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Better environmental decision-making – recent progress and future trends

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Abstract

Recent trends in risk-based decision-making are reviewed in relation to novel developments in comparative risk analysis, strategic risk analysis, weight of evidence frameworks, and participative decision-making. Delivery of these innovations must take account of organisational capabilities in risk management and the institutional culture that implements decision on risk. We stress the importance of managing risk knowledge within organisations, and emphasise the use of core criteria for effective risk-based decisions by reference to decision process, implementation and the security of strategic added value.

Keywords: decision, analysis, environmental, risk, policy, management

1. Introduction

Environment ministries and their regulatory agencies make decisions today that affect our long term future. Increasingly, the remit of these bodies is articulated in terms of an improved quality of life for current and future generations, and improved

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societal resilience against environmental threats (for example, Defra, 2003; US Environmental Protection Agency, 2006; Environment Canada, 2007). Risk management plays a central role in securing environmental safety and, within a modern culture of risk governance, a government's responsibilities for managing risks are shared with its stakeholders, its regulated communities, its partner departments in government and with citizens. Modern environmental policies need to be evidence-based and risk-informed, so that prioritised, high quality and implementable decisions can be made with the confidence of stakeholders. For policy makers, risk management is transdisciplinary, applied and practical. To be effective, risk management must be supported by peer-reviewed science that underpins an evidence base for a specific course of risk management action. When assembled in concert, the overall weight of evidence from individual threads of evidence then supports decisions on how risks are best managed; for example, on the selection and operation of radioactive waste management facilities, on the design of flood risk management strategies, or on the environmental safety of engineered nanomaterials released during manufacture.

In this paper, we are concerned with recent developments and future trends in environmental decision-making, particularly within the policy/regulatory landscape. The field of environmental decision-making has been moving apace since the 1990s, and the sustainable development agenda has had a marked impact on environmental decision tools; in that it has correctly forced the incorporation of economic and social issues, alongside environmental impacts that have historically had greater attention. Some of the important features of the debate discussed in this review are: (i) recent attempts among practitioners to grapple with risk comparisons where impact end points (benefits or detriments) differ markedly; (ii) the growing influence of strategic risk assessment for informing high-level policy priorities; (iii) the interaction between risk analysis and the evidence that supports risk assessments; and (iv) the development of participatory decision-making. In drawing together the literatures on these aspects, our review starts with a recent overview of risk-based decision-making, recording recent developments and setting the scene for the analysis that follows.

2. Risks and values

At their core, most environmental decisions are about balancing risk and reward; loss versus gain. For risk-informed decisions, we seek to understand the significance of a risk, decide whether it requires management and what that might cost, and then implement the decision effectively, so reducing the risk to an acceptable residual level; recognising that zero risk is not achievable. Though perhaps outmoded and admittedly reductionist in approach, practitioners still find it helpful to begin by considering risks as a combination of the consequences of an event occurring multiplied by the likelihood of those consequences. A managed risk that is reduced is one where either the probability of the event, or its consequences, or both, have been reduced (Figure 1) from what they were originally.

Figure 1. Risks and values

To manage risk well, we need to make judgements about the significance of initial levels of risk, about acceptable levels of residual risk (our risk appetite, post management), about the various strategies for risk reduction (P_2C_2 to P_1C_1; Figure 1), about the cost of risk reduction in light of the benefits that a managed risk brings, and critically, on our ability to implement risk management effectively and efficiently

(Figure 1). Whilst Figure 1 provides analytical rationality, most debates about risk boil down to discussions on individual and societal values (what is it we wish to protect, and why this particular subject of protection should have priority over other deserving subjects). Several valuable contributions exist (see, for example Wynne (1997); Stirling (1997); Löfstedt and Frewer (1998); Fischer, 2000; Kasperson and Kasperson, 2005). Defensible decisions on managing risk should generate confidence among stakeholder communities. Whilst zero risks are unattainable, most stakeholders seek confidence in the environmental safety of human activities, and so their perceptions of the likelihood of securing safety and their trust in its 'guarantors', is never far from the centre of debate. Increasingly, stakeholders are unconvinced by the risk management intentions of governments without an accompanying discussion of the motivations for risk management. They require an explanation of who will bear the cost and what the benefits will be to those who bear the risk, as well as demonstrable evidence on the long-term effectiveness of risk management actions and responsibilities for monitoring this. In times of economic trade-offs, there is a continual need to express the points at which risks are regarded as intolerable and risk reduction viewed as mandatory, without regard to cost.

An important technical development has been the need to consider risks to the total environment (air, water, soil, biota) within regulatory assessments, with the attending need to integrate risks from the source of a hazard through to a range of receptors (subjects at risk of detriment). We have progressed, over the last 30 years, from single-point deterministic risk analyses to sophisticated probabilistic expressions of risk for multiple ecological impacts, basing our environmental guidelines (for drinking water, air quality and land remediation, for example) on quantitative human health risk assessments. Alongside, contributions from the social sciences have highlighted the psychology of risk-taking, the centrality of good risk communication and have challenged our hitherto technocratic approach, calling for the democratisation of environmental decision-making (Figure 2).

Figure 2 Proposed decision framework for 'democratic science' (redrawn from Charnley, 2000)

The modern risk management frameworks (Stern and Fineberg, 1996; US Presidential Commission, 1997; Charnley, 2000; Petts *et al.*, 2003) that have emerged re-emphasise the critical role of evidence and institutional knowledge, a theme to which we return later. Implementing these frameworks, however, has proved challenging (Fischer, 2000). Whilst we approach 2010 having understood the limitations of quantitative analysis, the complexity of environmental decisions (Figure 3) and the essentiality of involving others in decisions that affect them, we do so with an ever pressing need to set and implement priorities that will secure our long term future, frequently having to make these decisions on incomplete and/or contradictory evidence. Do we have the risk management tools, capabilities and institutional capacities to meet this need?

Figure 3. Categorising incertitude within environmental decision-making (redrawn from Stirling, 2001)

3. Making better environmental decisions

A common a practical requirement for policy makers and regulators is to express and compare the value of environmental harm that might arise from a multitude of sources to a range of receptors. Comparisons have to be scientifically defensible, practical and offer demonstrable outcomes for a better environment (Environment Agency, 2000). However, the expression of environmental harm is by its nature controversial because it requires an explicit statement of values: (i) the value one places on environmental components at risk; (ii) the detriment in value that a risk, once realised, brings; and (iii) the relative value one assigns between receptors at risk (Pollard *et al.*, 2004).

3.1 Comparing and ranking risks

The issue of comparing different risks with disparate characteristics is not new. The difficulty is not so much the comparison of the relative likelihoods of occurrence, but the (adverse) impacts that may ensue; for example, how to compare ecosystem stress with the potential human health effects that might ensue from prolonged environmental exposure. The situation is difficult for environmental hazards because their consequences are felt both in a spatial and a temporal context, and multiple effects are expressed when hazards are realised – frequently to many receptors at any one time. The situation is complicated further by the latency of certain impacts and the irreversibility of others.

