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RISK ANALYSIS AND MANAGEMENT IN THE WATER UTILITY SECTOR—A REVIEW OF DRIVERS, TOOLS AND TECHNIQUES

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The provision of wholesome, affordable and safe drinking water that has the trust of customers is the goal of the international water utility sector. Risk management, in terms of protecting the public health from pathogenic and chemical hazards has driven and continues to drive developments within the sector. In common with much of industry, the water sector is formalizing and making explicit approaches to risk management and decision-making that have formerly been implicit. Here, we review the risk management frameworks and risk analysis tools and techniques used within the water sector, considering their application at the strategic, programme and operational levels of decision-making. Our analysis extends the application beyond that of public health to issues of financial risk management, reliability and risk-based maintenance and the application of business risk maturity models.

Keywords: risk; management; assessment; water; utility; decision-making

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INTRODUCTION

Providing wholesome, affordable and safe drinking water that has the trust of customers is the overarching goal of the water utility sector. The sector has publicly stated (AWWA *et al.*, 2001) that achieving this requires, at a minimum, that water is safe in microbiological and chemical terms, that it is acceptable to consumers in terms of taste, odour and appearance, and that the supply is reliable in terms of quality and quantity.

Delivering safety, acceptability and reliability within a multi-stakeholder, institutional and business context in which expectations are rising is challenging. Privatization, sector globalization, increased competition, emerging technologies, increasingly stringent regulatory control and the trend towards financial self-sufficiency are all serving to transform the water sector, and posing new risks and opportunities (Westerhoff, 2003; Huber, 2000; Westerhoff and Lane, 1996; Kucera, 1993). Many within the industry are now promoting an enterprise-wide approach to risk management as a means to ease and indeed exploit this transition (e.g. Lifton and Smeaton, 2003). This requires:

(1) integrated frameworks for the management of internal (e.g. from ageing infrastructure) and external (e.g. from market processes or competitor actions) risks to the utility;
(2) the support of board-level, executive management and operational staff as well as that of external stakeholders; and
(3) the effective communication of risk and engagement within decision-making processes both within companies and with external stakeholders.

Developing organizational cultures responsive and not necessarily wholly averse to risk is itself a challenge. Recent international reports (Stern and Fineberg, 1996; Economic and Social Research Council Global Environmental Change Programme, 2000; Prime Minister's Strategy Unit, 2002; Royal Academy of Engineering, 2003; Australian Academy of Technological Sciences and Engineering, 2002) have commented on the relationship between risk management and organizational performance and culture. Critical aspects include:

- the importance of openness, transparency, engagement, proportionality, precaution, evidence and responsibility to good decision-making;
- the critical role of taking a long-term perspective in assessing the potential indirect consequences of management actions; and
- a widely-held view that 'hard' quantitative risk analysis tools used in isolation of transparent decision-making does little to gain public confidence and can result in the long-term erosion of trust.

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Although the techniques of risk identification, analysis and management have been commonly applied within other process industries, their explicit and routine use within the water utility sector has historically been less widespread (Egerton, 1996). There is considerable scope for learning from the experiences of related utility sectors, for example the offshore (UK Offshore Oil Operators Association, 1999), energy supply and nuclear industries (European Commission, 2000), and from companies at the cutting edge of risk management. These combined experiences will prove invaluable to the water sector as it considers the risk analysis strategies and decision-making frameworks it might adopt for more defensible and rewarding utility decisions.

The transition to an explicit risk management philosophy within the water utility sector is reflected in recent revisions to the World Health Organization's (WHO) Guidelines for Drinking Water Quality (Fewtrell and Bartram, 2001; WHO, 2002, 2003). This is placing an emphasis on the development and implementation of water safety plans for water quality management and, within these, application of risk frameworks such as the 'hazard analysis and critical control points' (HACCP) approach (Dewettinck *et al.*, 2001; Hellier, 2000) as a basis for prioritizing risk management measures within the water supply chain from catchment to tap. The approaches place primary emphasis on achieving effective operational performance than a narrow focus of monitoring finished water quality (end-product testing) against numerical water quality standards. The latter approach is fundamentally reactive rather than preventative and is inherently less reliable given the limitations of monitoring in proportion and frequency.

RISK GOVERNANCE

Commentators increasingly refer to activity that integrates risk management across legal, financial, environmental and other risks as 'risk governance' (European Commission, 2000): 'governance', because the frameworks proposed extend to the broader institutional arrangements and responsibilities for managing risk (e.g. National Health and Medical Research Council, 2001; Council of Standards of Australia, 1999). Clarity over the accountabilities, both between and within organizations, is essential if risk management is to translate into practical procedures that deliver sustainable improvements in service and decision-making to the drinking water community. A critical aspect is the capabilities of institutions in managing risk. These can be thought of as the processes, people, reports, methodologies and technologies (collectively, 'risk infrastructure') acquired or developed to systematically identify, source, measure, manage and monitor risks (DeLoach, 2000). Although mostly qualitative, attempts have been made to categorize and rank institutional risk management expertise. For example, Sharp *et al.* (2002) describe a 'maturity' model in which organizations progress from being 'learner organizations' with *ad hoc* approaches to risk and reliability management through to 'adaptive organizations', which have an adaptive, responsive and proactive approach.

The structural hierarchy that exists even within 'flat' organizations requires that risks are actively managed at the strategic, programme and operational levels of an organization (Figure 1). Typically, there are split accountabilities for these risks such that the chief financial officer/financial director and board have overall responsibility, supported by an internal audit or control function for the management of strategic risks; executive management for programme level risks (e.g. asset management, maintenance planning) and operational (e.g. site) managers for operational risks (e.g. plant performance). Many companies have risk management committees in place that monitor and report on priority risk areas within the company, principally in response to requirements on internal control. Beyond these company boundaries, there are important risk interfaces with other institutions including the regulators (e.g. licenses to operate) and the capital markets (e.g. raising finance).

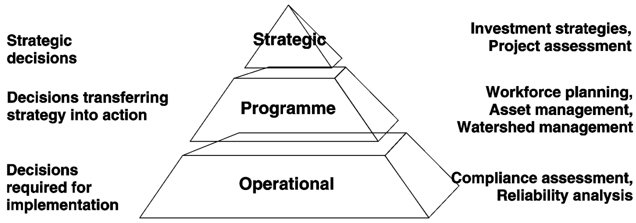

Figure 1. The risk hierarchy (after Prime Minister's Strategy Unit, 2002).

