the entire system response to action on all sub-units.	0	3	10	0	1	7	4	
D2	In our organisation, decentralisation is required to respond rapidly to unfolding failures. An emergency can be confined to one sub-unit, which is subsequently isolated from the entire system. The control over an emergency is decentralised to this subunit until the emergency is cleared.	0	5	8	0	3	5	3	
D1/2a	In our organisation, centralisation at collective level coexists with decentralisation at individual level. The organisation exhibits an adaptive, flexible or organic nature.	4	6	3	0	6	4	0	
D3	Our organisation enforces the stringent adherence to standard operating procedures aiming for repeatability of action and routines.	0	8	6	0	5	6	1	
D4	Our standard operating procedures are constantly updated and incorporate lessons learnt. Formal rules and procedures are effective elements to identify and control risk.	2	5	3	2	5	6	1	
D5	In our organisation, activities which are not defined in standard operating procedures are based on decisions a most senior individual makes, as they should have the best knowledge of the system.	0	4	8	0	3	5	1	
D6	Our organisation has a hierarchical structure for decision making which reflects expertise, know-how and seniority. Each level has controls and regulating mechanisms.	0	10	4	0	3	7	0	
D7	Our organisation requires staff to conform to organisational norms and avoids innovative, autonomous or creative behaviours.	0	1	7	4	3	2	5	
D8	Our decision-making processes have slack in-built in order to assess and challenge decisions to avoid faulty decisions to escalate into failure.	1	5	4	1	4	5	2	

Table 45 Combined results from 14 participants in the HRO survey (continued)

Ref	Description	1) Observations in the organisations				2) Cost – beneficial to implement and maintain			
1) Aggregated number of observed HRO characteristics by all survey participants 2) Aggregated number of cost benefit evaluations for HRO characteristics by all survey participants		Strongly agree	Agree	Disagree	Strongly disagree	Positive cost benefit	Balanced cost benefit	Negative cost benefit	
System and human redundancy									
E1	Our organisation maintains reserve capacity in the system. This includes back-up functions, overlapping tasks and responsibilities.	3	3	4	2	5	2	5	
E2	In our organisation, we are aware that redundancy can be counterproductive. Back-up functions can increase technical complexity, conceal errors and can lead individuals into not performing their required tasks under the assumptions that someone else takes care of his task.	1	4	6	1	1	4	6	
Precise procedures in managing technology									
F1	Our organisation does not use state of the art equipment to ensure that our technology does not add unnecessary complexity to the organisation.	0	4	8	1	1	6	3	
F2	In water supply systems design, our organisation aims to simplify complex technical systems and avoid unnecessary automation.	1	6	5	0	5	6	0	
F3	New technology acquisition is only justified if existing equipment does not perform to required specification.	3	2	7	0	4	6	3	
F4	In our organisation, existing technology is maintained to exceptionally high standards, as we do not tolerate defective, substandard or malfunctioning equipment.	1	3	8	0	4	3	6	
F5	In our organisation, maintenance activity and protocols as well as performance data are used to monitor the healthy operation of the system.	2	9	2	0	8	4	0	

Table 46 Combined results from 14 participants in the HRO survey (continued)

Ref.	Description	1) Observations in the organisations				2) Cost – beneficial to implement and maintain			
1) Aggregated number of observed HRO characteristics by all survey participants 2) Aggregated number of cost benefit evaluations for HRO characteristics by all survey participants		Strongly agree	Agree	Disagree	Strongly disagree	Positive cost benefit	Balanced cost benefit	Negative cost benefit	
Human resource management practices that support reliability									
G1	In recruitment and selection, our organisation acquires suitable and skilled candidates for the jobs aiming to match the complexity of the environment with an equally complex set of people to understand the system. Diverging backgrounds for staff offer different ways of looking at systems.	3	8	3	0	9	3	0	
G2	Since most people do what is rewarded, our organisation remunerates reliability with incentives, recognition and career opportunities.	2	5	5	1	4	4	3	
G3	In our organisation, job rotation increases networking between teams and helps the organisation to transfer and diffuse knowledge and lessons learnt.	0	6	5	1	3	6	3	
G4	Our organisation has systems in place to monitor the behaviour of staff.	1	6	3	2	5	6	1	

Table 47 Combined results from 14 participants from the HRO survey (continued)

The following table contains the statistical analysis of the above survey data.

Reference to HRO principle	Observation				CBA			Statistical analysis for observed HRO principles						Statistical analysis for Cost Benefit analysis					
								Total count	Av	SD	SE	CI 95 min	CI 95 max	Total count	Av	SD	SE	CI 95 min	CI 95 max
	100	80	20	0	10	0	-10												
	SA	A	D	SD	P	B	N												
A1	5	6	2	0	8	3	0	13.00	78.46	27.64	7.67	63.43	93.49	11.00	7.27	4.67	1.41	4.51	10.03
A2	2	9	1	0	8	4	0	12.00	78.33	19.92	5.75	67.06	89.61	12.00	6.67	4.92	1.42	3.88	9.45
A3	3	8	1	0	7	5	0	12.00	80.00	20.89	6.03	68.18	91.82	12.00	5.83	5.15	1.49	2.92	8.75
A4	6	5	1	0	9	3	0	12.00	85.00	22.76	6.57	72.12	97.88	12.00	7.50	4.52	1.31	4.94	10.06
A5	5	6	1	0	7	5	0	12.00	83.33	22.29	6.44	70.72	95.95	12.00	5.83	5.15	1.49	2.92	8.75
A6	1	7	4	0	3	8	1	12.00	61.67	31.29	9.03	43.97	79.37	12.00	1.67	5.77	1.67	-1.60	4.93
A7	2	8	2	0	2	7	1	12.00	73.33	26.05	7.52	58.59	88.07	10.00	1.00	5.68	1.80	-2.52	4.52
A8	0	0	10	2	1	2	5	12.00	16.67	7.78	2.25	12.26	21.07	8.00	-5.00	7.56	2.67	-10.24	0.24
A8a	2	10	0	0	7	6	0	12.00	83.33	7.78	2.25	78.93	87.74	13.00	5.38	5.19	1.44	2.56	8.21
A9	1	5	6	0	3	4	2	12.00	51.67	33.53	9.68	32.70	70.64	9.00	1.11	7.82	2.61	-4.00	6.22
A10	5	7	0	0	7	4	0	12.00	88.33	10.30	2.97	82.51	94.16	11.00	6.36	5.05	1.52	3.38	9.35
B1	3	8	1	0	6	5	0	12.00	80.00	20.89	6.03	68.18	91.82	11.00	5.45	5.22	1.57	2.37	8.54
B2	2	8	5	0	6	5	1	15.00	62.67	31.95	8.25	46.50	78.84	12.00	4.17	6.69	1.93	0.38	7.95
B3	2	8	4	0	3	9	1	14.00	65.71	30.81	8.24	49.57	81.86	13.00	1.54	5.55	1.54	-1.48	4.55
X1	1	7	3	1	3	4	3	12.00	60.00	34.11	9.85	40.70	79.30	10.00	0.00	8.16	2.58	-5.06	5.06
X2	1	7	4	0	4	5	2	12.00	61.67	31.29	9.03	43.97	79.37	11.00	1.82	7.51	2.26	-2.62	6.25
X3	7	4	1	0	6	5	1	12.00	86.67	23.09	6.67	73.60	99.73	12.00	4.17	6.69	1.93	0.38	7.95
B4	0	7	4	1	3	6	1	12.00	53.33	33.39	9.64	34.44	72.23	10.00	2.00	6.32	2.00	-1.92	5.92
B5	3	5	3	1	7	4	1	12.00	63.33	37.01	10.68	42.39	84.27	12.00	5.00	6.74	1.95	1.19	8.81
B6	0	4	6	2	4	5	2	12.00	36.67	32.84	9.48	18.08	55.25	11.00	1.82	7.51	2.26	-2.62	6.25
B7	0	6	7	1	3	7	1	14.00	44.29	32.51	8.69	27.25	61.32	11.00	1.82	6.03	1.82	-1.75	5.38
B8	0	7	4	1	3	7	1	12.00	53.33	33.39	9.64	34.44	72.23	11.00	1.82	6.03	1.82	-1.75	5.38
C1	1	7	4	0	3	8	0	12.00	61.67	31.29	9.03	43.97	79.37	11.00	2.73	4.67	1.41	-0.03	5.49
C2	1	7	5	0	3	5	3	13.00	58.46	32.11	8.90	41.01	75.91	11.00	0.00	7.75	2.34	-4.58	4.58
C3	1	9	3	0	5	7	0	13.00	67.69	27.74	7.69	52.62	82.77	12.00	4.17	5.15	1.49	1.25	7.08
X1	1	7	6	0	5	5	2	14.00	55.71	32.51	8.69	38.68	72.75	12.00	2.50	7.54	2.18	-1.76	6.76
X2	1	7	3	0	3	6	2	11.00	65.45	29.79	8.98	47.85	83.06	11.00	0.91	7.01	2.11	-3.23	5.05

C4	1	6	5	0	5	7	0	12.00	56.67	32.84	9.48	38.08	75.25	12.00	4.17	5.15	1.49	1.25	7.08
C5	0	11	1	0	4	7	2	12.00	75.00	17.32	5.00	65.20	84.80	13.00	1.54	6.89	1.91	-2.21	5.28
C6	0	8	5	1	4	4	3	14.00	52.86	32.92	8.80	35.61	70.10	11.00	0.91	8.31	2.51	-4.00	5.82
C7	0	0	10	2	0	4	5	12.00	16.67	7.78	2.25	12.26	21.07	9.00	-5.56	5.27	1.76	-9.00	-2.11
D1	0	3	10	0	1	7	4	13.00	33.85	26.31	7.30	19.54	48.15	12.00	-2.50	6.22	1.79	-6.02	1.02
D2	0	5	8	0	3	5	3	13.00	43.08	30.38	8.43	26.56	59.59	11.00	0.00	7.75	2.34	-4.58	4.58
D1/2/a	4	6	3	0	6	4	0	13.00	72.31	31.13	8.63	55.38	89.23	10.00	6.00	5.16	1.63	2.80	9.20
D3	0	8	6	0	5	6	1	14.00	54.29	30.81	8.24	38.14	70.43	12.00	3.33	6.51	1.88	-0.35	7.02
D4	2	5	3	2	5	6	1	12.00	55.00	39.20	11.32	32.82	77.18	12.00	3.33	6.51	1.88	-0.35	7.02
D5	0	4	8	0	3	5	1	12.00	40.00	29.54	8.53	23.29	56.71	9.00	2.22	6.67	2.22	-2.13	6.58
D6	0	10	4	0	3	7	0	14.00	62.86	28.13	7.52	48.12	77.59	10.00	3.00	4.83	1.53	0.01	5.99
D7	0	1	7	4	3	2	5	12.00	18.33	21.67	6.26	6.07	30.60	10.00	-2.00	9.19	2.91	-7.70	3.70
D8	1	5	4	1	4	5	2	11.00	52.73	36.08	10.88	31.40	74.05	11.00	1.82	7.51	2.26	-2.62	6.25
E1	3	3	4	2	5	2	5	12.00	51.67	41.30	11.92	28.30	75.04	12.00	0.00	9.53	2.75	-5.39	5.39
E2	1	4	6	1	1	4	6	12.00	45.00	35.29	10.19	25.03	64.97	11.00	-4.55	6.88	2.07	-8.61	-0.48
F1	0	4	8	1	1	6	3	13.00	36.92	30.38	8.43	20.41	53.44	10.00	-2.00	6.32	2.00	-5.92	1.92
F2	1	6	5	0	5	6	0	12.00	56.67	32.84	9.48	38.08	75.25	11.00	4.55	5.22	1.57	1.46	7.63
F3	3	2	7	0	4	6	3	12.00	50.00	37.66	10.87	28.69	71.31	13.00	0.77	7.60	2.11	-3.36	4.90
F4	1	3	8	0	4	3	6	12.00	41.67	32.43	9.36	23.32	60.01	13.00	-1.54	8.99	2.49	-6.42	3.35
F5	2	9	2	0	8	4	0	13.00	73.85	25.01	6.94	60.25	87.44	12.00	6.67	4.92	1.42	3.88	9.45
G1	3	8	3	0	9	3	0	14.00	71.43	29.05	7.76	56.21	86.65	12.00	7.50	4.52	1.31	4.94	10.06
G2	2	5	5	1	4	4	3	13.00	53.85	36.86	10.22	33.81	73.89	11.00	0.91	8.31	2.51	-4.00	5.82
G3	0	6	5	1	3	6	3	12.00	48.33	33.53	9.68	29.36	67.30	12.00	0.00	7.39	2.13	-4.18	4.18
G4	1	6	3	2	5	6	1	12.00	53.33	37.50	10.82	32.12	74.55	12.00	3.33	6.51	1.88	-0.35	7.02
All HRO	**81**	**307**	**221**	**27**	**224**	**263**	**87**	**636**	**58.30**	**33.23**	**1.32**	**55.72**	**60.88**	**574.00**	**2.39**	**6.97**	**0.29**	**1.82**	**2.96**
CBA AV>0	**79**	**292**	**162**	**17**	**213**	**235**	**53**	**550**	**62.73**	**31.92**	**1.36**	**60.06**	**65.40**	**501.00**	**3.19**	**6.56**	**0.29**	**2.62**	**3.77**
CBA CI95%min>0	**55**	**130**	**41**	**1**	**119**	**87**	**3**	**227**	**73.66**	**27.17**	**1.80**	**70.12**	**77.19**	**209.00**	**5.55**	**5.26**	**0.36**	**4.84**	**6.26**

Table 48 Statistical analysis of HRO survey data

4.2.1.1 Cost Benefit analysis of HRO from an international perspective

In the statistical analysis of the cost benefit data a 95% confidence interval was constructed. In addition to the HRO principles identified with an average positive for the cost benefit, those HRO principles were identified for which the minimum confidence interval exceeds zero. In other words, those HRO principles have a 97.5% chance to have a positive cost beneficial effect for the management of safe and reliable drinking water.

In Table 49 and Table 51, those HRO indicators are presented were the minimum confidence interval for cost benefit analysis exceeds the value zero. For these HRO indicators, the combined observations by the survey participants for their utilities are presented. The aggregated observation of these HRO principles in the table reflect whether the participants observed these principles being implemented or maintain in their organisations.

Ref	Description	**Observable in the organisations**			
Cost Beneficial at CI 95% min >0		Strongly agree	Agree	Disagree	Strongly disagree
Organisational culture of reliability					
A1	In my organisation, staff in operations have a strong sense for the primary mission of the organisation and share a common system of beliefs and perceptions.	5	6	2	0
A2	In my organisation, the water supply system is continuously monitoring so that failure events are foreseen and understood.	2	9	1	0
A3	In my organisation, our staff in operations have a highly developed understanding of their contribution to water safety and their role in the system.	3	8	1	0
A4	In a water quality incident, our staff in operations act in a collaborative and collegiate manner and the group interaction can be described as collective intelligent interaction.	6	5	1	0
A5	Our staff in operations are sensitive towards all events where water supply reliability is concerned. Staff know that a very small initial moment of inattention or misperception can lead to an escalation of failure, which can result in a water quality incident.	5	6	1	0
A8a	Our senior management is committed to the reliability of the organisation. This is communicated to all levels in the organisation and demonstrated with investments in technology, processes and personnel.	2	10	0	0
A10	In general, our staff are attentive, alert and act with care.	5	7	0	0

Table 49 HRO principles with a significantly positive cost benefit

Ref.	Description	Observable in the organisations			
	Cost Beneficial at CI 95% min >0	Strongly agree	Agree	Disagree	Strongly disagree
Continuous learning and intensive training					
B1	In order to facilitate continuous learning and intensive training, our organisation constantly reviews their processes and ways of operating.	3	8	1	0
B2	In preparation for a job, our staff in operations and maintenance staff receive training on the requirements of maintaining a safe system. These are embedded in formal rules, general guidelines and standardised frameworks.	2	8	5	0
X3	During a water quality incident, staff in operations establish an emergency response team for joint decision making in order to avoid overlooking complex circumstances.	7	4	1	0
B5	In our organisation we learn from failures, near misses and mistakes by other utilities and use these as a means to study the failure susceptibility of the own organisation.	3	5	3	1
Effective and varied patterns of communication					
C3	Our staff in operations are encouraged to share their experiences relating to the reliability of the system. Communication is designed as bottom up and top down to ensure rapid flow of information through the hierarchy of the system. Rapid dissemination of information helps the organisation to respond to water quality incidents with corrective action aiming to prevent the escalation of failure.	1	9	3	0
C4	In our organisation, communicating information shapes the 'big picture' of our organisational vision, mission and responsibility of individuals towards reliability.	1	6	5	0

Table 50 HRO principles with a significantly positive cost benefit (continued)

Ref.	Description	Observable in the organisations			
	Cost Beneficial at CI 95% min >0	Strongly agree	Agree	Disagree	Strongly disagree
Adaptable decision making dynamics and flexible organisational structures					
D1/2a	In our organisation, centralisation at collective level coexists with decentralisation at individual level. The organisation exhibits an adaptive, flexible or organic nature.	4	6	3	0
D6	Our organisation has a hierarchical structure for decision making which reflects expertise, know-how and seniority. Each level has controls and regulating mechanisms.	0	10	4	0
System and human redundancy					
	None				
Precise procedures in managing technology					
F2	In water supply systems design, our organisation aims to simplify complex technical systems and avoid unnecessary automation.	1	6	5	0
F5	In our organisation, maintenance activity and protocols as well as performance data are used to monitor the healthy operation of the system.	2	9	2	0
Human resource management practices that support reliability					
G1	In recruitment and selection, our organisation acquires suitable and skilled candidates for the jobs aiming to match the complexity of the environment with an equally complex set of people to understand the system. Diverging backgrounds for staff offer different ways of looking at systems.	3	8	3	0

Table 51 HRO principles with a significantly positive cost benefit (continued)

It can be seen that the number of HRO principles that are considered to have a 97.5% chance of being cost beneficial has significantly reduced to 18 in comparison to the initial HRO framework of 51 HRO indicators. It should also be noted that HRO principles relating to ‘Organisational culture of reliability’ now forms the largest group of relevant indicators.

For all indicators (18 out of 18), it can be identified that the majority of responses ‘strongly agree’ or ‘agree’ to having observed the stated HRO principle in their organisation. This is a significant improvement compared to the entire HRO framework or the HRO principles with an average positive cost benefit.

4.2.1.2 Detailed analysis of HRO survey for individual participants in an international perspective

Based on this scoring mechanism, individual returns of the survey questionnaire were analysed and summarised.

In Table 52 to Table 54, the survey returns from 12 participants are presented. The horizontal axis represents the 7 categories of HRO principles 'Organisational culture of reliability (A)', 'Continuous learning and intensive training (B)', 'Effective and varied patterns of communication (C)', 'Adaptable decision making dynamics and flexible organisational structures (D)', 'System and human redundancy (E)', 'Precise procedures in managing technology (F)' and 'Human resource management practices that support reliability (G)'.

The individual responses are anonymised. However, in tables the organisational type, size and country of operation are identified. The organisational type differentiates between private and public ownership as well as the corporate structure. 'Public' denotes public ownership and operated within government administration, 'Public corporate' denotes public ownership operated within financially accountable corporate structures and 'private' denotes private/shareholder ownership with a corporate structure. The utility size indicates the number of customers supplied by the utility. Small denotes less than 100,000 customers, 'Medium' represents a customer base between 100,000 and 1,000,000 and 'Large' denotes a water utility with more than 1,000,000 customers.

In Table 52, all HRO principles are taken into account regardless of their benefit in the context of cost for implementing or maintenance. The scores in the matrix columns represent the sum of scores for the HRO principles in those seven groups from A to G. Table 52 is ranked in descending order of the total sum of observed HRO principles in the participating water utilities.

The '#' symbol denotes a survey participant from the Regional Water Utility in the main study. The figures in italics exceed the 95% confidence interval based on the results from all survey participants for the respective group of HRO principles (A-G).

In Table 52 a whole range of observations or familiarity with HRO principles can be identified. The highest score for observed HRO principles has been obtained by a large, privatized water utility in the UK (Regional Water Utility). This is followed by a medium-sized, publicly owned Canadian water utility. Their HRO scores of 3780 and 3720, respectively, are more than double of the HRO score for the medium-sized, publicly operated US water utility at the bottom of Table 52.

On scrutiny of the results in Table 52, no clear trend or correlation between the sizes of the water utility, the ownerships model, the country of operation and the HRO score can be identified. Even the HRO scores for water utilities operating under a common regulatory regime in England and Wales vary considerably.

Company	Size	Country	A	B	C	D	E	F	G	Sum
Private #	Large	England	*980*	*1000*	700	500	160	160	280	3780
Public	Medium	Canada	*880*	*920*	540	*580*	100	320	380	3720
Private #	Large	England	*960*	*1000*	520	*560*	160	160	320	3680
Public	Small	Canada	840	680	580	*600*	120	300	340	3460
Public corporate	Large	Scotland	820	660	540	480	40	300	260	3100
Public	Medium	Canada	800	700	600	400	100	280	140	3020
Public	Medium	USA	720	660	600	600	40	160	200	2980
Public corporate	Medium	USA	820	700	420	220	100	340	260	2860
Private	Medium	England	780	420	160	360	200	360	220	2500
Public corporate	Large	Australia	720	280	280	180	20	280	180	1940
Private	Large	England	520	340	320	320	80	280	20	1880
Public	Medium	USA	480	440	320	260	20	140	20	1680
Average			776.67	650.00	465.00	421.67	95.00	256.67	218.33	2883.33
SD			152.04	243.83	162.51	152.90	58.54	79.01	114.88	740.90
SE			43.89	70.39	46.91	44.14	16.90	22.81	33.16	213.88
CI95 min			690.64	512.04	373.05	335.15	61.88	211.96	153.33	2464.13
CI95 max			*862.69*	*787.96*	*556.95*	*508.18*	*128.12*	*301.37*	*283.33*	*3302.54*
Results exceeding the confidence interval at 95% of the peer group are presented in italics										
# denotes a staff member of the Regional Water Utility in the main study										

Table 52 HRO performance of 12 participating water utilities considering all HRO principles

In Table 53, only scores of HRO principles were included that were perceived to have an average, positive cost benefit by the survey group.

In Table 52 a whole range of observations or familiarity with HRO principles can be identified. The highest score for observed HRO principles has been obtained by a large, privatized water utility in the UK (Regional Water Utility). This is followed by a medium-sized, publicly owned Canadian water utility. Their HRO scores of 3780 and 3720, respectively, are more than double of the HRO score for the medium-sized, publicly operated US water utility at the bottom of Table 52.

On scrutiny of the results in Table 52, no clear trend or correlation between the sizes of the water utility, the ownerships model, the country of operation and the HRO score can be identified. Even the HRO scores for water utilities operating under a common regulatory regime in England and Wales vary considerably.

Company	Size	Country	A	B	C	D	E	F	G	Sum
Private #	Large	England	*960*	*1000*	*680*	*480*	*80*	120	280	*3600*
Public	Medium	Canada	*860*	*920*	520	*540*	*100*	220	*380*	*3540*
Private #	Large	England	*940*	*1000*	500	*540*	*80*	120	*320*	*3500*
Public	Small	Canada	820	680	*560*	*560*	*100*	200	*340*	*3260*
Public corporate	Large	Scotland	800	660	520	440	20	*260*	260	2960
Public	Medium	Canada	780	700	*580*	380	*80*	180	140	2840
Public	Medium	USA	700	660	*580*	*500*	20	120	200	2780
Public corporate	Medium	USA	800	700	420	200	20	*240*	260	2640
Private	Medium	England	780	420	140	320	*100*	*260*	220	2240
Public corporate	Large	Australia	700	280	260	140	0	*240*	180	1800
Private	Large	England	500	340	300	300	0	200	20	1660
Public	Medium	USA	480	440	320	160	0	40	20	1460
Average			760.00	650.00	448.33	380.00	50.00	183.33	218.33	2690.00
SD			148.69	243.83	160.56	153.74	43.06	69.19	114.88	751.12
SE			42.92	70.39	46.35	44.38	12.43	19.97	33.16	216.83
CI95 min			675.87	512.04	357.49	293.01	25.63	144.18	153.33	2265.01
CI95 max			*844.13*	*787.96*	*539.18*	*466.99*	*74.37*	*222.48*	*283.33*	*3114.99*
Results exceeding the confidence interval at 95% of the peer group are presented in italics										
# denotes a staff member of the Regional Water Utility in the main study										

Table 53 HRO performance of 12 participating water utilities considering all HRO principles with an average, positive cost benefit

In Table 54, only those HRO principles are taken into account that were perceived to have a 97.5% chance to have a positive cost beneficial effect for the management of safe and reliable drinking water. In other words, those HRO principles whose minimum confidence interval for the cost benefit analysis exceeds the value of zero were used to calculate the sum of observed HRO principles.

In Table 54 a whole range of observations or familiarity with HRO principles can be identified. The highest score for observed HRO principles has been obtained by medium-sized, publicly owned Canadian water utility and a large, privatized water utility in the UK (Regional Water Utility). On scrutiny of the results in Table 54, no clear trend or correlation between the sizes of the water utility, the ownerships model, the country of operation and the HRO score can be identified. Even the HRO scores for water utilities operating under a common regulatory regime in England and Wales vary considerably.

Company	Size	Country	A	B	C	D	E	F	G	Sum
Public	Medium	Canada	*620*	*360*	*160*	*180*		*200*	*100*	*1620*
Private #	Large	England	*680*	*400*	*180*	*180*		100	80	*1620*
Private #	Large	England	*680*	*400*	*160*	*180*		100	80	*1600*
Public	Small	Canada	*640*	300	*180*	160		*180*	*100*	*1560*
Public corporate	Large	Scotland	560	280	*160*	160		160	80	1400
Public	Medium	USA	580	280	*160*	160		100	80	1360
Public	Medium	Canada	580	320	100	160		160	20	1340
Public corporate	Medium	USA	560	320	80	100		160	80	1300
Private	Medium	England	600	240	40	120		160	*100*	1260
Private	Large	England	440	260	20	160		100	0	980
Public	Medium	USA	420	260	100	100		20	0	900
Public corporate	Large	Australia	520	60	40	0		160	80	860
Average			573.33	290.00	115.00	138.33		133.33	66.67	1316.67
SD			82.39	89.65	59.16	52.19		49.97	37.50	275.00
SE			23.78	25.88	17.08	15.07		14.43	10.82	79.39
CI95 min			526.72	239.28	81.53	108.80		105.06	45.45	1161.07
CI95 max			*619.95*	*340.72*	*148.47*	*167.87*		*161.61*	*87.88*	*1472.26*
Results exceeding the confidence interval at 95% of the peer group are presented in italics										
# denotes a staff member of the Regional Water Utility in the main study										

Table 54 HRO performance of 12 participating water utilities considering all HRO principles with a 97.5% chance of being cost beneficial

4.2.2 HRO survey in Regional Water Utility

Ref	Description	1) Observations in the organisation				2) Cost – beneficial to implement and maintain			
1) Aggregated number of observed HRO characteristics by all survey participants 2) Aggregated number of cost benefit evaluations for HRO characteristics by all survey participants		Strongly agree	Agree	Disagree	Strongly disagree	Positive cost benefit	Balanced cost benefit	Negative cost benefit	
Organisational culture of reliability									
A1	In my organisation, staff in operations have a strong sense for the primary mission of the organisation and share a common system of beliefs and perceptions.	6	6	0	0	7	4	1	
A2	In my organisation, the water supply system is continuously monitoring so that failure events are foreseen and understood.	2	6	4	0	6	3	3	
A3	In my organisation, our staff in operations have a highly developed understanding of their contribution to water safety and their role in the system.	7	4	0	0	5	5	0	
A4	In a water quality incident, our staff in operations act in a collaborative and collegiate manner and the group interaction can be described as collective intelligent interaction.	8	4	0	0	6	6	0	
A5	Our staff in operations are sensitive towards all events where water supply reliability is concerned. Staff know that a very small initial moment of inattention or misperception can lead to an escalation of failure, which can result in a water quality incident.	5	7	0	0	7	5	0	
A6	All our employees take responsibility where problems are identified and immediate corrective action programmes are required.	1	7	4	0	3	7	2	
A7	Our staff in operations are obliged to report their mistakes without fear of punishment.	1	4	5	2	2	8	2	
A8	In our organisation, individual behaviours, which jeopardise the primary mission of reliability, are labelled as disgrace.	0	3	4	5	0	8	5	
A8a	Our senior management is committed to the reliability of the organisation. This is communicated to all levels in the organisation and demonstrated with investments in technology, processes and personnel.	3	6	3	0	6	6	0	
A9	In our organisation, individuals “monitor, advise, criticize and support” each other, in particular in situations where mistakes are more likely to occur.	1	4	6	1	2	8	2	
A10	In general, our staff are attentive, alert and act with care.	4	4	4	0	4	5	2	

Table 55 Results for HRO baseline survey in the Regional Water Utility

Ref.	Description	1) Observations in the organisation				2) Cost – beneficial to implement and maintain			
	1) Aggregated number of observed HRO characteristics by all survey participants 2) Aggregated number of cost benefit evaluations for HRO characteristics by all survey participants	Strongly agree	Agree	Disagree	Strongly disagree	Positive cost benefit	Balanced cost benefit	Negative cost benefit	
Continuous learning and intensive training									
B1	In order to facilitate continuous learning and intensive training, our organisation constantly reviews their processes and ways of operating.	4	4	4	0	4	6	2	
B2	In preparation for a job, our staff in operations and maintenance staff receive training on the requirements of maintaining a safe system. These are embedded in formal rules, general guidelines and standardised frameworks.	3	6	3	0	8	5	0	
B3	Our staff in operations must adhere to standard operating procedures but also pro-actively identify potential sources of failure and actions to stop faults from escalating.	4	5	3	0	7	4	1	
X1	Our staff question procedures when in doubt about their appropriateness.	0	5	5	2	3	4	5	
X2	In unforeseen situations, staff in operations don't follow rules blindly, but negotiate the course of action in a collegial manner with more experienced staff and supervisors.	1	6	5	0	4	5	3	
X3	During a water quality incident, staff in operations establish an emergency response team for joint decision making in order to avoid overlooking complex circumstances.	7	4	1	0	7	5	0	
B4	All our staff maintain a commitment to continuous learning and seek the acquisition and improvement of skills.	3	4	5	0	3	6	3	
B5	In our organisation we learn from failures, near misses and mistakes by other utilities and use these as a means to study the failure susceptibility of the own organisation.	2	3	7	0	2	7	3	
B6	In our organisation, even minor errors and incidents provide a source for learning which are assessed through root cause analysis.	1	5	7	0	5	7	0	
B7	Our organisation develops a collective memory for failures, incidents and root causes for failure, which helps the organisation to anticipate future problems.	0	2	7	2	2	5	5	
B8	In our organisation, we share a sense that learning from trial and error is not feasible to understand our water supply system. For staff training, we use offline methods of learning which consist of realistic drills, simulations and exercises to replicate potential failure scenarios.	0	4	6	2	2	5	5	

Table 56 Results for HRO baseline survey in the Regional Water Utility (continued)

Ref.		1) Observations in the organisation				2) Cost – beneficial to implement and maintain			
1) Aggregated number of observed HRO characteristics by all survey participants 2) Aggregated number of cost benefit evaluations for HRO characteristics by all survey participants		Strongly agree	Agree	Disagree	Strongly disagree	Positive cost benefit	Balanced cost benefit	Negative cost benefit	
Effective and varied patterns of communication									
C1	Our communication system makes our water supply system better understandable, predictable and controllable.	4	7	1	0	4	5	3	
C2	Our organisation operates in an information rich environment. All processes are measured and understood. Data are transparent and made available to all.	2	6	4	0	3	6	3	
C3	Our staff in operations are encouraged to share their experiences relating to the reliability of the system. Communication is designed as bottom up and top down to ensure rapid flow of information through the hierarchy of the system. Rapid dissemination of information helps the organisation to respond to water quality incidents with corrective action aiming to prevent the escalation of failure.	1	5	5	1	4	6	2	
X1	During a water quality incident, the response team maintains “closed loop” communication with all stakeholders within the organisation	1	7	4	0	6	6	0	
X2	During a water quality incident, the organisation maintains “closed loop” communication with the public, regulators and government authorities	0	4	6	2	3	5	4	
C4	In our organisation, communicating information shapes the ‘big picture’ of our organisational vision, mission and responsibility of individuals towards reliability.	3	5	4	0	5	6	1	
C5	Our organisation uses various channels to transmit different types data and information relating to monitoring and control of our assets (and ultimately water safety). Direct and complementary information enhance information reliability and provides a form of redundancy.	0	3	8	1	3	5	3	
C6	Multiple monitoring and control data from a variety of sources provide information density which allows individual signals to be scrutinised for fitting into the whole information pattern. Abnormal signals are treated as an indication for latent errors to unfold into failures.	1	2	5	4	0	8	4	
C7	In our organisation, interpersonal communications are formalised in a precise, unambiguous, impersonal and efficient structure, which denies individuals to communicate in their idiosyncratic communication style.	0	1	6	5	0	6	6	

Table 57 Results for HRO baseline survey in the Regional Water Utility (continued)

Ref.	Description	1) Observations in the organisation				2) Cost – beneficial to implement and maintain			
1) Aggregated number of observed HRO characteristics by all survey participants 2) Aggregated number of cost benefit evaluations for HRO characteristics by all survey participants		Strongly agree	Agree	Disagree	Strongly disagree	Positive cost benefit	Balanced cost benefit	Negative cost benefit	
Adaptable decision making dynamics and flexible organisational structures									
D1	Our organisation can only prevent outbreaks with a high level of centralisation, because low-level decision makers have insufficient understanding of the inter-relationship between their action and consequences on other elements of the water supply system. During an emergency, control has to be maintained highly centralised in order to maintain overview of the entire system response to action on all sub-units.	1	5	5	1	3	3	6	
D2	In our organisation, decentralisation is required to respond rapidly to unfolding failures. An emergency can be confined to one sub-unit, which is subsequently isolated from the entire system. The control over an emergency is decentralised to this subunit until the emergency is cleared.	2	5	5	0	2	5	5	
D1/2a	In our organisation, centralisation at collective level coexists with decentralisation at individual level. The organisation exhibits an adaptive, flexible or organic nature.	7	5	0	0	8	4	0	
D3	Our organisation enforces the stringent adherence to standard operating procedures aiming for repeatability of action and routines.	5	5	2	0	5	5	1	
D4	Our standard operating procedures are constantly updated and incorporate lessons learnt. Formal rules and procedures are effective elements to identify and control risk.	2	7	3	0	5	5	2	
D5	In our organisation, activities, which are not defined in standard operating procedures, are based on decisions a most senior individual makes, as they should have the best knowledge of the system.	3	5	4	0	4	6	2	
D6	Our organisation has a hierarchical structure for decision making which reflects expertise, know-how and seniority. Each level has controls and regulating mechanisms.	1	4	5	2	7	5	0	
D7	Our organisation requires staff to conform to organisational norms and avoids innovative, autonomous or creative behaviours.	0	4	7	1	0	5	7	
D8	Our decision-making processes have slack in-built in order to assess and challenge decisions to avoid faulty decisions to escalate into failure.	4	6	2	0	6	6	0	

Table 58 Results for HRO baseline survey in the Regional Water Utility (continued)

Ref	Description	1) Observations in the organisation				2) Cost – beneficial to implement and maintain			
1) Aggregated number of observed HRO characteristics by all survey participants 2) Aggregated number of cost benefit evaluations for HRO characteristics by all survey participants		Strongly agree	Agree	Disagree	Strongly disagree	Positive cost benefit	Balanced cost benefit	Negative cost benefit	
System and human redundancy									
E1	Our organisation maintains reserve capacity in the system. This includes back-up functions, overlapping tasks and responsibilities.	4	6	2	0	6	6	0	
E2	In our organisation, we are aware that redundancy can be counterproductive. Back-up functions can increase technical complexity, conceal errors and can lead individuals into not performing their required tasks under the assumptions that someone else takes care of his task.	0	2	4	6	0	4	8	
Precise procedures in managing technology									
F1	Our organisation does not use state of the art equipment to ensure that our technology does not add unnecessary complexity to the organisation.	2	2	6	2	0	6	6	
F2	In water supply systems design, our organisation aims to simplify complex technical systems and avoid unnecessary automation.	0	4	7	1	8	4	0	
F3	New technology acquisition is only justified if existing equipment does not perform to required specification.	3	5	4	0	3	7	2	
F4	In our organisation, existing technology is maintained to exceptionally high standards, as we do not tolerate defective, substandard or malfunctioning equipment.	0	1	5	6	0	3	9	
F5	In our organisation, maintenance activity and protocols as well as performance data are used to monitor the healthy operation of the system.	3	7	2	0	7	5	0	

Table 59 Results for HRO baseline survey in the Regional Water Utility (continued)

Ref.	Description	1) Observations in the organisation				2) Cost – beneficial to implement and maintain			
1) Aggregated number of observed HRO characteristics by all survey participants 2) Aggregated number of cost benefit evaluations for HRO characteristics by all survey participants		Strongly agree	Agree	Disagree	Strongly disagree	Positive cost benefit	Balanced cost benefit	Negative cost benefit	
Human resource management practices that support reliability									
G1	In recruitment and selection, our organisation acquires suitable and skilled candidates for the jobs aiming to match the complexity of the environment with an equally complex set of people to understand the system. Diverging backgrounds for staff offer different ways of looking at systems.	2	7	2	0	10	2	0	
G2	Since most people do what is rewarded, our organisation remunerates reliability with incentives, recognition and career opportunities.	0	6	6	0	6	5	1	
G3	In our organisation, job rotation increases networking between teams and helps the organisation to transfer and diffuse knowledge and lessons learnt.	1	4	5	2	2	6	4	
G4	Our organisation has systems in place to monitor the behaviour of staff.	2	4	4	2	4	6	2	

Table 60 Results for HRO baseline survey in the Regional Water Utility (continued)

In the following table, the survey data is statistically analysed.