Like many tools in environmental policy and regulation, comparative risk assessment has had its advocates and critics over the years following its emergence in the USA in the late 1980s. Most practitioners accept a compromise from theory in order to reap the benefits of application, although decision analysts continue to offer improved metrics and elegant approaches (Long and Fischoff, 2000) to the combination of risks that allow a more justifiable and transparent presentation of risk priorities. New developments in comparative risk analysis tend to be controversial because they force an explicit statement of values and infer (rather than evidence) varying degrees of understanding about the system under study. Comparative risk assessment tools can suffer from (i) an over-simplification of the problem through the use of user-selected surrogates for harm; (ii) over-sophisticated analysis through the use of complex metrics at levels of analytical precision that exceed the level of information available about the risk being assessed; (iii) a poor expression of probability (perhaps because quantification is seen as too difficult, i.e. tools become solely impact-focussed and thus lose their analytical power); (iv) a lack of empirical rigour to the comparison of risks; and (v) poor user-friendliness and a tendency to become bogged down in detail during application.

This said, these tools have seen wide application across the policy and regulatory arenas, and are being used internationally to target regulatory and other institutional resources towards key risks requiring management. There is a long-standing debate as to whether they prove useful as a communication tool and their application is usefully summarised for chemical exposures in the public health context by Williams (2004). Similarly, risk-ranking matrices have been employed that adopt simple probability consequence scores. Frodsham and Cardew (2000) used such an approach for evaluating new technologies for water treatment. In their work, risk scores for a number of technologies were informed by a failure mode and thus allow analysis of the treatment technology combined with expert judgement on the likely impacts of failure. Similar comparative analyses have been used widely in a range of forms, for example, in:

- technology assessment for:
  - energy supply technologies (Ramanathan, 2001);

- the reliability of bridges (combined with reliability assessment) (Stewart, 2001; Stewart *et al*., 2001);
- environmental remediation technologies (Bonano *et al*., 2000).

- managing chemicals and pathogens in the environment, e.g.
  - by ranking pollution inventories (Gamo *et. al.*, 2003; Lerche *et al*., 2004);
  - by ranking pesticide products (Finzio *et al*., 2001; Lee *et al.*, 2002; Low *et al.*, 2004);
  - assessing the relative risk from exposures to volatile organic compounds in drinking water (Williams *et al*., 2002), and to consumers from seafood (Sumner and Ross, 2002) and chicken products (Brown, 2002);
  - for ranking the risk of pharmaceuticals in surface waters (Sanderson *et al.*, 2004) and exposures from landfills (Vrijheld *et al*., 2002)
  - for prioritising contaminated site remediation (Grumbly, 1997).
- comparing ecosystem impacts (only) in catchment-level impact assessments (Serveiss *et al*., 2004).
- Developing the basis for environmental health policy priorities *(*Wong *et al.*, 2003).
- in policy development:
  - informing the health impact assessment of transport policies in Australia (Dora, 2003; Kjellstrom *et al*., 2003);
  - as input to bans on asbestos (Camus, 2001);
  - for informing pollution reduction strategies (Pennington and Bare, 2001; Lerche *et al.*, 2002);
  - for informing regional catchment management plans (Tran *et al*., 2002).

Informed by the comparative risk analysis carried out by the US Environmental Protection Agency in 1987 (USEPA, 1987) and application to a myriad of policy problems, consensus is developing on the relative merits and challenges of applying these techniques. Andrews *et al*. (2004a,b) note the use of spurious precision in risk rankings – so-called 'analytical over-reaching'; calls for normative approaches that are rarely applied in practice; and an unease among practitioners regarding the presentation of uncertainty in strategic level analysis with a tendency, having acknowledged uncertainty is inherent, to then ignore it in practice.

Perhaps the most comprehensive attempt to tackle the issue of metrics and uncertainty under authentic conditions was undertaken by the New Jersey comparative risk project (NJDEP, 2003). This study identified 88 individual environmental stressors in 11 broad hazard categories. In their summary, Andrews *et al.* (2004b) concluded that, despite considerable analysis and interrogation of data by multiple expert panels, the analytical 'constructed aggregation' methodology adopted threw little new light on the multiplicity of these risks. The project steering committee resorted to a risk sorting approach whereby the 88 threats were assessed using a range of risk prioritisation techniques, *e.g.* environmental threats with high human health, ecological and socio-economic impacts were ranked higher than those with lower impacts. The results of the individual techniques used were compared and those threats of consistent high priority across a range of techniques identified as high priority overall. Four clusters of threat were deemed of greatest importance; those associated with land use change, indoor pollution, outdoor pollution and invasive species. Andrews *et al.* (2004a) assert that a ranked list of priorities has only limited value when the science is not in place to support such a list and that, for future exercises, emphasis should be on gathering evidence in support of the prioritisation.

Recent developments in cumulative effects assessment (CEA) as required under the EU environmental impact assessment (EIA) directives (85/337/EEC and 97/11/EC) and strategic environmental assessment (SEA) directive (2001/42/EC) are requiring practitioners to manage the aggregation of environmental effects past, present and in the reasonably foreseeable future. At the strategic level (Therivel, 2004), a plan or programme of activity (e.g. a large multistage development) may be linked to infinite cumulative effects. The aggregation of impacts is usually focussed at the receptor level (James and Stewart, 2004) because the capacity of the receptor to accommodate the additional stress associated with a plan, project or programme of development, is a principal concern in a CEA. Critical factors, from a receptor standpoint, are the sensitivity and vulnerability of receptors to withstand the additional stress caused by the activity. Taken together, these represent the vulnerability of a receptor. Much of the guidance on the aggregated (cumulative) effects of past, present and future stresses, however, is light on the metrics of aggregation. The reflections of long-standing observers of comparative risk analysis are noteworthy, e.g. Fischoff, 1995; Morgan *et al.*, 1996; van Asselt, 1999; Morgenstern *et al.*, 2000; DeKay *et al.*, 2001; Andrews *et al.*, 2004b Linkov *et al*., 2005:

- Risk rankings are necessarily imperfect. At the strategic level, uncertainties are huge and stakeholder involvement in metrics and process offer no guarantee of the removal of this ambiguity.
- Few current exercises afford the time required to understand the process of ranking risks, let alone the data on which risks should be ranked. Morgan *et al.* (1996) suggested an approach involving five meetings and taking 9–11 days to complete. This contrasts with the 0.5–1 day workshops typically

used to rank a plethora of strategic risks. The clustering of issues as performed in the New Jersey Comparative Risk Project (NJDEP, 2003) may offer real merits in terms of time spent on these exercises.

- There is a danger, as with all risk analyses, that prioritisation becomes the end in itself rather than what is done to manage the risk.
- Notwithstanding the myriad of metrics and project-specific approaches, there appears to be a developing consensus of the value of the following approach to ranking risks (Figure 5).

Figure 4. Steps in a risk ranking model (after Florig *et al.*, 2001)

- There appears to be a move towards adopting multicriteria analysis (MCA) in preference to comparative risk analysis – perhaps in recognition of the analytical complexities and the ready availability of methods for MCA (Linkov *et al.*, 2005). These authors reject the concept of a risk optimised option or set of priorities in favour of an adaptive management style, where the dynamics of knowledge and data on risks are acknowledged and management strategies adapted accordingly.

3.2 Involving others

The modern analytic–deliberative approach to risk management (Stern and Fineberg, 1996; US Presidential/Congressional Commission, 1997a,b; RCEP, 1998; Charnley, 2000) suggests that wider stakeholder participation should be considered during the initial framing of the issue or problem; during the identification of data and information needs; as risk assessors discuss how uncertainty will be managed in the assessment; during the risk assessment itself; and during evaluation of risk estimates. There remains a need to establish at which of these stages, and in what ways, participation can be most meaningfully incorporated. The challenge is to develop informed processes that enable decisions involving science to be debated widely in a social context (Sexton *et al*., 1999; Fischer, 2000). Even at the international level experience is limited, though there are increasing attempts to apply participative processes to policy, plan and project-level decisions involving risk, with many projects now incorporating participative approaches to the framing of risk problems. These processes can be effective in reaching decisions, but a more inclusive and deliberative process does not automatically secure consensus. Indeed, involving publics may result in more diversity in opinion rather than consensus.