An important interface concerns the financing of infrastructure spend and the raising of capital. Over and above the levy of rates at the local level to support investment on the maintenance of water and wastewater treatment systems, capital spend within public sector utilities is supported through the tax base and granted via a series of government-aided revenue streams or funds. For example, in the US, the Clean Water State Revolving Fund (set up under the 1987 Clean Water Act) provides financial support to individual states to pay for sewage treatment works, and the Drinking Water State Revolving Fund (1996 Safe Drinking Water Act) supports capital investments in water treatment facilities. Within private sector utilities, capital (Figure 2) is typically raised from the markets, e.g. as shares or a bank loan and invested in a firm's operations (e.g. a treatment plant). These investments are treated as costs and include all capital and operational expenditure. Operation develops revenue, and if this income exceeds expenditure it is returned back to the investors or reinvested into the company. The latter is acceptable if it leads to an increase or securing of the current value of the share price (Strutt, 2003).

In the UK, the water regulators [the Office of Water Services for England and Wales (Ofwat), the Drinking

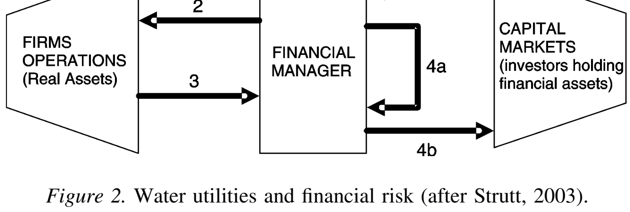

Figure 2. Water utilities and financial risk (after Strutt, 2003).

Water Inspectorate (DWI) and the Environment Agency (EA)] have raised the prominence of risk management for assessing company performance. Following the 1999 periodic review of the industry, Ofwat released 'Maintaining serviceability to customers (MD161)' to managing directors of all water and sewerage companies and water-only companies, underlining Ofwat's desire to formalize risk management within the asset planning process. The procedures developed by the UK water sector are of equal merit to public sector utilities abroad in that

> each company needs to demonstrate how the flow of services to customers can be maintained at least cost in terms of both capital maintenance and operating expenditure, recognizing the trade-off between cost and risk, whilst ensuring compliance with statutory duties.

Ofwat's position has since been further clarified under the 'common framework' outlining the requirements for the 2004 Periodic review, embedding risk management firmly in the process. The DWI in their letter (IL15/2002), 'Distribution Operation and Maintenance Strategies (DOMS), DWI requirements and expectations' expands the need for water utilities to demonstrably and explicitly manage the risks from their operational activities.

Utility managers manage cash flow, whether raised through public or private sector means, by optimizing expenditure and income in the context of providing good, safe drinking water. Events inevitably occur that reduce income and cause increased expenditure. For example, failures in the infrastructure/distribution network causing leaks lead to increased expenditure on leak detection and pipe repair, refurbishment or asset replacement. Public health incidents requiring emergency response and water advisories often incur substantial costs. The techniques of risk management are applied for at least one, and usually several of the following categories of risk:

(1) *Financial risk*. These are risks arising principally from the financial operations and management of the business. From an internal perspective, both capital and operating costs are reduced by carrying out assessments during the design stage of a scheme, whilst operating and maintenance costs can be optimised on existing plant. External financial risks are derived from market processes (e.g. currency rate fluctuations) and are of rapidly increasing significance to water utilities, given the increasing need for self-financing and the twin trends of privatization and globalization.
(2) *Commercial risk*. Formerly considered immune to such risks owing to their public sector monopoly, utilities are no longer insulated from competition or financial instability. They face an increasingly demanding public with powers to make significant changes if unsatisfied (Westerhoff, 2003; Westerhoff and Lane, 1996). A serious accident can depress the share price in publicly quoted companies, persuading boards to make management changes.
(3) *Public health risk*. Failure or inadequacy of the treatment and distribution process can result in an interruption of supply or derogation in water quality (microbiological or chemical). The underlying causes may include source contamination, human error, mechanical failure or network intrusion. The consequences can be immediate; there is often very little time to reduce exposure and the impacts can affect a large number of people simultaneously. The financial costs to the community of the fatal Walkerton outbreak, for example, were in excess of Cdn$65 million, with one-time costs to Ontario estimated at more than Cdn$100 million (O'Connor, 2002). The loss of consumer confidence has been enormous (Hrudey and Leiss, 2003).
(4) *Environmental risk*. Equipment failure or human error can lead to environmental impacts, including discharges to the atmosphere, ground or the water environment. These may occur directly or as a result of actions to mitigate the results of the failure, such as discharges of polluted water from a tank. Similarly, environmental change can affect water quality. The relationship between watershed management, source quality and water quality at the tap is inevitably one characterized by a need for sound risk management.
(5) *Reputation risk*. For most water utilities and regulators, the biggest fear is the loss of consumer confidence. If an organization has target levels in its customer charter, considerable time and effort can be taken up by customer service functions explaining to customers and the media when incidents occur. The Sydney Water crisis of 1998 (McClellan, 1998) was estimated to have cost Sydney Water Corporation over $37 million in directs costs with contingency costs estimated at over $100 million, for an episode with no health consequences (Quill, 1999).
(6) *Compliance/legal risk*. Legislation sets out minimum standards for water quality, the handling and storage of treatment chemicals, the discharge of wastes and the health and safety of the operational staff and the people living nearby. Aside from the inherent risk of failure to comply with legislation (with all its associated consequences), there is the risk arising from uncertainty regarding the future actions of the regulator/legislator. Even when there is no legislation covering some aspects, there can be claims of negligence against operating companies and litigation for civil damages have been prominent features following both the Walkerton outbreak (settled out of court) and the Sydney Water Crises (largely dismissed, costs still incurred).

Assessing risk across these and other categories then becomes essential for optimizing operations and cost/benefit trade-offs. A typical issue is the optimization of workforce planning (e.g. asset inspection or maintenance scheduling). In risk-based resourcing, human (and financial) resources are targeted towards addressing higher risk activities (Pollard *et al.*, 2002; Figure 3). The presumption is that moving to risk-based resourcing (focusing on poorly performing assets, the failure consequences from which are higher) yields greater risk reduction per unit resource of maintenance. Many water companies have risk ranking procedures in place to inform maintenance scheduling. Principles have been developed for the proper design (Long and Fischoff, 2000) of ranking systems following earlier criticism over the implications of bias within these systems.