								Statistical analysis for observed HRO principles						Statistical analysis for Cost Benefit analysis					
Reference to HRO principle	Observation				CBA			Total counts	Average	SD	SE	CI 95 min	CI 95 max	Total counts	Average	SD	SE	CI 95 min	CI 95 max
	100.00	80.00	20.00	0.00	10.00	0.00	-10.00												
	SA	A	D	SD	P	B	N												
A1	6	6	0	0	7	4	1	12.00	90.00	10.44	3.02	84.09	95.91	12.00	5.00	6.74	1.95	1.19	8.81
A2	2	6	4	0	6	3	3	12.00	63.33	32.84	9.48	44.75	81.92	12.00	2.50	8.66	2.50	-2.40	7.40
A3	7	4	0	0	5	5	0	11.00	92.73	10.09	3.04	86.76	98.69	10.00	5.00	5.27	1.67	1.73	8.27
A4	8	4	0	0	6	6	0	12.00	93.33	9.85	2.84	87.76	98.90	12.00	5.00	5.22	1.51	2.05	7.95
A5	5	7	0	0	7	5	0	12.00	88.33	10.30	2.97	82.51	94.16	12.00	5.83	5.15	1.49	2.92	8.75
A6	1	7	4	0	3	7	2	12.00	61.67	31.29	9.03	43.97	79.37	12.00	0.83	6.69	1.93	-2.95	4.62
A7	1	4	5	2	2	8	2	12.00	43.33	37.01	10.68	22.39	64.27	12.00	0.00	6.03	1.74	-3.41	3.41
A8	0	3	4	5	0	8	5	12.00	26.67	33.39	9.64	7.77	45.56	13.00	-3.85	5.06	1.40	-6.60	-1.09
A8a	3	6	3	0	6	6	0	12.00	70.00	31.33	9.05	52.27	87.73	12.00	5.00	5.22	1.51	2.05	7.95
A9	1	4	6	1	2	8	2	12.00	45.00	35.29	10.19	25.03	64.97	12.00	0.00	6.03	1.74	-3.41	3.41
A10	4	4	4	0	4	5	2	12.00	66.67	35.51	10.25	46.58	86.76	11.00	1.82	7.51	2.26	-2.62	6.25
B1	4	4	4	0	4	6	2	12.00	66.67	35.51	10.25	46.58	86.76	12.00	1.67	7.18	2.07	-2.39	5.73
B2	3	6	3	0	8	5	0	12.00	70.00	31.33	9.05	52.27	87.73	13.00	6.15	5.06	1.40	3.40	8.91
B3	4	5	3	0	7	4	1	12.00	71.67	32.43	9.36	53.32	90.01	12.00	5.00	6.74	1.95	1.19	8.81
X1	0	5	5	2	3	4	5	12.00	41.67	34.60	9.99	22.09	61.24	12.00	-1.67	8.35	2.41	-6.39	3.06
X2	1	6	5	0	4	5	3	12.00	56.67	32.84	9.48	38.08	75.25	12.00	0.83	7.93	2.29	-3.65	5.32
X3	7	4	1	0	7	5	0	12.00	86.67	23.09	6.67	73.60	99.73	12.00	5.83	5.15	1.49	2.92	8.75
B4	3	4	5	0	3	6	3	12.00	60.00	36.18	10.44	39.53	80.47	12.00	0.00	7.39	2.13	-4.18	4.18
B5	2	3	7	0	2	7	3	12.00	48.33	35.63	10.29	28.17	68.49	12.00	-0.83	6.69	1.93	-4.62	2.95
B6	1	5	7	0	5	7	0	13.00	49.23	33.28	9.23	31.14	67.32	12.00	4.17	5.15	1.49	1.25	7.08
B7	0	2	7	2	2	5	5	11.00	27.27	27.24	8.21	11.18	43.37	12.00	-2.50	7.54	2.18	-6.76	1.76
B8	0	4	6	2	2	5	5	12.00	36.67	32.84	9.48	18.08	55.25	12.00	-2.50	7.54	2.18	-6.76	1.76
C1	4	7	1	0	4	5	3	12.00	81.67	21.67	6.26	69.40	93.93	12.00	0.83	7.93	2.29	-3.65	5.32
C2	2	6	4	0	3	6	3	12.00	63.33	32.84	9.48	44.75	81.92	12.00	0.00	7.39	2.13	-4.18	4.18
C3	1	5	5	1	4	6	2	12.00	50.00	35.68	10.30	29.81	70.19	12.00	1.67	7.18	2.07	-2.39	5.73

X1	1	7	4	0	6	6	0	12.00	61.67	31.29	9.03	43.97	79.37	12.00	5.00	5.22	1.51	2.05	7.95
X2	0	4	6	2	3	5	4	12.00	36.67	32.84	9.48	18.08	55.25	12.00	-0.83	7.93	2.29	-5.32	3.65
C4	3	5	4	0	5	6	1	12.00	65.00	34.25	9.89	45.62	84.38	12.00	3.33	6.51	1.88	-0.35	7.02
C5	0	3	8	1	3	5	3	12.00	33.33	28.71	8.29	17.09	49.58	11.00	0.00	7.75	2.34	-4.58	4.58
C6	1	2	5	4	0	8	4	12.00	30.00	35.68	10.30	9.81	50.19	12.00	-3.33	4.92	1.42	-6.12	-0.55
C7	0	1	6	5	0	6	6	12.00	16.67	22.29	6.44	4.05	29.28	12.00	-5.00	5.22	1.51	-7.95	-2.05
D1	1	5	5	1	3	3	6	12.00	50.00	35.68	10.30	29.81	70.19	12.00	-2.50	8.66	2.50	-7.40	2.40
D2	2	5	5	0	2	5	5	12.00	58.33	34.60	9.99	38.76	77.91	12.00	-2.50	7.54	2.18	-6.76	1.76
D1/2/a	7	5	0	0	8	4	0	12.00	91.67	10.30	2.97	85.84	97.49	12.00	6.67	4.92	1.42	3.88	9.45
D3	5	5	2	0	5	5	1	12.00	78.33	28.87	8.33	62.00	94.67	11.00	3.64	6.74	2.03	-0.35	7.62
D4	2	7	3	0	5	5	2	12.00	68.33	30.10	8.69	51.30	85.36	12.00	2.50	7.54	2.18	-1.76	6.76
D5	3	5	4	0	4	6	2	12.00	65.00	34.25	9.89	45.62	84.38	12.00	1.67	7.18	2.07	-2.39	5.73
D6	1	4	5	2	7	5	0	12.00	43.33	37.01	10.68	22.39	64.27	12.00	5.83	5.15	1.49	2.92	8.75
D7	0	4	7	1	0	5	7	12.00	38.33	31.29	9.03	20.63	56.03	12.00	-5.83	5.15	1.49	-8.75	-2.92
D8	4	6	2	0	6	6	0	12.00	76.67	28.07	8.10	60.79	92.55	12.00	5.00	5.22	1.51	2.05	7.95
E1	4	6	2	0	6	6	0	12.00	76.67	28.07	8.10	60.79	92.55	12.00	5.00	5.22	1.51	2.05	7.95
E2	0	2	4	6	0	4	8	12.00	20.00	29.54	8.53	3.29	36.71	12.00	-6.67	4.92	1.42	-9.45	-3.88
F1	2	2	6	2	0	6	6	12.00	40.00	38.14	11.01	18.42	61.58	12.00	-5.00	5.22	1.51	-7.95	-2.05
F2	0	4	7	1	8	4	0	12.00	38.33	31.29	9.03	20.63	56.03	12.00	6.67	4.92	1.42	3.88	9.45
F3	3	5	4	0	3	7	2	12.00	65.00	34.25	9.89	45.62	84.38	12.00	0.83	6.69	1.93	-2.95	4.62
F4	0	1	5	6	0	3	9	12.00	15.00	22.76	6.57	2.12	27.88	12.00	-7.50	4.52	1.31	-10.06	-4.94
F5	3	7	2	0	10	2	0	12.00	75.00	27.14	7.83	59.65	90.35	12.00	8.33	3.89	1.12	6.13	10.54
G1	2	7	3	0	7	5	0	12.00	68.33	30.10	8.69	51.30	85.36	12.00	5.83	5.15	1.49	2.92	8.75
G2	0	6	6	0	6	5	1	12.00	50.00	31.33	9.05	32.27	67.73	12.00	4.17	6.69	1.93	0.38	7.95
G3	1	4	5	2	2	6	4	12.00	43.33	37.01	10.68	22.39	64.27	12.00	-1.67	7.18	2.07	-5.73	2.39
G4	2	4	4	2	4	6	2	12.00	50.00	39.54	11.42	27.63	72.37	12.00	1.67	7.18	2.07	-2.39	5.73
All HRO	**117.00**	**237.00**	**207.00**	**50.00**				**611.00**	**56.96**	**35.93**	**1.45**	**54.11**	**59.80**						
CBA Av>0	108.00	190.00	124.00	10.00				432.00	**65.93**	**32.95**	**1.59**	**62.82**	**69.03**						
CI95%min>0	66.00	99.00	48.00	3.00				216.00	**71.67**	**30.76**	**2.09**	**67.56**	**75.77**						

Table 61 Statistical analysis of HRO baseline survey in the Regional Water Utility

4.2.2.1 Comparison between HRO survey in the Regional Water Utility and HRO survey with international participants

	Statistical analysis for observed HRO principles in the RWU					Statistical analysis for observed HRO principles in international survey					Significance testing for observed HRO principles						
Ref.	Average	SD	SE	CI 95% min	CI 95% max	Average	SD	SE	CI 95% min	CI 95 % max	H0: X1-X2=0 at SL=5% H1: X1-X2 ≠ 0						
	X1					X2					X1-X2	Var	SE	CI 95% min	CI 95% max	H0	Comment
A1	90.00	10.44	3.02	84.09	95.91	78.46	27.64	7.67	63.43	93.49	11.54	67.87	8.24	-16.15	16.15	Accept	
A2	63.33	32.84	9.48	44.75	81.92	78.33	19.92	5.75	67.06	89.61	-15.00	122.98	11.09	-21.74	21.74	Accept	
A3	92.73	10.09	3.04	86.76	98.69	80.00	20.89	6.03	68.18	91.82	12.73	45.62	6.75	-13.24	13.24	Accept	
A4	93.33	9.85	2.84	87.76	98.90	85.00	22.76	6.57	72.12	97.88	8.33	51.26	7.16	-14.03	14.03	Accept	
A5	88.33	10.30	2.97	82.51	94.16	83.33	22.29	6.44	70.72	95.95	5.00	50.25	7.09	-13.89	13.89	Accept	
A6	61.67	31.29	9.03	43.97	79.37	61.67	31.29	9.03	43.97	79.37	0.00	163.13	12.77	-25.03	25.03	Accept	
A7	43.33	37.01	10.68	22.39	64.27	73.33	26.05	7.52	58.59	88.07	-30.00	170.71	13.07	-25.61	25.61	Reject	X1<<X2
A8	26.67	33.39	9.64	7.77	45.56	16.67	7.78	2.25	12.26	21.07	10.00	97.98	9.90	-19.40	19.40	Accept	
A8a	70.00	31.33	9.05	52.27	87.73	83.33	7.78	2.25	78.93	87.74	-13.33	86.87	9.32	-18.27	18.27	Accept	
A9	45.00	35.29	10.19	25.03	64.97	51.67	33.53	9.68	32.70	70.64	-6.67	197.47	14.05	-27.54	27.54	Accept	
A10	66.67	35.51	10.25	46.58	86.76	88.33	10.30	2.97	82.51	94.16	-21.67	113.89	10.67	-20.92	20.92	Reject	X1<<X2
B1	66.67	35.51	10.25	46.58	86.76	80.00	20.89	6.03	68.18	91.82	-13.33	141.41	11.89	-23.31	23.31	Accept	
B2	70.00	31.33	9.05	52.27	87.73	62.67	31.95	8.25	46.50	78.84	7.33	149.88	12.24	-24.00	24.00	Accept	
B3	71.67	32.43	9.36	53.32	90.01	65.71	30.81	8.24	49.57	81.86	5.95	155.44	12.47	-24.44	24.44	Accept	
X1	41.67	34.60	9.99	22.09	61.24	60.00	34.11	9.85	40.70	79.30	-18.33	196.72	14.03	-27.49	27.49	Accept	
X2	56.67	32.84	9.48	38.08	75.25	61.67	31.29	9.03	43.97	79.37	-5.00	171.46	13.09	-25.67	25.67	Accept	
X3	86.67	23.09	6.67	73.60	99.73	86.67	23.09	6.67	73.60	99.73	0.00	88.89	9.43	-18.48	18.48	Accept	
B4	60.00	36.18	10.44	39.53	80.47	53.33	33.39	9.64	34.44	72.23	6.67	202.02	14.21	-27.86	27.86	Accept	
B5	48.33	35.63	10.29	28.17	68.49	63.33	37.01	10.68	42.39	84.27	-15.00	219.95	14.83	-29.07	29.07	Accept	
B6	49.23	33.28	9.23	31.14	67.32	36.67	32.84	9.48	18.08	55.25	12.56	175.11	13.23	-25.94	25.94	Accept	
B7	27.27	27.24	8.21	11.18	43.37	44.29	32.51	8.69	27.25	61.32	-17.01	142.95	11.96	-23.43	23.43	Accept	
B8	36.67	32.84	9.48	18.08	55.25	53.33	33.39	9.64	34.44	72.23	-16.67	182.83	13.52	-26.50	26.50	Accept	
C1	81.67	21.67	6.26	69.40	93.93	61.67	31.29	9.03	43.97	79.37	20.00	120.71	10.99	-21.53	21.53	Accept	
C2	63.33	32.84	9.48	44.75	81.92	58.46	32.11	8.90	41.01	75.91	4.87	169.19	13.01	-25.49	25.49	Accept	

C3	50.00	35.68	10.30	29.81	70.19	67.69	27.74	7.69	52.62	82.77	-17.69	165.23	12.85	-25.19	25.19	Accept	
X1	61.67	31.29	9.03	43.97	79.37	55.71	32.51	8.69	38.68	72.75	5.95	157.08	12.53	-24.56	24.56	Accept	
X2	36.67	32.84	9.48	18.08	55.25	65.45	29.79	8.98	47.85	83.06	-28.79	170.56	13.06	-25.60	25.60	Reject	X1<<X2
C4	65.00	34.25	9.89	45.62	84.38	56.67	32.84	9.48	38.08	75.25	8.33	187.63	13.70	-26.85	26.85	Accept	
C5	33.33	28.71	8.29	17.09	49.58	75.00	17.32	5.00	65.20	84.80	-41.67	93.69	9.68	-18.97	18.97	Reject	X1<<X2
C6	30.00	35.68	10.30	9.81	50.19	52.86	32.92	8.80	35.61	70.10	-22.86	183.45	13.54	-26.55	26.55	Accept	
C7	16.67	22.29	6.44	4.05	29.28	16.67	7.78	2.25	12.26	21.07	0.00	46.46	6.82	-13.36	13.36	Accept	
D1	50.00	35.68	10.30	29.81	70.19	33.85	26.31	7.30	19.54	48.15	16.15	159.32	12.62	-24.74	24.74	Accept	
D2	58.33	34.60	9.99	38.76	77.91	43.08	30.38	8.43	26.56	59.59	15.26	170.75	13.07	-25.61	25.61	Accept	
D1/2/a	91.67	10.30	2.97	85.84	97.49	72.31	31.13	8.63	55.38	89.23	19.36	83.39	9.13	-17.90	17.90	Reject	X1>>X2
D3	78.33	28.87	8.33	62.00	94.67	54.29	30.81	8.24	38.14	70.43	24.05	137.26	11.72	-22.96	22.96	Reject	X1>>X2
D4	68.33	30.10	8.69	51.30	85.36	55.00	39.20	11.32	32.82	77.18	13.33	203.54	14.27	-27.96	27.96	Accept	
D5	65.00	34.25	9.89	45.62	84.38	40.00	29.54	8.53	23.29	56.71	25.00	170.45	13.06	-25.59	25.59	Accept	
D6	43.33	37.01	10.68	22.39	64.27	62.86	28.13	7.52	48.12	77.59	-19.52	170.66	13.06	-25.60	25.60	Accept	
D7	38.33	31.29	9.03	20.63	56.03	18.33	21.67	6.26	6.07	30.60	20.00	120.71	10.99	-21.53	21.53	Accept	
D8	76.67	28.07	8.10	60.79	92.55	52.73	36.08	10.88	31.40	74.05	23.94	184.00	13.56	-26.59	26.59	Accept	
E1	76.67	28.07	8.10	60.79	92.55	51.67	41.30	11.92	28.30	75.04	25.00	207.83	14.42	-28.26	28.26	Accept	
E2	20.00	29.54	8.53	3.29	36.71	45.00	35.29	10.19	25.03	64.97	-25.00	176.52	13.29	-26.04	26.04	Accept	
F1	40.00	38.14	11.01	18.42	61.58	36.92	30.38	8.43	20.41	53.44	3.08	192.22	13.86	-27.17	27.17	Accept	
F2	38.33	31.29	9.03	20.63	56.03	56.67	32.84	9.48	38.08	75.25	-18.33	171.46	13.09	-25.67	25.67	Accept	
F3	65.00	34.25	9.89	45.62	84.38	50.00	37.66	10.87	28.69	71.31	15.00	215.91	14.69	-28.80	28.80	Accept	
F4	15.00	22.76	6.57	2.12	27.88	41.67	32.43	9.36	23.32	60.01	-26.67	130.81	11.44	-22.42	22.42	Reject	X1<<X2
F5	75.00	27.14	7.83	59.65	90.35	73.85	25.01	6.94	60.25	87.44	1.15	109.49	10.46	-20.51	20.51	Accept	
G1	68.33	30.10	8.69	51.30	85.36	71.43	29.05	7.76	56.21	86.65	-3.10	135.79	11.65	-22.84	22.84	Accept	
G2	50.00	31.33	9.05	32.27	67.73	53.85	36.86	10.22	33.81	73.89	-3.85	186.35	13.65	-26.76	26.76	Accept	
G3	43.33	37.01	10.68	22.39	64.27	48.33	33.53	9.68	29.36	67.30	-5.00	207.83	14.42	-28.26	28.26	Accept	
G4	50.00	39.54	11.42	27.63	72.37	53.33	37.50	10.82	32.12	74.55	-3.33	247.47	15.73	-30.83	30.83	Accept	

Table 62 Significance test for observed HRO principles comparing the Regional Water Utility with the HRO survey in the pilot study

4.2.2.2 Cost benefit analysis for HRO principles in the Regional Water Utility

In the following Table 63 to Table 68 those HRO principles are presented for which the average of the cost benefit analysis exceeding the value zero. In other words, the participants in the survey evaluated these particular HRO indicators to have an average positive cost benefit for effectively contributing to the safety and reliability of drinking water supply. For these HRO indicators, the combined observations by the survey participants for their utilities are presented. The aggregated observation of these HRO principles in the table reflect whether the participants observed these principles being implemented or maintain in their organisations.

Ref	Description	Observable in the organisation			
CBA: Av>=0		Strongly agree	Agree	Disagree	Strongly disagree
Organisational culture of reliability					
A1	In my organisation, staff in operations have a strong sense for the primary mission of the organisation and share a common system of beliefs and perceptions.	6	6	0	0
A2	In my organisation, the water supply system is continuously monitoring so that failure events are foreseen and understood.	2	6	4	0
A3	In my organisation, our staff in operations have a highly developed understanding of their contribution to water safety and their role in the system.	7	4	0	0
A4	In a water quality incident, our staff in operations act in a collaborative and collegiate manner and the group interaction can be described as collective intelligent interaction.	8	4	0	0
A5	Our staff in operations are sensitive towards all events where water supply reliability is concerned. Staff know that a very small initial moment of inattention or misperception can lead to an escalation of failure, which can result in a water quality incident.	5	7	0	0
A6	All our employees take responsibility where problems are identified and immediate corrective action programmes are required.	1	7	4	0
A7	Our staff in operations are obliged to report their mistakes without fear of punishment.	1	4	5	2
A8a	Our senior management is committed to the reliability of the organisation. This is communicated to all levels in the organisation and demonstrated with investments in technology, processes and personnel.	3	6	3	0
A9	In our organisation, individuals "monitor, advise, criticize and support" each other, in particular in situations where mistakes are more likely to occur.	1	4	6	1
A10	In general, our staff are attentive, alert and act with care.	4	4	4	0

Table 63 HRO principles with a positive cost benefit in the Regional Water Utility

Ref.	Description	Observable in the organisations			
	Average CBA >0	Strongly agree	Agree	Disagree	Strongly disagree
Continuous learning and intensive training					
B1	In order to facilitate continuous learning and intensive training, our organisation constantly reviews their processes and ways of operating.	4	4	4	0
B2	In preparation for a job, our staff in operations and maintenance staff receive training on the requirements of maintaining a safe system. These are embedded in formal rules, general guidelines and standardised frameworks.	3	6	3	0
B3	Our staff in operations must adhere to standard operating procedures but also pro-actively identify potential sources of failure and actions to stop faults from escalating.	4	5	3	0
X2	In unforeseen situations, staff in operations don't follow rules blindly, but negotiate the course of action in a collegial manner with more experienced staff and supervisors.	1	6	5	0
X3	During a water quality incident, staff in operations establish an emergency response team for joint decision making in order to avoid overlooking complex circumstances.	7	4	1	0
B4	All our staff maintain a commitment to continuous learning and seek the acquisition and improvement of skills.	3	4	5	0
B6	In our organisation, even minor errors and incidents provide a source for learning which are assessed through root cause analysis.	1	5	7	0

Table 64 HRO principles with a positive cost benefit in the Regional Water Utility (continued)

Ref.		Observable in the organisations			
	Average CBA >0	Strongly agree	Agree	Disagree	Strongly disagree
Effective and varied patterns of communication					
C1	Our communication system makes our water supply system better understandable, predictable and controllable.	4	7	1	0
C2	Our organisation operates in an information rich environment. All processes are measured and understood. Data are transparent and made available to all.	2	6	4	0
C3	Our staff in operations are encouraged to share their experiences relating to the reliability of the system. Communication is designed as bottom up and top down to ensure rapid flow of information through the hierarchy of the system. Rapid dissemination of information helps the organisation to respond to water quality incidents with corrective action aiming to prevent the escalation of failure.	1	5	5	1
X1	During a water quality incident, the response team maintains “closed loop” communication with all stakeholders within the organisation	1	7	4	0
C4	In our organisation, communicating information shapes the ‘big picture’ of our organisational vision, mission and responsibility of individuals towards reliability.	3	5	4	0
C5	Our organisation uses various channels to transmit different types data and information relating to monitoring and control of our assets (and ultimately water safety). Direct and complementary information enhance information reliability and provides a form of redundancy.	0	3	8	1

Table 65 HRO principles with a positive cost benefit in the Regional Water Utility (continued)

Ref.	Description	Observable in the organisations			
	Average CBA >0	Strongly agree	Agree	Disagree	Strongly disagree
Adaptable decision making dynamics and flexible organisational structures					
D1/2a	In our organisation, centralisation at collective level coexists with decentralisation at individual level. The organisation exhibits an adaptive, flexible or organic nature.	7	5	0	0
D3	Our organisation enforces the stringent adherence to standard operating procedures aiming for repeatability of action and routines.	5	5	2	0
D4	Our standard operating procedures are constantly updated and incorporate lessons learnt. Formal rules and procedures are effective elements to identify and control risk.	2	7	3	0
D5	In our organisation, activities, which are not defined in standard operating procedures, are based on decisions a most senior individual makes, as they should have the best knowledge of the system.	3	5	4	0
D6	Our organisation has a hierarchical structure for decision making which reflects expertise, know-how and seniority. Each level has controls and regulating mechanisms.	1	4	5	2
D8	Our decision-making processes have slack in-built in order to assess and challenge decisions to avoid faulty decisions to escalate into failure.	4	6	2	0

Table 66 HRO principles with a positive cost benefit in the Regional Water Utility (continued)

Ref	Description	Observable in the organisations			
	Average CBA >0	Strongly agree	Agree	Disagree	Strongly disagree
System and human redundancy					
E1	Our organisation maintains reserve capacity in the system. This includes back-up functions, overlapping tasks and responsibilities.	4	6	2	0
Precise procedures in managing technology					
F2	In water supply systems design, our organisation aims to simplify complex technical systems and avoid unnecessary automation.	0	4	7	1
F3	New technology acquisition is only justified if existing equipment does not perform to required specification.	3	5	4	0
F5	In our organisation, maintenance activity and protocols as well as performance data are used to monitor the healthy operation of the system.	3	7	2	0

Table 67 HRO principles with a positive cost benefit in the Regional Water Utility (continued)

Ref.	Description	Observable in the organisations			
	Average CBA >0	Strongly agree	Agree	Disagree	Strongly disagree
Human resource management practices that support reliability					
G1	In recruitment and selection, our organisation acquires suitable and skilled candidates for the jobs aiming to match the complexity of the environment with an equally complex set of people to understand the system. Diverging backgrounds for staff offer different ways of looking at systems.	2	7	3	0
G2	Since most people do what is rewarded, our organisation remunerates reliability with incentives, recognition and career opportunities.	0	6	6	0
G4	Our organisation has systems in place to monitor the behaviour of staff.	2	4	4	2

Table 68 HRO principles with a positive cost benefit in the Regional Water Utility (continued)

It can be identified that the number of HRO principles has reduced from 51 HRO principles in the HRO framework to 36 HRO principles with an average, positive cost benefit. In 27 of the 36 HRO principles, i.e. 75%, the majority of respondents ‘strongly agree’ or ‘agree’ to having observed the stated HRO principle in their organisation

In the statistical analysis of the cost benefit data a 95% confidence interval was constructed. In addition to the HRO principles identified with an average positive for the cost benefit, those HRO principles were identified for which the minimum confidence interval exceeds zero. In other words, those HRO principles have a 97.5% chance to have a positive cost beneficial effect for the management of safe and reliable drinking water.

Here, HRO indicators are presented were the minimum confidence interval for cost benefit analysis exceeds the value zero. For these HRO indicators, the combined observations by the survey participants for their utilities are presented. The aggregated observation of these HRO principles in the table reflect whether the participants observed these principles being implemented or maintain in their organisation.

Ref	Description	Observable in the organisation			
Cost Beneficial at CI 95% min >0		Strongly agree	Agree	Disagree	Strongly disagree
Organisational culture of reliability					
A1	In my organisation, staff in operations have a strong sense for the primary mission of the organisation and share a common system of beliefs and perceptions.	6	6	0	0
A3	In my organisation, our staff in operations have a highly developed understanding of their contribution to water safety and their role in the system.	7	4	0	0
A4	In a water quality incident, our staff in operations act in a collaborative and collegiate manner and the group interaction can be described as collective intelligent interaction.	8	4	0	0
A5	Our staff in operations are sensitive towards all events where water supply reliability is concerned. Staff know that a very small initial moment of inattention or misperception can lead to an escalation of failure, which can result in a water quality incident.	5	7	0	0
A8a	Our senior management is committed to the reliability of the organisation. This is communicated to all levels in the organisation and demonstrated with investments in technology, processes and personnel.	3	6	3	0

Table 69 HRO principles with a significantly positive cost benefit in the Regional Water Utility

Ref.	Description	Observable in the organisations			
	Cost Beneficial at CI 95% min >0	Strongly agree	Agree	Disagree	Strongly disagree
Continuous learning and intensive training					
B2	In preparation for a job, our staff in operations and maintenance staff receive training on the requirements of maintaining a safe system. These are embedded in formal rules, general guidelines and standardised frameworks.	3	6	3	0
B3	Our staff in operations must adhere to standard operating procedures but also pro-actively identify potential sources of failure and actions to stop faults from escalating.	4	5	3	0
X3	During a water quality incident, staff in operations establish an emergency response team for joint decision making in order to avoid overlooking complex circumstances.	7	4	1	0
B6	In our organisation, even minor errors and incidents provide a source for learning which are assessed through root cause analysis.	1	5	7	0
Effective and varied patterns of communication					
X1	During a water quality incident, the response team maintains “closed loop” communication with all stakeholders within the organisation	1	7	4	0

Table 70 HRO principles with a significantly positive cost benefit in the Regional Water Utility (continued)

Ref.	Description	Observable in the organisations			
	Cost Beneficial at CI 95% min >0	Strongly agree	Agree	Disagree	Strongly disagree
Adaptable decision making dynamics and flexible organisational structures					
D1/2a	In our organisation, centralisation at collective level coexists with decentralisation at individual level. The organisation exhibits an adaptive, flexible or organic nature.	7	5	0	0
D6	Our organisation has a hierarchical structure for decision making which reflects expertise, know-how and seniority. Each level has controls and regulating mechanisms.	1	4	5	2
D8	Our decision-making processes have slack in-built in order to assess and challenge decisions to avoid faulty decisions to escalate into failure.	4	6	2	0
System and human redundancy					
E1	Our organisation maintains reserve capacity in the system. This includes back-up functions, overlapping tasks and responsibilities.	4	6	2	0
Precise procedures in managing technology					
F2	In water supply systems design, our organisation aims to simplify complex technical systems and avoid unnecessary automation.	0	4	7	1
F5	In our organisation, maintenance activity and protocols as well as performance data are used to monitor the healthy operation of the system.	3	7	2	0
Human resource management practices that support reliability					
G1	In recruitment and selection, our organisation acquires suitable and skilled candidates for the jobs aiming to match the complexity of the environment with an equally complex set of people to understand the system. Diverging backgrounds for staff offer different ways of looking at systems.	2	7	3	0
G2	Since most people do what is rewarded, our organisation remunerates reliability with incentives, recognition and career opportunities.	0	6	6	0

Table 71 HRO principles with a significantly positive cost benefit in the Regional Water Utility (continued)

It can be seen that the number of HRO principles that are considered to have a 97.5% chance of being cost beneficial has significantly reduced to 18 in comparison to the initial HRO framework of 51 HRO principles.

For 14 out of 18 HRO principles, i.e. 77%, it can be identified that the majority of responses ‘strongly agree’ or ‘agree’ to having observed the stated HRO principle in their organisation. This is higher in comparison to the entire HRO framework or the HRO principles with an average positive cost benefit.

4.2.3 Correlating the impact of incidents in the Regional Water Utility with documented HRO principles

In this study, documented incidents were investigated and evidence for HRO principles sought. For each incident, a HRO survey form was completed (Appendix 5.3.2) In the following figures, the individual groups of HRO principles are correlated with the impact of incidents. These HRO groups were previously identified as

- ‘Organisational culture of reliability (A)’,
- ‘Continuous learning and intensive training (B)’,
- ‘Effective and varied patterns of communication (C)’,
- ‘Adaptable decision making dynamics and flexible organisational structures (D)’,
- ‘System and human redundancy (E)’,
- ‘Precise procedures in managing technology (F)’, and
- ‘Human resource management practices that support reliability (G)’.

The case studies were drawn from the documented incidents identified in Table 72 to Table 74.