Criteria for effective participatory decision processes have been developed where risk is an important issue within the decision (Homan *et al.*, 2001). These reflect broader criteria for effective public participation incorporating the key principles of (i) clarity of objectives; (ii) representativeness; (iii) inclusivity; (iv) openness; (v) deliberation; (vi) social learning; and (vii) decision responsiveness. For environmental regulators, these are complex issues with far reaching consequences for policy, resources and practical issues, which require careful consideration. With participation an accepted feature of better environmental decision-making (Fischer, 1995; Perhac, 1998; Apostolakis and Picket, 1998) the quality of participatory decisions and tools for incorporating stakeholder views has been subject to scrutiny. Beierle (2002) presents an account of 239 published case studies of stakeholder involvement in decision-making, ranking the quality of the decisions by whether:

- decisions were more cost-effective than likely alternatives;

- decisions increased joint gains among parties compared with the likely alternatives;
- participants contributed innovative ideas, useful analysis or new information; and whether
- participants had access to scientific information and expertise.

In this analysis, the more intensive forms of stakeholder involvement (processes involving negotiations and mediations) produced higher quality decisions, suggesting that more effort and time are required to engage stakeholders in strategic risk issues than is currently provided. The companion papers by Florig *et al*. (2001) and Morgan *et al*. (2001) discuss the value of deliberation itself within a group. Using a deliberative quantitative method for ranking 22 high school health and safety risks, first by individuals and then following a group discussion, these authors demonstrate the value of group discussion to fostering consensus. They make the point that where risk rankings are to be used by regulatory agencies they must be both normatively justifiable and empirically validated if the rankings are to have credibility. The authors set out criteria for good ranking methods. For Florig *et al*. (2001), a good ranking method should:

- make use of available theory and empirical knowledge in behavioural social science, decision theory and risk analysis;
- encourage those ranking risks to systematically consider all relevant information;
- assist individual participants in expressing (or constructing) internally consistent rankings;
- ensure that participants understand the procedures and feel satisfied with both the process and products of a ranking exercise; and

- describe the level of agreement and the sources of disagreement among participants.

English (2000) argues that a shift towards emphasising the 'long term common good' in a spirit of 'collaborative learning' is required for those strategic risk issues commonly addressed by policy-makers, regulators and their advisers. However, it is also argued that the possibility of adequate representation for each stakeholder type and of securing an equal balance of types within the decision-making process diminishes substantially at this level. This is a long-term project that lacks methodological guidance. Meanwhile, policy-makers and regulators face the practical challenge of how to defensively and robustly take account of a multitude of stakeholder views on risk issues of strategic importance – many of which are viewed by interest groups as contentious single issues in their own right. In response, the gathering, structuring and presentation of evidence in support of risk-based decisions has gathered new momentum.

3.4 Direction, strength and weight of evidence

Policy decisions are required to be risk- and evidence-based, not least because stakeholders expect to see, and be able to critique the supporting science upon which decisions are based. Decision-makers need to assemble lines of evidence for complex, multi-attribute decisions (*e.g.* the long term performance of radioactive waste repositories, the viability of carbon capture and storage technology, the environmental safety of nanomaterials), make judgements on the direction (supportive of a hypothesis or not) of individuals lines of evidence, and then on the overall weight of evidence as a whole. This process in itself requires methodology and structure. There is an established literature on weight of evidence (WOE) approaches developed in the fields of medical evidence, forensic science and radioactive waste management, with some applications to environmental risk (Mayo and Hollander, 1991; US Nuclear Waste Technical Review Board, 2001; Smith *et al.*, 2002; Hrudey and Leiss, 2003; Weed, 2005; Krimsky, 2005). Among some users, presenting complementary and/or discordant lines of reasoning has been enhanced by the use of influence diagrams, evidential support logic (Benbow *et al.*, 2006) and belief nets, that act as visual mechanisms to support the presentation of interwoven evidence. Valuable examples exist. For example, Gray *et al*. (2004) provide an authoritative example of a WOE evaluation for the reproductive toxicity of bisphenol A, and Popp *et al.* (2006) offer a similar appraisal for the cancer dose-response characteristics of 2,3,78-TCDD. Burton *et al.* (2002) set out a WOE framework for assessing ecological detriment.

Environmental decisions make use of data, concepts and assumptions for which a range of evidence of varying quality exists. In these cases, the assessor may need to choose between competing theories (e.g. in low dose extrapolation), a range of individual baseline studies (e.g. arsenic in drinking water) or a palette of future environmental scenarios (e.g. climate change). Such analyses involve evaluating both complementary and potentially conflicting lines of reasoning, the direction and individual strength of which must be assessed in support of a specific line of argument (see Bowden, 2004). Assembling such evidence within a framework of precaution, has long been a requirement of the safety cases prepared for large process plant and radioactive waste disposal, but equally has application to emerging threats where there exists a paucity of supporting science, such as the management of exposures from engineering nanomaterials (Linkov *et al.*, 2007; Rocks *et al.*, *in press*). Generic questions on evidence and lines of reasoning pertinent to the risk assessment must be answered (US Nuclear Waste Technical Review Board, 2001):

- How does a policy advisor weigh/prioritise quantitative evidence alongside qualitative lines of reasoning that support other types of argument?
- How does this weighting change with time and the introduction of new evidence?
- Which arguments are most and least convincing to publics, in which formats, and why?
- How do policy implementers (e.g. regulators, operators) manage the integration of evidence?
- In what depth should policy advisors and or regulators develop an independent view of the evidence that support a specific policy outcome?

Criteria for evaluating the strength of evidence are published. For example, Bradford Hill's criteria (Hill, 1965) attempt to separate causal from non-causal associations between agents and disease (Hofler, 2005) by reference to:

1. strength of association (a strong association is likely to have a causal component);
2. consistency (reproducibility);
3. specificity;
4. temporality (effect succeeds action or factor);
5. biological gradient (dose response);
6. plausibility (biological explanations);
7. coherence (agrees with current knowledge);
8. randomised experiments (good study design); and
9. analogy (effect has already been shown).

Klimisch *et al.* (1997) present a systematic evaluation of the quality of toxicological data, adopting a ranking system:

1 = reliable without restrictions. Where the data was generated according to internationally accepted (or validated) testing guidelines and preferably secured under good laboratory practice (GLP) or where the test parameters are closely related to a guideline method;

2 = reliable with restrictions. Where the data was secured mostly according to GLP and where the test parameters do not totally comply with the testing guideline, but are considered sufficient to accept the data;

3 = not reliable. Where there were interferences between the measuring system and the test substance, or in which the test systems were used which are not relevant in relation to the exposure, or were generated using an unacceptable method;

4 = not assignable. The experimental details provided were not sufficient and were only listed in short abstracts or secondary literature.

These evaluation criteria have been applied to many chemical risk assessment methods and have proved to be an acceptable method of determining the quality of the data supporting chemical risk estimation and characterisation.