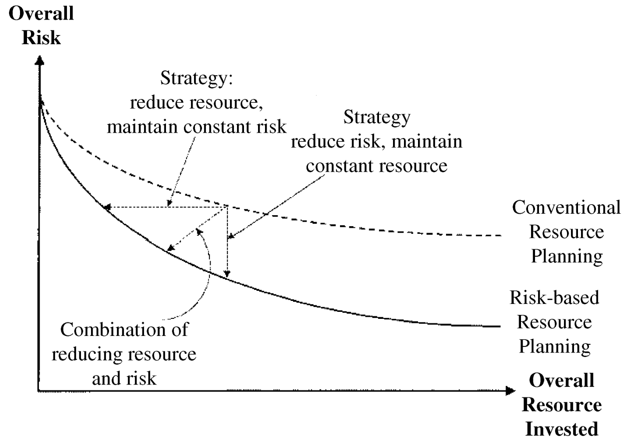

Figure 3. Risk-based workforce planning (after Pollard *et al.*, 2002).

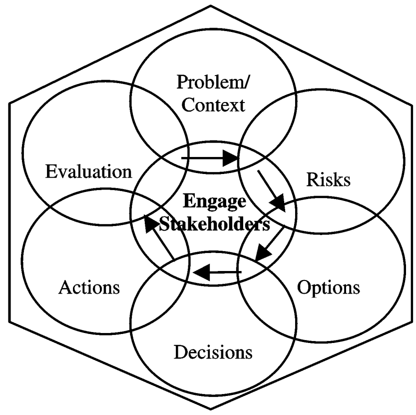

Figure 4. Risk Management Framework (after US Presidential/Congressional Commission on Risk Assessment and Risk Management, 1997).

RISK MANAGEMENT

Decisions on managing risk, if they are to be effective, need to be active rather than reactive and well structured (Pollard and Guy, 2001). Risk management frameworks set out the relationship between the processes of risk identification, evaluation and management (Jardine *et al.*, 2003). They can be regarded as 'route maps' for decision makers. The principles for water utility risk management have been outlined for the Australian water industry to illustrate the value of developing a preventative quality management approach (Hrudey, 2001). One of these, 'turning hindsight into foresight', has been developed as a compilation and analysis of case studies of drinking water outbreaks in developed countries (Hrudey and Hrudey, 2004).

Classical linear approaches to risk management have been replaced by iterative frameworks that adopt the management processes of 'assess–plan–do–monitor–revise' and that aim to engage stakeholders in decision-making. Their application has resulted in a reappraisal of risk analysis in which the relationship between the analysis of risk and the audience is recognized as central to defensible decisions. The US Presidential/Congressional Commission on Risk Assessment and Risk Management (1997) was among the first of government responses to take a fresh look at the issue of risk management. The framework (Figure 4) recognizes the continuous improvement necessary for organizations to develop a mature capacity in risk management and the central role of stakeholders to the decision-making process. It emphasises the importance of (a) good problem definition, (b) management feedback in making decisions, and (c) the central role of stakeholders within the decision-making process. Here, risk analysis is viewed not as an end in its own right, but as a means of selecting and prioritizing options for risk management, that themselves require evaluation after implementation, all set within a context of making better decisions. These frameworks can, however, inadvertently cloud the explicit role of science and evidence within decision-making. The 'process' and 'content' of decisions must be viewed as equally important to the outcome, thus developments since the US Presidential Commission are focusing on making more explicit the role for scientific evidence within democratic decision-making processes (e.g. USEPA, 1999; Charnley, 2000).

TOOLS AND TECHNIQUES FOR RISK ANALYSIS AT THE OPERATIONAL, PROGRAMME AND STRATEGIC LEVEL

Risk analysis plays a role alongside other decision tools for risk management. Not all risks require detailed analysis to be managed. In many industries there are accepted standards of performance and codes of practice (e.g. engineering standards; accepted best practice; Figure 5) that, if adhered to, provide high degrees of control. These are applied where uncertainties and system vulnerabilities are well understood. However, complex, uncertain and novel systems, and situations with a deviation from routine operation, may require risk analysis, so as to better understand what drives the risk from or to the plant, process or operation, thereby allowing management measures for the reduction of unacceptable risks to be targeted.

Tools and techniques for the analysis of these different types of risk vary by their sophistication and design. A wide range of approaches are available (Table 1) from distribution modelling for the analysis of contaminants and pathogens within catchments, to probabilistic fault tree models for the analysis of potential engineering failures at the works level. The implementation of a portfolio of risk techniques within a water utility is contingent on institutional capacity, data quality and the requirements of the decision that the risk analysis is informing.

Operational Risk Analysis

Here we are concerned with the assessment of risks associated with specific operations at plant level—for example, the risk of failure of a device or process component, or the risk of exceeding a particular water quality standard. A common technique used is a semiquantitative risk ranking of hazards according to their likelihood and consequence. Leverett (2000) describes the ranking of risks from and to routine and non-routine process operations within four risk categories: health and safety, water quality, water quantity and environmental. Analysis and prioritization assists treatment managers in identifying