					Score			
Date of Incident	**HRO study**	**Population (actual affected)**	**Duration (hr)**	**Hazard category**	**P**	**H**	**D**	**Sum**
11/05/2004	**Y**	250	48	Biological pathogens present, health effects envisaged	2.00	64.00	16.00	27.31
03/06/2004		75	72	Biological pathogens present, health effects envisaged	2.00	64.00	16.00	27.31
14/08/2004	**Y**	10	48	Biological pathogens present, health effects envisaged	2.00	64.00	16.00	27.31
30/07/2004		4	8	Biological pathogens present, health effects envisaged	2.00	64.00	2.00	22.64
05/08/2004	**Y**	85	8	Potential biological pathogens present, health effects envisaged	2.00	48.00	2.00	17.32
01/04/2004		2776	48	Aesthetics above guidelines	2.00	32.00	16.00	16.65
09/04/2004		1697	48	Aesthetics above guidelines	2.00	32.00	16.00	16.65
16/04/2004		200	48	Aesthetics above guidelines	2.00	32.00	16.00	16.65
25/09/2004		30,000	11	Aesthetics above guidelines	16.00	32.00	2.00	16.65
07/12/2004	**Y**	11669	24	Aesthetics above guidelines	4.00	32.00	8.00	14.65
18/12/2004	**Y**	7743	24	Aesthetics above guidelines	4.00	32.00	8.00	14.65
18/09/2004		2800	24	Aesthetics above guidelines	2.00	32.00	8.00	13.99
25/01/2004		7600	12	Aesthetics above guidelines	4.00	32.00	4.00	13.32
10/02/2004		8595	9	Aesthetics above guidelines	4.00	32.00	2.00	12.65
03/09/2004		213	15	Aesthetics above guidelines	2.00	32.00	4.00	12.65
10/02/2004	**Y**	1400	8	Aesthetics above guidelines	2.00	32.00	2.00	11.99
19/03/2004		2574	4	Aesthetics above guidelines	2.00	32.00	2.00	11.99
31/03/2004		4129	3	Aesthetics above guidelines	2.00	32.00	2.00	11.99
24/04/2004		2530	2	Aesthetics above guidelines	2.00	32.00	2.00	11.99
08/06/2004		4226	3	Aesthetics above guidelines	2.00	32.00	2.00	11.99
14/06/2004		5200	8	Aesthetics above guidelines	2.00	32.00	2.00	11.99
20/08/2004		3207	6	Aesthetics above guidelines	2.00	32.00	2.00	11.99
22/08/2004	**Y**	4661	8	Aesthetics above guidelines	2.00	32.00	2.00	11.99
15/09/2004	**Y**	985	2	Aesthetics above guidelines	2.00	32.00	2.00	11.99
28/09/2004		1,079	5	Aesthetics above guidelines	2.00	32.00	2.00	11.99
16/04/2004		200	48	Loss of supply	2.00	16.00	16.00	11.32
25/09/2004		30000	11	Loss of supply	16.00	16.00	2.00	11.32
01/01/2004		100	24	Loss of supply	2.00	16.00	8.00	8.66

03/03/2004		3000	27	Loss of supply	2.00	16.00	8.00	8.66
02/06/2004		1900	24	Loss of supply	2.00	16.00	8.00	8.66
27/08/2004		500	25	Loss of supply	2.00	16.00	8.00	8.66
25/01/2004		1100	12	Loss of supply	2.00	16.00	4.00	7.33
19/05/2004		600	12	Loss of supply	2.00	16.00	4.00	7.33
13/06/2004		86	16	Loss of supply	2.00	16.00	4.00	7.33
01/10/2004		246	12	Loss of supply	2.00	16.00	4.00	7.33
16/10/2004		1430	12	Loss of supply	2.00	16.00	4.00	7.33
17/02/2004		22	10	Loss of supply	2.00	16.00	2.00	6.66
19/03/2004		2574	4	Loss of supply	2.00	16.00	2.00	6.66
20/07/2004		6000	11	Loss of supply	2.00	16.00	2.00	6.66
27/07/2004		975	6	Loss of supply	2.00	16.00	2.00	6.66
07/08/2004		80	10	Loss of supply	2.00	16.00	2.00	6.66
28/09/2004		1079	5	Loss of supply	2.00	16.00	2.00	6.66
27/10/2004		300	6	Loss of supply	2.00	16.00	2.00	6.66
11/11/2004		1402	6	Loss of supply	2.00	16.00	2.00	6.66
20/11/2004		500	6	Loss of supply	2.00	16.00	2.00	6.66
01/12/2004		3500	8	Loss of supply	2.00	16.00	2.00	6.66
23/12/2004		20	6	Loss of supply	2.00	16.00	2.00	6.66
30/12/2004		974	8	Loss of supply	2.00	16.00	2.00	6.66
16/05/2004	**Y**	0	1	Chemicals present above guidelines	2.00	8.00	2.00	4.00
29/07/2004	**Y**	5000	4	Chemicals present above guidelines	2.00	8.00	2.00	4.00
07/09/2004	**Y**	0	8	Chemicals present above guidelines	2.00	8.00	2.00	4.00
20/04/2004		0	1	Potential biological pathogens present	2.00	6.00	2.00	3.33
28/05/2004	**Y**	0	8	Potential biological pathogens present	2.00	6.00	2.00	3.33
13/08/2004		0	1	Potential biological pathogens present	2.00	6.00	2.00	3.33
Average								**10.85**
SD								**5.82**
SE								**0.79**
CI95%min								**9.30**
CI95%max								**12.41**

Table 72 Selected, documented incidents in 2004 for HRO study

					Score			
Date of Incident	HRO study	Population (actual affected)	Duration (hr)	Hazard category	P	H	D	Sum
08/01/2005		4679000	48	Loss of supply	500.00	16.00	16.00	177.16
25/08/2005	Y	76	48	Biological pathogens present, health effects envisaged	2.00	64.00	16.00	27.31
17/06/2005	Y	6	8	Biological pathogens present, health effects envisaged	2.00	64.00	2.00	22.64
12/09/2005	Y	67	8	Biological pathogens present, health effects envisaged	2.00	64.00	2.00	22.64
10/01/2005	Y	122	3	Potential biological pathogens present, health effects envisaged	2.00	48.00	2.00	17.32
25/04/2005		6	8	Potential biological pathogens present, health effects envisaged	2.00	48.00	2.00	17.32
05/05/2005	Y	28	8	Potential biological pathogens present, health effects envisaged	2.00	48.00	2.00	17.32
20/06/2005		21	8	Potential biological pathogens present, health effects envisaged	2.00	48.00	2.00	17.32
29/06/2005	Y	100	8	Potential biological pathogens present, health effects envisaged	2.00	48.00	2.00	17.32
18/03/2005		10,000	24	Aesthetics above guidelines	4.00	32.00	8.00	14.65
23/05/2005		5,300	24	Aesthetics above guidelines	2.00	32.00	8.00	13.99
19/06/2005	Y	15278	8	Aesthetics above guidelines	8.00	32.00	2.00	13.99
06/09/2005		600	24	Aesthetics above guidelines	2.00	32.00	8.00	13.99
28/11/2005		2700	12	Aesthetics above guidelines	2.00	32.00	4.00	12.65
08/01/2005		6014	4	Aesthetics above guidelines	2.00	32.00	2.00	11.99
09/01/2005	Y	6852	2	Aesthetics above guidelines	2.00	32.00	2.00	11.99
18/01/2005		250	8	Aesthetics above guidelines	2.00	32.00	2.00	11.99
24/05/2005		1800	6	Aesthetics above guidelines	2.00	32.00	2.00	11.99
12/07/2005		700	8	Aesthetics above guidelines	2.00	32.00	2.00	11.99
08/10/2005		7000	5	Aesthetics above guidelines	2.00	32.00	2.00	11.99
18/03/2005		10000	24	Loss of supply	4.00	16.00	8.00	9.32
23/05/2005		5300	24	Loss of supply	2.00	16.00	8.00	8.66
17/09/2005		2100	48	Biological pathogens present	2.00	8.00	16.00	8.66
03/03/2005		100	12	Loss of supply	2.00	16.00	4.00	7.33
16/03/2005		80	15	Loss of supply	2.00	16.00	4.00	7.33
28/11/2005		500	12	Loss of supply	2.00	16.00	4.00	7.33
01/01/2005		500	10	Loss of supply	2.00	16.00	2.00	6.66
10/01/2005		122	3	Loss of supply	2.00	16.00	2.00	6.66

10/03/2005		4150	6	Loss of supply	2.00	16.00	2.00	6.66
25/05/2005		2590	8	Loss of supply	2.00	16.00	2.00	6.66
16/07/2005		1200	6	Loss of supply	2.00	16.00	2.00	6.66
20/09/2005		26	6	Loss of supply	2.00	16.00	2.00	6.66
18/10/2005		1	0.5	Loss of supply	2.00	16.00	2.00	6.66
26/10/2005		3500	8	Loss of supply	2.00	16.00	2.00	6.66
18/11/2005		97	11	Loss of supply	2.00	16.00	2.00	6.66
30/12/2005		1600	6	Loss of supply	2.00	16.00	2.00	6.66
19/01/2005		10	8	Chemicals present above guidelines	2.00	8.00	2.00	4.00
05/04/2005	Y	0	8	Chemicals present above guidelines	2.00	8.00	2.00	4.00
05/08/2005	Y	2	8	Biological pathogens present	2.00	8.00	2.00	4.00
17/11/2005	Y	0	4	Chemicals present above guidelines	2.00	8.00	2.00	4.00
11/12/2005		0	8	Chemicals present above guidelines	2.00	8.00	2.00	4.00
22/12/2005		0	4	Chemicals present above guidelines	2.00	8.00	2.00	4.00
17/11/2005	Y	0	3	Potential biological pathogens present	2.00	6.00	2.00	3.33
Average								**14.42**
SD								**26.04**
Count								**43.00**
SE								**3.97**
CI95%min								**6.6355**
CI95%max								**22.2038**

Table 73 Selected, documented incidents in 2005 for HRO study

					Score			
Date of Incident	HRO review	Population (actual affected)	Duration (hr)	Hazard category	P	H	D	Sum
14/08/2006		60000	48	Chemicals present above guidelines	32.00	8.00	16.00	18.65
10/08/2006		80	8	Potential biological pathogens present, health effects envisaged	2.00	48.00	2.00	17.32
18/07/2006		7000	24	Aesthetics above guidelines	2.00	32.00	8.00	13.99
05/02/2006		9453	2.5	Aesthetics above guidelines	4.00	32.00	2.00	12.65
17/06/2006	Y	9700	6	Aesthetics above guidelines	4.00	32.00	2.00	12.65
28/02/2006	Y	1300	8	Aesthetics above guidelines	2.00	32.00	2.00	11.99
28/03/2006		5439	8	Aesthetics above guidelines	2.00	32.00	2.00	11.99
01/04/2006	Y	2685	6	Aesthetics above guidelines	2.00	32.00	2.00	11.99
14/05/2006		2500	6	Aesthetics above guidelines	2.00	32.00	2.00	11.99
20/09/2006	Y	37000	4	Loss of supply	16.00	16.00	2.00	11.32
24/09/2006		37600	1	Loss of supply	16.00	16.00	2.00	11.32
29/01/2006		3832	48	Chemicals present above guidelines	2.00	8.00	16.00	8.66
05/02/2006		15150	2.5	Loss of supply	8.00	16.00	2.00	8.66
10/02/2006	Y	8000	4	Loss of supply	4.00	16.00	2.00	7.33
30/05/2006	Y	0	12	Loss of supply	2.00	16.00	4.00	7.33
04/06/2006		7500	6	Loss of supply	4.00	16.00	2.00	7.33
18/07/2006		500	18	Loss of supply	2.00	16.00	4.00	7.33
02/12/2006		70	18	Loss of supply	2.00	16.00	4.00	7.33
25/02/2006		7	8	Loss of supply	2.00	16.00	2.00	6.66
14/03/2006		175	8	Loss of supply	2.00	16.00	2.00	6.66
21/04/2006		420	10	Loss of supply	2.00	16.00	2.00	6.66
14/05/2006		10	8	Loss of supply	2.00	16.00	2.00	6.66
09/06/2006		80	6	Loss of supply	2.00	16.00	2.00	6.66
11/06/2006		340	8	Loss of supply	2.00	16.00	2.00	6.66
13/06/2006		300	8	Loss of supply	2.00	16.00	2.00	6.66
16/07/2006		250	6	Loss of supply	2.00	16.00	2.00	6.66
06/08/2006		400	8	Loss of supply	2.00	16.00	2.00	6.66

06/09/2006		1248	8	Loss of supply	2.00	16.00	2.00	6.66
10/10/2006	Y	1000	8	Loss of supply	2.00	16.00	2.00	6.66
25/08/2006	Y	24500	12	Potential biological pathogens present	8.00	6.00	4.00	5.99
04/01/2006	Y	0	24	Chemicals present above guidelines	2.00	8.00	8.00	5.99
17/01/2006	Y	0	8	Chemicals present above guidelines	2.00	8.00	2.00	4.00
22/05/2006	Y	0	6	Chemicals present above guidelines	2.00	8.00	2.00	4.00
17/06/2006	Y	50	8	Biological pathogens present	2.00	8.00	2.00	4.00
03/09/2006		6	8	Chemicals present above guidelines	2.00	8.00	2.00	4.00
16/09/2006		1300	8	Biological pathogens present	2.00	8.00	2.00	4.00
Average								8.47
SD								3.66
Count								36.00
SE								0.61
CI95%min								7.2784
CI95%max								9.6676

Table 74 Selected, documented incidents in 2006 for HRO study

Table 75 to Table 77 summarise the incidents, i.e. the incident impact on customers and the documented HRO principles adhered to prior to and during the incident.

Incident Date	**05/08/2004**	**07/09/2004**	**07/12/2004**	**10/02/2004**	**11/05/2004**	**14/08/2004**	**15/09/2004**	**16/05/2004**	**18/12/2004**	**19/03/2004**	**22/08/2004**	**28/05/2004**	**29/07/2004**
Population	85.00	0.00	11669.00	1400.00	250.00	10.00	985.00	0.00	7743.00	2574.00	4661.00	0.00	5000.00
Duration	8.00	8.00	24.00	8.00	48.00	48.00	2.00	1.00	24.00	4.00	8.00	8.00	4.00
Pop score	2.00	2.00	4.00	2.00	2.00	2.00	2.00	2.00	4.00	2.00	2.00	2.00	2.00
Duration score	2.00	2.00	8.00	2.00	16.00	16.00	2.00	2.00	8.00	2.00	2.00	2.00	2.00
Hazard score	48.00	8.00	32.00	32.00	64.00	64.00	32.00	8.00	32.00	32.00	32.00	6.00	8.00
Impact score	17.32	4.00	14.65	11.99	27.31	27.31	11.99	4.00	14.65	11.99	11.99	3.33	4.00
Comment													
Group A													
Total	800.00	780.00	680.00	700.00	900.00	900.00	800.00	760.00	760.00	800.00	700.00	780.00	780.00
Count	8.00	8.00	7.00	7.00	9.00	9.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Average	100.00	97.50	97.14	100.00	100.00	100.00	100.00	95.00	95.00	100.00	87.50	97.50	97.50
Total Av>0	800.00	780.00	680.00	700.00	900.00	800.00	800.00	760.00	760.00	800.00	700.00	780.00	780.00
Count	8.00	8.00	7.00	7.00	9.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Average	100.00	97.50	97.14	100.00	100.00	100.00	100.00	95.00	95.00	100.00	87.50	97.50	97.50
Total CIMIN>0	500.00	480.00	380.00	400.00	500.00	500.00	500.00	460.00	480.00	500.00	460.00	500.00	480.00
Count	5	5	4	4	5	5	5	5	5	5	5	5	5
Average	100	96	95	100	100	100	100	92	96	100	92	100	96
Group B													
Total	560.00	420.00	420.00	520.00	560.00	640.00	640.00	600.00	460.00	540.00	600.00	500.00	680.00
Count	6.00	8.00	6.00	7.00	6.00	7.00	8.00	7.00	6.00	7.00	9.00	7.00	7.00
Average	93.33	52.50	70.00	74.29	93.33	91.43	80.00	85.71	76.67	77.14	66.67	71.43	97.14
Total Av>0	480.00	380.00	400.00	500.00	560.00	560.00	480.00	500.00	440.00	460.00	500.00	480.00	580.00
Count	5.00	6.00	5.00	6.00	6.00	6.00	6.00	5.00	5.00	6.00	6.00	6.00	6.00
Average	96.00	63.33	80.00	83.33	93.33	93.33	80.00	100.00	88.00	76.67	83.33	80.00	96.67
Total CIMIN>0	300.00	280.00	220.00	340.00	380.00	380.00	360.00	300.00	260.00	360.00	340.00	300.00	380.00
Count	3	4	3	4	4	4	4	3	3	4	4	4	4
Average	100	70	73.33	85	95	95	90	100	86.66	90	85	75	95
Group C													

Total	480.00	460.00	600.00	600.00	520.00	500.00	500.00	600.00	500.00	800.00	440.00	600.00	540.00
Count	5.00	7.00	7.00	7.00	6.00	5.00	5.00	6.00	7.00	8.00	7.00	6.00	8.00
Average	96.00	65.71	85.71	85.71	86.67	100.00	100.00	100.00	71.43	100.00	62.86	100.00	67.50
Total Av>0	380.00	420.00	400.00	440.00	340.00	400.00	400.00	500.00	400.00	600.00	340.00	400.00	500.00
Count	4.00	5.00	4.00	5.00	4.00	4.00	4.00	5.00	5.00	6.00	5.00	4.00	6.00
Average	95.00	84.00	100.00	88.00	85.00	100.00	100.00	100.00	80.00	100.00	68.00	100.00	83.33
Total CIMIN>0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	80.00	100.00	80.00	100.00	100.00
Count	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Average	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	80.00	100.00	80.00	100.00	100.00
Group D													
Total	460.00	380.00	360.00	440.00	700.00	580.00	500.00	440.00	480.00	520.00	440.00	520.00	620.00
Count	5.00	7.00	5.00	6.00	7.00	7.00	7.00	7.00	6.00	7.00	6.00	7.00	9.00
Average	92.00	54.29	72.00	73.33	100.00	82.86	71.43	62.86	80.00	74.29	73.33	74.29	68.89
Total Av>0	460.00	360.00	360.00	440.00	600.00	500.00	480.00	400.00	460.00	500.00	340.00	440.00	440.00
Count	5.00	6.00	5.00	5.00	6.00	6.00	6.00	5.00	5.00	6.00	4.00	6.00	6.00
Average	92.00	60.00	72.00	88.00	100.00	83.33	80.00	80.00	92.00	83.33	85.00	73.33	73.33
Total CIMIN>0	260.00	180.00	260.00	200.00	300.00	300.00	280.00	200.00	280.00	300.00	180.00	220.00	180.00
Count	3.00	3.00	3.00	2.00	3.00	3.00	3.00	2.00	3.00	3.00	2.00	3.00	3.00
Average	86.67	60.00	86.67	100.00	100.00	100.00	93.33	100.00	93.33	100.00	90.00	73.33	60.00
Group E													
Total	80.00	100.00	120.00	80.00	20.00	20.00	80.00	80.00	120.00	120.00	160.00	80.00	100.00
Count	2.00	2.00	2.00	2.00	1.00	1.00	2.00	2.00	2.00	2.00	2.00	1.00	2.00
Average	40.00	50.00	60.00	100.00	20.00	20.00	40.00	40.00	60.00	60.00	80.00	80.00	50.00
Total Av>0	80.00	80.00	100.00	100.00	20.00	20.00	80.00	80.00	100.00	100.00	80.00	80.00	80.00
Count	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Average	80.00	80.00	100.00	100.00	20.00	20.00	80.00	80.00	100.00	100.00	80.00	80.00	80.00
Total CIMIN>0	80.00	80.00	100.00	100.00	20.00	20.00	80.00	80.00	100.00	100.00	80.00	80.00	80.00
Count	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Average	80.00	80.00	100.00	100.00	20.00	20.00	80.00	80.00	100.00	100.00	80.00	80.00	80.00
Group F													
Total	80.00	260.00	140.00	280.00	140.00	180.00	200.00	260.00	200.00	180.00	200.00	180.00	260.00

Count	**3.00**	**4.00**	**4.00**	**4.00**	**3.00**	**4.00**	**3.00**	**3.00**	**4.00**	**3.00**	**4.00**	**2.00**	**4.00**
Average	**26.67**	**65.00**	**35.00**	**70.00**	**46.67**	**45.00**	**66.67**	**86.67**	**50.00**	**60.00**	**50.00**	**90.00**	**65.00**
Total Av>0	**80.00**	**160.00**	**100.00**	**100.00**	**100.00**	**160.00**	**100.00**	**100.00**	**160.00**	**80.00**	**100.00**	**100.00**	**160.00**
Count	**2.00**	**2.00**	**2.00**	**2.00**	**1.00**	**2.00**	**1.00**	**1.00**	**2.00**	**1.00**	**2.00**	**1.00**	**2.00**
Average	**40.00**	**80.00**	**50.00**	**50.00**	**100.00**	**80.00**	**100.00**	**100.00**	**80.00**	**80.00**	**50.00**	**100.00**	**80.00**
Total CIMIN>0	**0.00**	**80.00**	**80.00**	**20.00**	**100.00**	**80.00**	**100.00**	**100.00**	**80.00**	**80.00**	**80.00**	**100.00**	**80.00**
Count	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
Average	**0.00**	**80.00**	**80.00**	**20.00**	**100.00**	**80.00**	**100.00**	**100.00**	**80.00**	**80.00**	**80.00**	**100.00**	**80.00**
Group G													
Total	**360.00**	**280.00**	**280.00**	**260.00**	**300.00**	**280.00**	**220.00**	**320.00**	**200.00**	**320.00**	**180.00**	**300.00**	**260.00**
Count	**4.00**	**4.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**	**4.00**	**3.00**	**4.00**	**3.00**	**4.00**	**4.00**
Average	**90.00**	**70.00**	**93.33**	**86.67**	**100.00**	**93.33**	**73.33**	**80.00**	**66.67**	**80.00**	**60.00**	**75.00**	**65.00**
Total Av>0	**280.00**	**260.00**	**180.00**	**260.00**	**300.00**	**200.00**	**200.00**	**300.00**	**180.00**	**300.00**	**160.00**	**280.00**	**240.00**
Count	**3.00**	**3.00**	**2.00**	**3.00**	**3.00**	**2.00**	**2.00**	**3.00**	**2.00**	**3.00**	**2.00**	**3.00**	**3.00**
Average	**93.33**	**86.67**	**90.00**	**86.67**	**100.00**	**100.00**	**100.00**	**100.00**	**90.00**	**100.00**	**80.00**	**93.33**	**80.00**
Total CIMIN>0	**200.00**	**180.00**	**180.00**	**180.00**	**200.00**	**200.00**	**200.00**	**200.00**	**180.00**	**200.00**	**160.00**	**200.00**	**160.00**
Count	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**	**2.00**
Average	**100.00**	**90.00**	**90.00**	**90.00**	**100.00**	**100.00**	**100.00**	**100.00**	**90.00**	**100.00**	**80.00**	**100.00**	**80.00**
Total Group score													
Total	2820.00	2680.00	2600.00	2880.00	3140.00	3100.00	2940.00	3060.00	2720.00	3280.00	2720.00	2960.00	3240.00
Count	33.00	40.00	34.00	36.00	35.00	36.00	36.00	37.00	36.00	39.00	39.00	35.00	42.00
Average	**85.45**	**67.00**	**76.47**	**80.00**	**89.71**	**86.11**	**81.67**	**82.70**	**75.56**	**84.10**	**69.74**	**84.57**	**77.14**
Total Av>0	2560.00	2440.00	2220.00	2540.00	2820.00	2640.00	2540.00	2640.00	2500.00	2840.00	2220.00	2560.00	2780.00
Count	28.00	31.00	26.00	29.00	30.00	29.00	28.00	28.00	28.00	31.00	28.00	29.00	32.00
Average	91.43	78.71	85.38	87.59	94.00	91.03	90.71	94.29	89.29	91.61	79.29	88.28	86.88
Total CIMIN>0	1440.00	1380.00	1320.00	1340.00	1600.00	1580.00	1620.00	1440.00	1460.00	1640.00	1380.00	1500.00	1460.00
Count	16.00	17.00	15.00	15.00	17.00	17.00	17.00	15.00	16.00	17.00	16.00	17.00	17.00
Average	90.00	81.18	88.00	89.33	94.12	92.94	95.29	96.00	91.25	96.47	86.25	88.24	85.88

Table 75 Incident statistics for HRO survey of incident management, selected incidents in 2004

Date	05/04/2005	05/05/2005	05/08/2005	09/01/2005	10/01/2005	12/09/2005	17/06/2005	17/11/2005	17/11/2005	19/06/2005	25/08/2005	29/06/2005
Pop	0.00	28.00	2.00	6852.00	122.00	67.00	6.00	0.00	0.00	15278.00	76.00	100.00
Duration	8.00	8.00	8.00	2.00	3.00	8.00	8.00	3.00	4.00	8.00	48.00	8.00
Pop score	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	8.00	2.00	2.00
Duration score	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	16.00	2.00
Hazard score	8.00	48.00	8.00	32.00	48.00	64.00	64.00	6.00	8.00	32.00	64.00	48.00
Impact score	4.00	17.32	4.00	11.99	17.32	22.64	22.64	3.33	4.00	13.99	27.31	17.32
Comment									Holm			
Group A												
Total	760.00	700.00	620.00	460.00	400.00	500.00	680.00	860.00	860.00	740.00	820.00	740.00
Count	8.00	8.00	9.00	8.00	8.00	7.00	9.00	9.00	9.00	8.00	9.00	8.00
Average	95.00	87.50	68.89	57.50	50.00	71.43	75.56	95.56	95.56	92.50	91.11	92.50
Total Av>0	760.00	700.00	620.00	460.00	400.00	500.00	680.00	860.00	860.00	740.00	820.00	740.00
Count	8.00	8.00	9.00	8.00	8.00	7.00	9.00	9.00	9.00	8.00	9.00	8.00
Average	95.00	87.50	68.89	57.50	50.00	71.43	75.56	95.56	95.56	92.50	91.11	92.50
Total CIMIN>0	480.00	480.00	420.00	340.00	280.00	320.00	460.00	500.00	500.00	460.00	400.00	460.00
Count	5.00	5.00	5.00	5.00	5.00	4.00	5.00	5.00	5.00	5.00	4.00	5.00
Average	96.00	96.00	84.00	68.00	56.00	80.00	92.00	100.00	100.00	92.00	100.00	92.00
Group B												
Total	800.00	620.00	560.00	520.00	620.00	420.00	580.00	860.00	860.00	520.00	600.00	740.00
Count	10.00	7.00	8.00	7.00	9.00	8.00	9.00	9.00	9.00	6.00	7.00	9.00
Average	80.00	88.57	70.00	74.29	68.89	52.50	64.44	95.56	95.56	86.67	85.71	82.22
Total Av>0	660.00	540.00	520.00	440.00	440.00	400.00	440.00	680.00	680.00	360.00	440.00	640.00
Count	7.00	6.00	6.00	6.00	6.00	7.00	6.00	7.00	7.00	4.00	5.00	7.00
Average	94.29	90.00	86.67	73.33	73.33	57.14	73.33	97.14	97.14	90.00	88.00	91.43
Total CIMIN>0	380.00	380.00	340.00	280.00	280.00	280.00	280.00	380.00	380.00	180.00	260.00	360.00
Count	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	2.00	3.00	4.00
Average	95.00	95.00	85.00	70.00	70.00	70.00	70.00	95.00	95.00	90.00	86.67	90.00
Group C												

Total	500.00	500.00	460.00	140.00	400.00	340.00	440.00	600.00	600.00	540.00	300.00	520.00
Count	9.00	7.00	8.00	7.00	8.00	8.00	7.00	8.00	8.00	7.00	9.00	8.00
Average	55.56	71.43	57.50	20.00	50.00	42.50	62.86	75.00	75.00	77.14	33.33	65.00
Total Av>0	440.00	400.00	360.00	100.00	240.00	240.00	340.00	500.00	500.00	440.00	240.00	420.00
Count	6.00	5.00	6.00	5.00	6.00	6.00	5.00	6.00	6.00	5.00	6.00	6.00
Average	73.33	80.00	60.00	20.00	40.00	40.00	68.00	83.33	83.33	88.00	40.00	70.00
Total CIMIN>0	80.00	80.00	80.00	20.00	20.00	20.00	80.00	100.00	100.00	100.00	20.00	80.00
Count	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Average	80.00	80.00	80.00	20.00	20.00	20.00	80.00	100.00	100.00	100.00	20.00	80.00
Group D												
Total	580.00	620.00	620.00	420.00	460.00	560.00	620.00	620.00	620.00	660.00	680.00	540.00
Count	9.00	8.00	9.00	8.00	8.00	9.00	9.00	8.00	8.00	9.00	9.00	8.00
Average	64.44	77.50	68.89	52.50	57.50	62.22	68.89	77.50	77.50	73.33	75.56	67.50
Total Av>0	460.00	520.00	440.00	320.00	360.00	380.00	440.00	520.00	520.00	480.00	480.00	380.00
Count	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
Average	76.67	86.67	73.33	53.33	60.00	63.33	73.33	86.67	86.67	80.00	80.00	63.33
Total CIMIN>0	260.00	260.00	260.00	140.00	180.00	200.00	240.00	260.00	260.00	240.00	280.00	120.00
Count	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Average	86.67	86.67	86.67	46.67	60.00	66.67	80.00	86.67	86.67	80.00	93.33	40.00
Group E												
Total	80.00	20.00	80.00	20.00	80.00	180.00	100.00	100.00	100.00	100.00	40.00	20.00
Count	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Average	40.00	10.00	40.00	10.00	40.00	90.00	50.00	50.00	50.00	50.00	20.00	10.00
Total Av>0	80.00	20.00	80.00	20.00	80.00	80.00	80.00	100.00	100.00	80.00	20.00	20.00
Count	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Average	80.00	20.00	80.00	20.00	80.00	80.00	80.00	100.00	100.00	80.00	20.00	20.00
Total CIMIN>0	80.00	20.00	80.00	20.00	80.00	80.00	80.00	100.00	100.00	80.00	20.00	20.00
Count	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Average	80.00	20.00	80.00	20.00	80.00	80.00	80.00	100.00	100.00	80.00	20.00	20.00
Group F												
Total	200.00	120.00	260.00	140.00	200.00	100.00	100.00	140.00	140.00	340.00	260.00	80.00

Count	4.00	3.00	4.00	4.00	4.00	2.00	3.00	4.00	4.00	5.00	4.00	1.00
Average	50.00	40.00	65.00	35.00	50.00	50.00	33.33	35.00	35.00	68.00	65.00	80.00
Total Av>0	160.00	20.00	160.00	100.00	100.00	0.00	20.00	100.00	100.00	240.00	160.00	0.00
Count	2.00	1.00	2.00	2.00	2.00	0.00	1.00	2.00	2.00	3.00	2.00	0.00
Average	80.00	20.00	80.00	50.00	50.00	0.00	20.00	50.00	50.00	80.00	80.00	0.00
Total CIMIN>0	80.00	20.00	80.00	20.00	20.00	0.00	20.00	80.00	80.00	160.00	80.00	0.00
Count	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	2.00	1.00	0.00
Average	80.00	20.00	80.00	20.00	20.00	0.00	20.00	80.00	80.00	80.00	80.00	0.00
Group G												
Total	260.00	280.00	140.00	140.00	200.00	260.00	260.00	280.00	280.00	260.00	200.00	260.00
Count	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Average	65.00	70.00	35.00	35.00	50.00	65.00	65.00	70.00	70.00	65.00	50.00	65.00
Total Av>0	240.00	260.00	120.00	120.00	180.00	240.00	240.00	260.00	260.00	240.00	180.00	240.00
Count	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Average	80.00	86.67	40.00	40.00	60.00	80.00	80.00	86.67	86.67	80.00	60.00	80.00
Total CIMIN>0	160.00	180.00	100.00	100.00	160.00	160.00	160.00	180.00	180.00	160.00	160.00	160.00
Count	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Average	80.00	90.00	50.00	50.00	80.00	80.00	80.00	90.00	90.00	80.00	80.00	80.00
Total Group score												
Total	3180.00	2860.00	2740.00	1840.00	2360.00	2360.00	2780.00	3460.00	3460.00	3160.00	2900.00	2900.00
Count	46.00	39.00	44.00	40.00	43.00	40.00	43.00	44.00	44.00	41.00	44.00	40.00
Average	69.13	73.33	62.27	46.00	54.88	59.00	64.65	78.64	78.64	77.07	65.91	72.50
Total Av>0	2800.00	2460.00	2300.00	1560.00	1800.00	1840.00	2240.00	3020.00	3020.00	2580.00	2340.00	2440.00
Count	33.00	30.00	33.00	31.00	32.00	30.00	31.00	34.00	34.00	30.00	32.00	31.00
Average	84.85	82.00	69.70	50.32	56.25	61.33	72.26	88.82	88.82	86.00	73.13	78.71
Total CIMIN>0	1520.00	1420.00	1360.00	920.00	1020.00	1060.00	1320.00	1600.00	1600.00	1380.00	1220.00	1200.00
Count	17.00	17.00	17.00	17.00	17.00	15.00	17.00	17.00	17.00	16.00	15.00	16.00
Average	89.41	83.53	80.00	54.12	60.00	70.67	77.65	94.12	94.12	86.25	81.33	75.00

Table 76 Incident statistics for HRO survey of incident management, selected incidents in 2005

Date of Incident	01/04/2006	04/01/2006	10/02/2006	10/10/2006	17/01/2006	17/06/2006	17/06/2006	20/09/2006	22/05/2006	25/08/2006	28/02/2006	30/05/2006
Population	2685.00	0.00	8000.00	1000.00	0.00	9700.00	50.00	37000.00	0.00	24500.00	1300.00	0.00
Duration	6.00	24.00	4.00	8.00	8.00	6.00	8.00	4.00	6.00	12.00	8.00	12.00
Pop score	2.00	2.00	4.00	2.00	2.00	4.00	2.00	16.00	2.00	8.00	2.00	2.00
Duration score	2.00	8.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	4.00	2.00	4.00
Hazard score	32.00	8.00	16.00	16.00	8.00	32.00	8.00	16.00	8.00	6.00	32.00	16.00
Impact score	11.99	5.99	7.33	6.66	4.00	12.65	4.00	11.32	4.00	5.99	11.99	7.33
Group A	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	20.00	20.00	0.00	20.00
Total	580.00	660.00	680.00	640.00	660.00	620.00	640.00	580.00	420.00	520.00	420.00	480.00
Count	8.00	9.00	9.00	8.00	9.00	7.00	8.00	8.00	11.00	11.00	10.00	10.00
Average	72.50	73.33	75.56	80.00	73.33	88.57	80.00	72.50	38.18	47.27	42.00	48.00
Total Av>0	580.00	660.00	680.00	640.00	660.00	620.00	640.00	580.00	320.00	500.00	320.00	460.00
Count	8.00	9.00	9.00	8.00	9.00	7.00	8.00	8.00	10.00	10.00	9.00	9.00
Average	72.50	73.33	75.56	80.00	73.33	88.57	80.00	72.50	32.00	50.00	35.56	51.11
Total CIMIN>0	400.00	400.00	360.00	400.00	400.00	380.00	400.00	340.00	100.00	340.00	220.00	340.00
Count	5.00	5.00	5.00	5.00	5.00	4.00	5.00	5.00	5.00	5.00	5.00	5.00
Average	80.00	80.00	72.00	80.00	80.00	95.00	80.00	68.00	20.00	68.00	44.00	68.00
Group B	20.00	20.00	0.00		20.00			20.00	20.00	20.00	0.00	20.00
Total	540.00	520.00	660.00	480.00	520.00	720.00	560.00	660.00	260.00	500.00	360.00	600.00
Count	8.00	8.00	10.00	6.00	8.00	8.00	7.00	9.00	8.00	10.00	10.00	9.00
Average	67.50	65.00	66.00	80.00	65.00	90.00	80.00	73.33	32.50	50.00	36.00	66.67
Total Av>0	500.00	480.00	500.00	400.00	480.00	560.00	480.00	480.00	220.00	360.00	320.00	420.00
Count	6.00	6.00	7.00	5.00	6.00	6.00	6.00	6.00	6.00	6.00	7.00	6.00
Average	83.33	80.00	71.43	80.00	80.00	93.33	80.00	80.00	36.67	60.00	45.71	70.00
Total CIMIN>0	340.00	320.00	260.00	240.00	320.00	280.00	320.00	240.00	120.00	260.00	200.00	260.00
Count	4.00	4.00	4.00	3.00	4.00	3.00	4.00	3.00	4.00	4.00	4.00	4.00
Average	85.00	80.00	65.00	80.00	80.00	93.33	80.00	80.00	30.00	65.00	50.00	65.00
Group C						20.00						
Total	200.00	400.00	380.00	400.00	400.00	420.00	400.00	580.00	220.00	180.00	280.00	240.00
Count	8.00	8.00	8.00	8.00	8.00	9.00	8.00	8.00	8.00	7.00	8.00	7.00

Average	25.00	50.00	47.50	50.00	50.00	46.67	50.00	72.50	27.50	25.71	35.00	34.29
Total Av>0	180.00	300.00	360.00	360.00	300.00	360.00	360.00	480.00	180.00	80.00	240.00	240.00
Count	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	5.00	6.00	6.00
Average	30.00	50.00	60.00	60.00	50.00	60.00	60.00	80.00	30.00	16.00	40.00	40.00
Total CIMIN>0	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	20.00	20.00	80.00	80.00
Count	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Average	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	20.00	20.00	80.00	80.00
Group D												
Total	600.00	520.00	620.00	580.00	520.00	540.00	580.00	520.00	360.00	560.00	360.00	520.00
Count	9.00	8.00	9.00	8.00	8.00	9.00	8.00	8.00	9.00	9.00	9.00	8.00
Average	66.67	65.00	68.89	72.50	65.00	60.00	72.50	65.00	40.00	62.22	40.00	65.00
Total Av>0	420.00	420.00	500.00	480.00	420.00	360.00	400.00	420.00	180.00	380.00	180.00	420.00
Count	6.00	6.00	6.00	6.00	6.00	6.00	5.00	6.00	6.00	6.00	6.00	6.00
Average	70.00	70.00	83.33	80.00	70.00	60.00	80.00	70.00	30.00	63.33	30.00	70.00
Total CIMIN>0	240.00	240.00	240.00	240.00	240.00	180.00	240.00	240.00	60.00	180.00	60.00	240.00
Count	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Average	80.00	80.00	80.00	80.00	80.00	60.00	80.00	80.00	20.00	60.00	20.00	80.00
Group E												
Total	0.00	40.00	20.00	20.00	40.00	80.00	20.00	0.00	100.00	20.00	20.00	20.00
Count	2.00	2.00	2.00	1.00	2.00	2.00	1.00	2.00	2.00	2.00	2.00	2.00
Average	0.00	20.00	10.00	20.00	20.00	40.00	20.00	0.00	50.00	10.00	10.00	10.00
Total Av>0	0.00	20.00	20.00	20.00	20.00	80.00	20.00	0.00	80.00	0.00	20.00	0.00
Count	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Average	0.00	20.00	20.00	20.00	20.00	80.00	20.00	0.00	80.00	0.00	20.00	0.00
Total CIMIN>0	0.00	20.00	20.00	20.00	20.00	80.00	20.00	0.00	80.00	0.00	20.00	0.00
Count	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Average	0.00	20.00	20.00	20.00	20.00	80.00	20.00	0.00	80.00	0.00	20.00	0.00
Group F												
Total	100.00	140.00	120.00	120.00	140.00	120.00	240.00	80.00	200.00	140.00	100.00	60.00
Count	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00

Average	25.00	35.00	30.00	30.00	35.00	30.00	60.00	20.00	50.00	35.00	25.00	15.00
Total Av>0	80.00	40.00	80.00	100.00	40.00	40.00	160.00	40.00	100.00	100.00	80.00	20.00
Count	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Average	40.00	20.00	40.00	50.00	20.00	20.00	80.00	20.00	50.00	50.00	40.00	10.00
Total CIMIN>0	0.00	20.00	0.00	20.00	20.00	20.00	80.00	20.00	20.00	20.00	0.00	0.00
Count	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Average	0.00	20.00	0.00	20.00	20.00	20.00	80.00	20.00	20.00	20.00	0.00	0.00
Group G												
Total	260.00	260.00	260.00	260.00	260.00	260.00	260.00	260.00	80.00	140.00	140.00	260.00
Count	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Average	65.00	65.00	65.00	65.00	65.00	65.00	65.00	65.00	20.00	35.00	35.00	65.00
Total Av>0	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	60.00	120.00	120.00	240.00
Count	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Average	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	20.00	40.00	40.00	80.00
Total CIMIN>0	160.00	160.00	160.00	160.00	160.00	160.00	160.00	160.00	40.00	100.00	100.00	160.00
Count	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Average	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	20.00	50.00	50.00	80.00
Total Group score												
Total	2280.00	2540.00	2740.00	2500.00	2540.00	2760.00	2700.00	2680.00	1640.00	2060.00	1680.00	2180.00
Count	43.00	43.00	46.00	39.00	43.00	43.00	40.00	43.00	46.00	47.00	47.00	44.00
Average	53.02	59.07	59.57	64.10	59.07	64.19	67.50	62.33	35.65	43.83	35.74	49.55
Total Av>0	2000.00	2160.00	2380.00	2240.00	2160.00	2260.00	2300.00	2240.00	1140.00	1540.00	1280.00	1800.00
Count	32.00	33.00	34.00	31.00	33.00	31.00	31.00	32.00	34.00	33.00	34.00	33.00
Average	62.50	65.45	70.00	72.26	65.45	72.90	74.19	70.00	33.53	46.67	37.65	54.55
Total CIMIN>0	1220.00	1240.00	1120.00	1160.00	1240.00	1180.00	1300.00	1080.00	440.00	920.00	680.00	1080.00
Count	17.00	17.00	17.00	16.00	17.00	15.00	17.00	16.00	17.00	17.00	17.00	17.00
Average	71.76	72.94	65.88	72.50	72.94	78.67	76.47	67.50	25.88	54.12	40.00	63.53

Table 77 Incident statistics for HRO survey of incident management, selected incidents in 2006

In Figure 21, three data sets are presented: firstly, the incident impact of 36 selected incidents is correlated with the average score for observed HRO principles using all indicators in Group A. The average score is calculated from the 11 HRO principles if sufficient data in the incident documentation was available to score individual HRO principles. Secondly, the incident impact of 36 selected incidents is correlated with the average score for observed HRO principles in Group A using those principles that were previously identified to have an average, positive cost benefit. The average score is calculated from the 10 HRO principles if sufficient data in the incident documentation was available to score individual HRO principles. Thirdly, the incident impact of 36 selected incidents is correlated with the average score for observed HRO principles in Group A using those principles that were previously identified to have a significant cost benefit, i.e. indicators with the minimum confidence interval of 95% exceeding zero. The average score is calculated from the five HRO principles if sufficient data in the incident documentation was available to score individual HRO principles.