Bowden (2004) presents a valuable suite of quality indicators for scientific evidence (Table 1), stressing the criticality of well-managed knowledge and describing the *sufficiency* (relative significance), *dependency* (commonality between contributing lines of evidence) and *necessity* of evidence.

Table 1 Quality indicators for scientific evidence (after Bowden, 2004)

In seeking to explicitly account for uncertainty, the evidence support logic proposed allows for evidence that supports a hypothesis; that which does not support a hypothesis and importantly, for a residual amount of uncommitted belief (Figure 6;

Bowden, 2004; Benbow *et al.*, 2006). Individual lines of evidence, simplified and illustrated in part for carbon capture and storage in Figure 6, may then be structured and evaluated in concert.

Possessing the institutional capacity to perform these evaluations of evidence is rare in practice. Further, evidence alone is insufficient for sound decision-making – there is an organisational cultural component that becomes increasingly important as the 'shelf-life' of organisational knowledge on how risks are best managed shortens. The practical and preventative management of environmental risk can only be secured by wise organizations that manage their science and evidence base, and that understand the institutional factors that influence the success of risk management measures (Pollard *et al.*, 2007; MacGillivray and Pollard, 2008).

Figure 5. Basis for, and application of, evidence based (3-value) logic to carbon storage and capture decisions (partial tree for illustration; after Benbow *et al.*, 2006)

4. Institutional issues

The delivery of risk management, be it in the design and build of new flood defences, in the operation of new technology for managing wastes as resources, or in the authorisation of new chemicals or novel materials, ultimately relies on institutional capabilities to assess, manage and communicate risk. People, the institutions in which they work, organisational structures and the management of knowledge all impact on the efficiency and effectiveness of risk management. Good environmental decisions are those that can be readily implemented and 'best-in-class' organisations are better at managing risks and opportunities wisely, learning from failure, and they exhibit resilience (robustness to shock) and agility (adaptive and forward-looking) within a changing business climate (Pollard *et al.*, 2007). They recognise that a maturity of capability is not secured solely through having risk frameworks, risk assessment tools, audit trails, risk champions and risk registers in place. Government departments are no different, in that they strive to develop policies that can have most effect, alongside other strategic objectives. The management of risk knowledge becomes central (Figure 6).

Figure 6. Managing risk knowledge is central to effective risk management.

For an organisation to make effective risk-based decisions it must be able to operate effective risk management processes, including the articulation of clear objectives and problem definition; it must be able to evaluate the implementation of risk management; and it must be able to secure, among other benefits, the strategic added value that comes with mature risk management - all this, within an organisational context in which decisions are made by people with access to data, information, knowledge and evidence.

Many authors view the organisation as a complex social system composed of a variety of organisational facets (Beer, 1998; Senior, 2002). Subsequently, when attempting to implement change at an organisational level there are many perspectives to consider. 'Organisational culture' is a term frequently used to describe the core personal, communal and organisational views, values and norms of an organisation (Denison, 1984; Cameron and Quinn, 1999). It is suggested that a strong organisational culture has the ability to influence behaviours including organisational performance, staff commitment, motivation and efficiency, and job satisfaction to name a few (Denison, 1984; de Gilder, 2003; Fischer, 2005).

The literature suggests that developing relationships with external organisations and the maintenance of a strong social network is a key component to sustained growth and the ability to respond to opportunities, challenges, risks and limitations presented by the external environment (Mullins, 2002). This is particularly crucial within environmental management where organisations are required to constantly keep up to date with rapidly developing requirements and legislation. Maintaining a well-built internal social network, supporting both formal (e.g. role based) and informal (e.g. casual, opportunistic interaction), is also central to the implementation of a risk based culture. Internal ties can have a substantial impact upon the commitment, motivation and performance of staff (Smith, 2007) and are possibly the most effective tool for the capture, assimilation and sharing of knowledge within an organisation (Claver-Cortes *et al.*, 2007). For this reason authors suggest that human relations should be valued above any technological tools or mechanisms for effective knowledge management (Pyoria, 2007).

Valuable knowledge is often tacitly tied to individuals within an organisation (Marouf, 2007); subsequently it has been suggested that organisations must adopt organisational structures that allow them to create and transfer as much knowledge as possible. Typically it has been suggested that adopting a flatter structure encourages the effective integration of knowledge (Claver-Cortes *et al.*, 2007). Effective communication, leadership style and the development of trust also have a substantial influence over how knowledge is managed within an organisational context. Effective communication is crucial within the context of a risk based culture as issues relating to risk are frequently misunderstood. By extension, communication has a strong influence over processes of organisational change. A transparent network (Moenaert *et al.*, 2000), face to face interaction (Pyoria, 2005) and a shared context of understanding are all thought to aid improved decision making and enhanced communication skills between members of a team or organisation.

Research into management and leadership within organisations has varied results (Andersen, 2006). The traits required of apparently successful leaders are vast (Senior, 2002) and the effects of individual behaviour and personalities of leaders upon organisational success are unclear. However, leaders do have influence over individual and organisational behaviours (Sadri and Lees, 2001) and this should be acknowledged within the implementation of effective risk management. The utility sectors (energy, water, waste) are currently expressing substantial interest in the mechanics of implementing risk management within their organisations because of the issues of security of supply, the perceived vulnerability and aging of national infrastructures and a re-emergence of the public health imperative, within drinking water supply for example. An executive lead on risk management is seen as crucial within these sectors and essential to setting the tone of the organisation.

Trust has also been highlighted as a component that has a strong influence over the other factors presented within this process (Burke *et al.*, 2007); enabling cooperation (Tyler, 2003), creating high morale and efficiency (Pyoria, 2007), and maintaining a competitive advantage (Young, 2006).

5. Conclusions - core criteria for better environmental decisions

Having reviewed the organisational aspects of decision-making and summarised the development of risk-based regulation, it would seem appropriate to pose the question: ‘what makes for a high quality, risk-informed decision?’ A substantive literature exists on decision analysis. Good decisions deliver the aims and objectives they set out to achieve. Better decisions adopt a participative approach and deliver costed options. The definition of the problem (what are we trying to achieve and why?) and identification of decision attributes are universal requirements. For risk-based decisions, these translate into a need to articulate the 'risk of what to whom?' and a level of tolerable residual risk (post management) – the risk appetite. Risk assessments should identify those features of the problem that contribute most to the risk and so, properly applied, an effective risk management process should deliver costed options and provide direction on the targeting of resources towards a prioritised set of risk management actions.

Decisions that are not implemented well are of little value. The project, programme and appraisal literature places a firm emphasis on the importance of implementation and post-implementation evaluation. All too often, risk analyses are undertaken, risk management actions designed and their effectiveness left unchecked. Thus implementation and evaluation are critical to ensuring the desired outcomes are secure.

Finally, effective decisions secure benefits and thus value. 'Value trees' are one means of presenting the benefits of a decision alongside the costs and thus allowing a qualitative weighted average of the benefits assigned to a decision. However captured, it is important that the collation of benefits from a decision is complete and suitably aggregated. Organisations frequently miss the strategic added value to the organisation itself that comes with risk-based decision-making, yet this is increasingly critical to securing executive buy-in to decisions. Organisations manage risks preventatively because they understand that prevention is better than cure, that threats to business interruption must be managed, and increasingly, because intangible consequences, such as reputational damage, can sometimes overwhelm monetisable losses. Most organisations manage risk in a climate of constrained resources however, and need to make risk-informed decisions because they have to target their top risks and apply resources to the features of a risk that makes the most contribution to reducing business exposure. Environmental policy makers and regulators are no different, in that they need to focus regulatory effort where they can have most effect, alongside other objectives. In adopting this approach, organisations seek the strategic added value of these decisions over and above the loss avoided through preventative risk management (Figure 1). In evaluating the quality of risk-based decisions, the authors seek to fulfil these basic criteria:

Criterion 1: an effective decision-making process has been adopted, complete with unambiguous problem definition;
Criterion 2: the decision has been subject to implementation and evaluation to ensure the intended outcomes have been secured; and
Criterion 3: that strategic added value has been secured as a result.