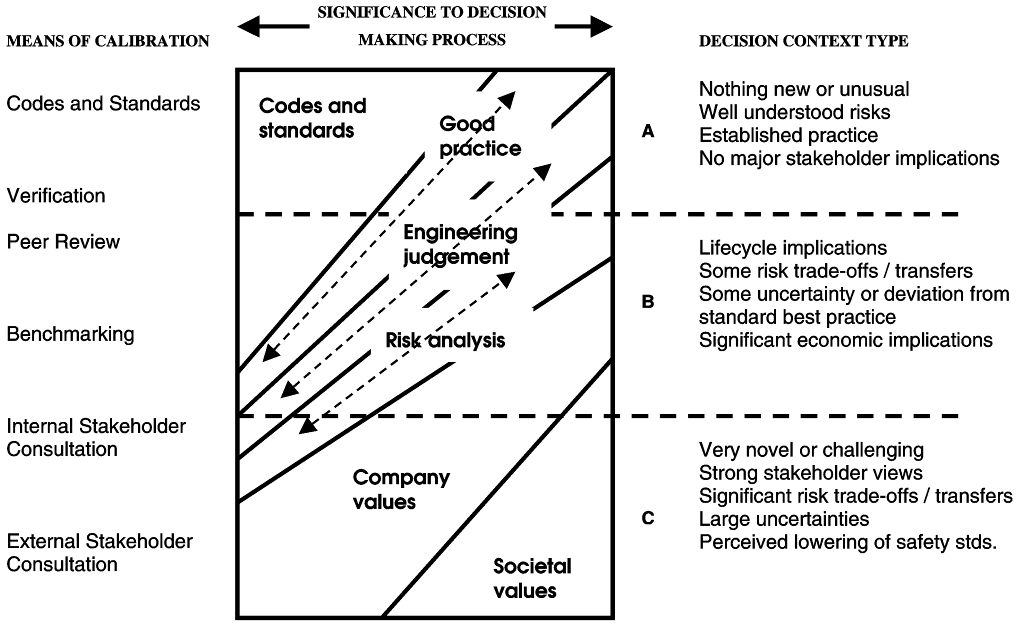

Figure 5. Decision framework for the offshore oil industry (after UK Offshore Oil Operators Association, 1999).

and mitigating previously unforeseen risks to operations, and the planning of projects such as the shut-down and maintenance of a strategic treated water reservoir. A similar ranking approach has been used to identify health and safety hazards at treatment works, e.g. with respect to hazardous chemical usage (Wirth and Siebert, 2000). Typically, risk ranking is used to screen risks as part of a more involved tiered risk assessment programme. The National Health and Medical Research Council (NHMRC), the body responsible for issuing drinking water guidelines to Australian water utilities, in their ‘Framework for management of drinking water quality’ (National Health and Medical Research Council, 2001, Rizak *et al.*, 2003) describe the incorporation of several risk assessment

Table 1. Risk analysis strategies for operational, programme level and strategic risks in the water utility sector.

Level	Example	Tools used	Reference
Operational	Assessing reservoir safety—operations and structural condition	Fault and event tree analysis	Parr and Cullen (1988)
	Health and safety hazard assessment—chemical use at water and wastewater treatment works	Risk ranking Hazard and operability studies (HAZOP) What if, checklists Failure mode and effect analysis (FMEA) Fault-tree analysis	Wirth and Siebert (2000)
	Process risk assessment and project contingency planning	Risk ranking	Leverett (2003)
	Individual pathogen risk assessment	Simulation (e.g. Monte Carlo)	Teunis *et al*, (1997) Masago *et al*, (2002)
Programme	Risk-based asset management	GIS-based infrastructure risk models	Doyle and Grabinsky (2003) Booth and Rogers (2001)
	Process risk assessment to help formulate asset management strategy	Risk ranking Failure mode and effect analysis (FMEA)	Abell and Askey (2001)
	Prioritising expenditure on mains rehabilitation.	Three tiered risk assessment: (1) Risk ranking (2) Generic quantitative risk assessment model (KANEW) (3) Monitoring programme with tailored QRA	Radovanovic and Marlin (2003)
Strategic	Investment risk analysis—Portfolio management for public utilities	Multi-attribute analysis Scenario planning and analysis	Rothstein and Kiyosaki (2003)
	Financial risks of public–private partnerships for infrastructure projects	Simple expected cost analysis Sensitivity analysis Monte Carlo simulation	Grimsey and Lewis (2002)

techniques within a single quality management system. In addition to risk ranking, the framework advocates the application of a HACCP (hazard analysis critical control points) methodology, namely the determination of 'critical control points' whereupon risks can be monitored and reduced. The NHMRC framework proposes that utilities should adopt a multiple barrier approach to risk management (Hrudey and Hrudey, 2003; Deere *et al.*, 2001), ensuring multiple levels of protection against specific contaminant threats. NHMRC presents an example of this from two treatment works, both with very different water sources: (a) a heavily protected catchment (Melbourne) and (b) a large river fed by multi-use catchments (Adelaide). In the Melbourne system, applied barriers include protected catchments, large catchment reservoirs, and good chlorination, whereas in the Adelaide system the barriers are more heavily weighted towards treatment and downstream controls. Risk analysis has long been the basis for the derivation of water quality guidelines for drinking water (WHO, 2002). The substance-specific health risk assessments that have historically informed the guidelines may, however, be somewhat distanced from the immediate operational context of individual utilities. The recent draft of the third edition of the WHO drinking water guidelines (WHO, 2003) provides explicit reference to chemical and pathogenic risk management for water quality control. Risk analysis tools are available for informing utility decisions on risk management.

The New Zealand Ministry of Health (NZHOH) has developed a pragmatic programme for encouraging public health management plans (NZMOH, 2001). Their approach was developed with full awareness of HACCP but a conscious decision was made to focus on 'events' defined as incidents or situations that may lead to hazards being introduced into, or not being removed from, the water (Nokes and Taylor, 2003). In developing this approach, four barriers were identified that, if maintained effective, will adequately control hazards:

- prevention of contamination entering the raw water of the supply;
- removal of particles from the water;
- inactivation of microorganisms in the water; and
- maintenance of the quality of the water during distribution.

The NZMOH approach targets smaller systems and particularly valuable for systems with limited technical resources.

Teunis *et al.* (1997) and Masago *et al.* (2002) describe the application of quantitative microbial risk assessment in an operational context, in determining the risk posed by pathogens from specific source waters. The process begins with the definition of the relationship between pathogen source levels and the consumed dose, followed by the construction of a deterministic model mathematically describing this relationship. The relevant dose–response relationship is applied in order to determine the 'unconditional' probability of infection—unconditional because at this stage no consideration has been given to the distribution spread of the outcome. In order to determine this spread, the first step is to generate the range of values for the input variables and specify their probability distributions. The authors input these values into a Monte Carlo simulation, which through a process of iterative sampling provides a frequency distribution for the probability of infection. Similar approaches can be adopted for determining the risk of exceeding water quality compliance standards at a particular plant. In assessing the potential threats to water supplies from ongoing or accidental releases within catchments, Halfacree (1998) describes the use of PRAIRIE, a PC-based software tool for assessing chemical pollution risks to water bodies. The main elements are an aquatic dispersion model; hydrological, substance and standards databases; and a tabular/graphical output facility. The model has a deterministic mode (used to 'screen out' low risk sites) and a probabilistic mode (for more detailed analysis of high risk sites). The output results (e.g. frequency vs concentration curves) are compared with predetermined criteria to inform regulatory actions on risk management from hazardous activities within a sensitive catchment.