It can be identified that all datasets have a positive correlationship between the incident impact on customers and the average score for observed HRO principles.
Considering all HRO principles regardless of their cost benefit, a positive correlation described with y=0.4215x + 77.106 between the incident impact and the average score for observed HRO principles in Group A can be identified. The coefficient of determination R^2=0.0276 explains 2.76% of the variation in the average score for observed HRO principle as a function of the impact scores.
Considering those HRO principles that were previously evaluated with an average, positive cost benefit, a positive correlation described with y=0.4293x + 76.834 between the incident impact and the average score for observed HRO principles in Group A can be identified. The coefficient of determination R^2=0.0269 explains 2.69% of the variation in the average score for observed HRO principles as a function of the impact scores.
Finally, considering those HRO principles that were previously evaluated with a significant positive cost benefit, a positive correlation described with y=0.5379x + 79.194 between the incident impact and the average score for observed HRO principles in Group A can be identified. The coefficient of determination R^2=0.0483 explains

4.83% of the variation in the average score for observed HRO principles as a function of the impact scores.

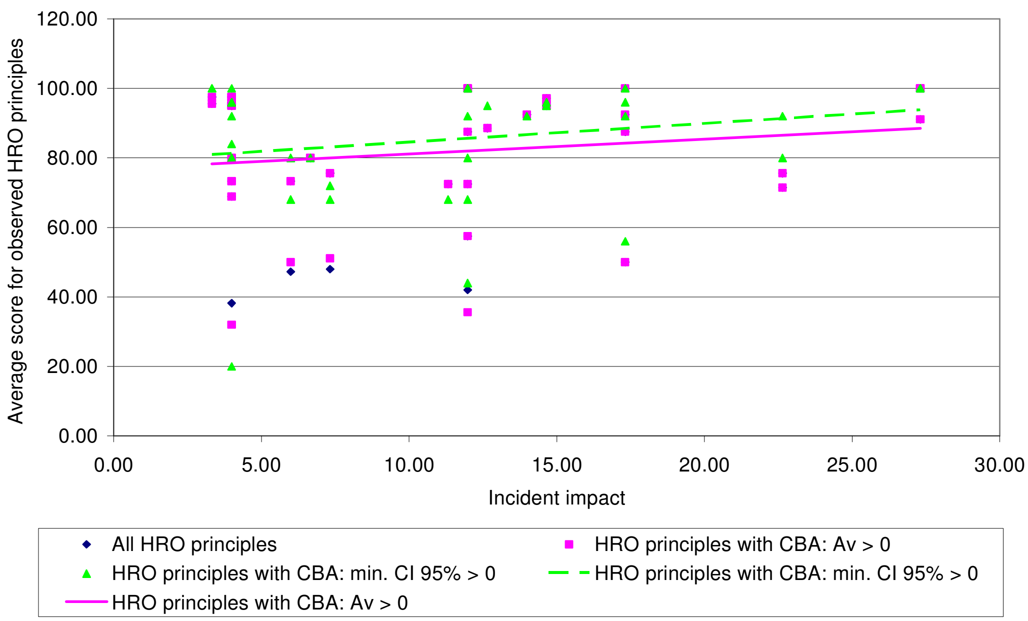

Figure 21 Correlating the incident impact on customers with the average score for observed HRO principles in Group A

In Figure 22, three data sets are presented: firstly, the incident impact of 36 selected incidents is correlated with the average score for observed HRO principles using all indicators in Group B. The average score is calculated from the 11 HRO principles if sufficient data in the incident documentation was available to score individual HRO principles. Secondly, the incident impact of 36 selected incidents is correlated with the average score for observed HRO principles in Group B using those principles that were previously identified to have an average, positive cost benefit. The average score is calculated from the seven HRO principles if sufficient data in the incident documentation was available to score individual HRO principles. Thirdly, the incident impact of 36 selected incidents is correlated with the average score for observed HRO principles in Group B using those principles that were previously identified to have a significant cost benefit, i.e. indicators with the minimum confidence interval of 95% exceeding zero. The average score is calculated from the four HRO principles if sufficient data in the incident documentation was available to score individual HRO principles.

It can be identified that all datasets have a positive correlationship between the incident impact on customers and the average score for observed HRO principles.
Considering all HRO principles regardless of their cost benefit, a positive correlation described with y=0.4059x + 69.571 between the incident impact and the average score for observed HRO principles in Group B can be identified. The coefficient of determination R^2=0.0358 explains 3.58% of the variation in the average score for observed HRO principle as a function of the impact scores.
Considering those HRO principles that were previously evaluated with an average, positive cost benefit, a positive correlation described with y=0.2003x + 78.417 between the incident impact and the average score for observed HRO principles in Group B can be identified. The coefficient of determination R^2=0.0105 explains 1.05% of the variation in the average score for observed HRO principles as a function of the impact scores.
Finally, considering those HRO principles that were previously evaluated with a significant positive cost benefit, a positive correlation described with y=0.3391x + 77.334 between the incident impact and the average score for observed HRO principles in Group B can be identified. The coefficient of determination R^2=0.0286 explains 2.86% of the variation in the average score for observed HRO principles as a function of the impact scores.

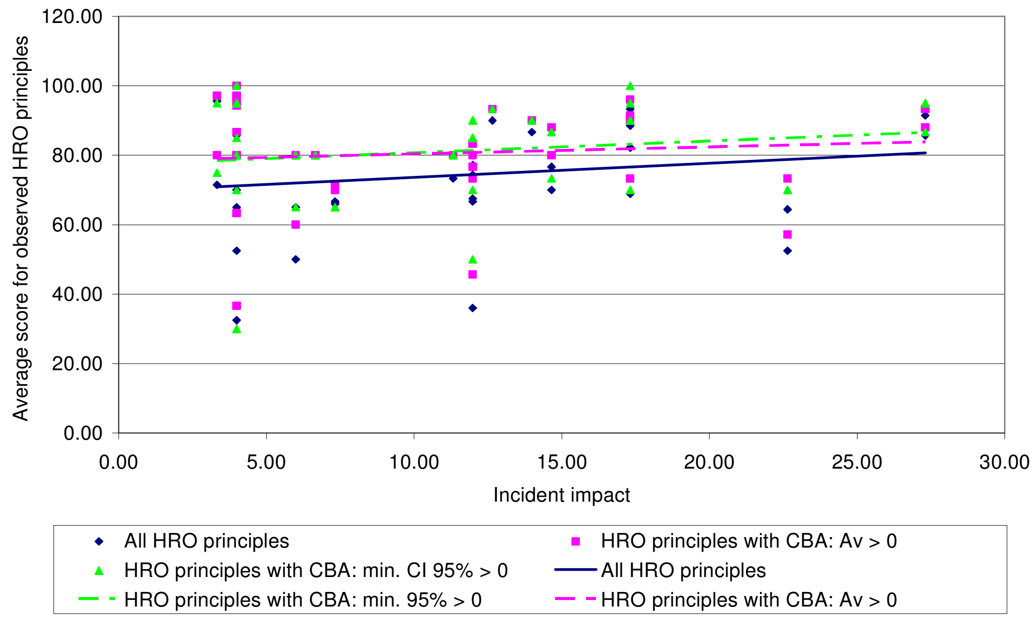

Figure 22 Correlating the incident impact on customers with the average score for observed HRO principles in Group B

In Figure 23, three data sets are presented: firstly, the incident impact of 36 selected incidents is correlated with the average score for observed HRO principles using all indicators in Group C. The average score is calculated from the nine HRO principles if sufficient data in the incident documentation was available to score individual HRO principles. Secondly, the incident impact of 36 selected incidents is correlated with the average score for observed HRO principles in Group C using those principles that were previously identified to have an average, positive cost benefit. The average score is calculated from the six HRO principles if sufficient data in the incident documentation was available to score individual HRO principles. Thirdly, the incident impact of 36 selected incidents is correlated with the average score for observed HRO principles in Group C using those principles that were previously identified to have a significant cost benefit, i.e. indicators with the minimum confidence interval of 95% exceeding zero. The score from the one HRO principles is used if sufficient data in the incident documentation was available to score that individual HRO principle.

It can be identified that all but one dataset have a positive correlationship between the incident impact on customers and the average score for observed HRO principles.

Considering all HRO principles regardless of their cost benefit, a positive correlation described with y=0.4185x + 57.941 between the incident impact and the average score for observed HRO principles in Group C can be identified. The coefficient of determination R^2=0.0164 explains 1.64% of the variation in the average score for observed HRO principle as a function of the impact scores.

Considering those HRO principles that were previously evaluated with an average, positive cost benefit, a positive correlation described with y=0.1848x + 65.596 between the incident impact and the average score for observed HRO principles in Group C can be identified. The coefficient of determination R^2=0.003 explains 0.3% of the variation in the average score for observed HRO principles as a function of the impact scores.

Finally, considering those HRO principles that were previously evaluated with a significant positive cost benefit, a negative correlation described with y=-0.6533x + 85.317 between the incident impact and the score for the observed HRO principle in Group C can be identified. The coefficient of determination R^2=0.00303 explains 0.303% of the variation in the average score for observed HRO principles as a function of the impact scores.

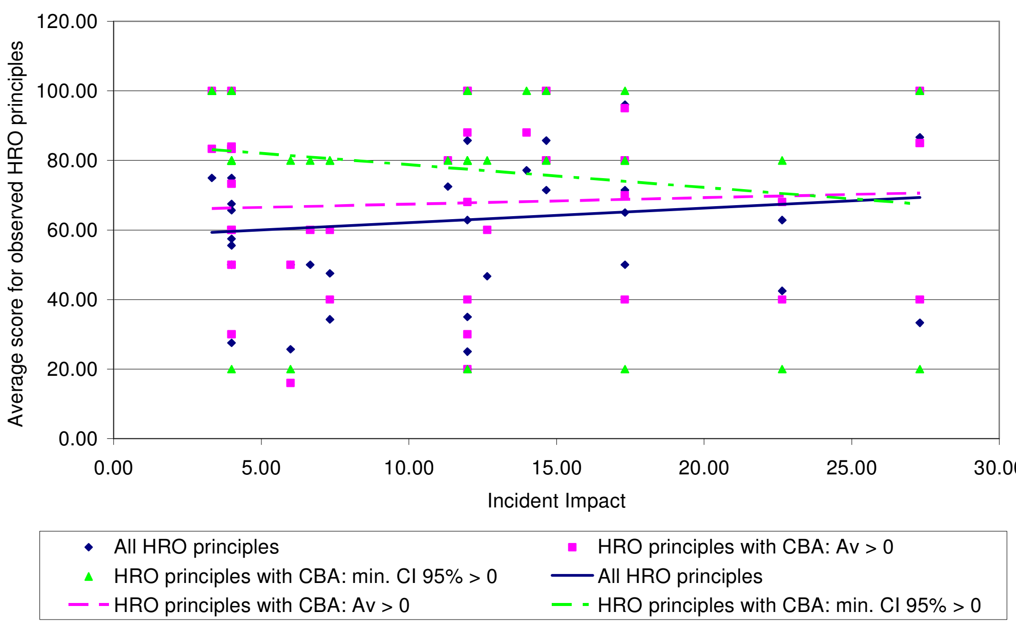

Figure 23 Correlating the incident impact on customers with the average score for observed HRO principles in Group C

In Figure 24, three data sets are presented: firstly, the incident impact of 36 selected incidents is correlated with the average score for observed HRO principles using all indicators in Group D. The average score is calculated from the nine HRO principles if sufficient data in the incident documentation was available to score individual HRO principles. Secondly, the incident impact of 36 selected incidents is correlated with the average score for observed HRO principles in Group D using those principles that were previously identified to have an average, positive cost benefit. The average score is calculated from the six HRO principles if sufficient data in the incident documentation was available to score individual HRO principles. Thirdly, the incident impact of 36 selected incidents is correlated with the average score for observed HRO principles in Group D using those principles that were previously identified to have a significant cost benefit, i.e. indicators with the minimum confidence interval of 95% exceeding zero. The average score is calculated from the three HRO principles if sufficient data in the incident documentation was available to score individual HRO principles.

It can be identified that all datasets have a positive correlationship between the incident impact on customers and the average score for observed HRO principles.

Considering all HRO principles regardless of their cost benefit, a positive correlation described with $y=0.6089x + 61.831$ between the incident impact and the average score for observed HRO principles in Group D can be identified. The coefficient of determination $R^2=0.1478$ explains 14.78% of the variation in the average score for observed HRO principle as a function of the impact scores.

Considering those HRO principles that were previously evaluated with an average, positive cost benefit, a positive correlation described with $y=0.4158x + 68.816$ between the incident impact and the average score for observed HRO principles in Group D can be identified. The coefficient of determination $R^2=0.042$ explains 4.2% of the variation in the average score for observed HRO principles as a function of the impact scores.

Finally, considering those HRO principles that were previously evaluated with a significant positive cost benefit, a positive correlation described with $y=0.5219x + 70.872$ between the incident impact and the average score for observed HRO principles in Group D can be identified. The coefficient of determination $R^2=0.0356$ explains

3.56% of the variation in the average score for observed HRO principles as a function of the impact scores.

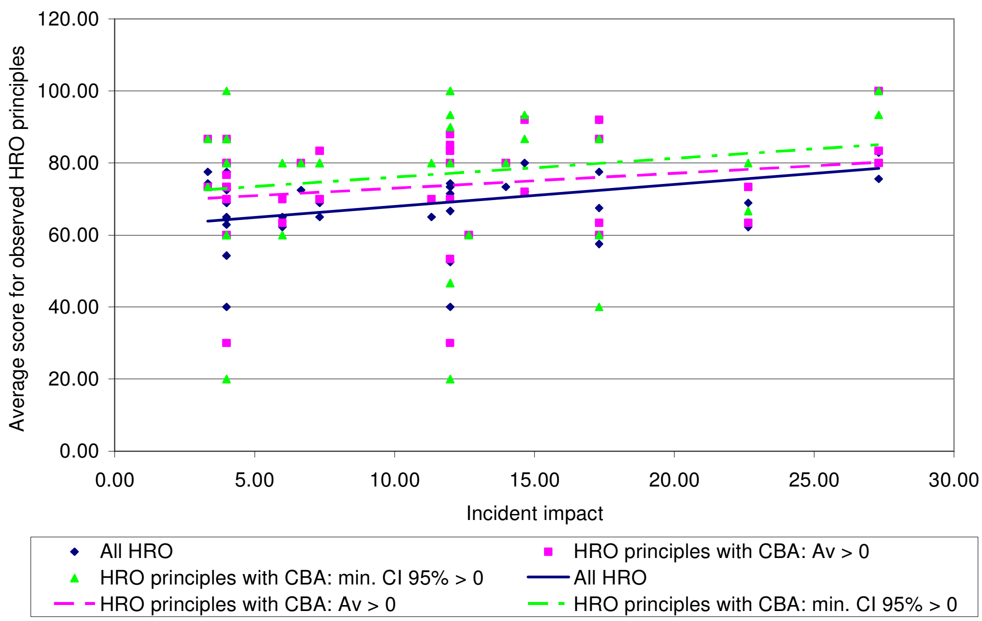

Figure 24 Correlating the incident impact on customers with the average score for observed HRO principles in Group D

In Figure 25, three data sets are presented: firstly, the incident impact of 36 selected incidents is correlated with the average score for observed HRO principles using all indicators in Group E. The average score is calculated from the two HRO principles if sufficient data in the incident documentation was available to score individual HRO principles. Secondly, the incident impact of 36 selected incidents is correlated with the score for the observed HRO principle in Group E using the principle that was previously identified to have an average, positive cost benefit. The score of the one HRO principle is used if sufficient data in the incident documentation was available to score the HRO principle. The third dataset is identical to the former and reflects the HRO principle that was previously identified to have a significant cost benefit, i.e. indicators with the minimum confidence interval of 95% exceeding zero

It can be identified that all datasets have a negative correlationship between the incident impact on customers and the average score for observed HRO principles.

Considering all HRO principles regardless of their cost benefit, a negative correlation described with y=0.1314x + 38.532 between the incident impact and the average score for observed HRO principles in Group E can be identified. The coefficient of determination R^2=0.0014 explains 0.14% of the variation in the average score for observed HRO principle as a function of the impact scores.
Considering the HRO principle that was previously evaluated with an average, positive cost benefit, a negative correlation described with y=-0.6745x + 62.857 between the incident impact and the average score for observed HRO principles in Group E can be identified. The coefficient of determination R^2=0.0181explains 1.81% of the variation in the average score for observed HRO principles as a function of the impact scores.
Finally, the third data set for the HRO principle that was previously evaluated with a significant positive cost benefit is identical to the previous dataset with the HRO principle that was evaluated with an average, positive cost benefit.

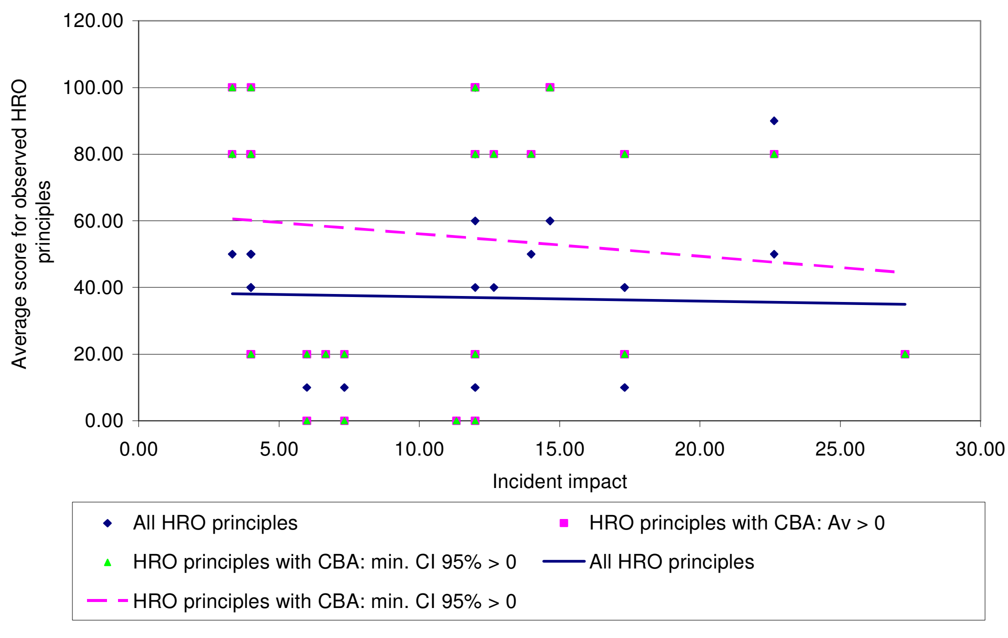

Figure 25 Correlating the incident impact on customers with the average score for observed HRO principles in Group E

In Figure 26, three data sets are presented: firstly, the incident impact of 36 selected incidents is correlated with the average score for observed HRO principles using all indicators in Group F. The average score is calculated from the five HRO principles if sufficient data in the incident documentation was available to score individual HRO principles. Secondly, the incident impact of 36 selected incidents is correlated with the average score for observed HRO principles in Group F using those principles that were previously identified to have an average, positive cost benefit. The average score is calculated from the three HRO principles if sufficient data in the incident documentation was available to score individual HRO principles. Thirdly, the incident impact of 36 selected incidents is correlated with the average score for observed HRO principles in Group F using those principles that were previously identified to have a significant cost benefit, i.e. indicators with the minimum confidence interval of 95% exceeding zero. The average score is calculated from the two HRO principles if sufficient data in the incident documentation was available to score individual HRO principles.

It can be identified that all datasets have a negative correlationship between the incident impact on customers and the average score for observed HRO principles.

Considering all HRO principles regardless of their cost benefit, a negative correlation described with y=-0.1611x + 49.222 between the incident impact and the average score for observed HRO principles in Group F can be identified. The coefficient of determination R^2=0.0039 explains 0.39% of the variation in the average score for observed HRO principle as a function of the impact scores.

Considering those HRO principles that were previously evaluated with an average, positive cost benefit, a negative correlation described with y=-0.4216x + 58.611 between the incident impact and the average score for observed HRO principles in Group F can be identified. The coefficient of determination R^2=0.0111 explains 1.11% of the variation in the average score for observed HRO principles as a function of the impact scores.

Finally, considering those HRO principles that were previously evaluated with a significant positive cost benefit, a negative correlation described with y=-0.4758x + 53.014 between the incident impact and the average score for observed HRO principles in Group F can be identified. The coefficient of determination R^2=0.0086 explains 0.86% of the variation in the average score for observed HRO principles as a function of the impact scores.

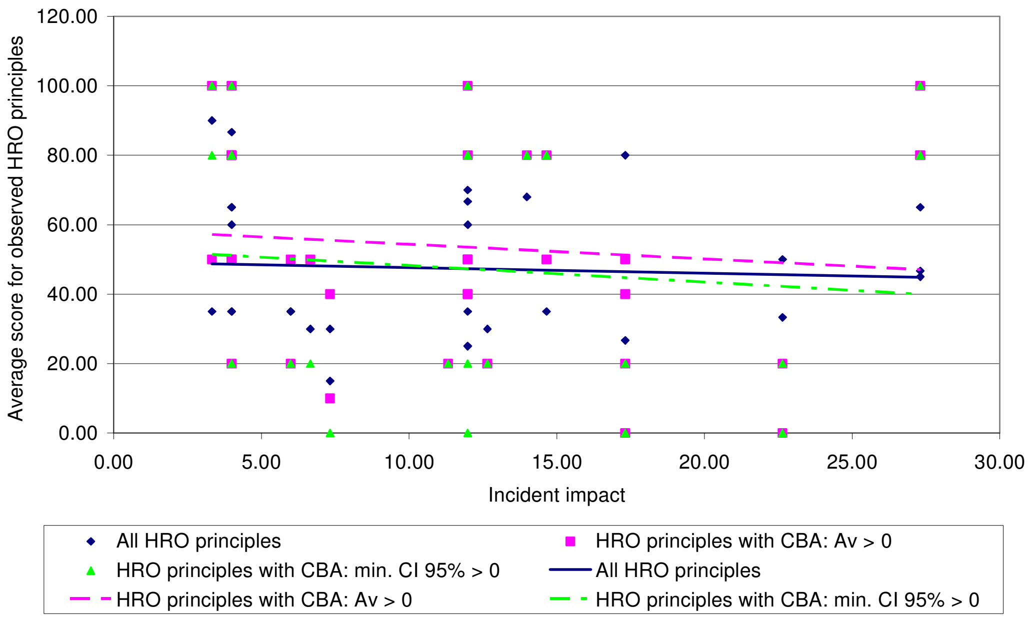

Figure 26 Correlating the incident impact on customers with the average score for observed HRO principles in Group F

In Figure 27, three data sets are presented: firstly, the incident impact of 36 selected incidents is correlated with the average score for observed HRO principles using all indicators in Group G. The average score is calculated from the four HRO principles if sufficient data in the incident documentation was available to score individual HRO principles. Secondly, the incident impact of 36 selected incidents is correlated with the average score for observed HRO principles in Group G using those principles that were previously identified to have an average, positive cost benefit. The average score is calculated from the three HRO principles if sufficient data in the incident documentation was available to score individual HRO principles. Thirdly, the incident impact of 36 selected incidents is correlated with the average score for observed HRO principles in Group G using those principles that were previously identified to have a significant cost benefit, i.e. indicators with the minimum confidence interval of 95% exceeding zero. The average score is calculated from the two HRO principles if sufficient data in the incident documentation was available to score individual HRO principles.

It can be identified that all datasets have a positive correlationship between the incident impact on customers and the average score for observed HRO principles.

Considering all HRO principles regardless of their cost benefit, a positive correlation described with y=0.7049x + 57.155 between the incident impact and the average score for observed HRO principles in Group G can be identified. The coefficient of determination R^2=0.0888 explains 8.88% of the variation in the average score for observed HRO principle as a function of the impact scores.

Considering those HRO principles that were previously evaluated with an average, positive cost benefit, a positive correlation described with y=0.4767x + 72.38 between the incident impact and the average score for observed HRO principles in Group G can be identified. The coefficient of determination R^2=0.0326 explains 3.26% of the variation in the average score for observed HRO principles as a function of the impact scores.

Finally, considering those HRO principles that were previously evaluated with a significant positive cost benefit, a positive correlation described with y=0.6047x + 73.888 between the incident impact and the average score for observed HRO principles in Group G can be identified. The coefficient of determination R^2=0.0658 explains 6.58% of the variation in the average score for observed HRO principles as a function of the impact scores.

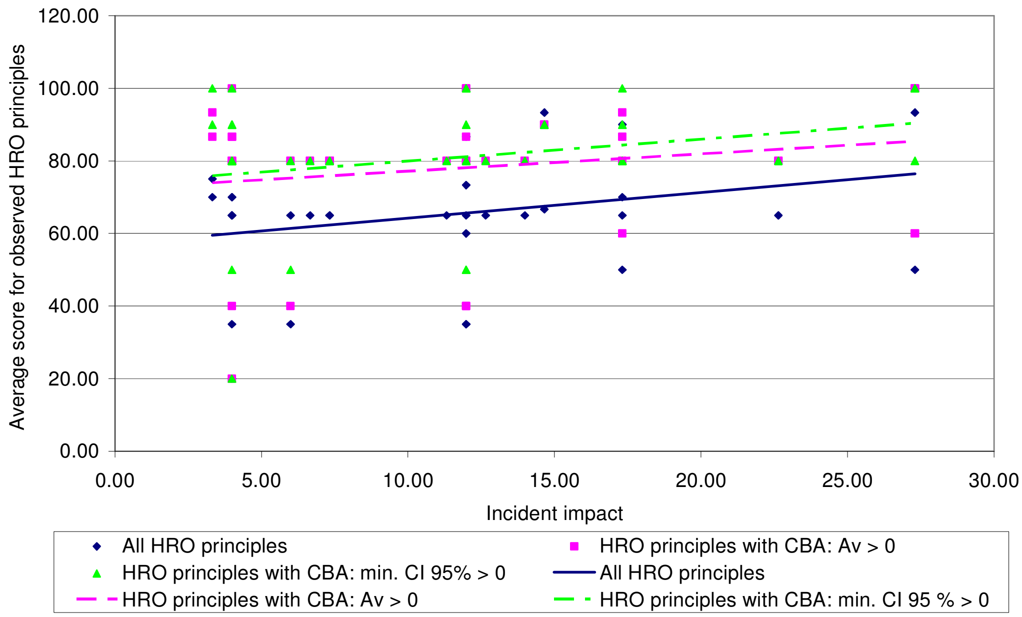

Figure 27 Correlating the incident impact on customers with the average score for observed HRO principles in Group G

Throughout the analysis, the coefficient of determination did not exceed 15% and in most instances does not exceed 1%. This suggests that variation in the average score for observed HRO principles can hardly be explained as a function of the incident impact scores.

In the following section, a significance tests are presented that compare the average score of observed HRO principles during incidents with a significantly high incident impact on customers to the average score of observed HRO principles during incidents with a significantly low incident impact on customers.

The significance tests for the years 2004 to 2006 are presented in Table 78, Table 79 and Table 80, respectively.

In 2004, the overall, average score for observed HRO principles for significantly high and low incident impacts is not significantly different.

Within the individual groups (A-G), it was found that

- Group D considering those HRO principles with an average, positive cost benefit,

- Group D considering those HRO principles with a 97.5% chance of being cost beneficial, and
- Group G for all HRO principles

had a significantly higher average HRO score for high incident impacts.

Within the individual groups (A-G), it was found that

- Group C considering those HRO principles with an average, positive cost benefit, and
- Group F for all HRO principles

had a significantly higher average HRO score for low incident impacts.

In 2004, the individual HRO principles A8, B4, C3, CX2, C7, D1, D8 and G3 had a significantly higher average score for high incident impacts. The individual HRO principles B5, B8 and F1 had a significantly higher average score for low impact incidents.

In 2005, the overall, average score for observed HRO principles for significantly high and low incident impacts is significantly different and a significantly high average score for HRO principles were determined for incidents with a significantly low incident impact.

Within the individual groups (A-G), it was found that

- Group C considering those HRO principles with an average, positive cost benefit,
- Group C considering those HRO principles with a 97.5% chance of being cost beneficial,
- Group B considering those HRO principles with an average, positive cost benefit, and
- Group B considering those HRO principles with a 97.5% chance of being cost beneficial

had a significantly higher average HRO score for low incident impacts.

In 2005, the individual HRO principles A8a, A9, B1, B3, B4, B6, B8, C2 and CX1 had a significantly higher average score for low incident impacts. The individual HRO principle F1 had a significantly higher average HRO score for high impact incidents.

In 2006, the overall, average score for observed HRO principles for significantly high and low incident impacts is not significantly different.

Within the individual groups (A-G), it was found that Group F considering all HRO principles had a significantly higher average HRO score for low incident impacts.

In 2006, the individual HRO principles A7, A9, CX2, D4 and E2 had a significantly higher average score for low incident impacts. The individual HRO principles B4 and C7 had a significantly higher average HRO score for high impact incidents.

4.2.3.1 Comparing the adherence to HRO principles for incidents with significantly high customer impact with adherence to HRO principles for incidents with significantly low customer impact

Significance test were conducted comparing the average score of observed HRO principles during incidents with a significantly high incident impact on customers to the average score of observed HRO principles during incidents with a significantly low incident impact on customers. The significance tests for the years 2004 to 2006 are presented in Table 78, Table 79 and Table 80, respectively.

											Significance testing							
											H0: X1 - X2 = 0			**X1**	**high**			
											H1: X1 - X2 <>0			**X2**	**low**			
											SL: 5%							
	Incidents with significantly high incident impact in 2004					**Incidents with significantly low incident impact in 2004**												
Date	**Av**	**Count**	**SD**	**SE**		**Av**	**Count**	**SD**	**SE**		**mean X1 - mean X2**	**Variance X1-X2**	**SE**	**CI 95% min**	**CI 95% max**	**H0**	**SL**	**Comment**
Pop	3951.40	5.00	5434.19	2430.24		1250.00	4.00	2500.00	1250.00		2701.40	7468581.26	2732.87	-5356.43	5356.43	Accept	0.05	Not significant
Duration	30.40	5.00	17.34	7.76		5.25	4.00	3.40	1.70		25.15	63.06	7.94	-15.56	15.56	Reject	0.05	Significant
Pop score	2.80	5.00	1.10	0.49		2.00	4.00	0.00	0.00		0.80	0.24	0.49	-0.96	0.96	Accept	0.05	Not significant
Duration score	10.00	5.00	6.00	2.68		2.00	4.00	0.00	0.00		8.00	7.20	2.68	-5.26	5.26	Reject	0.05	Significant
Hazard score	48.00	5.00	16.00	7.16		7.50	4.00	1.00	0.50		40.50	51.45	7.17	-14.06	14.06	Reject	0.05	Significant
Impact score	20.25	5.00	6.54	2.92		3.83	4.00	0.33	0.17		16.42	8.57	2.93	-5.74	5.74	Reject	0.05	Significant
Comment																		
A1	96.00	5.00	8.94	4.00		95.00	4.00	10.00	5.00		1.00	41.00	6.40	-12.55	12.55	Accept	0.05	Not significant
A2	100.00	5.00	0.00	0.00		100.00	4.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	Accept	0.05	Not significant
A3	100.00	5.00	0.00	0.00		100.00	4.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	Accept	0.05	Not significant
A4	100.00	5.00	0.00	0.00		100.00	4.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	Accept	0.05	Not significant
A5	100.00	5.00	0.00	0.00		100.00	4.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	Accept	0.05	Not significant
A6	96.00	5.00	8.94	4.00		100.00	4.00	0.00	0.00		-4.00	16.00	4.00	-7.84	7.84	Accept	0.05	Not significant
A7		0.00					0.00				0.00	0.00	0.00	0.00	0.00	Accept	0.05	Not significant
A8	100.00	1.00	0.00	0.00			0.00				100.00	0.00	0.00	0.00	0.00	Reject	0.05	Significant
A8a	95.00	4.00	10.00	5.00		85.00	4.00	10.00	5.00		10.00	50.00	7.07	-13.86	13.86	Accept	0.05	Not significant
A9	100.00	1.00	0.00	0.00			0.00				100.00							
A10	100.00	5.00	0.00	0.00		95.00	4.00	10.00	5.00		5.00	25.00	5.00	-9.80	9.80	Accept	0.05	Not significant
Total	808.00	5.00	94.45	42.24		775.00	4.00	10.00	5.00		33.00	1809.00	42.53	-83.36	83.36	Accept	0.05	Not significant
Count	8.20	5.00	0.84	0.37		8.00	4.00	0.00	0.00									
Average	98.43	5.00	2.28	1.02		96.88	4.00	1.25	0.63		1.55	1.43	1.20	-2.35	2.35	Accept	0.05	Not significant

Total Av>0	788.00	5.00	79.50	35.55		775.00	4.00	10.00	5.00		13.00	1289.00	35.90	-70.37	70.37	Accept	0.05	Not significant
Count	8.00	5.00	0.71	0.32		8.00	4.00	0.00	0.00									
Average	98.43	5.00	2.28	1.02		96.88	4.00	1.25	0.63		1.55	1.43	1.20	-2.35	2.35	Accept	0.05	Not significant
Total CIMIN>0	472.00	5.00	52.15	23.32		480.00	4.00	16.33	8.16		-8.00	610.67	24.71	-48.43	48.43	Accept	0.05	Not significant
Count	4.80	5.00	0.45	0.20		5.00	4.00	0.00	0.00									
Average	98.20	5.00	2.49	1.11		96.00	4.00	3.27	1.63		2.20	3.91	1.98	-3.87	3.87	Accept	0.05	Not significant
B1	88.00	5.00	10.95	4.90		75.00	4.00	37.86	18.93		13.00	382.33	19.55	-38.32	38.32	Accept	0.05	Not significant
B2	80.00	3.00	0.00	0.00		80.00	3.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	Accept	0.05	Not significant
B3	100.00	4.00	0.00	0.00		95.00	4.00	10.00	5.00		5.00	25.00	5.00	-9.80	9.80	Accept	0.05	Not significant
X1		0.00	0.00	0.00			0.00				0.00	0.00	0.00	0.00	0.00	Accept	0.05	Not significant
X2	95.00	4.00	10.00	5.00		95.00	4.00	10.00	5.00		0.00	50.00	7.07	-13.86	13.86	Accept	0.05	Not significant
X3	100.00	5.00	0.00	0.00		100.00	4.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	Accept	0.05	Not significant
B4	80.00	1.00	0.00	0.00			0.00				80.00	0.00	0.00	0.00	0.00	Reject	0.05	Significant
B5		0.00				20.00	1.00	0.00	0.00		-20.00	0.00	0.00	0.00	0.00	Reject	0.05	Significant
B6	80.00	5.00	34.64	15.49		60.00	4.00	46.19	23.09		20.00	773.33	27.81	-54.51	54.51	Accept	0.05	Not significant
B7	50.00	4.00	34.64	17.32		55.00	4.00	41.23	20.62		-5.00	725.00	26.93	-52.77	52.77	Accept	0.05	Not significant
B8		0.00				20.00	1.00	0.00	0.00		-20.00	0.00	0.00	0.00	0.00	Reject	0.05	Significant
Total	528.00	5.00	87.86	39.29		550.00	4.00	113.72	56.86		-22.00	4777.33	69.12	-135.47	135.47	Accept	0.05	Not significant
Count	6.20	5.00	0.45	0.20		7.25	4.00	0.50	0.25									
Average	84.95	5.00	10.89	4.87		76.70	4.00	19.26	9.63		8.26	116.45	10.79	-21.15	21.15	Accept	0.05	Not significant
Total Av>0	488.00	5.00	71.55	32.00		485.00	4.00	82.26	41.13		3.00	2715.67	52.11	-102.14	102.14	Accept	0.05	Not significant
Count	5.40	5.00	0.55	0.24		5.75	4.00	0.50	0.25									
Average	90.13	5.00	6.37	2.85		85.00	4.00	16.89	8.44		5.13	79.40	8.91	-17.47	17.47	Accept	0.05	Not significant
Total CIMIN>0	308.00	5.00	71.55	32.00		315.00	4.00	44.35	22.17		-7.00	1515.67	38.93	-76.31	76.31	Accept	0.05	Not significant
Count	3.40	5.00	0.55	0.24		3.75	4.00	0.50	0.25									