In setting out these base criteria, we emphasise the need to be very clear about the starting and finishing points for risk reduction – one must understand what the residual risk will be, post management – and the need to accrue both the monetisable and non-monetisable costs and benefits, in order that the true value of the decision can be evaluated. Further, an emphasis on the strategic added value of risk management is representative of the observation that best-in-class organisations turn a high capability in risk management to their strategic advantage. Their risk management capability becomes a strategic asset; their stakeholders have greater confidence in the decisions the organisation makes; and the organisation correspondingly finds it easier to secure investment and support for their future business strategy. This should not be underestimated for government organisations, which are increasingly under the behest of spending reviews and efficiency savings in times of expanding regulatory remits and reduced public finance.

Good environmental decision-making is more than being risk-informed and evidenced-based. It embodies the expectations of participative involvement, of technical competency in decision analysis and of organisational maturity that ensure that decisions 'stick' and that residual risk is monitored. Risk analysis has contributed much to the field, allowing us to focus on the critical parts of the problem and so prioritise actions. We expect the issues raised in this review to develop further – with more in-depth exploration of risk comparisons, bespoke weight of evidence frameworks for individual risks and the benchmarking of organisational risk management capabilities. The language of risk remains a problem for most audiences and despite a wide literature, risk managers, researchers and policy specialists continue to become unseated in media and public settings when explaining risk management actions. Publics understand 'safety' as a concept and imbue the term with notions of confidence and responsibility. In contrast, risk is often negatively associated with official attempts to 'soften the blow' from something hazardous and likely to cause harm. In some settings, risk assessments themselves have become highly contentious. We view this as a critical ongoing issue on which to provide advice to Governments, as they seek to better explain their actions to citizens and their stakeholders.

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References

Anderson JA. Leadership, personality and effectiveness. J Socio Econ 2006;35:1078-91.

Andrews CJ, Apul DS, Linkov I. Comparative risk assessment: Past experience, current trends, and future directions. In I. Linkov & A. Ramadan (Eds.), Comparative Risk Assessment. Amsterdam: Kluwer 2004.

Andrews CJ, Hassenzahl DM, Johnson BB. Accommodating uncertainty in comparative risk. Risk Anal 2004b;24(5):1323–35.

Apostolakis GE, Pickett SE. Deliberation: integrating analytical results into environmental decisions involving multiple stakeholders. Risk Anal 1998;18(5):621–34.

Beer M. Organizational Behaviour and Development. Harvard Business School Working Paper Series 1998;98. Available at http://www.hbs.edu/research/facpubs/workingpapers/papers2/9798/98-115.pdf. Accessed on August 11, 2007.

Benbow S., Metcalfe R. and Egan M., Handling uncertainty in safety assessments for long term geological storage of CO_2, in Proc. 8th International Conference on Greenhouse Gas Control Technologies, 19-22 June 2006, Trondheim, Norway, 2006; 6pp.

Beierle TB. The quality of stakeholder-based decisions. Risk Anal 2002;22(4):739-49.

Bonano EJ, Apostolakis GE, Salter PF, Ghassemi A, Jennings S. Application of risk assessment and decision analysis to the evaluation, ranking and selection of environmental remediation alternatives. J Hazard Mater 2000;71:35–57.

Bowden R. Building confidence in geological models. In: Curtis A and Wood R (eds.) Geological prior information: informing science and engineering. Geological Sociaety, London, Special Publications, 2004; 239: 157-173.

Brown MH. Quantitative microbiological risk assessment: principles applied to determining the comparative risk of salmonellosis from chicken products. Int Biodeter Biodegr 2002;50:155–160.

Burton Jr GA, Batley GE, Chapman PM, Forbes VE, Smith EP, Reynoldson T, Schlekat CE, Den Besten PJ, Bailer AJ, Green AS, Dwyer RL. A weight-of-evidence framework for assessing sediment (or other) contamination: Improving certainty in the decision-making process. Hum Ecol Risk Assess 2002;8(7):1675-96.

Burke C, Sims D, Lazzara E, Salas E. Trust in leadership: a multi-level review and integration. Leadersh Q 2007;18:606-32.

Cameron KS, Quinn RE. Diagnosing and Changing Organisational Culture: Based on the Competing Values Framework. Addison-Wesley, New York; 1999. p. 72-104.

Camus M. A ban on asbestos must be based on a comparative risk assessment. Can Med Assoc J 2001;164(4):491–4.

Charnley G. Enhancing the role of science in stakeholder-based risk management decision-making [online]. Knoxville, Tennessee, USA: RiskWorld, 2000. Available at: http://www.riskworld.com/Nreports/2000/Charnley/NR00GC00.htm. Accessed on August 11, 2005.

Claver-Cortes E, Zaragoza-Saez P, Pertusa-Ortega E. Organizational structure features supporting knowledge management processes. J Know Manage 2007;11(4):45-57.

Defra. Department for Environment, Food and Rural Affairs. Our strategic plan 2003-2006. Defra, London, 44pp.

de Gilder D. Commitment, trust and work behaviour: The case of contingent workers. Pers Rev 2003;32(5):588-672.

DeKay ML, Florig HK, Fischbeck PS, Morgan MG, Morgan KM, Fischhoff B, Jenni KE. The use of public risk ranking in regulatory development. In Improving Regulation: Cases in Environment, Health, and Safety. ed. P S Fischbeck and R S Farrow. Washington, DC: Resources for the Future 1984:208–230.

Denison DR. Bringing corporate culture to the bottom line. Organ Dyn 1984;13(2):4-22.

Dora C. What can health impact assessment add to comparative risk assessment in decision-making? B World Health Organ 2003;81(6):460.

English MR. Stakeholders in environmental risk decisions. RISK: Health, Safety and Environment. Book Reviews 2000;11(3):243–56.

EA. Environment Agency. A strategic approach to the consideration of environmental harm. National Centre for Risk Analysis and Options Appraisal (NCRAOA) Bristol: Environment Agency Report, 36; 2000a.

EA. Environment Agency. Environment 2000 and beyond. Bristol: Environment Agency; 2000b. p. 76–77.

Environment Canada. Sustainable development strategy 2007-2009, Environment Canada, Ontario, 2007: 35pp.

Finizio A, Calliera M, Vighi M. Rating systems for pesticide risk classification on different ecosystems. Ecotoxicol Environ Saf 2001;49:262–74.

Fischer F. Revisiting organizational politics: the postempiricist challenge. Policy and Society 2005:1-23.

Fischer G. Social Creativity: turning barriers into opportunities for collaborative design. Proceedings of the Participatory Design Conference (PDC'04). University of Toronto, Canada; 2005:152-161.

Fischer F. Hazardous waste policy, community movements and the politics of Nimby: participatory risk assessment in the USA and Canada. In Fischer F, Black M, editors. Greening Environmental Policy: The Politics of a Sustainable Future. St. Martin Press, New York; 1995. p. 165–182.