Risk analysis at the operational level is further concerned with the reliability of the system components, for example in determining the risk of failure of a particular treatment step. The analysis may be summarized (Egerton, 1996):

- What can go wrong with the system?
- What are the effects and consequences of failure?
- How often will that failure occur?

For unreliable or heavily used equipment, an analysis of the historical data is often sufficient for determining frequencies of failure. In the absence of such data, there exist a number of techniques for assessing the frequency and consequences of system failure, including fault tree analysis (e.g. Parr and Cullen, 1988) and failure mode and effect analysis (e.g. Demotier *et al.*, 2002).

Programme Level Risk Analysis

At the programme level, we are concerned primarily with techniques used to evaluate the risks posed by a similar hazard at a variety of locations (e.g. mains bursts, progressive failure of filter media—in asset management, for example) or with the wide variety of risks existing within a watershed. The availability of geographic information systems has facilitated the ease by which such assessments can be performed. Programme level risk assessments are typically concerned with the implementation of strategies across multiple sites and geographic regions (catchment/watershed planning).

Risk analysis of infrastructure assets is widespread within the sector, and is a critical tool in asset management. Approaches range from the simple coupling of GIS techniques with infrastructure data in order to visually track utility assets and examine their associated risk factors (e.g. Doyle and Grabinsky, 2003; Booth and Rogers, 2001) to the complex integration of data intensive GIS with hydraulic simulations in order to assess the risk of distribution system intrusion (e.g. Lindley and Buchberger, 2002). On a national scale, the US Natural Resources Defence Council (NRDC, 2003) recently reported on the risk to drinking water quality from aging pipes and process plant across the USA with individual city 'rankings' being informed by water quality data, USEPA compliance records and water utility annual reports. Similar risk ranking techniques have been used internationally to inform threat assessments of water systems in light of recent terrorist activities (e.g. Anonymous, 2001).

The assessment of hazards to the quality of water resources within a catchment or watershed is increasingly subject to formal risk assessment and can be expected as part of routine water safety plans (Umweltbudesamt, 2003; WHO, 2003; UKWIR, 2003). In Europe, the DPSIR approach to identifying key hazards within a watershed, by reference to the driving forces (e.g. population growth), pressures (sewer discharge), state (increased nutrient load), impacts (anthropogenic eutrophication) and policy response (discharge control) is being adopted under the European Water Framework Directive (IMPRESS Management, 2002). Here, risk assessments are intended to inform a programme of activities targeted at raising the ecological status of the watershed. Various tools are available for the analysis of catchment risks. For example, Wickham and Wade (2002) have developed a watershed risk model of nitrogen and phosphorus export based on the surrounding land cover class, whilst Verro *et al.* (2002) describe a GIS-based mass balance model for use in risk assessments of agricultural chemicals. Given the plethora of potential catchment management issues in any improvement programme, there is a need to prioritize risk management within the watershed by concentrating on those measures that reduce the significant likelihood of severe impacts being realised. Lytton *et al.* (2003) describe a generic methodology based on the source—pathway—receptor model (Environment Agency, 2000) that enables the evaluation and ranking of potential pollution risks to groundwater abstractions. This ranking is designed to be used in prioritizing risk management or mitigation procedures.

Programme level risk analysis invariably involves trading costs and benefits, such as in risk-based resourcing previously described (Figure 3). When designed well, piloted and implemented with feedback, these systems can provide a sound basis for distinguishing greater risks from lesser ones, and for investing resources in risk management that are proportional to the risks posed (Pollard *et al.*, 2002). However, these systems, whether for driving maintenance schedules, monitoring regimes or workforce planning, may also incur risk unless the consequences of resource trade-offs are themselves assessed. An example relevant to drinking water safety arose from the actions of the Saskatchewan Department of Environment and Resource Management (SERM) prior to the North Battleford *Cryptosporidoisis* outbreak in April 2001. This provincial department held legislative responsibility for the drinking water programme in Saskatchewan and, when faced with budget cuts in the mid 1990s, it drastically reduced the already limited field inspection and enforcement of municipal drinking water facilities. This culminated in a SERM proposal to eliminate its drinking water programme altogether that was tentatively approved by the Treasury Board in 2000/2001 and justified as being based on risk-based decision-making. The subsequent North Battleford outbreak, infecting between 5800 and 7100 persons in the immediate community plus a large numbers of visitors from three other provinces, led to a public inquiry into the outbreak and the provincial drinking water regulatory system. Justice Laing concluded in his Inquiry report:

> that the current risk-based model employed by SERM since 1996 is arrived at on the basis of economics, and has nothing to do with how best to safeguard the health of the population, all of whom consume water. (Laing, 2002).

For a provincial regulator to use 'risk' as a basis for eliminating altogether inspections and field support at a time when a substantial number of utilities were out of compliance with the drinking water guidelines appears to be a serious distortion of the concept of risk as the basis for decision-making.

Strategic Risk Analysis

Risks at the strategic level include project, commercial and financial risks, such as those associated with infrastructure investment; merger and acquisition activity; company reputation; outsourcing; and the long term viability of investment decisions. Louis and Rogers (2001) provide a strategic risk analysis of three investment strategies and describe a multi-objective planning model that seeks to optimize operational capacity and economic, environmental and social gains. The project and investment risks associated with public-private partnerships are reviewed by Grimsey and Lewis (2002). Using the financing of Stirling Water, a Scottish design–build–operate contractor as an illustrative example, they discuss the complexity of the contractual arrangements within such partnerships and use a quantitative analysis of returns on investment to characterize the robustness of cash flows from each of the senior lenders to this public–private venture. Rothstein and Kiyosaki (2003) describe the application of portfolio management theory to utility investments in order to provide a balance of risk and return that is consistent with the utility's strategic goals and objectives. This approach, facilitated by tools including multi-attribute analysis and scenario planning, involves: (a) determining the set of investments available to the water utility and their characteristics in terms of risks (both monetary and non-monetary), returns and resource requirements; (b) prioritizing investment opportunities across functional areas (i.e. looking beyond departmental barriers within organisations); and (c) selecting investment options by virtue of their alignment with established corporate goals and objectives.