Average	90.00	5.00	10.47	4.68		85.00	4.00	14.72	7.36		5.00	76.11	8.72	-17.10	17.10	Accept	0.05	Not significant
C1	86.67	3.00	11.55	6.67		90.00	4.00	11.55	5.77		-3.33	77.78	8.82	-17.29	17.29	Accept	0.05	Not significant
C2	92.00	5.00	10.95	4.90		90.00	4.00	11.55	5.77		2.00	57.33	7.57	-14.84	14.84	Accept	0.05	Not significant
C3	93.33	3.00	11.55	6.67		80.00	1.00	0.00	0.00		13.33	44.44	6.67	-13.07	13.07	Reject	0.05	Significant
X1	96.00	5.00	8.94	4.00		100.00	4.00	0.00	0.00		-4.00	16.00	4.00	-7.84	7.84	Accept	0.05	Not significant
X2	100.00	4.00	0.00	0.00		46.67	3.00	46.19	26.67		53.33	711.11	26.67	-52.27	52.27	Reject	0.05	Significant
C4	90.00	2.00	14.14	10.00		86.67	3.00	11.55	6.67		3.33	144.44	12.02	-23.56	23.56	Accept	0.05	Not significant
C5	86.67	3.00	11.55	6.67		90.00	4.00	11.55	5.77		-3.33	77.78	8.82	-17.29	17.29	Accept	0.05	Not significant
C6	80.00	3.00	0.00	0.00		60.00	4.00	46.19	23.09		20.00	533.33	23.09	-45.26	45.26	Accept	0.05	Not significant
C7	20.00	2.00	0.00	0.00			0.00				20.00	0.00	0.00	0.00	0.00	Reject	0.05	Significant
Total	520.00	5.00	46.90	20.98		550.00	4.00	66.33	33.17		-30.00	1540.00	39.24	-76.92	76.92	Accept	0.05	Not significant
Count	6.00	5.00	1.00	0.45		6.75	4.00	0.96	0.48									
Average	87.96	5.00	11.06	4.95		83.30	4.00	19.29	9.65		4.66	117.54	10.84	-21.25	21.25	Accept	0.05	Not significant
Total Av>0	384.00	5.00	26.08	11.66		455.00	4.00	52.60	26.30		-71.00	827.67	28.77	-56.39	56.39	Reject	0.05	Significant
Count	4.20	5.00	0.45	0.20		5.00	4.00	0.82	0.41									
Average	92.00	5.00	9.08	4.06		91.83	4.00	9.43	4.72		0.17	38.75	6.22	-12.20	12.20	Accept	0.05	Not significant
Total CIMIN>0	96.00	5.00	8.94	4.00		100.00	4.00	0.00	0.00		-4.00	16.00	4.00	-7.84	7.84	Accept	0.05	Not significant
Count	1.00	5.00	0.00	0.00		1.00	4.00	0.00	0.00									
Average	96.00	5.00	8.94	4.00		100.00	4.00	0.00	0.00		-4.00	16.00	4.00	-7.84	7.84	Accept	0.05	Not significant
D1	100.00	1.00		0.00		40.00	3.00	34.64	20.00		60.00	400.00	20.00	-39.20	39.20	Reject	0.05	Significant
D2	20.00	1.00	0.00	0.00		40.00	3.00	34.64	20.00		-20.00	400.00	20.00	-39.20	39.20	Accept	0.05	Not significant
D1/2/a	92.00	5.00	10.95	4.90		90.00	4.00	11.55	5.77		2.00	57.33	7.57	-14.84	14.84	Accept	0.05	Not significant
D3	92.00	5.00	10.95	4.90		85.00	4.00	10.00	5.00		7.00	49.00	7.00	-13.72	13.72	Accept	0.05	Not significant
D4	46.67	3.00	46.19	26.67		35.00	4.00	30.00	15.00		11.67	936.11	30.60	-59.97	59.97	Accept	0.05	Not significant
D5	95.00	4.00	10.00	5.00		95.00	4.00	10.00	5.00		0.00	50.00	7.07	-13.86	13.86	Accept	0.05	Not significant
D6	96.00	5.00	8.94	4.00		90.00	4.00	11.55	5.77		6.00	49.33	7.02	-13.77	13.77	Accept	0.05	Not significant

D7	80.00	1.00	0.00	0.00		80.00	1.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	Accept	0.05	Not significant
D8	92.00	5.00	10.95	4.90		20.00	3.00	0.00	0.00		72.00	24.00	4.90	-9.60	9.60	Reject	0.05	Significant
Total	516.00	5.00	129.15	57.76		490.00	4.00	103.92	51.96		26.00	6036.00	77.69	-152.28	152.28		0.05	Significant
Count	6.00	5.00	1.00	0.45		7.50	4.00	1.00	0.50									
Average	85.37	5.00	10.86	4.86		65.08	4.00	8.58	4.29		20.29	41.99	6.48	-12.70	12.70	Accept	0.05	Not significant
Total Av>0	476.00	5.00	86.49	38.68		410.00	4.00	38.30	19.15		66.00	1862.67	43.16	-84.59	84.59	Accept	0.05	Not significant
Count	5.40	5.00	0.55	0.24		5.75	4.00	0.50	0.25									
Average	87.87	5.00	10.65	4.76		71.67	4.00	8.39	4.19		16.20	40.28	6.35	-12.44	12.44	Reject	0.05	Significant
Total CIMIN>0	280.00	5.00	20.00	8.94		195.00	4.00	19.15	9.57		85.00	171.67	13.10	-25.68	25.68	Reject	0.05	Significant
Count	3.00	5.00	0.00	0.00		2.75	4.00	0.50	0.25									
Average	93.33	5.00	6.67	2.98		73.33	4.00	18.86	9.43		20.00	97.78	9.89	-19.38	19.38	Reject	0.05	Significant
E1	64.00	5.00	40.99	18.33		80.00	4.00	0.00	0.00		-16.00	336.00	18.33	-35.93	35.93	Accept	0.05	Not significant
E2	13.33	3.00	11.55	6.67		13.33	3.00	11.55	6.67		0.00	88.89	9.43	-18.48	18.48	Accept	0.05	Not significant
Total	72.00	5.00	50.20	22.45		90.00	4.00	11.55	5.77		-18.00	537.33	23.18	-45.43	45.43	Accept	0.05	Not significant
Count	1.60	5.00	0.55	0.24		1.75	4.00	0.50	0.25									
Average	40.00	5.00	20.00	8.94		55.00	4.00	17.32	8.66		-15.00	155.00	12.45	-24.40	24.40	Accept	0.05	Not significant
Total Av>0	64.00	5.00	40.99	18.33		80.00	4.00	0.00	0.00		-16.00	336.00	18.33	-35.93	35.93	Accept	0.05	Not significant
Count	1.00	5.00	0.00	0.00		1.00	4.00	0.00	0.00									
Average	64.00	5.00	40.99	18.33		80.00	4.00	0.00	0.00		-16.00	336.00	18.33	-35.93	35.93	Accept	0.05	Not significant
Total CIMIN>0	64.00	5.00	40.99	18.33		80.00	4.00	0.00	0.00		-16.00	336.00	18.33	-35.93	35.93	Accept	0.05	Not significant
Count	1.00	5.00	0.00	0.00		1.00	4.00	0.00	0.00									
Average	64.00	5.00	40.99	18.33		80.00	4.00	0.00	0.00		-16.00	336.00	18.33	-35.93	35.93	Accept	0.05	Not significant
F1	16.00	5.00	8.94	4.00		80.00	4.00	0.00	0.00		-64.00	16.00	4.00	-7.84	7.84	Reject	0.05	Significant
F2	0.00	1.00	0.00	0.00			0.00				0.00	0.00	0.00	0.00	0.00	Accept	0.05	Not significant

F3	65.00	4.00	30.00	15.00		80.00	2.00	0.00	0.00		-15.00	225.00	15.00	-29.40	29.40	Accept	0.05	Not significant
F4	15.00	4.00	10.00	5.00		40.00	3.00	34.64	20.00		-25.00	425.00	20.62	-40.41	40.41	Accept	0.05	Not significant
F5	85.00	4.00	10.00	5.00		90.00	4.00	11.55	5.77		-5.00	58.33	7.64	-14.97	14.97	Accept	0.05	Not significant
Total	148.00	5.00	46.04	20.59		240.00	4.00	40.00	20.00		-92.00	824.00	28.71	-56.26	56.26	Reject	0.05	Significant
Count	3.60	5.00	0.55	0.24		3.25	4.00	0.96	0.48									
Average	40.67	5.00	9.62	4.30		76.67	4.00	13.54	6.77		-36.00	64.33	8.02	-15.72	15.72	Reject	0.05	Significant
Total Av>0	120.00	5.00	37.42	16.73		130.00	4.00	34.64	17.32		-10.00	580.00	24.08	-47.20	47.20	Accept	0.05	Not significant
Count	1.80	5.00	0.45	0.20		1.50	4.00	0.58	0.29									
Average	70.00	5.00	24.49	10.95		90.00	4.00	11.55	5.77		-20.00	153.33	12.38	-24.27	24.27	Accept	0.05	Not significant
Total CIMIN>0	68.00	5.00	38.99	17.44		90.00	4.00	11.55	5.77		-22.00	337.33	18.37	-36.00	36.00	Accept	0.05	Not significant
Count	1.00	5.00	0.00	0.00		1.00	4.00	0.00	0.00									
Average	68.00	5.00	38.99	17.44		90.00	4.00	11.55	5.77		-22.00	337.33	18.37	-36.00	36.00	Accept	0.05	Not significant
G1	96.00	5.00	8.94	4.00		90.00	4.00	11.55	5.77		6.00	49.33	7.02	-13.77	13.77	Accept	0.05	Not significant
G2	96.00	5.00	8.94	4.00		95.00	4.00	10.00	5.00		1.00	41.00	6.40	-12.55	12.55	Accept	0.05	Not significant
G3	70.00	4.00	34.64	17.32		20.00	4.00	0.00	0.00		50.00	300.00	17.32	-33.95	33.95	Reject	0.05	Significant
G4	90.00	2.00	14.14	10.00		85.00	4.00	10.00	5.00		5.00	125.00	11.18	-21.91	21.91	Accept	0.05	Not significant
Total	284.00	5.00	57.27	25.61		290.00	4.00	25.82	12.91		-6.00	822.67	28.68	-56.22	56.22	Accept	0.05	Not significant
Count	3.20	5.00	0.45	0.20		4.00	4.00	0.00	0.00									
Average	88.67	5.00	12.82	5.73		72.50	4.00	6.45	3.23		16.17	43.31	6.58	-12.90	12.90	Reject	0.05	Significant
Total Av>0	228.00	5.00	57.62	25.77		270.00	4.00	25.82	12.91		-42.00	830.67	28.82	-56.49	56.49	Accept	0.05	Not significant
Count	2.40	5.00	0.55	0.24		3.00	4.00	0.00	0.00									
Average	94.67	5.00	5.06	2.26		90.00	4.00	8.61	4.30		4.67	23.63	4.86	-9.53	9.53	Accept	0.05	Not significant
Total CIMIN>0	192.00	5.00	10.95	4.90		185.00	4.00	19.15	9.57		7.00	115.67	10.75	-21.08	21.08	Accept	0.05	Not significant
Count	2.00	5.00	0.00	0.00		2.00	4.00	0.00	0.00									
Average	96.00	5.00	5.48	2.45		92.50	4.00	9.57	4.79		3.50	28.92	5.38	-10.54	10.54	Accept	0.05	Not significant

Total Group score																		
Total	2876.00	5.00	236.39	105.72		2985.00	4.00	234.02	117.01		-109.00	24867.67	157.69	-309.08	309.08	Accept	0.05	Not significant
Count	34.80	5.00	1.30	0.58		38.50	4.00	3.11	1.55									
Average	82.66	5.00	6.29	2.81		77.85	4.00	7.89	3.95		4.81	23.49	4.85	-9.50	9.50	Accept	0.05	Not significant
Total Av>0	2548.00	5.00	219.36	98.10		2605.00	4.00	142.71	71.36		-57.00	14715.67	121.31	-237.76	237.76	Accept	0.05	Not significant
Count	28.20	5.00	1.48	0.66		30.00	4.00	1.83	0.91									
Average	90.23	5.00	3.19	1.43		87.04	4.00	6.41	3.21		3.19	12.32	3.51	-6.88	6.88	Accept	0.05	Not significant
Total CIMIN>0	1480.00	5.00	114.02	50.99		1445.00	4.00	50.00	25.00		35.00	3225.00	56.79	-111.31	111.31	Accept	0.05	Not significant
Count	16.20	5.00	0.84	0.37		16.50	4.00	1.00	0.50									
Average	91.26	5.00	2.41	1.08		87.82	4.00	6.19	3.10		3.44	10.74	3.28	-6.42	6.42	Accept	0.05	Not significant

Table 78 Significance test for HRO observations comparing incidents with significantly low impact to incidents with significantly high impact for 2004

											Significance testing							
											H0: X1 - X2 = 0			X1	high			
											H1: X1 - X2 <>0			X2	low			
											SL: 5%							
	Incidents with significantly high incident impact in 2005					Incidents with significantly low incident impact in 2005												
Date	Av	Count	SD	SE		Av	Count	SD	SE		mean X1 - mean X2	Variance X1-X2	SE	CI 95% min	CI 95% max	H0	SL	Comment
Pop	49.67	3.00	38.08	21.99		0.50	4.00	1.00	0.50		49.17	483.69	21.99	-43.11	43.11	Reject	0.05	Significant
Duration	21.33	3.00	23.09	13.33		5.75	4.00	2.63	1.31		15.58	179.51	13.40	-26.26	26.26	Accept	0.05	Not significant
Pop score	2.00	3.00	0.00	0.00		2.00	4.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	Accept	0.05	Not significant
Duration score	6.67	3.00	8.08	4.67		2.00	4.00	0.00	0.00		4.67	21.78	4.67	-9.15	9.15	Accept	0.05	Not significant
Hazard score	64.00	3.00	0.00	0.00		7.50	4.00	1.00	0.50		56.50	0.25	0.50	-0.98	0.98	Reject	0.05	Significant
Impact score	24.20	3.00	2.69	1.55		3.83	4.00	0.33	0.17		20.37	2.44	1.56	-3.06	3.06	Reject	0.05	Significant
A1	93.33	3.00	11.55	6.67		95.00	4.00	10.00	5.00		-1.67	69.44	8.33	-16.33	16.33	Accept	0.05	Not significant
A2	40.00	3.00	34.64	20.00		65.00	4.00	30.00	15.00		-25.00	625.00	25.00	-49.00	49.00	Accept	0.05	Not significant
A3	93.33	3.00	11.55	6.67		95.00	4.00	10.00	5.00		-1.67	69.44	8.33	-16.33	16.33	Accept	0.05	Not significant
A4	93.33	3.00	11.55	6.67		95.00	4.00	10.00	5.00		-1.67	69.44	8.33	-16.33	16.33	Accept	0.05	Not significant
A5	86.67	3.00	11.55	6.67		95.00	4.00	10.00	5.00		-8.33	69.44	8.33	-16.33	16.33	Accept	0.05	Not significant
A6	86.67	3.00	11.55	6.67		85.00	4.00	10.00	5.00		1.67	69.44	8.33	-16.33	16.33	Accept	0.05	Not significant
A7	50.00	2.00	42.43	30.00		80.00	1.00	0.00	0.00		-30.00	900.00	30.00	-58.80	58.80	Accept	0.05	Not significant
A8		0.00					0.00				0.00	0.00	0.00	0.00	0.00	Accept	0.05	Not significant
A8a	80.00	1.00	0.00	0.00		95.00	4.00	10.00	5.00		-15.00	25.00	5.00	-9.80	9.80	Reject	0.05	Significant
A9	80.00	1.00	0.00	0.00		100.00	2.00	0.00	0.00		-20.00	0.00	0.00	0.00	0.00	Reject	0.05	Significant
A10	86.67	3.00	11.55	6.67		80.00	4.00	40.00	20.00		6.67	444.44	21.08	-41.32	41.32	Accept	0.05	Not significant
Total	666.67	3.00	160.42	92.62		775.00	4.00	113.58	56.79		-108.33	11802.78	108.64	-212.94	212.94	Accept	0.05	Not significant
Count	8.33	3.00	1.15	0.67		8.75	4.00	0.50	0.25									
Average	79.37	3.00	10.38	5.99		88.75	4.00	13.24	6.62		-9.38	79.76	8.93	-17.50	17.50	Accept	0.05	Not significant

Total Av>0	666.67	3.00	160.42	92.62		775.00	4.00	113.58	56.79		-108.33	11802.78	108.64	-212.94	212.94	Accept	0.05	Not significant
Count	8.33	3.00	1.15	0.67		8.75	4.00	0.50	0.25								0.05	
Average	79.37	3.00	10.38	5.99		88.75	4.00	13.24	6.62		-9.38	79.76	8.93	-17.50	17.50	Accept	0.05	Not significant
Total CIMIN> 0	393.33	3.00	70.24	40.55		475.00	4.00	37.86	18.93		-81.67	2002.78	44.75	-87.71	87.71	Accept	0.05	Not significant
Count	4.33	3.00	0.58	0.33		5.00	4.00	0.00	0.00								0.05	
Average	90.67	3.00	10.07	5.81		95.00	4.00	7.57	3.79		-4.33	48.11	6.94	-13.59	13.59	Accept	0.05	Not significant
B1	60.00	3.00	34.64	20.00		100.00	4.00	0.00	0.00		-40.00	400.00	20.00	-39.20	39.20	Reject	0.05	Significant
B2	80.00	3.00	0.00	0.00		90.00	4.00	11.55	5.77		-10.00	33.33	5.77	-11.32	11.32	Accept	0.05	Not significant
B3	80.00	3.00	0.00	0.00		95.00	4.00	10.00	5.00		-15.00	25.00	5.00	-9.80	9.80	Reject	0.05	Significant
X1	100.00	1.00	0.00	0.00		100.00	3.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	Accept	0.05	Not significant
X2	86.67	3.00	11.55	6.67		95.00	4.00	10.00	5.00		-8.33	69.44	8.33	-16.33	16.33	Accept	0.05	Not significant
X3	100.00	3.00	0.00	0.00		95.00	4.00	10.00	5.00		5.00	25.00	5.00	-9.80	9.80	Accept	0.05	Not significant
B4	20.00	1.00	0.00	0.00		93.33	3.00	11.55	6.67		-73.33	44.44	6.67	-13.07	13.07	Reject	0.05	Significant
B5	50.00	2.00	42.43	30.00		20.00	1.00	0.00	0.00		30.00	900.00	30.00	-58.80	58.80	Accept	0.05	Not significant
B6	20.00	2.00	0.00	0.00		90.00	4.00	11.55	5.77		-70.00	33.33	5.77	-11.32	11.32	Reject	0.05	Significant
B7	40.00	3.00	34.64	20.00		50.00	4.00	34.64	17.32		-10.00	700.00	26.46	-51.86	51.86	Accept	0.05	Not significant
B8		0.00				20.00	1.00	0.00	0.00		-20.00	0.00	0.00	0.00	0.00	Reject	0.05	Significant
Total	533.33	3.00	98.66	56.96		770.00	4.00	142.83	71.41		-236.67	8344.44	91.35	-179.04	179.04	Accept	0.05	Not significant
Count	8.00	3.00	1.00	0.58		9.00	4.00	0.82	0.41		-1.00	0.50	0.71	-1.39	1.39	Accept	0.05	Not significant
Average	67.55	3.00	16.82	9.71		85.28	4.00	12.55	6.28		-17.72	133.73	11.56	-22.67	22.67	Accept	0.05	Not significant
Total Av>0	426.67	3.00	23.09	13.33		635.00	4.00	77.24	38.62		-208.33	1669.44	40.86	-80.08	80.08	Reject	0.05	Significant
Count	6.00	3.00	1.00	0.58		6.75	4.00	0.50	0.25								0.05	
Average	72.83	3.00	15.43	8.91		93.81	4.00	4.95	2.47		-20.98	85.53	9.25	-18.13	18.13	Reject	0.05	Significant
Total CIMIN>	273.33	3.00	11.55	6.67		370.00	4.00	20.00	10.00		-96.67	144.44	12.02	-23.56	23.56	Reject	0.05	Significant

0																		
Count	3.67	3.00	0.58	0.33		4.00	4.00	0.00	0.00								0.05	
Average	75.56	3.00	9.62	5.56		92.50	4.00	5.00	2.50		-16.94	37.11	6.09	-11.94	11.94	Reject	0.05	Significant
C1	60.00	3.00	34.64	20.00		70.00	4.00	34.64	17.32		-10.00	700.00	26.46	-51.86	51.86	Accept	0.05	Not significant
C2	40.00	3.00	34.64	20.00		80.00	4.00	0.00	0.00		-40.00	400.00	20.00	-39.20	39.20	Reject	0.05	Significant
C3	50.00	2.00	42.43	30.00		80.00	4.00	0.00	0.00		-30.00	900.00	30.00	-58.80	58.80	Accept	0.05	Not significant
X1	40.00	3.00	34.64	20.00		90.00	4.00	11.55	5.77		-50.00	433.33	20.82	-40.80	40.80	Reject	0.05	Significant
X2	60.00	3.00	34.64	20.00		35.00	4.00	30.00	15.00		25.00	625.00	25.00	-49.00	49.00	Accept	0.05	Not significant
C4	80.00	3.00	0.00	0.00		80.00	4.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	Accept	0.05	Not significant
C5	20.00	3.00	0.00	0.00		50.00	4.00	34.64	17.32		-30.00	300.00	17.32	-33.95	33.95	Accept	0.05	Not significant
C6	20.00	3.00	0.00	0.00		50.00	4.00	34.64	17.32		-30.00	300.00	17.32	-33.95	33.95	Accept	0.05	Not significant
C7	20.00	1.00	0.00	0.00		20.00	1.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	Accept	0.05	Not significant
Total	360.00	3.00	72.11	41.63		540.00	4.00	71.18	35.59		-180.00	3000.00	54.77	-107.35	107.35	Reject	0.05	Significant
Count	8.00	3.00	1.00	0.58		8.25	4.00	0.50	0.25									
Average	46.23	3.00	15.11	8.72		65.76	4.00	10.69	5.35		-19.53	104.71	10.23	-20.06	20.06	Accept	0.05	Not significant
Total Av>0	273.33	3.00	57.74	33.33		450.00	4.00	66.33	33.17		-176.67	2211.11	47.02	-92.16	92.16	Accept	0.05	Not significant
Count	5.67	3.00	0.58	0.33		6.00	4.00	0.00	0.00								0.05	
Average	49.33	3.00	16.17	9.33		75.00	4.00	11.06	5.53		-25.67	117.67	10.85	-21.26	21.26	Reject	0.05	Significant
Total CIMIN> 0	40.00	3.00	34.64	20.00		90.00	4.00	11.55	5.77		-50.00	433.33	20.82	-40.80	40.80	Reject	0.05	Significant
Count	1.00	3.00	0.00	0.00		1.00	4.00	0.00	0.00								0.05	
Average	40.00	3.00	34.64	20.00		90.00	4.00	11.55	5.77		-50.00	433.33	20.82	-40.80	40.80	Reject	0.05	Significant
D1	80.00	3.00	0.00	0.00		80.00	4.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	Accept	0.05	Not significant
D2	20.00	3.00	0.00	0.00		20.00	4.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	Accept	0.05	Not significant
D1/2/a	86.67	3.00	11.55	6.67		90.00	4.00	11.55	5.77		-3.33	77.78	8.82	-17.29	17.29	Accept	0.05	Not significant
D3	86.67	3.00	11.55	6.67		80.00	4.00	0.00	0.00		6.67	44.44	6.67	-13.07	13.07	Accept	0.05	Not significant

D4	20.00	3.00	0.00	0.00		50.00	4.00	34.64	17.32		-30.00	300.00	17.32	-33.95	33.95	Accept	0.05	Not significant
D5	86.67	3.00	11.55	6.67		95.00	4.00	10.00	5.00		-8.33	69.44	8.33	-16.33	16.33	Accept	0.05	Not significant
D6	86.67	3.00	11.55	6.67		90.00	4.00	11.55	5.77		-3.33	77.78	8.82	-17.29	17.29	Accept	0.05	Not significant
D7	86.67	3.00	11.55	6.67		50.00	2.00	42.43	30.00		36.67	944.44	30.73	-60.23	60.23	Accept	0.05	Not significant
D8	66.67	3.00	41.63	24.04		80.00	4.00	0.00	0.00		-13.33	577.78	24.04	-47.11	47.11	Accept	0.05	Not significant
Total	620.00	3.00	60.00	34.64		610.00	4.00	20.00	10.00		10.00	1300.00	36.06	-70.67	70.67	Accept	0.05	Not significant
Count	9.00	3.00	0.00	0.00		8.50	4.00	0.58	0.29								0.05	
Average	68.89	3.00	6.67	3.85		72.08	4.00	6.51	3.26		-3.19	25.42	5.04	-9.88	9.88	Accept	0.05	Not significant
Total Av>0	433.33	3.00	50.33	29.06		485.00	4.00	41.23	20.62		-51.67	1269.44	35.63	-69.83	69.83	Accept	0.05	Not significant
Count	6.00	3.00	0.00	0.00		6.00	4.00	0.00	0.00								0.05	
Average	72.22	3.00	8.39	4.84		80.83	4.00	6.87	3.44		-8.61	35.26	5.94	-11.64	11.64	Accept	0.05	Not significant
Total CIMIN>0	240.00	3.00	40.00	23.09		260.00	4.00	0.00	0.00		-20.00	533.33	23.09	-45.26	45.26	Accept	0.05	Not significant
Count	3.00	3.00	0.00	0.00		3.00	4.00	0.00	0.00								0.05	
Average	80.00	3.00	13.33	7.70		86.67	4.00	0.00	0.00		-6.67	59.26	7.70	-15.09	15.09	Accept	0.05	Not significant
E1	60.00	3.00	34.64	20.00		90.00	4.00	11.55	5.77		-30.00	433.33	20.82	-40.80	40.80	Accept	0.05	Not significant
E2	46.67	3.00	46.19	26.67		0.00	4.00	0.00	0.00		46.67	711.11	26.67	-52.27	52.27	Accept	0.05	Not significant
Total	106.67	3.00	70.24	40.55		90.00	4.00	11.55	5.77		16.67	1677.78	40.96	-80.28	80.28	Accept	0.05	Not significant
Count	2.00	3.00	0.00	0.00		2.00	4.00	0.00	0.00								0.05	
Average	53.33	3.00	35.12	20.28		45.00	4.00	5.77	2.89		8.33	419.44	20.48	-40.14	40.14	Accept	0.05	Not significant
Total Av>0	60.00	3.00	34.64	20.00		90.00	4.00	11.55	5.77		-30.00	433.33	20.82	-40.80	40.80	Accept	0.05	Not significant
Count	1.00	3.00	0.00	0.00		1.00	4.00	0.00	0.00								0.05	
Average	60.00	3.00	34.64	20.00		90.00	4.00	11.55	5.77		-30.00	433.33	20.82	-40.80	40.80	Accept	0.05	Not significant
Total CIMIN>0	60.00	3.00	34.64	20.00		90.00	4.00	11.55	5.77		-30.00	433.33	20.82	-40.80	40.80	Accept	0.05	Not significant

Count	1.00	3.00	0.00	0.00		1.00	4.00	0.00	0.00								0.05	
Average	60.00	3.00	34.64	20.00		90.00	4.00	11.55	5.77		-30.00	433.33	20.82	-40.80	40.80	Accept	0.05	Not significant
F1	80.00	3.00	0.00	0.00		35.00	4.00	30.00	15.00		45.00	225.00	15.00	-29.40	29.40	Reject	0.05	Significant
F2		0.00					0.00				0.00	0.00	0.00	0.00	0.00	Accept	0.05	Not significant
F3	80.00	1.00	0.00	0.00		50.00	4.00	34.64	17.32		30.00	300.00	17.32	-33.95	33.95	Accept	0.05	Not significant
F4	13.33	3.00	11.55	6.67		20.00	4.00	0.00	0.00		-6.67	44.44	6.67	-13.07	13.07	Accept	0.05	Not significant
F5	50.00	2.00	42.43	30.00		80.00	4.00	0.00	0.00		-30.00	900.00	30.00	-58.80	58.80	Accept	0.05	Not significant
Total	153.33	3.00	92.38	53.33		185.00	4.00	57.45	28.72		-31.67	3669.44	60.58	-118.73	118.73	Accept	0.05	Not significant
Count	3.00	3.00	1.00	0.58		4.00	4.00	0.00	0.00								0.05	
Average	49.44	3.00	15.84	9.15		46.25	4.00	14.36	7.18		3.19	135.20	11.63	-22.79	22.79	Accept	0.05	Not significant
Total Av>0	60.00	3.00	87.18	50.33		130.00	4.00	34.64	17.32		-70.00	2833.33	53.23	-104.33	104.33	Accept	0.05	Not significant
Count	1.00	3.00	1.00	0.58		2.00	4.00	0.00	0.00								0.05	
Average	33.33	3.00	41.63	24.04		65.00	4.00	17.32	8.66		-31.67	652.78	25.55	-50.08	50.08	Accept	0.05	Not significant
Total CIMIN> 0	33.33	3.00	41.63	24.04		80.00	4.00	0.00	0.00		-46.67	577.78	24.04	-47.11	47.11	Accept	0.05	Not significant
Count	0.67	3.00	0.58	0.33		1.00	4.00	0.00	0.00								0.05	
Average	33.33	3.00	41.63	24.04		80.00	4.00	0.00	0.00		-46.67	577.78	24.04	-47.11	47.11	Accept	0.05	Not significant
G1	80.00	3.00	0.00	0.00		90.00	4.00	11.55	5.77		-10.00	33.33	5.77	-11.32	11.32	Accept	0.05	Not significant
G2	80.00	3.00	0.00	0.00		65.00	4.00	30.00	15.00		15.00	225.00	15.00	-29.40	29.40	Accept	0.05	Not significant
G3	20.00	3.00	0.00	0.00		20.00	4.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	Accept	0.05	Not significant
G4	60.00	3.00	34.64	20.00		65.00	4.00	30.00	15.00		-5.00	625.00	25.00	-49.00	49.00	Accept	0.05	Not significant
Total	240.00	3.00	34.64	20.00		240.00	4.00	67.33	33.67		0.00	1533.33	39.16	-76.75	76.75	Accept	0.05	Not significant
Count	4.00	3.00	0.00	0.00		4.00	4.00	0.00	0.00								0.05	
Average	60.00	3.00	8.66	5.00		60.00	4.00	16.83	8.42		0.00	95.83	9.79	-19.19	19.19	Accept	0.05	Not significant
Total Av>0	220.00	3.00	34.64	20.00		220.00	4.00	67.33	33.67		0.00	1533.33	39.16	-76.75	76.75	Accept	0.05	Not significant

Count	3.00	3.00	0.00	0.00		3.00	4.00	0.00	0.00								0.05	
Average	73.33	3.00	11.55	6.67		73.33	4.00	22.44	11.22		0.00	170.37	13.05	-25.58	25.58	Accept	0.05	Not significant
Total CIMIN>0	160.00	3.00	0.00	0.00		155.00	4.00	37.86	18.93		5.00	358.33	18.93	-37.10	37.10	Accept	0.05	Not significant
Count	2.00	3.00	0.00	0.00		2.00	4.00	0.00	0.00								0.05	
Average	80.00	3.00	0.00	0.00		77.50	4.00	18.93	9.46		2.50	89.58	9.46	-18.55	18.55	Accept	0.05	Not significant
																	0.05	
Total Group score																	0.05	
Total	2680.00	3.00	283.55	163.71		3210.00	4.00	340.00	170.00		-530.00	55700.00	236.01	-462.58	462.58	Reject	0.05	Significant
Count	42.33	3.00	2.08	1.20		44.50	4.00	1.00	0.50								0.05	
Average	63.19	3.00	3.68	2.12		72.17	4.00	7.98	3.99		-8.98	20.42	4.52	-8.86	8.86	Reject	0.05	Significant
Total Av>0	2140.00	3.00	264.58	152.75		2785.00	4.00	339.56	169.78		-645.00	52158.33	228.38	-447.63	447.63	Reject	0.05	Significant
Count	31.00	3.00	1.00	0.58		33.50	4.00	0.58	0.29								0.05	
Average	68.91	3.00	6.57	3.79		83.05	4.00	9.10	4.55		-14.14	35.08	5.92	-11.61	11.61	Reject	0.05	Significant
Total CIMIN>0	1200.00	3.00	131.15	75.72		1520.00	4.00	113.14	56.57		-320.00	8933.33	94.52	-185.25	185.25	Reject	0.05	Significant
Count	15.67	3.00	1.15	0.67		17.00	4.00	0.00	0.00								0.05	
Average	76.55	3.00	5.42	3.13		89.41	4.00	6.66	3.33		-12.86	20.86	4.57	-8.95	8.95	Reject	0.05	Significant

Table 79 Significance test for HRO observations comparing incidents with significantly low impact to incidents with significantly high impact for 2005

											Significance testing							
											H0: X1 - X2 = 0			X1	high			
											H1: X1 - X2 <>0			X2	low			
											SL: 5%							
	Incidents with significantly high incident impact in 2006					Incidents with significantly low incident impact in 2006												
Date	Av	Count	SD	SE		Av	Count	SD	SE		mean X1 - mean X2	Variance X1-X2	SE	CI 95% min	CI 95% max	H0	SL	Comment
Pop	12671.25	4.00	16630.76	8315		4258.33	6.00	9924.23	4051.55		8412.92	85560646	9249.90	-18129.80	18129.80	Accept	0.05	Not significant
Duration	6.00	4.00	1.63	0.82		11.00	6.00	6.66	2.72		-5.00	8.07	2.84	-5.57	5.57	Accept	0.05	Not significant
Pop score	6.00	4.00	6.73	3.37		3.00	6.00	2.45	1.00		3.00	12.33	3.51	-6.88	6.88	Accept	0.05	Not significant
Duration score	2.00	4.00	0.00	0.00		3.33	6.00	2.42	0.99		-1.33	0.98	0.99	-1.94	1.94	Accept	0.05	Not significant
Hazard score	28.00	4.00	8.00	4.00		9.00	6.00	3.52	1.44		19.00	18.07	4.25	-8.33	8.33	Reject	0.05	Significant
Impact score	11.99	4.00	0.54	0.27		5.11	6.00	1.24	0.51		6.88	0.33	0.57	-1.13	1.13	Reject	0.05	Significant
A1	85.00	4.00	10.00	5.00		70.00	6.00	24.49	10.00		15.00	125.00	11.18	-21.91	21.91	Accept	0.05	Not significant
A2	50.00	4.00	34.64	17.32		50.00	6.00	32.86	13.42		0.00	480.00	21.91	-42.94	42.94	Accept	0.05	Not significant
A3	70.00	4.00	34.64	17.32		70.00	6.00	24.49	10.00		0.00	400.00	20.00	-39.20	39.20	Accept	0.05	Not significant
A4	70.00	4.00	34.64	17.32		70.00	6.00	24.49	10.00		0.00	400.00	20.00	-39.20	39.20	Accept	0.05	Not significant
A5	60.00	3.00	34.64	20.00		60.00	6.00	30.98	12.65		0.00	560.00	23.66	-46.38	46.38	Accept	0.05	Not significant
A6	80.00	4.00	0.00	0.00		80.00	6.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	Accept	0.05	Not significant
A7		0.00				20.00	2.00	0.00	0.00		-20.00	0.00	0.00	0.00	0.00	Reject	0.05	Significant
A8	100.00	1.00	0.00	0.00		60.00	2.00	56.57	40.00		40.00	1600.00	40.00	-78.40	78.40	Accept	0.05	Not significant
A8a	65.00	4.00	30.00	15.00		70.00	6.00	24.49	10.00		-5.00	325.00	18.03	-35.33	35.33	Accept	0.05	Not significant
A9	0.00	1.00	0.00	0.00		50.00	4.00	34.64	17.32		-50.00	300.00	17.32	-33.95	33.95	Reject	0.05	Significant
A10	60.00	4.00	40.00	20.00		60.00	6.00	30.98	12.65		0.00	560.00	23.66	-46.38	46.38	Accept	0.05	Not significant
Total	550.00	4.00	88.69	44.35		590.00	6.00	98.59	40.25		-40.00	3586.67	59.89	-117.38	117.38	Accept	0.05	Not significant
Count	8.25	4.00	1.26	0.63		9.33	6.00	1.37	0.56									
Average	68.89	4.00	19.46	9.73		65.35	6.00	18.01	7.35		3.54	148.76	12.20	-23.91	23.91	Accept	0.05	Not significant