Fischer F. Citizens, experts, and the environment – the politics of local knowledge. Duke University Press, Durham, 2000.

Fischhoff B. Ranking risks. RISK: Health, Safety and Environment 1995;6:191–202.

Florig HK, Morgan MG, Morgan KM, Jenni KE, Fischhoff B, Fischbeck PS, DeKay ML. A deliberate method for ranking risks (I): overview and test bed development. Risk Anal 2001;21(5):913–921.

Frodsham DA, Cardew PT. Using comparative risk assessment in the evaluation and development of new technologies. Bristol Business School Teaching and Research Review 2000;(2). Available at http://www.uwe.ac.uk/bbs/trr/Issue2/Is2-4_4.htm. Accessed on August 11 2005.

Gamo M, Oka T, Nakanishi J. Ranking the risks of 12 major environmental pollutants that occur in Japan. Chemosphere 2003;53:277–84.

Gray GM, Cohen JT, Cunha G, Hughes C, McConnell EE, Rhomberg L, Sipes IG, Mattison D. Weight of the evidence evaluation of low-dosereproductive and developmental effects of bisphenol A. Hum Ecol Risk Assess 2004;10(5):875-921.

Grumbly TP. Comparative risk analysis in the department of energy. In Risk in the Republic: Comparative Risk Analysis and Public Policy. Proceedings of Second Annual Cummings Colloquium on Environmental Law. Duke Environmental Law and Policy Forum 1997;8(1):23–32.

Hill, AB. The environment and disease: association or causation? Proc. Roy Soc Med, London, 1965; 58:295-300

Hofler, M. The Bradford Hill considerations on causality: a counterfactual perspective. Emerg Themes Epidemiol, 2005; 2:11-20

Homan J, Petts J, Pollard SJT, Twigger-Ross C. Participatory risk assessment for environmental decision-making. In Proceedings VALDOR 2001: 2nd VALDOR Symposium Addressing Transparency in Risk Assessment and Decision-Making (Stockholm, 10–14 June 2001), edited by Andersson K. 2001:398–406.

Hrudey SE, Leiss W. Risk management and precaution: Insights on the cautious use of evidence. Environ Health Persp 2003;111(13):1577-81.

James E, Stewart G. Cumulative effects assessments and SEA. Environmentalist 2004;23:25–7.

Kasperson, JX and Kasperson, RE (eds.). The social contours of risk, Volume II, Earthscan, London, 2005; 326pp.

Kjellstrom T, Kerkhoff LV, Bammer G, McMicheal T. Comparative assessment of transport risks – how it can contribute to health impact assessment of transport policies. B World Health Organ 2003;81(6):451–7.

Klimisch, HJ, Andreae M, Tillmann, U. A systematic approach for evaluating the quality of experimental toxicological and ecotoxicological data. Reg Toxicol Pharmacol 1997; 25:1-5

Krimsky, S. The weight of scientific evidence in policy and law. Am. J. Public Health 2005; 95(S1): S129-S136.

Lee S, McLaughlin R, Harnly M, Gunier R, Kreutzer R. Community exposures to airborne agricultural pesticides in California: ranking of inhalation risks. Environ Health Persp 2002;110(12):1175–84.

Lerche D, Brüggemann R, Sørensen P, Carlsen L, Nielson OJ. A comparison of partial order technique with three methods of multi-criteria analysis for ranking of chemical substances. J Chem Info Comp Sci 2002;42:1086–98.

Lerche D, Matsuzaki SY, Sørensen PB, Carlsen L, Neilson OJ. Ranking of chemical substances based on the Japanese pollutant release and transfer register using partial order theory and random linear extensions. Chemosphere 2004;55:1005–25.

Linkov I, Satterstrom K, Kiker G, Ferguson E, Bridges T. Multi-criteria decision analysis and adaptive management: a review and framework for application to Superfund sites. In Macey GP, Cannon J, editors. Reclaiming the Land: Rethinking Superfund Institutions, Methods and Practices. Springer, New York, 2004.

Linkov, I., Satterstrom, K, Steevens, J, Ferguson, E, Pleus, RC. Multicriteria decision analysis and nanotechnology, J. Nanoparticle Res. 2007; 9:543-554.

Löfstedt R and Frewer L (eds.) The Earthscan reader in risk and modern society, Earthscan, London, 1998; 278pp.

Long J, Fischhoff B. Setting risk priorities: a formal model. Risk Anal 2000;20(3):339–51.

Low F, Lin H, Gerrard JA, Cressey PJ, Shaw IC. Ranking the risk of pesticide dietary intake. Pest Manag Sci 2004;60:842–48.

MacGillivray, BH and Pollard, SJT What can water utilities do to improve risk management within their business functions? An improved tool and application of process benchmarking, Environ. Intl. 2008; *in press*

Mayo D, Hollander R. Acceptable Evidence: Science and Values in Risk Management. Oxford University Press, New York, 1991.

Moenaert RK, Caeldries F, Lievens A, Wauters E. Communication flows in international product innovation teams. J Prod Innovat Manag 2000;17(5):360-77.

Morgan MG, Fischhoff B, Lave L, Fischbeck P. A proposal for ranking risk within federal agencies. In: Davies JC, editor. Comparing Environmental Risks: Tools for Setting Government Priorities. Washington, DC: Resources for the Future; 1996. p. 111–147

Marouf L. Social networks and knowledge sharing in organizations: a case study. J Knowl Manage 2007;11(6):110-25.

Morgan KM, DeKay ML, Fischbeck PS, Morgan MG, Fischhoff B, Florig HK. A deliberate method for ranking risks (II): evaluation of validity and agreement among risk managers. Risk Anal 2001;21(5):923–37.

Morgenstern RD, Shih JS, Sessions SL. Comparative risk assessment: an international comparison of methodologies and results. J Hazard Mater 2000;78:19-39.

Mullins LJ. Management and organisational behaviour, 6th ed. London: Financial Times Prentice Hall 2002.

New Jersey Department of Environmental Protection (NJDEP). Final report of the New Jersey Comparative Risk Project. Trenton, NJ: NJDEP 2003. Available at http://www.state.nj.us/dep/dsr/njcrp/ Accessed on August 12, 2005

Pennington DW, Bare JC. Comparison of chemical screening and ranking approaches: The waste minimization prioritization tool versus toxic equivalency potentials. Risk Anal 2001;21(5):897–912.

Perhac RM. Comparative risk assessment: where does the public fit in? Sci Technol Hum Val 1998;23:221–41.

Petts J, Homan J and Pollard S. Participatory risk assessment – involving lay audiences in decisions on risk: literature review and stakeholder interviews. R&D Report E2-043/TR01. Bristol: Environment Agency, Bristol; 2003.

Pollard, SJT, Kemp RV, Crawford, M, Duarte-Davidson, R, Irwin, JG and Yearsley R. Characterising environmental harm: Developments in an approach to strategic risk assessment and risk management, Risk Anal 2004; 24(6): 1551-1560

Pollard, S, Hrudey, SE, Hamilton, P, MacGillivray, B, Strutt, J, Sharp, J Bradshaw, R, Leiss, W and Godfree, A Risk analysis strategies for credible and defensible utility decisions, Awwa Research Foundation Research Report 91168, Awwa Research Foundation, American Water Works Association and IWA Publishing, Denver, CO; 2007, Ref 1P-3.25C-91168-02/07-NH, 88pp.