Group risk managers also need to consider risks external to their operations. Water utilities are becoming increasingly exposed to commercial and market risks (Rothstein and Kiyosaki, 2003; Westerhoff and Lane, 1996), exposing them to a climate of operational uncertainty, including currency and interest rate fluctuations, competitive dynamics (the interactions between utilities in a liberalised market), and stock market volatility. In this context, recognizing the link between risk and opportunity becomes crucial. Tools and techniques to evaluate these risks include value at risk models, which examine gross or notional assets at risk (e.g. currency exposure) from a change in a key market variable (exchange rates); and scenario/simulation modelling, which can offer insights into how aspects of the market may evolve. As privatization and globalization take root within the water utility sector, in concert with an increasingly demanding regulatory and consumer environment (Westerhoff, 2003), the evaluation and management of these risks will become increasingly important.

IMPLEMENTING AND IMPROVING RISK MANAGEMENT IN ORGANIZATIONS

Making credible and defensible decisions in organizations requires an institutional capacity to be predictive rather than reactive when managing risk and an aptitude to learn from experience. Implementing risk analysis strategies and decision-making frameworks requires clear, straightforward procedures that can be understood, agreed and operated by all levels in an organization. 'Keeping it as simple as it needs to be' has been a mantra of risk analysts (Morgan and Henrion, 1990). The implementation of a working framework should not be seen as the end-point of risk management (DeLoach, 2000). Businesses must strive to continuously re-assess and improve their capabilities for dealing with risk. Senior management must be able to define their risk management capabilities (both current and desired) and assess the costs and benefits of improvement (DeLoach, 2000). An increasingly applied tool that can assist in achieving this goal is the capability maturity model. Initially developed for the improvement of software processes (Paulk *et al.*, 1993), the model has been adapted and applied for use more broadly (IACCM, 2003), for example in the oil and gas sector (Sharp *et al.*, 2002). Risk mature organisations have the following key processes in place (Strutt, 2003):

(1) *Core risk management processes*, including (i) setting and allocation of safety risk and reliability requirements, (ii) performance of risk analyses including reliability and safety studies to inform decisions, (iii) design and operation of plant to meet specified risk and reliability requirements, and (iv) risk assurance to the customers, stakeholders and regulators.
(2) *Typical organizational implementation processes* include (i) the verification of management processes and validation of risk models and data, (ii) project risk management (ensures risks managed to cost and delivery schedules), (iii) emergency response management, (iv) reliability, qualification and safety testing (provides assurance of performance), (v) measurement and analysis of data (assurance of what is achieved in service), (vi) procedures for the management of change (identifying key differences), and (vii) supply chain management (sometimes failures and incidents have their causes in products supplied down the supply chain).
(3) *Institutional support.* Finally, there is an expectation that the implementation of a risk management framework will be supported by organizational learning, education and training and research and development.

Capability maturity models have a set of well-defined attributes that can be used to benchmark organizations within a sector. A company's capability in risk management can be evaluated by reference to these attributes and well-defined 'scores' representing a scale from poor to best practice in the demonstration of that attribute. 'Spider diagrams' (Figure 6) allow comparisons between organizations and cross-sector similarities to be established, showing where further improvements can be made. Using these models, it is possible to rank an organization's progression from a learner to exemplar of best practice in risk management. Sharp *et al.* (2002) describe five levels of maturity. At level 5 (highest), the organization is at 'best practice', capable of learning and adapting itself. It not only uses experience to correct any problems, but also to change the nature of the way it operates. Level 4 organizations are 'managed organizations' controlling what they do in the way of processes with requirements, ensuring these are met through feedback. A level 3 'defined organization' can say what it does and how it goes about it, whilst level 2 can repeat what it has done before, but not necessarily define what it does or adapt previous experience to a new situation. Finally, a level 1 organization is characterized by an absence of the above qualities. Of fundamental importance is the acceptance that resources are finite, and so desired capabilities should be selectively pursued according to particular risks or risk types (DeLoach, 2000). The value of these models of course is in identifying what measures are required for an organization to progress between levels of maturity in risk analysis and management. Ultimately, of course, risk analysis as only as good as the decision it informs and risk management activity should reflect sensible and meaningful conclusions rather than theoretical perspectives that may run counter to sound judgements (Hrudey and Hrudey, 2003).

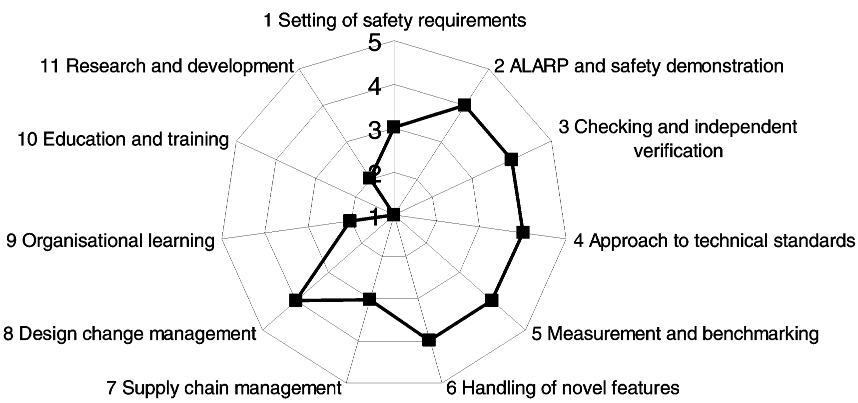

Figure 6. Illustrative spider diagram showing organisation profile (red) by reference to key aspects of safety and design (after Sharp *et al.*, 2002).

CONCLUSIONS

The water utility sector has made substantial progress to recognizing the value of risk analysis strategies and decision-making frameworks within its business, evidenced by a number of current international water sector initiatives. Embedding these systems within organizations and making them fit for purpose is the next step.

REFERENCES

Abell, P. and Askey, M., 2001, Process risk assessment: water supply systems, in *Risk Assessment for Environmental Professionals*, Pollard, S.J. and Guy, J.A. (eds) (Chartered Institution of Water and Environmental Management, Lavenham Press, Suffolk), pp 51–55.

Anonymous, 2001, *Sandia Offers Procedure, Tool to Help Protect Water Systems*, McGraw-Hill's Federal Technology Report (McGraw Hill, New York), p 7.