Total Av>0	525.00	4.00	137.96	68.98		570.00	6.00	136.67	55.80		-45.00	7871.67	88.72	-173.90	173.90	Accept	0.05	Not significant
Count	8.00	4.00	0.82	0.41		9.00	6.00	0.89	0.37									
Average	67.28	4.00	22.47	11.23		64.78	6.00	19.51	7.96		2.50	189.61	13.77	-26.99	26.99	Accept	0.05	Not significant
Total CIMIN>0	335.00	4.00	80.62	40.31		340.00	6.00	120.00	48.99		-5.00	4025.00	63.44	-124.35	124.35	Accept	0.05	Not significant
Count	4.75	4.00	0.50	0.25		5.00	6.00	0.00	0.00									
Average	71.75	4.00	21.55	10.77		68.00	6.00	24.00	9.80		3.75	212.06	14.56	-28.54	28.54	Accept	0.05	Not significant
B1	85.00	4.00	10.00	5.00		80.00	6.00	0.00	0.00		5.00	25.00	5.00	-9.80	9.80	Accept	0.05	Not significant
B2	80.00	2.00	0.00	0.00		68.00	5.00	26.83	12.00		12.00	144.00	12.00	-23.52	23.52	Accept	0.05	Not significant
B3	65.00	4.00	30.00	15.00		60.00	6.00	30.98	12.65		5.00	385.00	19.62	-38.46	38.46	Accept	0.05	Not significant
X1	50.00	2.00	42.43	30.00		20.00	1.00	0.00	0.00		30.00	900.00	30.00	-58.80	58.80	Accept	0.05	Not significant
X2	70.00	4.00	34.64	17.32		68.00	5.00	26.83	12.00		2.00	444.00	21.07	-41.30	41.30	Accept	0.05	Not significant
X3	90.00	4.00	11.55	5.77		66.67	6.00	32.66	13.33		23.33	211.11	14.53	-28.48	28.48	Accept	0.05	Not significant
B4	60.00	3.00	34.64	20.00		20.00	1.00	0.00	0.00		40.00	400.00	20.00	-39.20	39.20	Reject	0.05	Significant
B5	80.00	1.00	0.00	0.00		80.00	1.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	Accept	0.05	Not significant
B6	70.00	4.00	34.64	17.32		80.00	6.00	0.00	0.00		-10.00	300.00	17.32	-33.95	33.95	Accept	0.05	Not significant
B7	50.00	4.00	34.64	17.32		40.00	6.00	30.98	12.65		10.00	460.00	21.45	-42.04	42.04	Accept	0.05	Not significant
B8	13.33	3.00	11.55	6.67		20.00	4.00	0.00	0.00		-6.67	44.44	6.67	-13.07	13.07	Accept	0.05	Not significant
Total	570.00	4.00	158.75	79.37		473.33	6.00	107.83	44.02		96.67	8237.78	90.76	-177.89	177.89	Accept	0.05	Not significant
Count	8.75	4.00	0.96	0.48		7.83	6.00	1.33	0.54									
Average	66.71	4.00	22.58	11.29		62.08	6.00	18.33	7.48		4.62	183.51	13.55	-26.55	26.55	Accept	0.05	Not significant
Total Av>0	465.00	4.00	102.47	51.23		403.33	6.00	103.09	42.08		61.67	4396.11	66.30	-129.95	129.95	Accept	0.05	Not significant
Count	6.25	4.00	0.50	0.25		5.83	6.00	0.41	0.17									
Average	75.60	4.00	20.71	10.36		69.44	6.00	17.94	7.32		6.15	160.87	12.68	-24.86	24.86	Accept	0.05	Not significant
Total CIMIN>0	265.00	4.00	59.72	29.86		263.33	6.00	78.40	32.01		1.67	1916.11	43.77	-85.80	85.80	Accept	0.05	Not significant
Count	3.50	4.00	0.58	0.29		3.83	6.00	0.41	0.17									

Average	77.08	4.00	18.87	9.44		69.17	6.00	20.10	8.21		7.92	156.42	12.51	-24.51	24.51	Accept	0.05	Not significant
C1	60.00	4.00	40.00	20.00		36.67	6.00	34.45	14.06		23.33	597.78	24.45	-47.92	47.92	Accept	0.05	Not significant
C2	30.00	4.00	34.64	17.32		20.00	6.00	0.00	0.00		10.00	300.00	17.32	-33.95	33.95	Accept	0.05	Not significant
C3	65.00	4.00	30.00	15.00		68.00	5.00	26.83	12.00		-3.00	369.00	19.21	-37.65	37.65	Accept	0.05	Not significant
X1	80.00	4.00	0.00	0.00		60.00	6.00	30.98	12.65		20.00	160.00	12.65	-24.79	24.79	Accept	0.05	Not significant
X2	15.00	4.00	10.00	5.00		50.00	6.00	32.86	13.42		-35.00	205.00	14.32	-28.06	28.06	Reject	0.05	Significant
C4	50.00	4.00	34.64	17.32		60.00	6.00	30.98	12.65		-10.00	460.00	21.45	-42.04	42.04	Accept	0.05	Not significant
C5	30.00	4.00	34.64	17.32		30.00	6.00	24.49	10.00		0.00	400.00	20.00	-39.20	39.20	Accept	0.05	Not significant
C6	35.00	4.00	30.00	15.00		20.00	6.00	0.00	0.00		15.00	225.00	15.00	-29.40	29.40	Accept	0.05	Not significant
C7	20.00	1.00	0.00	0.00			0.00				20.00	0.00	0.00	0.00	0.00	Reject	0.05	Significant
Total	370.00	4.00	166.93	83.47		333.33	6.00	104.05	42.48		36.67	8771.11	93.65	-183.56	183.56	Accept	0.05	Not significant
Count	8.25	4.00	0.50	0.25		7.83	6.00	0.41	0.17									
Average	44.79	4.00	20.48	10.24		42.20	6.00	12.09	4.94		2.59	129.28	11.37	-22.29	22.29	Accept	0.05	Not significant
Total Av>0	315.00	4.00	133.04	66.52		263.33	6.00	111.30	45.44		51.67	6489.44	80.56	-157.89	157.89	Accept	0.05	Not significant
Count	6.00	4.00	0.00	0.00		5.83	6.00	0.41	0.17									
Average	52.50	4.00	22.17	11.09		44.33	6.00	17.68	7.22		8.17	175.03	13.23	-25.93	25.93	Accept	0.05	Not significant
Total CIMIN>0	80.00	4.00	0.00	0.00		60.00	6.00	30.98	12.65		20.00	160.00	12.65	-24.79	24.79	Accept	0.05	Not significant
Count	1.00	4.00	0.00	0.00		1.00	6.00	0.00	0.00									
Average	80.00	4.00	0.00	0.00		60.00	6.00	30.98	12.65		20.00	160.00	12.65	-24.79	24.79	Accept	0.05	Not significant
D1	80.00	4.00	0.00	0.00		80.00	6.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	Accept	0.05	Not significant
D2	20.00	4.00	0.00	0.00		30.00	6.00	24.49	10.00		-10.00	100.00	10.00	-19.60	19.60	Accept	0.05	Not significant
D1/2/a	65.00	4.00	30.00	15.00		70.00	6.00	24.49	10.00		-5.00	325.00	18.03	-35.33	35.33	Accept	0.05	Not significant
D3	80.00	4.00	0.00	0.00		70.00	6.00	24.49	10.00		10.00	100.00	10.00	-19.60	19.60	Accept	0.05	Not significant
D4	20.00	4.00	0.00	0.00		60.00	5.00	37.42	16.73		-40.00	280.00	16.73	-32.80	32.80	Reject	0.05	Significant
D5	65.00	4.00	30.00	15.00		60.00	6.00	30.98	12.65		5.00	385.00	19.62	-38.46	38.46	Accept	0.05	Not significant
D6	65.00	4.00	30.00	15.00		70.00	6.00	24.49	10.00		-5.00	325.00	18.03	-35.33	35.33	Accept	0.05	Not significant

D7	80.00	3.00	0.00	0.00		60.00	3.00	34.64	20.00		20.00	400.00	20.00	-39.20	39.20	Accept	0.05	Not significant
D8	50.00	4.00	34.64	17.32		60.00	6.00	30.98	12.65		-10.00	460.00	21.45	-42.04	42.04	Accept	0.05	Not significant
Total	505.00	4.00	102.47	51.23		520.00	6.00	82.95	33.86		-15.00	3771.67	61.41	-120.37	120.37	Accept	0.05	Not significant
Count	8.75	4.00	0.50	0.25		8.33	6.00	0.52	0.21									
Average	57.92	4.00	12.28	6.14		62.87	6.00	11.98	4.89		-4.95	61.61	7.85	-15.38	15.38	Accept	0.05	Not significant
Total Av>0	345.00	4.00	113.58	56.79		380.00	6.00	103.54	42.27		-35.00	5011.67	70.79	-138.75	138.75	Accept	0.05	Not significant
Count	6.00	4.00	0.00	0.00		5.83	6.00	0.41	0.17									Significant
Average	57.50	4.00	18.93	9.46		65.56	6.00	18.58	7.58		-8.06	147.11	12.13	-23.77	23.77	Accept	0.05	Not significant
Total CIMIN>0	180.00	4.00	84.85	42.43		200.00	6.00	72.66	29.66		-20.00	2680.00	51.77	-101.47	101.47	Accept	0.05	Not significant
Count	3.00	4.00	0.00	0.00		3.00	6.00	0.00	0.00									
Average	60.00	4.00	28.28	14.14		66.67	6.00	24.22	9.89		-6.67	297.78	17.26	-33.82	33.82	Accept	0.05	Not significant
E1	25.00	4.00	37.86	18.93		26.67	6.00	27.33	11.16		-1.67	482.78	21.97	-43.07	43.07	Accept	0.05	Not significant
E2	0.00	4.00	0.00	0.00		20.00	4.00	0.00	0.00		-20.00	0.00	0.00	0.00	0.00	Reject	0.05	Significant
Total	25.00	4.00	37.86	18.93		40.00	6.00	30.98	12.65		-15.00	518.33	22.77	-44.62	44.62	Accept	0.05	Not significant
Count	2.00	4.00	0.00	0.00		1.67	6.00	0.52	0.21									
Average	12.50	4.00	18.93	9.46		23.33	6.00	13.66	5.58		-10.83	120.69	10.99	-21.53	21.53	Accept	0.05	Not significant
Total Av>0	25.00	4.00	37.86	18.93		26.67	6.00	27.33	11.16		-1.67	482.78	21.97	-43.07	43.07	Accept	0.05	Not significant
Count	1.00	4.00	0.00	0.00		1.00	6.00	0.00	0.00									
Average	25.00	4.00	37.86	18.93		26.67	6.00	27.33	11.16		-1.67	482.78	21.97	-43.07	43.07	Accept	0.05	Not significant
Total CIMIN>0	25.00	4.00	37.86	18.93		26.67	6.00	27.33	11.16		-1.67	482.78	21.97	-43.07	43.07	Accept	0.05	Not significant
Count	1.00	4.00	0.00	0.00		1.00	6.00	0.00	0.00									
Average	25.00	4.00	37.86	18.93		26.67	6.00	27.33	11.16		-1.67	482.78	21.97	-43.07	43.07	Accept	0.05	Not significant
F1	35.00	4.00	30.00	15.00		60.00	6.00	30.98	12.65		-25.00	385.00	19.62	-38.46	38.46	Accept	0.05	Not significant
F2		0.00					0.00				0.00	0.00	0.00	0.00	0.00	Accept	0.05	Not significant

F3	50.00	4.00	34.64	17.32		60.00	6.00	30.98	12.65		-10.00	460.00	21.45	-42.04	42.04	Accept	0.05	Not significant
F4	5.00	4.00	10.00	5.00		13.33	6.00	10.33	4.22		-8.33	42.78	6.54	-12.82	12.82	Accept	0.05	Not significant
F5	10.00	4.00	11.55	5.77		30.00	6.00	24.49	10.00		-20.00	133.33	11.55	-22.63	22.63	Accept	0.05	Not significant
Total	100.00	4.00	16.33	8.16		163.33	6.00	46.33	18.92		-63.33	424.44	20.60	-40.38	40.38	Reject	0.05	Significant
Count	4.00	4.00	0.00	0.00		4.00	6.00	0.00	0.00									
Average	25.00	4.00	4.08	2.04		40.83	6.00	11.58	4.73		-15.83	26.53	5.15	-10.10	10.10	Reject	0.05	Significant
Total Av>0	60.00	4.00	23.09	11.55		90.00	6.00	45.17	18.44		-30.00	473.33	21.76	-42.64	42.64	Accept	0.05	Not significant
Count	2.00	4.00	0.00	0.00		2.00	6.00	0.00	0.00									
Average	30.00	4.00	11.55	5.77		45.00	6.00	22.58	9.22		-15.00	118.33	10.88	-21.32	21.32	Accept	0.05	Not significant
Total CIMIN>0	10.00	4.00	11.55	5.77		30.00	6.00	24.49	10.00		-20.00	133.33	11.55	-22.63	22.63	Accept	0.05	Not significant
Count	1.00	4.00	0.00	0.00		1.00	6.00	0.00	0.00									
Average	10.00	4.00	11.55	5.77		30.00	6.00	24.49	10.00		-20.00	133.33	11.55	-22.63	22.63	Accept	0.05	Not significant
G1	80.00	4.00	0.00	0.00		70.00	6.00	24.49	10.00		10.00	100.00	10.00	-19.60	19.60	Accept	0.05	Not significant
G2	65.00	4.00	30.00	15.00		60.00	6.00	30.98	12.65		5.00	385.00	19.62	-38.46	38.46	Accept	0.05	Not significant
G3	20.00	4.00	0.00	0.00		20.00	6.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	Accept	0.05	Not significant
G4	65.00	4.00	30.00	15.00		60.00	6.00	30.98	12.65		5.00	385.00	19.62	-38.46	38.46	Accept	0.05	Not significant
Total	230.00	4.00	60.00	30.00		210.00	6.00	79.75	32.56		20.00	1960.00	44.27	-86.77	86.77	Accept	0.05	Not significant
Count	4.00	4.00	0.00	0.00		4.00	6.00	0.00	0.00									
Average	57.50	4.00	15.00	7.50		52.50	6.00	19.94	8.14		5.00	122.50	11.07	-21.69	21.69	Accept	0.05	Not significant
Total Av>0	210.00	4.00	60.00	30.00		190.00	6.00	79.75	32.56		20.00	1960.00	44.27	-86.77	86.77	Accept	0.05	Not significant
Count	3.00	4.00	0.00	0.00		3.00	6.00	0.00	0.00									
Average	70.00	4.00	20.00	10.00		63.33	6.00	26.58	10.85		6.67	217.78	14.76	-28.92	28.92	Accept	0.05	Not significant
Total CIMIN>0	145.00	4.00	30.00	15.00		130.00	6.00	50.20	20.49		15.00	645.00	25.40	-49.78	49.78	Accept	0.05	Not significant
Count	2.00	4.00	0.00	0.00		2.00	6.00	0.00	0.00									
Average	72.50	4.00	15.00	7.50		65.00	6.00	25.10	10.25		7.50	161.25	12.70	-24.89	24.89	Accept	0.05	Not significant

Total Group score											0.00	0.00	0.00	0.00	0.00	Accept	0.05	Not significant
Total	2350.00	4.00	493.56	246.78		2330.00	6.00	400.75	163.61		20.00	87666.67	296.09	-580.33	580.33	Accept	0.05	Not significant
Count	44.00	4.00	2.00	1.00		43.00	6.00	3.16	1.29									
Average	53.82	4.00	13.00	6.50		54.87	6.00	12.42	5.07		-1.05	67.97	8.24	-16.16	16.16	Accept	0.05	Not significant
Total Av>0	1945.00	4.00	458.80	229.40		1923.33	6.00	472.17	192.76		21.67	89782.78	299.64	-587.29	587.29	Accept	0.05	Not significant
Count	32.25	4.00	1.26	0.63		32.50	6.00	1.22	0.50									
Average	60.76	4.00	16.02	8.01		59.59	6.00	16.05	6.55		1.17	107.13	10.35	-20.29	20.29	Accept	0.05	Not significant
Total CIMIN>0	1040.00	4.00	247.12	123.56		1050.00	6.00	327.35	133.64		-10.00	33126.67	182.01	-356.73	356.73	Accept	0.05	Not significant
Count	16.25	4.00	0.96	0.48		16.83	6.00	0.41	0.17									
Average	64.48	4.00	16.96	8.48		62.48	6.00	19.62	8.01		2.01	136.04	11.66	-22.86	22.86	Accept	0.05	Not significant

Table 80 Significance test for HRO observations comparing incidents with significantly low impact to incidents with significantly high impact for 2006

In 2004, the overall, average score for observed HRO principles for significantly high and low incident impacts is not significantly different. Within the individual groups (A-G), it was found that

- Group D considering those HRO principles with an average, positive cost benefit,
- Group D considering those HRO principles with a 97.5% chance of being cost beneficial, and
- Group G for all HRO principles

had a significantly higher average HRO score for high incident impacts. Within the individual groups (A-G), it was found that

- Group C considering those HRO principles with an average, positive cost benefit, and
- Group F for all HRO principles

had a significantly higher average HRO score for low incident impacts. In 2004, the individual HRO principles A8, B4, C3, CX2, C7, D1, D8 and G3 had a significantly higher average score for high incident impacts. The individual HRO principles B5, B8 and F1 had a significantly higher average score for low impact incidents.

In 2005, the overall, average score for observed HRO principles for significantly high and low incident impacts is significantly different and a significantly high average score for HRO principles were determined for incidents with a significantly low incident impact. Within the individual groups (A-G), it was found that

- Group C considering those HRO principles with an average, positive cost benefit,
- Group C considering those HRO principles with a 97.5% chance of being cost beneficial,
- Group B considering those HRO principles with an average, positive cost benefit, and
- Group B considering those HRO principles with a 97.5% chance of being cost beneficial

had a significantly higher average HRO score for low incident impacts. In 2005, the individual HRO principles A8a, A9, B1, B3, B4, B6, B8, C2 and CX1 had a significantly higher average score for low incident impacts. The individual HRO principle F1 had a significantly higher average HRO score for high impact incidents.

In 2006, the overall, average score for observed HRO principles for significantly high and low incident impacts is not significantly different. Within the individual groups (A-G), it was found that Group F considering all HRO principles had a significantly higher average HRO score for low incident impacts. In 2006, the individual HRO principles A7, A9, CX2, D4 and E2 had a significantly higher average score for low incident impacts. The individual HRO principles B4 and C7 had a significantly higher average HRO score for high impact incidents.

4.2.3.2 Comparison between HRO survey and documented adherence to HRO principles during incidents

Finally, in the following analysis the HRO scores derived from studying HRO principles during incident management were compared to the responses of the participants in the HRO survey in the Regional Water Utility. A significance test was performed to compare the average score for observation of individual HRO principles under trying conditions (Weick, 1987) during incidents with the average score for HRO principles perceived and evaluated by survey participants. The statistical analysis is presented in Table 81 .

										Significance testing							
										H0: X1 - X2 = 0		X1	Incidents				
										H1: X1 - X2 <>0		X2	Baseline				
										SL: 5%							
	Incident data					Baseline survey data											
	Av.	SE	CI 95% min	CI 95% max		Av.	SD	SE		mean X1 - mean X2	Variance X1-X2	SE	CI 95% min	CI 95% max	H0	SL	Comment
A1	89.73	2.53	84.78	94.68		90.00	10.44	3.02		-0.27	15.47	3.93	-7.71	7.71	Accept	0.05	
A2	67.03	5.81	55.64	78.42		63.33	32.84	9.48		3.69	123.66	11.12	-21.80	21.80	Accept	0.05	
A3	85.95	3.62	78.84	93.05		92.73	10.09	3.04		-6.78	22.39	4.73	-9.27	9.27	Accept	0.05	
A4	88.65	3.15	82.47	94.83		93.33	9.85	2.84		-4.68	18.02	4.24	-8.32	8.32	Accept	0.05	
A5	80.00	4.78	70.63	89.37		88.33	10.30	2.97		-8.33	31.70	5.63	-11.03	11.03	Accept	0.05	
A6	86.49	2.46	81.67	91.30		61.67	31.29	9.03		24.82	87.60	9.36	-18.35	18.35	Reject	0.05	Better performance during incidents
A7	44.00	14.70	15.19	72.81		43.33	37.01	10.68		0.67	330.14	18.17	-35.61	35.61	Accept	0.05	
A8	68.00	19.60	29.59	106.41		26.67	33.39	9.64		41.33	476.93	21.84	-42.80	42.80	Accept	0.05	
A8a	80.61	3.74	73.27	87.94		70.00	31.33	9.05		10.61	95.82	9.79	-19.19	19.19	Accept	0.05	
A9	67.27	10.88	45.95	88.60		45.00	35.29	10.19		22.27	222.13	14.90	-29.21	29.21	Accept	0.05	
A10	77.84	5.13	67.79	87.89		66.67	35.51	10.25		11.17	131.35	11.46	-22.46	22.46	Accept	0.05	
B1	78.92	3.71	71.64	86.20		66.67	35.51	10.25		12.25	118.83	10.90	-21.37	21.37	Accept	0.05	
B2	78.00	3.09	71.95	84.05		70.00	31.33	9.05		8.00	91.34	9.56	-18.73	18.73	Accept	0.05	
B3	78.89	4.29	70.49	87.29		71.67	32.43	9.36		7.22	106.00	10.30	-20.18	20.18	Accept	0.05	
X1	75.00	12.39	50.71	99.29		41.67	34.60	9.99		33.33	253.32	15.92	-31.20	31.20	Reject	0.05	Better performance during incidents
X2	84.57	3.18	78.33	90.81		56.67	32.84	9.48		27.90	100.04	10.00	-19.60	19.60	Reject	0.05	Better performance during incidents
X3	91.89	2.95	86.12	97.67		86.67	23.09	6.67		5.23	53.13	7.29	-14.29	14.29	Accept	0.05	
B4	67.27	9.45	48.76	85.79		60.00	36.18	10.44		7.27	198.35	14.08	-27.60	27.60	Accept	0.05	
B5	63.64	8.45	47.07	80.20		48.33	35.63	10.29		15.30	177.21	13.31	-26.09	26.09	Accept	0.05	
B6	73.14	4.78	63.78	82.51		49.23	33.28	9.23		23.91	108.03	10.39	-20.37	20.37	Reject	0.05	Better performance during incidents
B7	50.56	5.19	40.38	60.74		27.27	27.24	8.21		23.28	94.41	9.72	-19.04	19.04	Reject	0.05	Better performance during incidents
B8	24.29	6.69	11.18	37.40		36.67	32.84	9.48		-12.38	134.64	11.60	-22.74	22.74	Accept	0.05	
C1	63.43	5.65	52.35	74.50		81.67	21.67	6.26		-18.24	71.06	8.43	-16.52	16.52	Reject	0.05	Better performance in baseline survey
C2	60.00	5.85	48.53	71.47		63.33	32.84	9.48		-3.33	124.13	11.14	-21.84	21.84	Accept	0.05	

C3	75.00	4.54	66.09	83.91		50.00	35.68	10.30		25.00	126.71	11.26	-22.06	22.06	Reject	0.05	Better performance during incidents
X1	77.84	4.50	69.01	86.67		61.67	31.29	9.03		16.17	101.86	10.09	-19.78	19.78	Accept	0.05	
X2	53.53	6.19	41.40	65.66		36.67	32.84	9.48		16.86	128.20	11.32	-22.19	22.19	Accept	0.05	
C4	69.70	4.70	60.49	78.90		65.00	34.25	9.89		4.70	119.79	10.94	-21.45	21.45	Accept	0.05	
C5	51.76	5.86	40.28	63.25		33.33	28.71	8.29		18.43	103.00	10.15	-19.89	19.89	Accept	0.05	
C6	43.53	5.76	32.25	54.81		30.00	35.68	10.30		13.53	139.19	11.80	-23.12	23.12	Accept	0.05	
C7	20.00	0.00	20.00	20.00		16.67	22.29	6.44		3.33	41.41	6.44	-12.61	12.61	Accept	0.05	
D1	76.55	2.99	70.69	82.41		50.00	35.68	10.30		26.55	115.00	10.72	-21.02	21.02	Reject	0.05	Better performance during incidents
D2	25.00	3.24	18.65	31.35		58.33	34.60	9.99		-33.33	110.23	10.50	-20.58	20.58	Reject	0.05	Better performance in baseline survey
D1/2/a	82.70	3.48	75.88	89.52		91.67	10.30	2.97		-8.96	20.95	4.58	-8.97	8.97	Accept	0.05	
D3	82.16	2.16	77.92	86.40		78.33	28.87	8.33		3.83	74.12	8.61	-16.87	16.87	Accept	0.05	
D4	45.45	5.66	34.36	56.55		68.33	30.10	8.69		-22.88	107.53	10.37	-20.32	20.32	Reject	0.05	Better performance in baseline survey
D5	80.00	3.90	72.35	87.65		65.00	34.25	9.89		15.00	112.97	10.63	-20.83	20.83	Accept	0.05	
D6	81.62	3.41	74.93	88.31		43.33	37.01	10.68		38.29	125.78	11.22	-21.98	21.98	Reject	0.05	Better performance during incidents
D7	69.33	6.72	56.16	82.51		38.33	31.29	9.03		31.00	126.77	11.26	-22.07	22.07	Reject	0.05	Better performance during incidents
D8	63.53	5.37	53.00	74.06		76.67	28.07	8.10		-13.14	94.51	9.72	-19.05	19.05	Accept	0.05	
E1	55.14	6.02	43.33	66.94		76.67	28.07	8.10		-21.53	101.94	10.10	-19.79	19.79	Reject	0.05	Better performance in baseline survey
E2	16.88	4.76	7.54	26.21		20.00	29.54	8.53		-3.13	95.40	9.77	-19.14	19.14	Accept	0.05	
F1	49.19	5.23	38.93	59.45		40.00	38.14	11.01		9.19	148.60	12.19	-23.89	23.89	Accept	0.05	
F2	40.00	40.00	-38.40	118.40		38.33	31.29	9.03		1.67	1681.57	41.01	-80.37	80.37	Accept	0.05	
F3	60.71	5.39	50.14	71.28		65.00	34.25	9.89		-4.29	126.81	11.26	-22.07	22.07	Accept	0.05	
F4	24.71	4.23	16.42	32.99		15.00	22.76	6.57		9.71	61.05	7.81	-15.31	15.31	Accept	0.05	
F5	51.76	6.21	39.59	63.94		75.00	27.14	7.83		-23.24	99.95	10.00	-19.60	19.60	Reject	0.05	Better performance in baseline survey
G1	84.86	2.38	80.21	89.52		68.33	30.10	8.69		16.53	81.15	9.01	-17.66	17.66	Accept	0.05	
G2	76.76	3.99	68.94	84.58		50.00	31.33	9.05		26.76	97.74	9.89	-19.38	19.38	Reject	0.05	Better performance during incidents
G3	25.71	3.24	19.37	32.06		43.33	37.01	10.68		-17.62	124.61	11.16	-21.88	21.88	Accept	0.05	
G4	68.75	4.75	59.45	78.05		50.00	39.54	11.42		18.75	152.83	12.36	-24.23	24.23	Accept	0.05	

Table 81 Significance test of scores for HRO principles during incidents compared to HRO survey

It was found that the majority of HRO principles are not significantly different for both datasets. Significant differences at a significance level of 5% were identified for the following HRO principles: In Table 82, the HRO principles are presented that were identified to perform significantly better under trying conditions during incidents compared to the HRO survey.

Ref	Description
Organisational culture of reliability	
A6	All our employees take responsibility where problems are identified and immediate corrective action programmes are required.
Continuous learning and intensive training	
X1	Our staff question procedures when in doubt about their appropriateness.
X2	In unforeseen situations, staff in operations don't follow rules blindly, but negotiate the course of action in a collegial manner with more experienced staff and supervisors.
B6	In our organisation, even minor errors and incidents provide a source for learning which are assessed through root cause analysis.
B7	Our organisation develops a collective memory for failures, incidents and root causes for failure, which helps the organisation to anticipate future problems.
Effective and varied patterns of communication	
C3	Our staff in operations are encouraged to share their experiences relating to the reliability of the system. Communication is designed as bottom up and top down to ensure rapid flow of information through the hierarchy of the system. Rapid dissemination of information helps the organisation to respond to water quality incidents with corrective action aiming to prevent the escalation of failure.
Adaptable decision making dynamics and flexible organisational structures	
D1	Our organisation can only prevent outbreaks with a high level of centralisation, because low-level decision makers have insufficient understanding of the inter-relationship between their action and consequences on other elements of the water supply system. During an emergency, control has to be maintained highly centralised in order to maintain overview of the entire system response to action on all sub-units.
D6	Our organisation has a hierarchical structure for decision making which reflects expertise, know-how and seniority. Each level has controls and regulating mechanisms.
D7	Our organisation requires staff to conform to organisational norms and avoids innovative, autonomous or creative behaviours.
Human resource management practices that support reliability	
G1	In recruitment and selection, our organisation acquires suitable and skilled candidates for the jobs aiming to match the complexity of the environment with an equally complex set of people to understand the system. Diverging backgrounds for staff offer different ways of looking at systems.

Table 82 HRO principles that were identified to perform significantly better under trying conditions

In Table 83, the HRO principles are presented that were identified to perform significantly worse under trying conditions during incidents compared to the baseline survey.

Ref.	Description
Effective and varied patterns of communication	
C1	Our communication system makes our water supply system better understandable, predictable and controllable.
Adaptable decision making dynamics and flexible organisational structures	
D2	In our organisation, decentralisation is required to respond rapidly to unfolding failures. An emergency can be confined to one sub-unit, which is subsequently isolated from the entire system. The control over an emergency is decentralised to this subunit until the emergency is cleared.
D4	Our standard operating procedures are constantly updated and incorporate lessons learnt. Formal rules and procedures are effective elements to identify and control risk.
System and human redundancy	
E1	Our organisation maintains reserve capacity in the system. This includes back-up functions, overlapping tasks and responsibilities.
Precise procedures in managing technology	
F5	In our organisation, maintenance activity and protocols as well as performance data are used to monitor the healthy operation of the system.

Table 83 HRO principles that were identified to perform significantly worse under trying conditions

4.2.4 Observational study in the incident control centre

Organisational culture of reliability						
Ref	HRO Indicator	Johnson	Asset type	Type of evidence in addition to observation	Example	
A1	During the incident, staff in the incident management team and operators involved had a strong sense for the company objectives of the organisation and shared a common system of beliefs and perceptions.	Culture	Human Intangible	Actions and event described in the root cause analysis for the incident indicating concern for the safety and reliability of drinking water prior to or during human intervention in the technical water supply system. Actions taken in response to the incident described in the incident report	In this organisation incidents frequently occur. The organisation has a dedicated team of incident managers who take control over the situation and company resources at first sight of an incident. Due to the experience in incident management, the procedures to reduce the impact and re-instate normal operation are well tried and tested routines. During an incident, personnel in the incident management organisation are determined to protect customers from exposure to hazards, aim to reduce the impact of the incident by using all feasible resources and ensure that the supply system is re-instated to safe and reliable operation. The team of incident managers are highly skilled and problem orientated managers who are capable of managing personnel and resources in highly uncertain and trying conditions.	

A2	During the incident, the water supply system was continuously monitored so that failure events were foreseen and understood.	Control systems	Physical Information Human	Monitoring data of the water supply system provided in the incident report, minutes of the incident review meeting and notification of incident to the regulator.	The organisation defines failure as impact on customers and uses the classification of event, incident, significant incident and emergency. For physical assets, identification of failure at source of the problem is more likely associated to "assets above ground". Here, asset failures can be detected early and, if appropriate action is taken, impact on customers can be eliminated. E.g., a WTW will have significant numbers of monitoring equipment, in particular for process control and operational status of the plant. These are tied into hardwired control loops, PLC, SCADA and – via telemetry – to the centralised control room. For "assets below ground" such as water mains, the monitoring of physical asset failure is only limited. In distribution, incident awareness is commonly generated by customer contact who call the organisation to report or complain about "no water" or discolouration. The organisation has a dedicated call centre to receive customer contacts. When commenting on water quality or supply reliability issues, customers are challenged to describe their observation. In discolouration events, a protocol is followed by call centre staff to identify the location of the customer, the severity of discolouration (in terms of colour or any other observation). Customer call and the type of observation are displayed on a visual display unit as a geo-referenced symbol of a regional map in the control room. With increasing customer call, the displayed symbol increases to indicate the magnitude of the exposure. Proxy indicators based on flow and pressure gauges can indicate abnormal flow patterns that may suggest physical asset failure of a water main. Only recently, a scheme was initiated in one area to fit sufficient numbers of flow meters and pressure gauges to monitor any abnormal operational patterns against expected system performance. Water quality failure in distribution assets can only be detected with monitoring and sampling regimes.	

A3	During the incident, our staff in operations had a highly developed understanding of their contribution to water safety and their role in the system.	Rituals & Routines, Culture	Human, Intangible	General observation in the Regional Operations & Control Centre; Description of chronological actions and event prior to or during the incident which contributed to or reduced the likelihood and severity of this incident;	Considerable long periods between the actual failure or initial hazard exposure and the awareness of an incident can elapse. On incident awareness, the incident management team is pressed for time to devise an adequate incident response. In the following example, the response to an incident is demonstrated. This incident was made aware to the organisation by customer calls reporting “no water”. This was caused by the rupture of a large diameter ring main. The primary task for the incident management team was to isolate the ruptured pipe at the nearest isolation valves. A quick valving operation ensured that an additional 100.000’s of properties did not loose their water supply or experienced low pressure. Furthermore, it reduced the impact on the burst site: There was a potential impact of undermining the foundation of the adjacent road and overwhelming the surface drainage with potential to experience sewer collapses. Unfortunately, due to the burst and subsequent valving operation, flow patterns changed and re-suspended deposits so that discolouration was experienced by many customers. This case demonstrates that speedy intervention is required to limit the damage but also additional problems may arise whilst aiming to reduce the impact of the incident. In this case, the main was repaired, a sample of the pipe section for analysis by asset management was taken and the ring main was re-instated.	

A4	During the incident, staff in the incident management team and operators involved acted in a collaborative and collegiate manner.	Culture; Control systems;	Human, Intangible	Description of chronological events which highlights the key activities of personnel involved in the incident	In areas with high population density, failures in the distribution network can affect a large numbers of stakeholders. Primarily, customers may experience the inconvenience of "loss of supply" and low pressure but also may be exposed to discolouration from re-suspended deposits in the water mains or hazardous water quality from contamination due to ingress of surface water or the sewerage system. Customers reporting their observations are often the primary indicator for problems in the distribution network. From an incident management viewpoint, the reported hazard type determines the immediate action e.g. by issuing a "boil notice", "advise to boil" or "do not drink". Less hazardous incidents may be sufficiently managed by providing information and advice to customers. The incident management team needs to understand the geographic spread of the hazard and size of population. This will determine the "reach out" in issuing information, notices or boil orders. Whereas large-scale incidents require the involvement of regional media, localised incidents may be manageable by an operator providing information to customers by "knocking on doors". Whereas a localised mains burst can be responded to by issuing a repair notice to a contractor (or in-house mains repair gang) a region-wide incident requires the collaboration of distribution management teams across the region. The incident procedure for a large-scale incident will also require some collaboration from water resource management teams and the production management teams if rezoning and alternative supplies are required to reduce the impact of an incident. Depending on the hazard type, alternative water supply needs to be made available, in particular for special needs customers (hospitals, health centres, etc).	
A6	During the incident, staff in the incident management team and operators involved took responsibility where problems were identified and immediate corrective action programmes were required.	Culture; Control systems;	Human	Description of chronological events and root cause of incident in the incident report how the awareness of the incident was generated and immediate actions taken	The incident management team are well aware of the impact any failure has on organisational objectives. Yet, every incident is a test of competency. Although many incidents affecting the distribution of drinking water have similar patterns, e.g. a burst main resulting in loss of supply and possible discolouration, there are always unique features to accommodate. Some areas have vulnerable or special customers, which require special attention during an incident. In other incidents, the actual incident site is difficult to access. Other areas have historically grown, complex pipe and valving arrangements so that re-zoning efforts might not be fully understood until desired or undesired effects become visible. Although principle guideline – often implicit – exist to assess the situation of an incident, novel features or site specific circumstances have to be taken into account when devising an action plan to reduce the incident impact or re-instating the system.	