Popp JA, Crouch E, McConnell EE. A weight-of-evidence analysis of the cancer dose-response characteristics of 2,3,7,8-tetrachlorodibenzodioxin (TCDD). Toxicol Sci 2006;89(2):361-9.

Pyoria P. Informal organizational culture: the foundation of knowledge workers' performance. J Knowl Manage 2007;11(3):16-30.

Ramanathan R. Comparative risk assessment of energy supply technologies: a data envelopment analysis approach. Energy 2001;26:197–203.

Rocks, SA, Pollard SJ, Dorey, RA, Harrison PTC, Levy LS, Handy, RD, Garrod, JF and Owen, R. Risk assessment of manufactured nanomaterials. In: J. Lead, E. Smith (eds) *Environmental and human health effects of nanoparticles*, Blackwell Science, *in press*

Royal Commission on Environmental Pollution (RCEP). Setting environmental standards. London: HMSO 1998:21st report.

Sadri G, Lees B. Developing corporate culture as a competitive advantage. J Manage Dev 2001;20(10):853-9.

Sanderson H, Johnson DJ, Reitsma T, Brain RA, Wilson CJ, Solomon KR. Ranking and prioritization of environmental risks of pharmaceuticals in surface waters. Regul Toxicol Pharm 2004;39:158–83.

Senior B. Organisational Change. London: Prentice Hall; 2002.

Serveiss VB, Bowen JL, Dow D, Valiela I. Using ecological risk assessment to identify the major anthropogenic stressor in the Waquoit Bay watershed, Cape Cod, Massachusetts. Environ Manage 2004;33(5):730–40.

Sexton K, Marcus AA, Easter KW, Burkhardt TD (eds.) Better Environmental Decisions – Strategies for Governments, Businesses and Communities. Washington, DC: Island Press; 1999.

Smith AD. Collaborative commerce through Web-Based Information Integration technologies. Int J Innov Learn 2007;4(2):127-44.

Smith, EP, Lipkovich, I, Ye, K. Weight of evidence (WOE): quantitative estimation of probability of impact. Virginia Tech Department of Statistics Report, Blacksburg, VA, 2002; 33pp.

Stewart MG. Reliability-based assessment of ageing bridges using risk ranking life

cycle cost decision analyses. Reliab Eng Syst Safe 2001;74:263–73.
Stewart MG, Rosowsky DV, Val DV. Reliability-based bridge assessment using risk-ranking decision analysis. Struct Saf 2001;23:397–405.
Stern PC, Fineberg HV (eds.) Understanding Risk – Informing Decisions in a Democratic Society. Washington, DC: National Academic Press; 1996.
Stirling, A. Multi-criteria mapping. Mitigating the problems of environmental valuation. In: Foster, J. (ed.) Valuing nature. Economics, ethics and environment. Routledge, London, 1997; 186-210
Stirling A. (ed.) On science and precaution in the management of technological risk. European Commission Joint Research Centre publication 19056/EN/2. Ispra, Italy: Joint Research Centre, 2001
Sumner J, Ross T. A semi-quantitative seafood safety risk assessment. Int J Food Microbiol 2002;77:55–9.
Therivel R. Strategic environmental assessment in action. London: Earthscan 2004.
Tran LT, Knight CG, O'Neill RV, Smith ER, Riitters KH, Wickham J. Environmental assessment: fuzzy decision analysis for integrated environmental vulnerability assessment of the mid-Atlantic region. Environ Manage 2002;29(6):845–59.
Tyler TR. Trust within organisations. Pers Rev 2003;32(5):556-68.
US Environmental Protection Agency. Unfinished business: a comparative assessment of environmental problems. NTIS # PB-88-127048. Washington, DC: US Environmental Protection Agency 1987.
US Environmental Protection Agency. 2006-2011 EPA Strategic plan. USEPA, Washington DC; 2006; 180pp.
US Presidential/Congressional Commission on Risk Assessment and Risk Management. Framework for Environmental Health Risk Management.

Washington, DC: Commission on Risk Assessment and Risk Management. 1997a(I). Available at http://www.riskworld.com/riskcommission/Default.html. Accessed on August 11, 2005.

US Nuclear Waste Technical Review Board. Developing multiple lines of evidence. Meeting report, April 13, 2001; 214pp.

US Presidential/Congressional Commission on Risk Assessment and Risk Management. Risk Assessment and Risk Management in Regulatory Decision-Making. Washington, DC: Commission on Risk Assessment and Risk Management. 1997b(II). Available at http://www.riskworld.com/riskcommission/Default.html. Accessed on August 11, 2005.

van Asselt MBA. Improving decision-making under uncertainty: an integrated approach to strategic risk analysis. In Facing the New Millennium. Proceedings of the 9th Annual Conference on Risk Analysis (Rotterdam, 10–13 October 1999), edited by L H J Goosens. Delft, Netherlands: Delft University Press 1999.

Vrijheid M, Dolk H, Armstrong B, Boschi G, Busby A, Jorgensen T, Pointer P. Hazard potential ranking of hazardous waste landfill sites and risk of congenital anomalies. Occup Environ Med 2002;59:768–76.

Weed DL. Weight of evidence: A review of concept and methods. Risk Anal 2005;25(6):1545-57.

Williams PRD. Health risk communication using comparative risk analyses. J Expo Anal Env Epid 2004;14:498–515.

Williams P, Benton L, Warmerdam J, Sheehan P. Comparative risk analysis of six volatile organic compounds in California drinking water. Environ Sci Technol 2002;36:4721–8.

Wong EY, Ponce RA, Farrow S, Bartell SM, Lee RC, Faustman EM. Comparative risk and policy analysis in environmental health. Risk Anal 2003;23(6):1337–49.

Wynne, B. Methodology and institutions. Value as seen from the risk field. In: Foster, J. (ed.) Valuing nature. Economics, ethics and environment. Routledge, London, 1997; 135-152.

Young L. Trust: looking forward and back. J Bus Ind Mark 2006;21(7):439-45.