Australian Academy of Technological Sciences and Engineering, 2002, Living with risk in our society, in *Proceedings of the New South Wales Division 2002 Workshop*, Sydney, 14 May 2002; available at www.atse.org.au/publications/reports/nsw-risk-2002.htm

AWWA, EUREAU, WSAA and DVGW, 2001, *Bonn Workshop 2001—Key Principles in Establishing a Framework for Assuring the Quality of Drinking Water: a Summary* (AWWA, Denver, CO) 6pp.

Booth, R. and Rogers, J., 2001, Using GIS technology to manage infrastructure capital assets, *J AWWA*, 93(11): 62–68.

Charnley, G., 2000, *Democratic Science: Enhancing the Role of Science in Stakeholder-Based Risk Management Decision-Making*; available at www.riskworld.com/Nreports/2000/Charnley/NR00GC00.htm#TOC

Council of Standards of Australia, 1999, *Australian/New Zealand Risk Management Standard no. 4360: 1999*; available at www.standards.com.au/catalogue/script/Details.asp?DocN = stds000023835.

Deere, D., Stevens, M., Davison, A., Helm, G. and Dufour A., 2001, *Management Strategies in Water Quality: Guidelines, Standards and Health*, Fewtrell, L. and Bartram, J. (eds) (IWA Publishing, London), pp 257–288.

DeLoach, J.W., 2000, *Enterprise-wide Risk Management: Strategies for Linking Risk and Opportunity* (Financial Times–Prentice Hall, London).

Demotier, S., Odeh, K., Schon, W., Charles, P., Fotoohi, F. and Allioux, J-F., 2002, *Risk Assessment for Drinking Water Production Process*; available at www.hds.utc.fr/~tdenoeux/sime/publis/esrel2002.pdf

Dewettinck, T., Van Houtte, E., Geenens, D., Van Hege, K. and Verstraete, W., 2001, HACCP (Hazard Analysis and Critical Control Points) to guarantee safe water reuse and drinking water production—a case study, *Water Sci Technol*, 43(12): 31–38.

Doyle, G. and Grabinsky, M., 2003, Applying GIS to a water main corrosion study, *J AWWA*, 95(5): 90–104.

Economic and Social Research Council Global Environmental Change Programme, 2000, *Risky Choices, Soft Disasters: Environmental Decision-making under Uncertainty* (University of Sussex, Brighton).

Egerton, A. J., 1996, Achieving reliable and cost effective water treatment, *Water Sci Technol*, 33(2): 143–149.

Environment Agency, 2000, *Introducing Environmental Risk Assessment*, ref HO-06-00 (Environment Agency Centre for Risk and Forecasting, Reading), 12pp.

European Commission, 2000, *The TRUSTNET framework: a New Perspective on Risk Governance*, Directorate-General for Research, Report EUR 19150 EN (European Commission, Brussels).

Fewtrell, L. and Bartram, J., 2001, *Water Quality: Guidelines, Standards and Health—Assessment of Risk and Risk Management for Water-related Infectious Disease* (IWA Publishing (on behalf of WHO), London).

Grimsey, D. and Lewis, M.K., 2002, Evaluating the risks of public private partnerships for infrastructure projects, *Int J Project Mgmt*, 20: 107–118.

Halfacree, S., 1998, Pollution risk management, *Issues Environ Sci Technol*, 9: 37–56.

Hellier, K., 2000, Hazard analysis and critical control points for water supplies, in *Proceedings of 63rd Annual Water Industry Engineers and Operator's Conference*, Warrnambool, 6–7 September 2000, 101–109.

Hrudey, S.E., 2001, Drinking water quality—a risk management approach, *Water*, 26(1): 29–32.

Hrudey, S.E., 2003, Drinking water risk management principles for a total quality management framework in *Drinking Water Safety—a Total Quality Management Approach*, Hrudey, S.E. (ed.) (NERAM, Institute for Risk Research, University of Waterloo), pp 3–14. Q1

Hrudey, S.E. and Hrudey, E.J., 2003, Response to Woo, D.M. and Vicente, K.J. (2003), *Reliab Eng Syst Safety*, 82: 343–345.

Hrudey, S.E. and Hrudey, E.J., 2004, *Safe Drinking Water—Lessons from Recent Outbreaks in Affluent Nations* (IWA Publishing, London).

Hrudey, S.E. and Leiss, W. 2003, Risk management and precaution—insights on the cautious use of evidence, *Environ Health Persp*, 111: 1577–1581.

Huber, J.L., 2000, The evolving competitive marketplace, *J AWWA*, 92(1): 50–51.

IACCM, 2003, *Organisational Maturity in Business Risk Management: the IACCM Business Risk Management Maturity Model (BRM3)* (International Association of Commercial and Contract Managers, Ridgefield, USA) 14pp.

IMPRESS Management, 2002, *IMPRESS Guidance. Guidance for the Analysis of Pressures and Impacts in Accordance with the Water Framework Directive*, Draft 5.2 (European Commission, Brussels).

Jardine C., Hrudey, S.E *et al.*, 2003. Risk management frameworks for environmental, human health and occupational health risk, *J Toxicol Environ Health PB*, 6(6): 569–718. Q2

Kucera, D.J., 1993, Rate making for risk: the law, *Water Eng Mgmt.*, 140(5): 8.

Laing, R.D., 2002, *Report of the Commission of Inquiry into Matters Relating to the Safety of the Public Drinking Water in the City of North Battleford, Saskatchewan, March 28, 2002* (The Queen's Printer, Regina, Saskatchewan); available at www.northbattlefordwaterinquiry.ca.

Leverett, S., 2003, Eating the elephant, *Water*, 166: 8–9.

Lifton, G. and Smeaton, P. (2003) Asset risk management in Scottish Water, in *Proceedings of the ICE/CIWEM Water Environment Conference Risk and Reward in Asset Management Delivery—who is Best Prepared for the Challenges Ahead?*, 14 November, 2003, London.

Lindley, T.R. and Buchberger, S.G., 2002, Assessing intrusion susceptibility in distribution systems, *J AWWA*, 94(6): 66–79.

Long, J. and Fischoff, B., 2000, Setting risk priorities: a formal model, *Risk Anal*, 20: 339–351.

Louis, G.E. and Rogers, J.W., 2001, Strategic risk management: risk and opportunity in upgrading US water/wastewater infrastructure, in *Annual Meeting of the Society for Risk Analysis, 2001*.

Lytton, L., Howe, S., Sage, R. and Greenway, P., 2003, Groundwater abstraction pollution risk assessment, *Water Sci Technol*, 47(9): 1–7.