A7	During the incident, staff in the incident management team and operators involved were obliged to report their mistakes without fear of punishment.	Culture; Control systems;	Human Intangible		During one incident, a number of alarms were received in the central control room due to a power failure at one WTW affecting chemical dosing systems. The power was reset and the attention of the called-out operators was drawn to further problems at the lime batching plant used for pH correction in the treatment process. The amount of alarms raised in the control room and on the SCADA disguised additional problems with the chlorination equipment that too had been affected during the power outage. After the lime-batching unit had been restored, the operators were called to another site that also had been affected by the power outage and the WTW continued production of drinking water without chlorination. The problem with the chlorination equipment was discovered after a short while and operators were called out again to assess the problem. The WTW discharges into a water tank containing chlorinated water. Due to the dilution effect, free chlorine was always present in the water distributed to customers and posed no health risk. This incident demonstrates that immediate corrective action programmes can easily overlook problems, in particular when the incident management organisation is overwhelmed by multiple failures and alarms received in the control room. On detection of the chlorine failure, the system was restored and supply continued under normal conditions. The controller had not immediately detected the chlorine failure alarm or has not passed the alarm on to the field staff, the main problem of the alarm system was a lack of prioritising critical alarms. The organisation did not blame the controller but enhanced the alarm systems design to reduce the opportunity to oversee critical alarms.	.
A8	In our organisation, individual behaviours, which jeopardise the company objectives, are recognised as unacceptable.	Culture; Control systems	Human		After an incident, personnel who were involved in the build-up or during the incident attend an incident review meeting. This meeting is primarily designed to learn from this incident and provide feedback to personnel involved. It is not designed to lay blame at individuals but encourages a critical perspective on actions and activities carried out prior and during the incident. A number of cases have been recorded where efforts to reduce incident impact and re-instating normal operations have resulted in secondary, knock-on effects. E.g., the re-zoning of supply zones generating disturbance of deposited material in pipe work causing unanticipated discolouration of drinking water. Operators and the incident management team acted in good faith, under trying conditions and pressed for an immediate or timely incident response. Staff are aware that substitutional or additional risks exist in designing an incident response. The recent introduction of DOMS plans enables a qualified, explicit assessment of substitutional or additional risk for incidents management in the distribution network.	

A8a	During the incident, our senior management was (and still is) committed to the reliability of the organisation. This was communicated to all levels in the organisation and demonstrated with investments in technology, processes and personnel.	Organisation structure; Control systems; Power structure;	Human; Intangible; Physical; Information;	Evidence of investments or maintenance spending at this site, training of operators and/or design and maintenance of incident detection and response procedures. Evidence for senior management involvement during the incident	The organisation has invested resources into early detection and rapid response to abnormal operating conditions. The incident management organisation is significantly contributing to efficient minimisation of adverse impacts on customers. It uses the regulatory objectives and targets as a measure of its effectiveness. Increasingly, the organisation manages events that have no or very low impact on customers. The organisation has "learned" to react rapidly to forego significant impact on customers. It uses its physical assets to effectively minimise the impact of e.g. a burst main. In distribution management, the incident management team has an overview over its re-zoning capability and instructs distribution field operators to carry out revalving operations aimed at minimising the impact on customers. It has access to information relating to potential discolouration of individual distribution management zones. These are prepared in accordance with DOMS – a risk assessment for adverse effects relating to regulatory objectives.	
A9	During the incident, individuals "monitor, advise, criticize and support" each other, in particular in situations where mistakes were more likely to occur.	Control systems; Rituals & Routines	Human Intangible	Description of "what went well" and improvement areas in the minutes of the incident review meeting.	During an incident in the distribution infrastructure, the incident management team has access to personnel most familiar with the particular distribution zone affected. These experts advise the incident manager who co-ordinates effort but is not necessarily the expert of this particular asset. The incident manager will investigate all resources available to reduce the impact of the incident or needs to re-instate normal operations, whereas the experts will identify possible means of achieving this with the resources available to the organisation.	
A10	During the incident, staff in the incident management team and operators involved were attentive, alert and acted with care.	Rituals & routines; Control systems;	Human Information	General evaluation based on actions and events described in the incident report, minutes of incident review meeting and notification of event to the regulator.	The incident management team draws on highly experienced and "proven" personnel who advise on and devise an action plan for mitigating the impact of an incident. Water safety objectives and supply reliability considerations are the ultimate test for the due course of action. Acting with care does not, however, mitigate against unforeseen circumstances that do arise. These are a result of the diverse nature of physical asset arrangements, the many different needs of customers, 3rd party impacts an incident can have. Interdependency of incident effects may produce additional adverse circumstances to be monitored and controlled with adequate intervention.	

Continuous learning and intensive training						
Ref.	HRO Indicator	Johnson	Asset type	Type of evidence in addition to observation	Example	
B1	After the incident, continuous learning and training were facilitated in a review of processes and ways of operating.	Rituals & routines	Information Human Intangible	Minutes of incident review meeting and incident report describing "what went well" and improvement areas. Actions raised on the Lotus notes "Action tracker" database.	The incident log captures data and information on physical, information and human assets involved during the incident, in particular a measure for the incident impact on customers and 3rd parties with particular emphasis on the hazard types, the size of affected population and the timing between incident occurrence and incident awareness as well as the incident response times. It records data of the condition and performance of the drinking water supply system, the planning, implementation and operation of an incident response, actions taken to reduce the impact of the incident, monitoring data and information relating to the water supply systems response to any intervention but also any actions, behaviours by incident management team members, operators, field staff and 3rd parties. After an incident, a review meeting takes place to evaluate actions and activities prior to and during the incident. It identifies causes and contributing factors in the build-up to the incidents and, secondly, the effectiveness and efficiency of reducing the incident impact and re-instating of normal supply. The agenda of the incident review meeting takes the form of identifying who is present, update and current situation of the incident, ongoing effect on the customer, a review of the log events, issues arising and further data/investigation requirements, issues that went well, what has occurred that could be done better, lessons learnt and recommendations arising, confirmation of next steps.	

B2	Prior to the incident, staff in the incident management team and operators involved received training on the requirements of maintaining a safe system. These are embedded in formal rules, general guidelines and standardised frameworks.	Rituals & routines;	Human; Intangible; Information;	Professional qualification and experience of operators and incident management staff. BTEC qualification and "license to operate" plant and equipment for operators. Evidence of actions compliant with "Standard Operating Procedures"	The organisation plans, implements and operates staff development programmes leading to appreciation, knowledge, experience and ability in the identification of abnormal operating conditions, events and incidents with potential impact on the safety and reliability of drinking water. Staff development emphasises the means of operating and maintaining a safe and reliability drinking water supply system using the physical, information and human asset base of the organisation. Risk assessments for operational activities are increasingly promoted to anticipate failure scenarios and their probability. They guide the planning of method statement and contingency planning. The organisation plans, implements and operates staff development programmes leading to appreciation, knowledge, experience and ability in managing abnormal operating conditions, events and incidents with potential impact on the safety and reliability of drinking water. Staff development emphasises the means of eliminating, reducing, isolating and controlling hazards during an incident using the physical, information and human asset base of the organisation. The organisation provides information, training, instructions and supervision. Staff development is monitored audited and reviewed.	
B3	During the incident, staff in the incident management team and operators involved adhered to standard operating procedures but also pro-actively identified potential sources of failure and actions to stop faults from escalating.	Routines	Information	Assessment of actions building up to or during the incident to be in compliance with policies and operating procedures of the organisation	Standard Operating Procedures are highly modularised and can be applied to the appropriate incident scenario. In one incident, contractors were working on site following all formalities between the utility and 3rd parties. When digging, the contractor did not come across any warning tape or sand that is used to identify a power cable further below. As no warning was visible, the contractor continued and hit the power cable that caused a power failure and subsequently a chlorination failure. Power failure and chlorination failure were received in the control room and incident management procedures instigated. The incident manager followed procedures to call out personnel to investigate the causes of the incident, on confirmation of the problem a contractor was called out to repair the power supply. In the meantime, procedures were followed to assess the water quality implications of the chlorination failure on forward supply. The advisors to the incident manager anticipated a dilution effect of the un-chlorinated water with the content of the forward SR, which deemed slug dosing unnecessary. The water quality monitoring data at the SR outlet were carefully monitored for the remainder of the day and confirmed that the dilution had not reduced free chlorine to zero.	

X3	During the incident, staff in the incident management team and operators involved established an emergency response team for joint decision making in order to avoid overlooking complex circumstances.	Organisational structure; Control systems; Power structure	Human	Evidence of timing and actions taken by the central incident response team	In operations, personnel pre-plan their activities, in particular when interfacing with the physical asset system. SOP guide the work planning. Decision-making procedures are increasingly demanding risk assessments, risk mitigation and contingency planning for pre-planning work. These are tied into a review process by staff that are more expert. The water utility makes provisions for the organisation to establish an incident/emergency response team during abnormal operating conditions, events, incidents and emergencies. The incident response team is composed of an incident manager, operations resource managers, water quality scientists, operators, field staff, and representatives from asset management, liaison and press officer. These are tasked to evaluate the incident impact on customer and business, plan and implement an emergency response to reduce the incident impact and re-instate the safety and reliability of the drinking water supply. The emergency response team evaluates the incident impact and considers options to eliminate, reduce, isolate or control hazards, minimises the affected population whilst monitoring the hazard exposure time of the affected population. To this end, it deploys its resources so that critical incident impacts are minimised. The leadership during the incident is provided by the incident manager who is advised by an expert team.	
B4	Staff in the incident management team and operators maintain a commitment to continuous learning and seek the acquisition and improvement of skills.	Organisational structure;	Human; Intangible	Evidence of contributions to the incident review meeting, actions raised for improvement, assessment of the quality of root cause analysis.	Incident review meeting provides a systematic facility of learning and understanding the failure modes the water supply system can experience. Learning from incidents can be used as a reminder to check other, similar systems and provides an audit facility for the accuracy of risk assessments (in particular for the severity of an assessed risk) In the organisation, incident review meetings aim to identify "issues arising and further data/investigation requirements, issues that went well, what has occurred that could be done better, lessons learnt and recommendations arising, confirmation of next steps".	
B5	We learn from failures, near misses and mistakes by other utilities and use these as a means to study the failure susceptibility of the own organisation.	Stories; Rituals & Routines	Information		The outbreaks of cryptosporidium experienced by other water utilities triggered a large-scale risk assessment exercise for all catchments and water supply systems. These risk assessments were used to close down abstraction assets, initiating programmes to upgrade treatment processes and inform incident management procedures for incidents affecting the treatment process at these sites.	
B6	Even minor errors and incidents provide us with a source for learning.	Stories; Rituals & Routines;	Information	Evidence in the minutes of the incident review meeting and the root cause analysis	Using impact data from mains bursts is also actively used for assessing the risk in distribution networks. Whilst the failure frequency or probability is a function of pipe age, material, soil condition, etc., the impact of failure is estimated from systems configurations, topography and hydraulic arrangements. On design completion, the prediction models are then audited against previously experienced failure. Predictability of failure exceeding 60 % of cases have been reported.	

B7	Our organisation develops a collective memory for failures, incidents and root causes for failure, which helps the organisation to anticipate future problems.	Symbols Stories	Information	Recording of incidents in a centralised database which is used as a source of learning (e.g. via statistical analysis)	The organisation uses a database for recording incidents; this database provides an opportunity to investigate incidents in a structured fashion. The organisation captures data in compliance with regulatory requirements. These data emphasise the exposure of population to hazards and measures taken to reduce the incident impact.	
B8	We share a sense that learning from trial and error is not feasible to understand our water supply system. For staff training, we use offline methods of learning which consist of realistic drills, simulations and exercises to replicate potential failure scenarios.	Rituals & Routines	Information; Control systems	Evidence and assessment of incident impact on customers and the business (cost and reputation). Evidence of professional accreditation, training standards and "learning on the job" strategy	The analysis of failure, root causes and contributing factors during incidents as well as minor errors and incidents provides a source for learning for different disciplines in the organisation. Directed data analysis enables to identify trends, patterns and correlations, if conceptual frameworks are used to analyse incidents. Patterns and trends relating to the safety and reliability of drinking water supply allows decision makers in operations management and asset management to assess the need for policy development and organisational amendments to plan and implement programmes to reduce the frequency and/or hazard impact.	

Effective and varied patterns of communication						
Ref.	HRO Indicator	Johnson	Asset type	Type of evidence in addition to observation	Examples	
C1	During the incident, our communication systems make our water supply system better understandable, predictable and controllable.	Rituals & Routines; Control systems;	Information	Evidence reflecting the infrastructure of inter-personnel communication and IT systems for monitoring and control of assets, in particular incident detection and reporting mechanisms. E.g., P&I diagrams; PF diagrams; schematics of telemetry; control philosophy, in particular fail safe mechanisms; monitoring and control schedules for processes; SCADA, PLC and telemetry architecture; hardwired alarm monitoring and control loops; alarm schedules for on-site SCADA or PLC; schedule of clustered alarms for off-site SCADA;	This case study portrays the handling of alarms from production and distribution assets in the regional control centre. In normal working hours, telemetric alarms are acknowledged by the shift controllers in the control centre who then pass the alarms verbally to the production coordinator for that area. He/she will then interrogate the SCADA via a remote access to the site-SCADA and decide whether corrective action can be taken or if they need to call someone on site or to site if it is unmanned. Out of working hours, on receipt of a telemetric alarm the shift controller will interrogate the SCADA of the alarming site and decide if any corrective action can be taken. If there is any uncertainty about which course of action to take, the standby process engineer will be called.	
C2	During the incident, our organisation operated in an information rich environment. Processes were measured and understood. Data is transparent and made available to all.	Control systems	Information	Evidence of data availability and quality for monitoring and control of assets. Redundancy strategy for data. Alarm schedules. Evidence that information systems design distinguishes between normal and abnormal operating conditions with a variety of different signals that allow fast identification of incident root cause. Monitoring of water safety and reliability (process monitoring) complemented by direct asset performance and condition monitoring. (Monitoring elevated pH is an observation of the effect of an asset or process failure e.g. asset dosing pump failure). Early detection of incident potential and early warning systems of potential failure. Measured availability of redundancy. Failure prediction capability, measure of resilience and capacities to endure during trying conditions. Predictability of continued safe and reliable operation during incident (e.g. duty failure)	Operating in an information rich environment is particularly important when critical assets fail. Although this case study is not representative, it demonstrates the criticality of information at the time in the right place. In this particular incident, a duty chlorinator of a WTW failed and the standby chlorinator did not start up. No alarms were raised by the failure on the local PLC, SCADA and central control room (although the system was designed to do so) and, hence, no WTW shutdown was initiated. In effect, water receiving no chlorine dose entered the contact tank and a low chlorine alarm at the inlet of the contact tank was raised in the control centre. The plant was shutdown. Although, this was primarily a technical problem, the availability of site information also had an impact on effective decision making during the incident management. The incident review meeting concluded that more detailed site schematics and drawings were required to enable informed decisions to be made. This has been put into a rolling programme to update or create site drawings on a regional basis. Furthermore, the knowledge of personnel on site was limited. This will be addressed by ensuring accurate data is held on site.	

C5	During the incident, our organisation used various channels to transmit different types of data and information relating to monitoring and control of our assets (and ultimately water safety). Direct and complementary information enhanced information reliability.	Control systems;	Information	Evidence of using a data redundancy strategy: e.g. duty standby monitoring of processes, different monitoring systems to measure same processes and assets; architecture of data reporting based on telemetry, SCADA and PLC. Evidence for data monitoring for abnormal operating conditions and redundancy and/or fail-safe data transmission infrastructure.	The man machine interface requires critical signal to be prioritised and made aware to operators. In this case study, a critical alarm went undetected in a whole series of alarms "flooding" the site-SCADA. "There are audible enunciator panels in various parts of the works, including the control room and lime areas, which sound a common alarm that does not differentiate between types of alarm. They do not give any visual indication as to the type of alarm, or indeed, what part of the process it is from. To differentiate, the process engineers must interrogate the SCADA in the control room to view what type of alarm has been raised. The process engineers on site were dealing with a number of problems with the lime system and were working in the lime area for a substantial part of the day. The lime system is in an area remote from the control room and has no separate access to the SCADA. Whilst the process engineers viewed the SCADA in the control room on a number of occasions throughout the day, they were unaware of any problems with the chlorine system, so only viewed SCADA pages pertaining to the lime system. Prior to leaving site the process engineers checked the SCADA pages pertaining to the lime system and ascertained that all was well. They did not check any pages pertaining to the chlorine system, as they had no reason to suspect there was any problem due to the lack of local alarms or telephone calls from the production coordinator to indicate this. "	
C6	During the incident, multiple monitoring and control data from a variety of sources provided information density, which allowed individual signals to be verified.	Control systems;	Information Physical	Evidence of using a data redundancy strategy: e.g. duty standby monitoring of processes, different monitoring systems to measure same processes and assets; architecture of data reporting based on telemetry, SCADA and PLC. Evidence for data monitoring for abnormal operating conditions and redundancy and/or fail-safe data transmission infrastructure. Evidence for data and information systems infrastructure enabling the analysis of cause and effect relationships during incidents.	In this case study, the need for accuracy of information is highlighted to prevent incidents from occurring. "Contractors working on a ring main rehabilitation project refurbishment deliberately damaged a live section of a 24" main resulting in a serious burst. Supplies were maintained by rezoning and the burst was repaired promptly but not before the increased flow rates had caused significant increases in velocity in the mains serving the area leading to re-suspension of historic mains deposits. Further detailed investigations have since found that two parallel mains are located in the area. However, their location on the drawing records was inaccurate. Both mains are ca. 3 metres further north compared to the lines shown on the drawings. The main found in the excavation was mistaken for the other main and assumed to be de-commissioned for the construction work.	

Dynamic decision making and flexible organisational structures						
Ref.	HRO Indicator	Johnson	Asset type	Type of evidence in addition to observation	Examples	
D1/2a	During the incident, centralisation at collective level coexists with decentralisation at individual level. The organisation exhibits an adaptive, flexible or organic nature.	Organisation structure; Power structure; Control system;	Human; Intangible;	Evidence depicting the organisational structure and hierarchy in operations, incident and emergency management. Communication and reporting diagrams. Power, roles and responsibility of stakeholders during the incident in their job description. Explicit description of reportable observations, events, incidents. Explicit description of human intervention following the detection of an abnormal observation, event or incident. Evaluation of leadership during the incident in the chronological incident management record.	This case study demonstrates the need for central control during an incident that can have follow-n effects on many other business areas. Centralisation exists for incident co-ordination alongside with decentralised tasks to be completed by field staff. An unplanned shutdown of a WTW led to the discovery of water damage to the lime batching system. An incident support team was assembled in the incident control centre to co-ordinate the rezoning, prepare and implement contingency plans. Contractors were called to site and rezoning of the distribution system undertaken to protect supplies and service reservoir levels. The team co-ordinated and assisted with deployment of alternative supplies. Rezoning led to some low pressures and no waters in some areas. This was resolved by further rezoning. Following re-zoning, discolouration contacts started to be received from another area. The alternative supplies deployed as a contingency against loss of supplies from the WTW were used to respond to discolouration complaints. The contractors finished remedial work on the lime system over night and the works was restarted early next morning.	

D4	After the incident, the standard operating procedures were updated and incorporated lessons learnt. These formal rules and procedures are effective elements to identify and control risk.	Ritual & routines;	Human; Intangible;	Review of the minutes of the incident review meeting, in particular sections relating to improvement areas and formulated recommendations. Review of the dissemination strategy to action personnel, in particular SOP for operations management, plant and equipment operation and asset management procedures, and track actions from review meeting. Identify the communication strategy to stakeholders and implementation of updated SOP.	Following an incident, the incident review meeting will raise actions to be pursued by individual or teams in the organisation. One of these actions could be to review certain SOP. The organisation uses a database system to keep track on the pursuit of actions. Actions are assigned to a person with a specific date of completion. On the expected date, the system raises an alarm and a project manager will pursue the actionee for concluding his task or arranging a new deadline. Increasing experience with novel assets and technologies require the updating of SOP for a particular and similar assets. Changing conditions in the environment are also reviewed, assessed for additional risk and, if managed without capital investment, actions and activities prescribed in the SOP.	
D5	During the incident, activities, which were not defined in standard operating procedures, were based on decisions a most senior individual made, as they should have the best knowledge of the system.	Rituals & routines; Power structure;	Human; Intangible;	Review of SOP applicable for plant and equipment involved/affected, SOP for managing causes and effects of incidents on the safety and reliability of drinking water provided to customers. In particular, identify evidence for assessments of risk immediate during the incident but also the potential implications and risks arising from the options available to the incident management team to reinstate safe and reliable drinking water supplies.	During an incident, decision-making is centralised with the incident manager having ultimate control over resources and personnel. The incident manager takes advice from experts and field staff to make decisions, design a contingency plan and direct resources at re-instating normal operations.	
D6	During the incident, our organisation had a hierarchical structure for decision making which reflected expertise, know-how and seniority. Each level had controls and regulating mechanisms.	Organisational structure; Power structure;	Human; Intangible;	Identify the organisational structure and hierarchy in operations, incident and emergency management with particular emphasis on academic qualifications, professional experience and expertise, records of continuous professional development and performance reviews. Review of personality types for particular roles, in particular within the operations, incident and emergency management teams. Processes and procedures for monitoring, auditing and review of decision-making. Organisational structure and hierarchy for asset management capability.		

System flexibility and redundancy						
Ref	HRO Indicator	Johnson	Asset type	Type of evidence in addition to observation	Examples	
E1	Our organisation maintains reserve capacity in the system. This included back-up functions, overlapping tasks and responsibilities.	Control systems;	Physical; Information; Human;	Identify redundancies relating to physical, human and information assets. Identify deployment of stand-by technical equipment, plant, systems or strategies but also stand-by human capacities and information systems designed for abnormal operating conditions.	This case study demonstrates the use of redundancy and the fallacy it can create when common cause failure inhibit its use The electricity supply to a Pumping Station failed resulting in low pressure or an interruption to supply to up to 32,700 properties. Electricity supplies were restored approximately 4 hours later and the system rapidly returned to normal operating pressure. The pumping station has its own electricity sub-station that is provided with two independent electrical feeds. An informal risk review carried out some years ago concluded that this provided sufficient security of supply and that the cost of standby generators could not be justified. The electricity supply company have confirmed that the pumping station is fed by two separate feeders as part of the High Voltage inter-connecting ring main and hence complies with the Companies current requirements for secondary power supplies. A feasibility study was undertaken as part of a contingency planning programme. The WPS does not have a permanent connection for a mobile generator because of size of connection required. However, it is possible to connect a generator direct on to the incoming busmain via a flexible cable.	
E2	Our organisation is aware that redundancy can also be counterproductive. Back-up functions can increase technical complexity, conceal errors and can lead individuals into not performing their required tasks under the assumptions that someone else takes care of his task.	Control systems;	Physical; Information; Human;	Evidence for using redundancy as duty equipment, plant systems in the incident report. Identify detrimental behaviours in contradiction to the interests of maintaining or re-instating the safety and reliability of drinking water supply.	One incident manager reported that on occasion information systems provide too much detailed information without providing an overview of capacities and resources available to plan an incident response. He also mentioned that maintenance programmes sometimes have an adverse effect on planning an incident response. A maintenance programme will temporarily de-commission assets until their refurbishment is completed. This, however, reduces the capacity and redundancy available for designing an incident response. In another case study, the duty pump of a WPS failed due to its high age. The stand-by pump started to operate but also failed due to the same reason. This is a good example for common cause failure.	

Precise procedures in managing technology						
Ref	HRO Indicator	Johnson	Asset type	Type of evidence in addition to observation	Examples	
F1	The technology employed to deliver service on this site/ within this system was not unnecessarily complex to operate and had no detrimental effect on the incident.	Control systems;	Physical; Information; Human;	Evidence of equipment, plant and systems description in the incident report possibly depicted in a schematic process flow diagram, monitoring and control in process & instrumentation diagrams alongside with the control philosophy and boundary condition for asset operations (design rationale). Perceived understanding of the system by the incident management team described in the chronological incident description. Predictability of failure scenarios. Systems response to human intervention indicating the predictability of intervention outcomes.	Here, we are revisiting an earlier incident, where the duty and standby chlorinator system failed at a WTW without to trigger an alarm or initiate a plant shutdown. After the incident, it was concluded, “that the understanding of the impact of remote SCADA on resetting systems for critical systems such as chlorination needs to be better understood and communicated. This is an implication of the new technology introduced through a new initiative although its limitations are probably not fully understood.” A similar problem occurred at another WTW. The Process Engineer attended the WTW as part of his regular visiting programme. He found that the works was shutdown and that the Treated Water Reservoir was too low to allow the High Lift pumps to operate. At a similar time, the control centre received a Low Alarm for the downstream water tower. The SCADA system seems to have lost connection to the control centre and the works shut down. No alarms from this WTW were received. The problem was immediately rectified and had no impact on customers. The telemetry lines between SCADA and control centre are now fitted with watchdogs to monitor their ability to transmit data.	
F3	Prior to or after the incident, new technology acquisition was only justified if existing equipment did not perform to required specification.	Control systems; Rituals & routines	Physical;	Identify asset investment and maintenance strategy for asset, site or system, in particular relating to risks or reliability information and potential severity of incidents whilst taking into account any systems redundancy.	In one incident, a PLC on a WTW failed due to a UPS charging system fault. This affected the PLC and SCADA and shut down the treatment process. All chemical dosing was lost. In addition, un-chlorinated water continued to flow to the clear water tank on site causing reduction in free chlorine in the final water. During the investigation, a few problem areas were identified. E.g., a more robust monitoring of the PLC is required, in particular the impact of UPS fault on PLC and MCC systems needed to be investigated. After this incident, a PLC health watchdog was installed at this and other sites.	

F4	Prior to or during the incident, the existing technology was maintained to exceptionally high standards, as we do not tolerate defective, substandard or malfunctioning equipment.	Control systems; Rituals & routines	Physical;	Identify evidence for maintenance policy of asset taking into account the probability of asset failure and the consequence of asset failure and maintenance cost in a cost benefit relationship. Identify the causal relationship of asset condition deterioration, asset failures and consequences of failures on the safety and reliability of drinking water supply and considerations of asset maintenance, replacement or refurbishment needs.	Assets are not maintained to exceptionally high standard but to balance maintenance cost with the benefit of risk reduction. The asset management organisation has designed a risk assessment model for assets to evaluate their potential of failure. Failure in this sense is defined as an impact on organisational objectives. At the highest level, they reflect safety and reliability of drinking water supply derived from indicators to monitor the performance of water companies set by the economic and water quality regulators. The organisation uses these indicators, amongst others, to define and assess risk. These are simplified cause and effect relationships in which the probability of asset failure and other "root " causes are linked to the probability of impacting on regulatory objectives. The risk assessments are used to evaluate the cost and benefit of asset investment and maintenance.	

Human resource management practices that support reliability					
Ref.	HRO indicator	Johnson	Asset type	Type of evidence in addition to observation	Examples
G1	Prior to the incident, the recruitment and selection process acquired suitable and skilled candidates for the jobs aiming to match the complexity of the environment with an equally complex set of people who would understand the system.	Rituals & routines;	Human	Identify the academic qualifications, professional accreditation, and professional experience, training and continuous professional development records of personnel in operations, incident and emergency management. Identify the personality profiles of personnel and compare to job descriptions.	Operators require a BTEC qualification as an entry condition for “licence to operate”. This vocational training is specifically targeted for water utility operations and has been designed specifically for organisational requirements of the water utility. In this training programme, “students” are taught the fundamental concepts of public health relating to the water sector as well as treatment processes commonly used in the sector. This training requirement was introduced a few years ago and operators who were already in employment but without the qualification were financially sponsored to obtain their qualification. License to operate plant is warranted on candidates based on experience and ability.
G2	During the incident, most people did what was rewarded. Our organisation remunerates reliability with incentives, recognition and career opportunities.	Rituals & routines;	Human	Evidence of human intervention effectively contributing to re-instating the safety and reliability of the water supply system or reducing the impact of the incident. Evidence of considering the impact of the incident and assessing residual, additional or substitutional risks arising from the due course of action to re-instate a safe and reliable drinking water supply (chronological incident record)	After a significant mains burst, the incident review meeting notes “Network Technicians responded promptly to identify valves to isolate the section of damaged main and to rezone the two zones that would be affected by the isolation such that supplies were maintained throughout. The repair was straightforward and the fact that only three discoloured water contacts were received after the main was flushed and returned to supply would suggest that this operation was well planned and executed.” After an incident, positive contributions to the incident response are recognised and awards are available for distinguished service to the company. Careful consideration is given to avoid incentivising “heroism”.
G3	After the incident, job rotation increased networking between teams and helped the organisation to transfer and diffuse knowledge and lessons learnt.	Ritual & routines; Stories; Symbols;	Human	Evidence for internal job markets and opportunities for staff to take up roles in different department. In particular, identify transfers between operations and asset management but also operators and operations management	The organisation maintains an internal job market and suitable candidates can progress a career based on their experience within the organisation. Reputation for acting in the interest of the organisation is recognised by managers that are more senior and reflect positive on individuals.
G4	During the incident, our organisation had systems in place to monitor the behaviour of staff.	Control system;	Human	Identify mention of individual or group behaviour with detrimental/contributing effect on the objective of operating a safe and reliable water supply or the reinstatement thereof.	Good as well as poor behaviour is monitored in instant assessments. Every office maintains a notice board where good practice is highlighted, alternatively where poor practice by an anonymised employee put a company objective at risk. Usually, the word spreads fast as to who that person is and nobody likes to feature in a bad light on the announcement board.

Table 84 HRO observation in operations and incident management

4.3 Research tools

4.3.1 HRO survey template

Risk management culture in water utilities

Name[1]:

____

Organisation[1]:

____

Responsibility and experience in the organisation[2]:

____

____

____

____

Instructions

This questionnaire has contains 45 statements relating to risk management cultures in organisations. This questionnaire has twofold purposes:

Firstly, we would like to identify if you can observe any of these attributes in your organisation. Please use the following key to make your choice:

Choice of answer	**Criteria**
Strongly Agree	"This attribute is observable throughout my organisation without any exception!"
Agree	"This attribute is observable throughout my organisation with some exceptions!"
Disagree	"This attribute is not observable throughout my organisation. There are, however, some exceptions!"
Strongly Disagree	"This attribute is not observable throughout my organisation.

Secondly, we would like to understand the perceived value of the described organisational attribute and the associated cost you would anticipate to implement and maintain these attributes.
Please use the following key to make your choice:

Choice of answer	**Criteria**
Highly cost beneficial	The benefits significantly outweigh the costs incurred
Balanced cost benefit	Approximate parity between cost and benefits
Negative cost benefit	The costs significantly outweigh the benefits

[1] The analysis of this questionnaire will treat your name, your organisation, role, responsibility and experience in the organisation as anonymous information and is classed as confidential.
[2] Please briefly outline your roles and responsibilities in the various organisational departments.

When making your choice, please consider the benefit of the described attribute in contributing to the water safety objective.

Your estimate (or knowledge) of the cost should consider capital and operational expenditure for physical assets, human resource management and information assets required to implement and/or maintain the attribute. In estimating the cost, the following framework might be of use:

Change management model	**Criteria**
Policy	Consider the policy required to implement and maintain the described attribute
Organisation	Consider the cost for providing an organisation structure required to plan, implement, monitor, audit and review a policy which facilitates the described attribute
Planning and Implementation	Consider the cost for planning and implementing a policy which facilitates the described attribute
Monitoring	Consider the cost for a monitoring programme required to measure the success of the policy
Auditing	Consider the cost for auditing requirements to verify the successful operation of the policy
Review	Consider the cost for review procedures to ascertain the effectiveness of the policy

Figure 1 is a representation on how the research question relates to the column provided to state your answer. Please tick the relevant boxes in the columns provided.

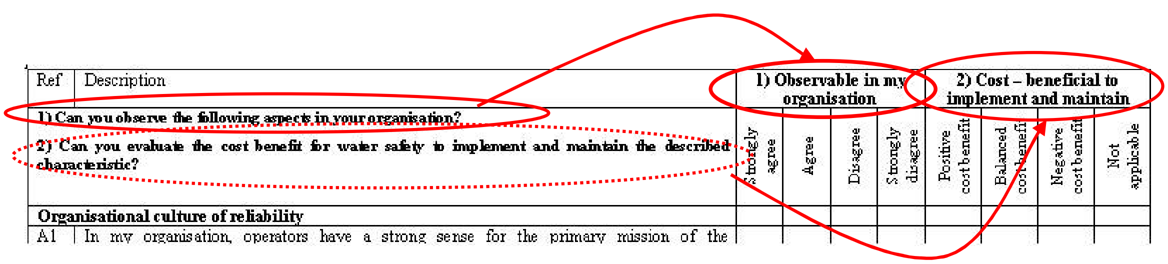

Figure 1 Example

In designing this questionnaire, we aimed to reduce ambiguity that often arises from the use of terminology. Since this is a pilot study, we welcome any feedback on the use and clarity of terminology that would then be clearly defined in the main study ahead.

Thank you for participating in this survey!

Ref	Description	1) Observable in my organisation				2) Cost – beneficial to implement and maintain			
1) Can you observe the following aspects in your organisation? 2) Can you evaluate the cost benefit for water safety to implement and maintain the described characteristic?		Strongly agree	Agree	Disagree	Strongly disagree	Positive cost benefit	Balanced cost benefit	Negative cost benefit	Not applicable
Organisational culture of reliability									
A1	In my organisation, staff in operations have a strong sense for the primary mission of the organisation and share a common system of beliefs and perceptions.								
A2	In my organisation, the water supply system is continuously monitoring so that failure events are foreseen and understood.								
A3	In my organisation, our staff in operations have a highly developed understanding of their contribution to water safety and their role in the system.								
A4	In a water quality incident, our staff in operations act in a collaborative and collegiate manner and the group interaction can be described as collective intelligent interaction.								
A5	Our staff in operations are sensitive towards all events where water supply reliability is concerned. Staff know that a very small initial moment of inattention or misperception can lead to an escalation of failure, which can result in a water quality incident.								
A6	All our employees take responsibility where problems are identified and immediate corrective action programmes are required.								
A7	Our staff in operations are obliged to report their mistakes without fear of punishment.								
A8	In our organisation, individual behaviours, which jeopardise the primary mission of reliability, are labelled as disgrace.								
A8a	Our senior management is committed to the reliability of the organisation. This is communicated to all levels in the organisation and demonstrated with investments in technology, processes and personnel.								
A9	In our organisation, individuals "monitor, advise, criticize and support" each other, in particular in situations where mistakes are more likely to occur.								
A10	In general, our staff are attentive, alert and act with care.								

Ref.	Description	1) Observable in my organisation				2) Cost – benefit to implement and maintain			
	1) Can you observe the following aspects in your organisation? **2) Can you evaluate the cost benefit for water safety to implement and maintain the described characteristic?**	Strongly agree	Agree	Disagree	Strongly disagree	Positive cost benefit	Balanced cost benefit	Negative cost benefit	Not applicable
Continuous learning and intensive training									
B1	In order to facilitate continuous learning and intensive training, our organisation constantly reviews their processes and ways of operating.								
B2	In preparation for a job, our staff in operations and maintenance staff receive training on the requirements of maintaining a safe system. These are embedded in formal rules, general guidelines and standardised frameworks.								
B3	Our staff in operations must adhere to standard operating procedures but also pro-actively identify potential sources of failure and actions to stop faults from escalating.								
X1	Our staff question procedures when in doubt about their appropriateness.								
X2	In unforeseen situations, staff in operations don't follow rules blindly, but negotiate the course of action in a collegial manner with more experienced staff and supervisors.								
X3	During a water quality incident, staff in operations establish an emergency response team for joint decision making in order to avoid overlooking complex circumstances.								
B4	All our staff maintain a commitment to continuous learning and seek the acquisition and improvement of skills.								
B5	In our organisation we learn from failures, near misses and mistakes by other utilities and use these as a means to study the failure susceptibility of the own organisation.								
B6	In our organisation, even minor errors and incidents provide a source for learning which are assessed through root cause analysis.								
B7	Our organisation develops a collective memory for failures, incidents and root causes for failure, which helps the organisation to anticipate future problems.								
B8	In our organisation, we share a sense that learning from trial and error is not feasible to understand our water supply system. For staff training, we use offline methods of learning which consist of realistic drills, simulations and exercises to replicate potential failure scenarios.								

Ref.		**1) Observable in my organisation**				**2) Cost – benefit to implement and maintain**			
	1) Can you observe the following aspects in your organisation? **2) Can you evaluate the cost benefit for water safety to implement and maintain the described characteristic?**	Strongly agree	Agree	Disagree	Strongly disagree	Positive cost benefit	Balanced cost benefit	Negative cost benefit	Not applicable
Effective and varied patterns of communication									
C1	Our communication system makes our water supply system better understandable, predictable and controllable.								
C2	Our organisation operates in an information rich environment. All processes are measured and understood. Data are transparent and made available to all.								
C3	Our staff in operations are encouraged to share their experiences relating to the reliability of the system. Communication is designed as bottom up and top down to ensure rapid flow of information through the hierarchy of the system. Rapid dissemination of information helps the organisation to respond to water quality incidents with corrective action aiming to prevent the escalation of failure.								
X1	During a water quality incident, the response team maintains "closed loop" communication with all stakeholders within the organisation								
X2	During a water quality incident, the organisation maintains "closed loop" communication with the public, regulators and government authorities								
C4	In our organisation, communicating information shapes the 'big picture' of our organisational vision, mission and responsibility of individuals towards reliability.								
C5	Our organisation uses various channels to transmit different types data and information relating to monitoring and control of our assets (and ultimately water safety). Direct and complementary information enhance information reliability and provides a form of redundancy.								
C6	Multiple monitoring and control data from a variety of sources provide information density which allows individual signals to be scrutinised for fitting into the whole information pattern. Abnormal signals are treated as an indication for latent errors to unfold into failures.								
C7	In our organisation, interpersonal communications are formalised in a precise, unambiguous, impersonal and efficient structure, which denies individuals to communicate in their idiosyncratic communication style.								

Ref.	Description	1) Observable in my organisation				2) Cost – benefit to implement and maintain			
	1) Can you observe the following aspects in your organisation? **2) Can you evaluate the cost benefit for water safety to implement and maintain the described characteristic?**	Strongly agree	Agree	Disagree	Strongly disagree	Positive cost benefit	Balanced cost benefit	Negative cost benefit	Not applicable
Adaptable decision making dynamics and flexible organisational structures									
D1	Our organisation can only prevent outbreaks with a high level of centralisation, because low-level decision makers have insufficient understanding of the inter-relationship between their action and consequences on other elements of the water supply system. During an emergency, control has to be maintained highly centralised in order to maintain overview of the entire system response to action on all sub-units.								
D2	In our organisation, decentralisation is required to respond rapidly to unfolding failures. An emergency can be confined to one sub-unit, which is subsequently isolated from the entire system. The control over an emergency is decentralised to this subunit until the emergency is cleared.								
D1/2a	In our organisation, centralisation at collective level coexists with decentralisation at individual level. The organisation exhibits an adaptive, flexible or organic nature.								
D3	Our organisation enforces the stringent adherence to standard operating procedures aiming for repeatability of action and routines.								
D4	Our standard operating procedures are constantly updated and incorporate lessons learnt. Formal rules and procedures are effective elements to identify and control risk.								
D5	In our organisation, activities, which are not defined in standard operating procedures, are based on decisions a most senior individual makes, as they should have the best knowledge of the system.								
D6	Our organisation has a hierarchical structure for decision making which reflects expertise, know-how and seniority. Each level has controls and regulating mechanisms.								
D7	Our organisation requires staff to conform to organisational norms and avoids innovative, autonomous or creative behaviours.								
D8	Our decision-making processes have slack in-built in order to assess and challenge decisions to avoid faulty decisions to escalate into failure.								

Ref	Description	1) Observable in my organisation				2) Cost – benefit to implement and maintain			
	1) Can you observe the following aspects in your organisation? **2) Can you evaluate the cost benefit for water safety to implement and maintain the described characteristic?**	Strongly agree	Agree	Disagree	Strongly disagree	Positive cost benefit	Balanced cost benefit	Negative cost benefit	Not applicable
System and human redundancy									
E1	Our organisation maintains reserve capacity in the system. This includes back-up functions, overlapping tasks and responsibilities.								
E2	In our organisation, we are aware that redundancy can be counterproductive. Back-up functions can increase technical complexity, conceal errors and can lead individuals into not performing their required tasks under the assumptions that someone else takes care of his task.								
Precise procedures in managing technology									
F1	Our organisation does not use state of the art equipment to ensure that our technology does not add unnecessary complexity to the organisation.								
F2	In water supply systems design, our organisation aims to simplify complex technical systems and avoid unnecessary automation.								
F3	New technology acquisition is only justified if existing equipment does not perform to required specification.								
F4	In our organisation, existing technology is maintained to exceptionally high standards, as we do not tolerate defective, substandard or malfunctioning equipment.								
F5	In our organisation, maintenance activity and protocols as well as performance data are used to monitor the healthy operation of the system.								

Ref.	Description	1) Observable in my organisation				2) Cost – benefit to implement and maintain			
	1) Can you observe the following aspects in your organisation? **2) Can you evaluate the cost benefit for water safety to implement and maintain the described characteristic?**	Strongly agree	Agree	Disagree	Strongly disagree	Positive cost benefit	Balanced cost benefit	Negative cost benefit	Not applicable
Human resource management practices that support reliability									
G1	In recruitment and selection, our organisation acquires suitable and skilled candidates for the jobs aiming to match the complexity of the environment with an equally complex set of people to understand the system. Diverging backgrounds for staff offer different ways of looking at systems.								
G2	Since most people do what is rewarded, our organisation remunerates reliability with incentives, recognition and career opportunities.								
G3	In our organisation, job rotation increases networking between teams and helps the organisation to transfer and diffuse knowledge and lessons learnt.								
G4	Our organisation has systems in place to monitor the behaviour of staff.								

4.3.2 HRO framework for incident reviews

Ref	Description	Observable in the organisation from evidence found in the incident documentation			
Based on the incident documentation, could the following aspects be observed prior to, during and /or after the incident?		Strongly agree	Agree	Disagree	Strongly disagree
Organisational culture of reliability					
A1	During the incident, staff in the incident management team and operators involved had a strong sense for the company objectives of the organisation and shared a common system of beliefs and perceptions.				
A2	During the incident, the water supply system was continuously monitored so that failure events were foreseen and understood.				
A3	During the incident, our staff in operations had a highly developed understanding of their contribution to water safety and their role in the system.				
A4	During the incident, staff in the incident management team and operators involved acted in a collaborative and collegiate manner.				
A5	During the incident, staff in the incident management team and operators involved were sensitive towards all events where water supply reliability is concerned. Staff knew that a very small initial moment of inattention or misperception could have lead to an escalation of failure, which could have resulted in a major water quality incident.				
A6	During the incident, staff in the incident management team and operators involved took responsibility where problems were identified and immediate corrective action programmes were required.				
A7	During the incident, staff in the incident management team and operators involved were obliged to report their mistakes without fear of punishment.				
A8	In our organisation, individual behaviours, which jeopardise the company objectives, are recognised as unacceptable.				
A8a	During the incident, our senior management was (and still is) committed to the reliability of the organisation. This was communicated to all levels in the organisation and demonstrated with investments in technology, processes and personnel.				
A9	During the incident, individuals “monitor, advise, criticize and support” each other, in particular in situations where mistakes were more likely to occur.				
A10	During the incident, staff in the incident management team and operators involved were attentive, alert and acted with care.				

Table 85 HRO framework for incident reviews

Ref.	Description	Observable in the organisation from evidence found in the incident documentation			
	Based on the incident documentation, could the following aspects be observed prior to, during and /or after the incident?	Strongly agree	Agree	Disagree	Strongly disagree
Continuous learning and intensive training					
B1	After the incident, continuous learning and training were facilitated in a review of processes and ways of operating.				
B2	Prior to the incident, staff in the incident management team and operators involved received training on the requirements of maintaining a safe system. These are embedded in formal rules, general guidelines and standardised frameworks.				
B3	During the incident, staff in the incident management team and operators involved adhered to standard operating procedures but also pro-actively identified potential sources of failure and actions to stop faults from escalating.				
X1	During the incident, staff in the incident management team and operators involved would have questioned procedures if they were inappropriate.				
X2	During the incident, staff in the incident management team and operators involved didn't follow rules blindly, but negotiated the course of action in a collegial manner (teamwork) with more experienced staff and supervisors.				
X3	During the incident, staff in the incident management team and operators involved established an emergency response team for joint decision making in order to avoid overlooking complex circumstances.				
B4	Staff in the incident management team and operators maintain a commitment to continuous learning and seek the acquisition and improvement of skills.				
B5	We learn from failures, near misses and mistakes by other utilities and use these as a means to study the failure susceptibility of the own organisation.				
B6	Even minor errors and incidents provide us with a source for learning.				
	After the incident, we carried out a root cause analysis.				
B7	Our organisation develops a collective memory for failures, incidents and root causes for failure, which helps the organisation to anticipate future problems.				
B8	We share a sense that learning from trial and error is not feasible to understand our water supply system. For staff training, we use offline methods of learning which consist of realistic drills, simulations and exercises to replicate potential failure scenarios.				

Table 86 HRO framework for incident reviews (continued)

Ref.		Observable in the organisation from evidence found in the incident documentation			
	Based on the incident documentation, could the following aspects be observed prior to, during and /or after the incident?	Strongly agree	Agree	Disagree	Strongly disagree
Effective and varied patterns of communication					
C1	During the incident, our communication systems make our water supply system better understandable, predictable and controllable.				
C2	During the incident, our organisation operated in an information rich environment. Processes were measured and understood. Data is transparent and made available to all.				
C3	During the incident, staff in the incident management team and operators involved are encouraged to share their experiences relating to the reliability of the system. Communication is designed as bottom up and top down to ensure rapid flow of information through the hierarchy of the system. Rapid dissemination of information helps the organisation to respond to water quality incidents with corrective action aiming to prevent the escalation of failure.				
X1	During the incident, staff in the incident management team and operators involved maintained "closed loop" communication with all stakeholders within the organisation. (Closed loop means that actions are issued, acknowledged, implemented and the implementation confirmed, etc)				
X2	During the incident, the organisation maintained "closed loop" communication with the public, regulators and government authorities				
C4	During the incident, communicating information shaped the 'big picture' of our organisational vision, objective and responsibility of individuals towards reliability.				
C5	During the incident, our organisation used various channels to transmit different types of data and information relating to monitoring and control of our assets (and ultimately water safety). Direct and complementary information enhanced information reliability.				
C6	During the incident, multiple monitoring and control data from a variety of sources provided information density, which allowed individual signals to be verified.				
C7	During the incident, staff communications was formalised in a precise, unambiguous, impersonal and efficient structure.				

Table 87 HRO framework for incident reviews (continued)

Ref.	Description	Observable in the organisation from evidence found in the incident documentation			
	Based on the incident documentation, could the following aspects be observed prior to, during and /or after the incident?	Strongly agree	Agree	Disagree	Strongly disagree
Dynamic decision making and flexible organisational structures					
D1	During an incident, our organisation maintains centralised control to provide an overview of the entire system				
D2	During the incident, decentralisation was required to respond rapidly to the unfolding failure. The incident could be confined to one sub-unit, which was subsequently isolated from the entire system. The control over the incident was decentralised to this subunit until the emergency was cleared.				
D1/2a	During the incident, centralisation at collective level coexists with decentralisation at individual level. The organisation exhibits an adaptive, flexible or organic nature.				
D3	During the incident, the organisation enforced the stringent adherence to standard operating procedures aiming for repeatability of action and routines.				
D4	After the incident, the standard operating procedures were updated and incorporated lessons learnt. These formal rules and procedures are effective elements to identify and control risk.				
D5	During the incident, activities, which were not defined in standard operating procedures, were based on decisions a most senior individual made, as they should have the best knowledge of the system.				
D6	During the incident, our organisation had a hierarchical structure for decision making which reflected expertise, know-how and seniority. Each level had controls and regulating mechanisms.				
D7	During the incident, our organisation required staff to conform to organisational norms and avoids innovative, autonomous or creative behaviours.				
D8	During the incident, our decision-making processes had slack in-built in order to assess and challenge decisions to avoid faulty decisions that may escalate further into failure.				

Table 88 HRO framework for incident reviews (continued)

Ref	Description	Observable in the organisation from evidence found in the incident documentation			
	Based on the incident documentation, could the following aspects be observed prior to, during and /or after the incident?	Strongly agree	Agree	Disagree	Strongly disagree
System flexibility and redundancy					
E1	Our organisation maintains reserve capacity in the system. This included back-up functions, overlapping tasks and responsibilities.				
E2	Our organisation is aware that redundancy can also be counterproductive. Back-up functions can increase technical complexity, conceal errors and can lead individuals into not performing their required tasks under the assumptions that someone else takes care of his task.				
	During the incident, was the system redundancy effectively exploited to mitigate the customer impact?				
Precise procedures in managing technology					
F1	The technology employed to deliver service on this site/ within this system was not unnecessarily complex to operate and had no detrimental effect on the incident.				
F3	Prior to or after the incident, new technology acquisition was only justified if existing equipment did not perform to required specification.				
F4	Prior to or during the incident, the existing technology was maintained to exceptionally high standards, as we do not tolerate defective, substandard or malfunctioning equipment.				
F5	Prior to or during the incident, maintenance activity and protocols as well as performance data were used to monitor the healthy operation of the system.				

Table 89 HRO framework for incident reviews (continued)

Ref.	Description	Observable in the organisation from evidence found in the incident documentation			
	Based on the incident documentation, could the following aspects be observed prior to, during and /or after the incident?	Strongly agree	Agree	Disagree	Strongly disagree
Human resource management practices that support reliability					
G1	Prior to the incident, the recruitment and selection process acquired suitable and skilled candidates for the jobs aiming to match the complexity of the environment with an equally complex set of people who would understand the system.				
G2	During the incident, most people did what was rewarded. Our organisation remunerates reliability with incentives, recognition and career opportunities.				
G3	After the incident, job rotation increased networking between teams and helped the organisation to transfer and diffuse knowledge and lessons learnt.				
G4	During the incident, our organisation had systems in place to monitor the behaviour of staff.				

Table 90 HRO framework for incident reviews (continued)

4.3.3 Interview template – International interviewees

Risk management culture in operations, incident management and asset management

A Introduction

Name:
____

Organisation:
____

Responsibilities and experience in the organisation:
____

B Organisational objectives

1) What are the primary objectives of your organisation?
____
____
____

C Public Health
1) What are the principle means of your organisation to ensure that drinking water is safe and reliable?
____
____
____

2) How would you define a public health risk and which parameters would you monitor in water supply operations?*

____
____
____

* E.g., considering the probability of a water quality events or incidents to occur, the hazards, its duration and the affected population

2a) Can you outline the process your organisation has in place to monitor public health risks? Do you use public health risk assessments and/or asset management decision processes for planning and operating physical assets?

____
____
____

3) Drinking water quality in your country is of high standard and drinking water legislation is primarily based on the control of hazards (e.g. water quality parameters). In your opinion, could the

regulation of drinking water quality be more risk based, i.e. taking into consideration the probability of a water quality event or incident to occur, its duration and the affected population?

____
____
____

4) How would you determine an acceptable level of public health risk?

____
____
____

D Asset management

1) Could you please outline your asset management decision process or procedure?*

____
____
____

*Please state the objectives, assessment procedure, acceptability criteria and the integration of the process in your organisation (e.g. Policy, Organisation, Planning & Implementation, Monitoring, Audit and Review)?

2) What are the outcomes of the asset management decision process and how are the costs for investments or operational changes incorporated in the decision?

____
____

E Incident management and organisational learning

1) Can you briefly outline your water quality incident procedure?*

____
____
____

* Please state the objectives for incident management, any guidelines you have to contain hazards, decision support for the incident manager, training in incident management, and communication infrastructure to support the emergency response team!

2) Do you have guidelines to reduce the impact of an incident on the affected population and the duration of the incident? Does your organisation have guidelines for an acceptable duration for different hazard types (chemical, biological, and aesthetics) during an incident?

____
____
____

4.3.4 Interview template – Regional Water Utility

Technical & organisational reliability in Regional Water Utility

The learning organisation

A) For the Operations Engineer & Manager / Duty Manager

1) What was the main learning outcome from the incident for your job role?

2) What was the main learning outcome from the incident for the organisation?

Did the Decision Making Process work effectively?

Did communication during the incident work effectively?

3) Will you / did you carry out an incident review?

Are there criteria to decide if a review is necessary to be carried out?

4) In an incident review,

a) Do you review what happened, when, why and where it happened and who was involved?

b) Do you involve a representative from asset management in the incident review?

5) Following the incident, were the company procedures (e.g. for incident, operations and /or asset management) reviewed and, if necessary, amended?

6) After the incident, was a review carried out whether the same failure (risk) could occur on other, similar assets?

7) Can you describe the co-operation between the asset management department and operations?

8) Can you describe the interaction of staff in operations with the business risk model?

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5 Appendix Asset management

5.1 Risk assessment inconsistency experiment

The finding of the risk assessment experiment are presented. Six risk assessors were tasked to assess a water main for its potential to have an adverse impact on customers.

Assessment 1

For this asset, the risk assessor identified three failure scenarios describing the same problem, i.e. water mains failure resulting in "loss of supply", "leakage" and "security of supply". A risk assessment for "low pressure" and "discolouration" have been omitted.

In the description of the failure scenario it is highlighted that further investigatory work needs to be done which should to determine the actual risk. It seems that the risk assessor approximated the probability and severity score rather than assessing the problem prior to the risk assessment. The level of risk is assumed but actually reflects uncertainty in probability and impact.

Based on the proposed engineered solution, the post risk score is reduced in terms of probability and severity. According to my assessment of the engineering solution, the severity should remain unchanged.

For one risk assessment, the probability score is erroneous and suggest continuous asset failure once a year for 365 days. This is obviously wrong unless the water main has failed and has not been repaired. In this case, the other two probability scores would be erroneous.

Assessment 2

The risk assessor for this asset uses one Failure scenario for a water mains burst to result in water quality issues. However, in the description of the failure scenario the risk assessor identifies a few more potential effects on customer objectives. These are discolouration, loss of supply and low pressure. The post solution scenario reduces risk in terms of probability and severity. Considering the engineering solution, this is erroneous and the severity assessment should be left unchanged.

Assessment 3

This asset has two identified failure scenarios for the same problem of water mains burst. Two risk assessments identify loss of supply and low pressure. From our review of incidents, it was identified that water main bursts commonly result in the loss of supply for some properties whereas others experience temporary low pressures. It is also common for a mains burst to experience discolouration due to transient pressure and changes in flow which resuspends deposited sediments in the water mains.

It is also problematic to use a duration as an indicator for "loss of supply" in the severity scale. The severity scale should emphasis a hazard exposure, the affected population and the duration of an incident.

Although "loss of supply" is related to the reliability of drinking water supply, there are also hazardous implications from de-pressurising a water main. For such an incident, low-pressure zones can cause the ingress of ground- or contaminated water into the distribution network. This hazardous effect also applies to the severity assessment for "low pressure".

Assessment 4
This asset has four identified and assessed failure scenarios to describe the effect of a perceived incident due to a burst main. According to the risk assessments, a water mains failure results in “discolouration”, “loss of supply”, “leakage” as well as “compliance with legal obligation”. The latter risk assessment has been primarily designed for the assessment of impounding reservoirs to comply with statutory obligations detailed in the Reservoirs Act.
A risk assessment for “low pressure” has been omitted although this effect would be highly likely for certain properties in the distribution management area.

Assessment 5
Two failure scenarios describe one root cause. A water mains failure is assessed for “loss of supply” and “leakage”. It appears that the asset engineer does not know the difference between “loss of supply” and “leakage”. According to current definitions, “loss of supply” is instantaneous whereas “leakage” is continuous. There is a flawed logic with respect to designing a risk assessment for leakage since it reflects a continuous problem. Therefore, the probability for leakage always requires to be 100% to reflect its continuous nature. The assessment of leakage due to water mains burst has been noted also for previous asset assessments.
Risk assessments for “low pressure” and “discolouration” have been omitted.

Assessment 6
The assessment for this water mains failure uses three failure scenarios and risk assessments. Again, there is confusion as to whether mains failure should be assessed as "loss of supply" or "leakage". The third risk assessment uses “discolouration” as severity type.
Here, the probability assessment refers to probability of water mains failure rather than referring to the probability that discolouration may be experienced by customers.

In this study, six identical assets that have been assessed by risk assessors are investigated. The asset under investigation was a water main and risk assessors were tasked to assess all perceivable risks for this asset using the risk assessment model of the Regional Water Utility. In addition, the author surveyed a further 30 risk assessments for a variety of assets. Across the 36 risk assessments under review, evidence for inconsistency in risk assessments and scope for the enhancement for the risk assessment process was found.
The risk assessment process allows for multiple risk assessments for a common asset failure type. In the case studies described above, we investigated “water mains failure” as a failure type. In all six asset assessments, a varying range of risk assessments had been constructed to assess the probable consequences of this asset failure type.
The ability to assess more than one risk for a failure scenario reflects the reality of incidents. Incidents and consequences of failure can be multicausal with multiple effects with varying interdependency. This reflects my investigation into incidents experienced in the organisation. Often, one cause can have multiple effects. A mains burst can result in reduced pressure, loss of supply and/or discolouration. These scenarios would be assessed in three failure scenarios.
In a risk assessment, it is in the remit of the risk assessor to identify the appropriate consequences of failure and the number of risk assessments he/she will conduct.

In some cases, it was found that the choice of a severity category for consequences of failure is inappropriately selected. In one example, the risk assessor used "compliance with legal obligations" to assess the risk of a mains failure. Although a creative choice for a severity assessment, this indicator has been designed for compliance with statutory obligations expressed in the Reservoir Act. In this instance, the use of this indicator artificially boosts the overall risk of the asset, increases the chance of attracting cash for main refurbishment or rehabilitation and therefore distorts the cost benefit analysis.
In some cases, some confusion was identifed about the definitions of the severity descriptions. A good example is leakage and loss of supply. Both indicators have been used to assess the impact of a water mains burst. The definition for leakage anticipates continuous leakage rather than being instantaneous due to a water main burst. Leakage is a continuous process and occurs at a probability of 100%. It could be argued that a risk assessment for leakage is no severity indicator to reflect customer exposure. The effect of leakage may result in loss of supply and low pressure due to the reduced availability of drinking water at customer tap.

In the investigation into the derivation of probabilities for risks arising due to water mains failure it was also observed that, in one instance, the risk assessors only derived the probability of the asset to fail but not the probability of this asset failure to have an impact as described in the severity assessment. This would assume that the impact of asset failure is evaluated at 100% probability to have an impact on the customer and discards any system redundancy.
In general, the asset assessments do not explicitly state that two probability assessments are required to determine the overall probability of impact. It would be advantageous to split the probability assessments into a) the probability of main failure and b) the probability of having an impact on customers described by the severity indicator.

The structure of the probability tree was also investigated. It was noticed that a failure may occur more than once a year, yet, the probability factor does not exceed 100%. The design of the probability tree asks whether the asset may fail within this year. It does not ask how often it may fail and as a result, repeated annual failure is always assessed as 100 %. Basically, it doesn't matter if a main burst occurs once or 10 times a year.

In conclusion, of this case study, a number of improvements may enhance the risk assessment process.
Firstly, the severity scale may require revising in order to provide better and unbundled definitions for severity. The current definition use a number of different approaches to severity assessment which may not enable the risk assessor to make an accurate assessment. During my placement in the Regional Water Utility, the author designed enhanced severity indicators to distinguish between hazard exposure, affected population and the duration of an incident.
A higher definition may be required for the risk assessor to make better choices from the list of severity indicators. It may be recommendable to provide a structured decision tree to enter failure scenarios and their respective impact severities. This could be structured similar to the decision tree for assessing probabilities. This would also help in reducing the confusion that seems to arise in selecting the appropriate severity indicators.
In a structured decision tree, the appropriate use of indicators could be customised to the asset type.
Currently, the process of risk identification and assessment allows for much flexibility on behalf of the risk assessor. In the 36 case studies, the consistency in risk assessment varies

greatly. In turn, the organisation relies on the competency of the risk assessor. For a decentralised data acquisition system and process, it is recommendable to enhance the process towards high process definition to achieve data consistency.

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5.2 Enhanced risk assessment template

This is a copy of the semi-automated MS Excel risk assessment model

Enhanced risk assessment template for assets					
		Data Input fields			
		Assessment Example		Probability of failure	List
At which installation type would the failure occur?		WTW			1
Asset reference					
At which process group would the failure occur?		Secondary Treatment			23
Asset reference					
At which process would the failure occur?		Secondary filtration			2
Asset reference					
At which element would the failure occur?		Process			22
Asset reference					
At which component would the failure occur?		WTW - Chemical dosing pumps			3
Asset reference					
At which type of IT/IS asset would the failure occur?		N/A			4
What would happen (Symptom or effect)?		Treatment process failure			5
Why would it happen (cause of failure)?		Pollution			5
The failure scenario can be attributed to ….		Corrosion			7
It can also be attributed to….		Corrosion			7
It can also be attributed to….		Corrosion			7
It can also be attributed to….		Corrosion			7

It can also be attributed to….		Corrosion			7
Would Human factor play a role in causing the failure?		N/A			8
Would any aspects of organisational culture contribute?		N/A			9
What type of probability assessment for the equipment is used?		Weibull			10
Probability/frequency of equipment to trip or failure per year?		0.7		70.00%	
How long does it take to reset/repair/replace asset? Max repair time in days is the lower of the following : 365 or	521	30.00		30.00	
Equipment non-availability in days				21.00	
Equipment non-availability in percent				5.75%	
Does the asset have redundancy (e.g. duty standby)?		Duty/Standby	1		11
Probability/frequency of redundancy to trip or failure per year?		0.6		60.00%	
How long does it take to reset/repair/replace redundant asset? Max repair time in days is the lower of the following : 365 or	608	20.00		20.00	
Element non-availability in days				0.7	
Element non-availability in percent				0.19%	
What is the probability that other, alternative or parallel elements will compensate for the loss of one element?		VH		10.00%	13
Process non-availability in days				0.1	
Process non-availability in percent				0.000189154	
What is the probability that other, alternative or parallel processes will compensate for the loss of one process?		L		70.00%	13
Process group non-availability in days				0.0	
Process group non-availability in percent				0.01%	
What is the probability that other, alternative or parallel process groups will compensate for the loss of one process group?		M		50.00%	13
Installation non-availability in days				0.02	
Probability that installation non-availability				0.01%	
Installation availability in days per year				364.98	
Are there any installations between the failed installation and the customer which may reduce the impact?		SRE		0	15
What is the probability that these installations avoid an impact on customers?		L		70.00%	16
Customer impact in days				0.0	

Customer impact probability in percent				0.00%	
Can you characterise the impact on customers?		Biological pathogens present, health effects envisaged, Boil order as risk of illness through drinking water	1	64	17
How many people would be affected?		0 - 7500		2	24
Can you characterise other impact on customers?		N/A	0	0	17
How many people would be affected?		0 - 7500		2	
Can you characterise other impact on customers?		N/A	0	0	17
How many people would be affected?		0 - 7500		2	
How would the failure of the component be noticed?		customer contact			18
Are other installations available in the region to compensate for the loss of this installation?		BH			19
What other redundancy is available should the asset fail (e.g. alternative plant, system)?		Bottled water			20
How long would it take to identify the source of failure (up to X hrs)?		1			21
How long would it take to re-instate a safe system (up to X hrs)?		3			21
Time exposure to incident			4	2	
Incident impact				22.6644	
Incident impact				1.3332	
Incident impact				1.3332	
Total incident impact				22.6644	
Risk score				0.001050328	
What type of management intervention might effectively reduce the risk?		Capital maintenance			

Figure 28 Risk assessment template

The following tables represent the drop-down menu on the risk assessment template referred to in the right-hand column of the model in Figure 28.

5	24		6	1	23	2	22	4	3	18	21		7	8
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
What happened first?	0 - 7500	2		Which physical asset type is the source of the incident?	Primary Treatment	Process group	Building	Was an IT/IS asset the source of the incident?	Can the incident be attributed to a specific component?	How was it notified?	How long did it take to identify the source of failure?		The failure scenario can be attributed to ….	Did Human factor play a role in causing the incident?
Asset failure	7500 - 15000	4		Asset type	Secondary Treatment	Intake	Civil	Information assets	Component type	customer contact	0		Material fatigue	N/A
Component failure	15000 - 30000	8		Aquifer	Tertiary Treatment	Sedimentation	Mechanical	Monitoring equipment	N/A	3rd party	1		Corrosion	Operator error
Civil failure	30000 - 60000	16		BH	N/A	coagulation	Electrical	Control equipment (e.g. MCC)	Dam	Member of public	2		Wear&Tear	lack of experience
Water main failure	60000 - 125000	32		Catchment		Flocculation	Process	SCADA	Reservoir intake	Operator	3		operating environment (climate, soil condition)	Lack of knowledge
Mechanical failure	125000 - 250000	64		IRE		DAF		PLC	Reservoir embankment	Manager	4		3 rd part impact	Lack of information
Electrical failure	250000 - 500000	125		River abstraction		Primary filtration		Telemetry	BH/River - Structure (Well/Bore)	Emergency services	5		Unfit for purpose	Lack of training
Treatment process failure	500000 - 1000000	250		Raw water pumping station		Secondary filtration		IT architecture	BH/River - Pump & motor	PLC	6		Lack of maintenance	Lack of instructions
ICA failure	> 1000000	500		Raw water main/Aqueduct		Chemical treatment equipment		N/A	BH/River - water main	SCADA	7		Lack of standby	Lack of supervision
Power failure	N/A			WTW		N/A			BH/River - valve		8		Poor design	

Pollution				SRE					BH/River - Flowmeter		9		Poor operational use	
Raw water quality				Water tower					BH/River - monitoring equipment		10		Poor access	
Adverse weather				Drinking water trunk main (>300mm)					BH/river - control equipment		11		Poor lifting facilities	
Pollution				Water main (distribution)					Catchment - Structures		12		Poor maintainability	
3rd party				Power generation/power supply					WTW - Structure		13		Poor SOP	
Ingress of contamination				customer installation					WTW - Inlet		14		Poor condition	
security failure				WPS					WTW - Screening		15		Age	
Asset does not meet requirement to meet demand									WTW - Coagulation		16		Inappropriate use	
Asset does not meet water quality objectives									WTW - Flocculation		17		Adverse weather	
Asset failed to deliver service/product									WTW - Sedimentation		18		Water hammer/Transient pressure	
Hydraulic effect									WTW - Filtration		19		Differential settlement	
Insufficient capacity									WTW - Contact tank		20		Quality of chemicals	
Change in demand									WTW - Chemical storage		21		Draught	
No water									WTW - Chemical dosing equipment		22		flooding	
Too much water									WTW - Chemical dosing pumps		23		N/A	
									WTW - Pump & motor		24			

									WTW - Valve		25			
									WTW - Flowmeter		26			
									WTW - Monitoring equipment		27			
									WTW - control equipment		28			
									SRE/WT - Structure		29			
									SRE/WT - Pump & motor		30			
									SRE/WT - Valve		31			
									SRE/WT - Flowmeter		32			
									SRE/WT - water main		33			
									SRE/WT - monitoring equipment		34			
									SRE/WT - control equipment		35			
									Distribution - Structure		36			
									Distribution - water main		37			
									distribution - pump & motor		38			
									Distribution - Valve		39			
									Distribution - flowmeter		40			
									distribution - monitoring equipment		41			
									distribution - control equipment		42			
									WPS - Structure		43			

									WPS - Pump & motor		44			
									WPS - Valve		45			
									WPS - water main		46			
									WPS - monitoring equipment		47			
									WPS - control equipment		48			
											49			

Figure 29 Drop-down menu for risk assessment template

9		10	11	12	15	19	20	17	22	14	13	16	25
Culture	Was this type of incident previously assessed for this type of risk?	Type of prob assessment	D/D/S	Redundancy	Other installations	Other installations	Other redundancy	Can you characterise the impact on customers?	What type of management intervention might effectively reduce the risk?	Installation failure	Alternative processes	Customer impact	Duration
N/A	Unpredicted failure	Manual decision tree	Duty only	No redundancy	No other installations available	No other installations available	Water tankering	Biological pathogens present, Public health effect. Illness through drinking water	Capital investment	It will not fail	No other element/process/process group available	A customer impact cannot be avoided	0
Poor attitude	Predicted failure	Weibull	Duty/Standby	Common cause failure	WTW	Aquifer	Bottled water	Biological pathogens present, health effects envisaged, Boil order as risk of illness through drinking water	Capital maintenance	VL	The cause of failure affects other units too	VL	1
Poor behaviour	Predicted failure, but unanticipated impact		Duty/Duty/Standby	VH	SRE	BH		Biological pathogens present, PCV failure leading to an undertaking	Asset replacement	L	VL	L	2
Carelessness	Operate to fail policy		No redundancy	H	Water tower	Catchment		Biological pathogens present, Trivial sample failure	Asset refurbishment	M	L	M	3
Poor work processes	Low risk			M	WPS	IRE		Potential biological pathogens present, health effects envisaged	Operator training	H	M	H	4
Poor training	Medium risk			L		River abstraction		Potential biological pathogens present	operator information	VH	H	VH	5
Poor decision making	High risk			VL		Raw water pumping station		Chemicals present above guidelines, health effects envisaged, PCV failure leading to an undertaking	Operator instruction	It will certainly fail	VH	customer impact can be avoided	6
Poor communication	Asset failure predicted but not impact on customer			Failsafe		Raw water main/Aqueduct		Chemicals present above guidelines, Trivial sample failure	Operator supervision		Yes, other elements/processes /process groups can fully compensate	N/A	7
						WTW		Aesthetics above guidelines, >200ug/l Iron or DWI reportable incident. Highly discoloured, resembles beer or Guinness					8
						SRE		Aesthetics, >150 ug/l or notable events. Opaque and discoloured resembles weak milky tea.					9

						Water tower		Aesthetics, 100-150ug/l Iron or minor events. Translucent and discoloured resembles orange juice or lager.						10
						Drinking water trunk main (>300mm)		Aesthetics, 50-100 ug/l Iron and no events. Particulate material visible in clear water						11
						Water main (distribution)		Aesthetics, < 50ug/l Iron and no events - Slight discolouration noticed in customer bath, Compliance but customer complaint						12
						Power generation/ power supply		Loss of supply						13
						WPS		Potential contaminant ingress						14
								Pressure <15m pressure						15
								Pressure - No flow upstairs at peak demand period (<10m pressure)						16
								Pressure - No flow at peak demand period (<5m pressure)						17
								Accident (Staff)						18
								Accident (3rd party)						19
								Injury (Staff)						20
								Injury (3rd party)						21
								N/A						22

Figure 30 Drop-down menu for risk assessment template

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5.3 Research tools

5.3.1 Interview template – Regional Water Utility

Technical & organisational reliability in Regional Water Utility

The learning organisation

In your job role as Asset Engineer, how do you get involved in the daily operations of water production and distribution?

Can you briefly describe the process of identifying asset needs towards capital and operational solutions!

How would you evaluate the Business Risk Model (BRM) and what improvements would you suggest?

How do you -as an Asset Engineer- get involved in incidents?

From your experience or knowledge, is the emphasis of incident review meetings more on technical issues or on human error and operating procedures?

After an incident, is the risk of re-occurrence of an incident logged on BRM?

After an incident happened at one site/asset, is a review carried out whether the same technical failure could occur on other, similar assets?

6 List of participants

Participant No.	Name	Job title	Organisation	Country
1		Process Engineer	RWU	UK
2		Asset Engineer	RWU	
3		Process Engineer	RWU	
4		Specialist Engineer (Distribution systems)	RWU	
5		Senior Ops Manager	RWU	
6		Ops Manager	RWU	
7		Incident/Ops. Manager	RWU	
8		Ops Manager	RWU	
9		Asset Engineer	RWU	
10		Ops Manager	RWU	
11		Asset Engineer	RWU	
12		Asset Engineer	RWU	
13		Asset Manager (Rationalisation)	RWU	
14		Asset Engineer (Distribution)	RWU	
15		Process Engineer	RWU	
16		Senior Manager (Risk)		UK
17		Senior Manager (Risk)		UK
18		General Manager		UK
19		Asset Manager		Canada
20		Asset Manager		Canada
21		Asset Manager		Canada
22		Ops Incident Manager	RWU	
23		Ops Manager	RWU	
24		Asset Engineer	RWU	
25		Asset Planning Manager	RWU	
26		Senior Asset Manager	RWU	
27		Asset Engineer	RWU	
28		Senior Asset Manager	RWU	
29		Asset Manager	RWU	
30		IT Manager	RWU	
31		Asset Manager	RWU	
32		Process Manager	RWU	
33		Asset Engineer	RWU	
34		Asset Manager	RWU	
35				

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