Masago, Y., Katayama, H., Hashimoto, A., Hirata, T. and Ohgaki, S., 2002, Assessment of risk of infection due to *Cryptosporidium parvum* in drinking water, *Water Sci Technol*, 46: 319–324.

McClellan, P., 1998, *Sydney Water Inquiry*, (New South Wales Premier's Department, Australia).

Morgan, M.G. and Henrion, M, 1990, *Uncertainty: a Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis* (Cambridge University Press, New York).

National Health and Medical Research Council (NHMRC), 2001, *Framework for Management of Drinking Water Quality* (NHMRC, New Zealand).

Nokes, C. and Taylor, M., 2003, Towards public health risk management plan implementation in New Zealand, in *Umweltbundesamt, 2003, Water Safety Conference Abstracts*, Scholl, O. and Chorus, I. (eds), Berlin, 28–30 April 2003.

NRDC, 2003, *What's on Tap? Grading Drinking Water in US Cities* (Natural Resources Defense Council, Washington, DC); available at www2.nrdc.org/water/drinking/uscities/pdf

NZMOH, 2001, *How to Prepare and Develop Public Health Risk Management Plans for Drinking-water Supplies* Ministry of Health, Wellington, p12; available at www.moh.govt.nz/water

O'Connor D.R., 2002, *Report of the Walkerton Inquiry. Part 1. The Events of May 2000 and Related Issues* (The Attorney General of Ontario, Toronto, Canada).

Parr, N.M. and Cullen, N., 1988, Risk management and reservoir maintenance, *J IWEM*, 2: 587–593.

Paulk, M., Curtis, B., Chrissis, M. and Webber, C., 1993, *Capability Maturity Model (SW-CMM) for Software, Version 1.1*, Technical Report CMU/SEI-93-TR-024 ESC-TR-93-177, February 1993; available at www.sei.cmu.edu/publications/documents/93.reports/93.tr.024.html

Pollard S.J. and Guy, J., 2001, *Risk Assessment for Environmental Professionals*, (Chartered Institution of Water and Environmental Management, Lavenham Press, Suffolk), 94pp.

Pollard, S.J.T., Yearsley, R., Reynard, N., Meadowcroft, I.C., Duarte-Davidson, R. and Duerden, S., 2002, Current directions in the practice of environmental risk assessment in the United Kingdom, *Environ Sci Technol*, 36(4): 530–538.

Prime Minister's Strategy Unit, 2002, *Risk: Improving Government's Capability to Handle Risk and Uncertainty* (The Strategy Unit, London); available at www.number-10.gov.uk/SU/RISK/risk/home.html

Quill, R., 1999, The 1998 Sydney water crisis: view from the inside, in *Annual Conference of the AWWA, Chicago* (AWWA, Denver, CO).

Radovanovic, R. and Marlin, A., 2003, Critical water mains—the need for risk analysis, *Water (Australia)*, 30(2): 42–46.

Rizak, S., Cunliffe, D., Sinclair, M., Vulcano, R., Howard, J., Hrudey, S. and Callan, P., 2003, Drinking water quality management: a holistic approach, *Water Sci Technol*, 47(9): 31–36.

Rothstein, E. and Kiyosaki, D., 2003, Development of a strategic plan: portfolio management for public utilities, *J AWWA*, 95(1): 52–65.

Royal Academy of Engineering, 2003, *The Societal Aspects of Risk* (The Royal Academy of Engineering, London).

Sharp, J.V., Strutt, J.E., Busby, J. and Terry, E., 2002, Measurement of organizational maturity in designing safe offshore installations, in *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering*, 2: 383–390.

Stern P.C. and Fineberg, H.V. (eds), 1996, *Understanding Risk—Informing Decisions in a Democratic Society* (National Academic Press, Washington, DC).

Strutt, J.E., 2003, *Corporate Risk Management. Lectures in Risk Management for Water and Wastewater Engineers* (Cranfield University, Cranfield).

Teunis, P.F.M., Medema, G.J, Kruidenier, L. and Havelaar, A.H., 1997, Assessment of the risk of infection by *Cryptosporidium* or *Giardia* in drinking water from a surface water source, *Water Res*, 31(6): 1333–1346.

UK Offshore Oil Operators Association (UKOOA), 1999, *Industry Guidelines on a Framework for Risk Related Decision Support* (UKOOA, London).

UKWIR, 2003, *Managing Microbial and Chemical Risks from Source to Tap*, Report 03/DW/02/31 (UW Water Industry Research Limited, London), 103pp.

Umweltbundesamt, 2003, *Water Safety Conference Abstracts*, Scholl, O. and Chorus, I. (eds), Berlin, 28–30 April 2003, 248pp.

US Presidential/Congressional Commission on Risk Assessment and Risk Management, 1997, *Volume I, Framework for Environmental Health Risk Management; and Volume II, Risk Assessment and Risk Management in Regulatory Decision-Making*; available at www.riskworld.com/Nreports/nr7me001.htm

USEPA, 1999, *Integrated Environmental Decision-making in the 21st Century*, Peer review draft, May 1999; available at www.epa.gov/sab/pdf/intenv20.pdf

Verro, R., Calliera, M., Maffioli, G., Auteri, D., Serenella, S., Finizio, A. and Vighi, M., 2002, GIS-based system for surface water risk assessment of agricultural chemicals. 1. Methodological approach, *Environ Sci Technol*, 36(7): 1532–1538.

Westerhoff, G.P, 2003, Pathways to higher performance, *J AWWA*, 95(7): 50–57.

Westerhoff, G.P. and Lane, T.J., 1996, Competitive ways to run water utilities, *J AWWA*, 88(4): 96–101.

WHO, 2002, *Water Safety Plans (Revised Draft)*, Report publication WHO/SDE/WSH/02.09 (World Health Organization, Geneva).

WHO, 2003, *Guidelines for Drinking Water Quality, 3rd edn* (draft) (World Health Organization, Geneva), available at www.who.int/water_sanitation_health/dwq/guidelines3rd/en/

Wickham, J.D. and Wade, T.G., 2002, Watershed level risk assessment of nitrogen and phosphorus export, *Comput Electron Agric*, 37: 15–24.

Wirth, N. and Siebert, A.J., 2000, Identifying and evaluating process hazards with process hazard analysis, *Pollut Eng*, 32(13): 38–40.

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