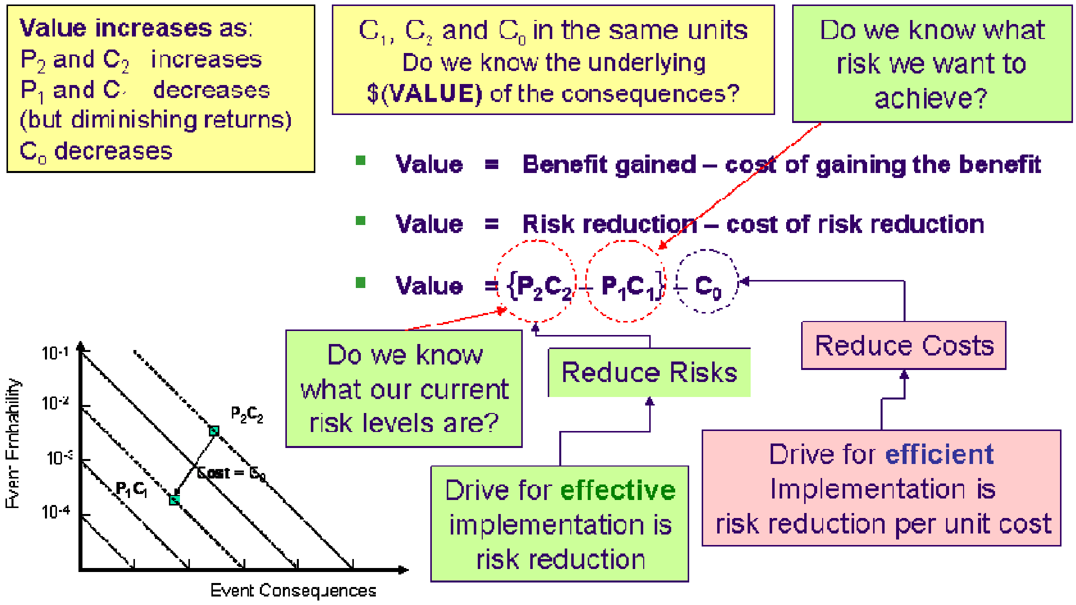

Figure 1 Risks and values

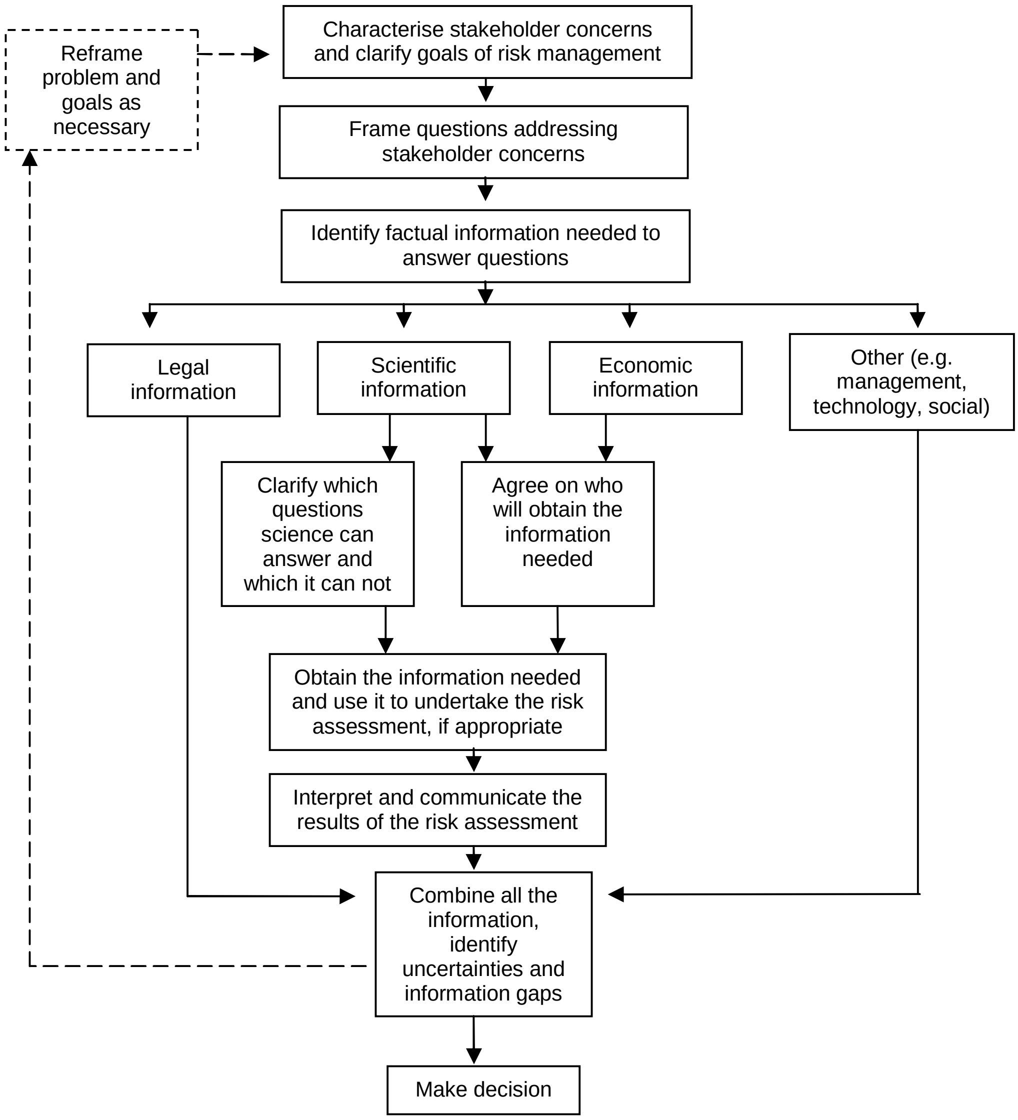

Figure 2 Proposed decision framework for 'democratic science' (redrawn from Charnley, 2000)

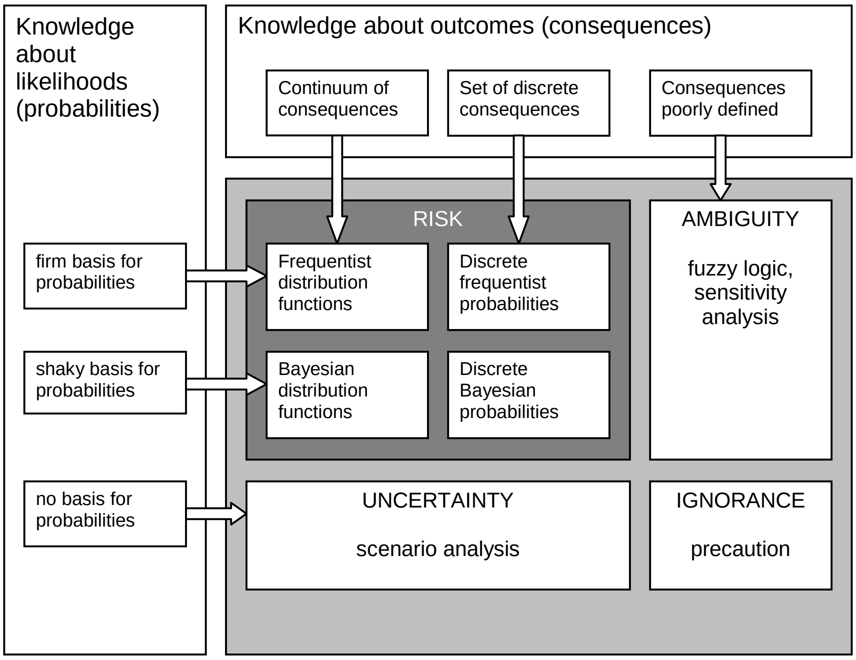

Figure 3. Categorising incertitude within environmental decision-making (redrawn from Stirling, 2001)

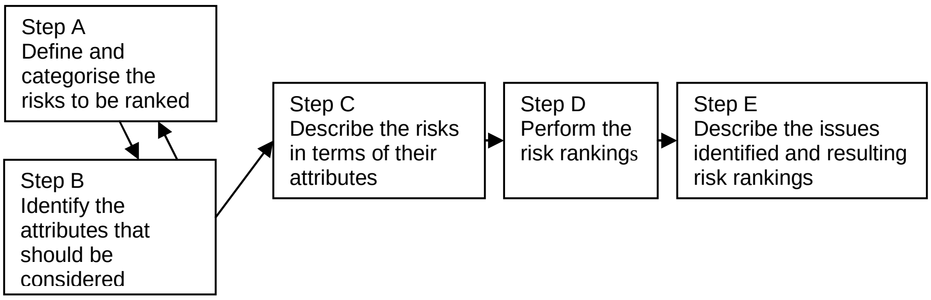

Figure 4. Steps in a risk ranking model (after Florig *et al.*, 2001)

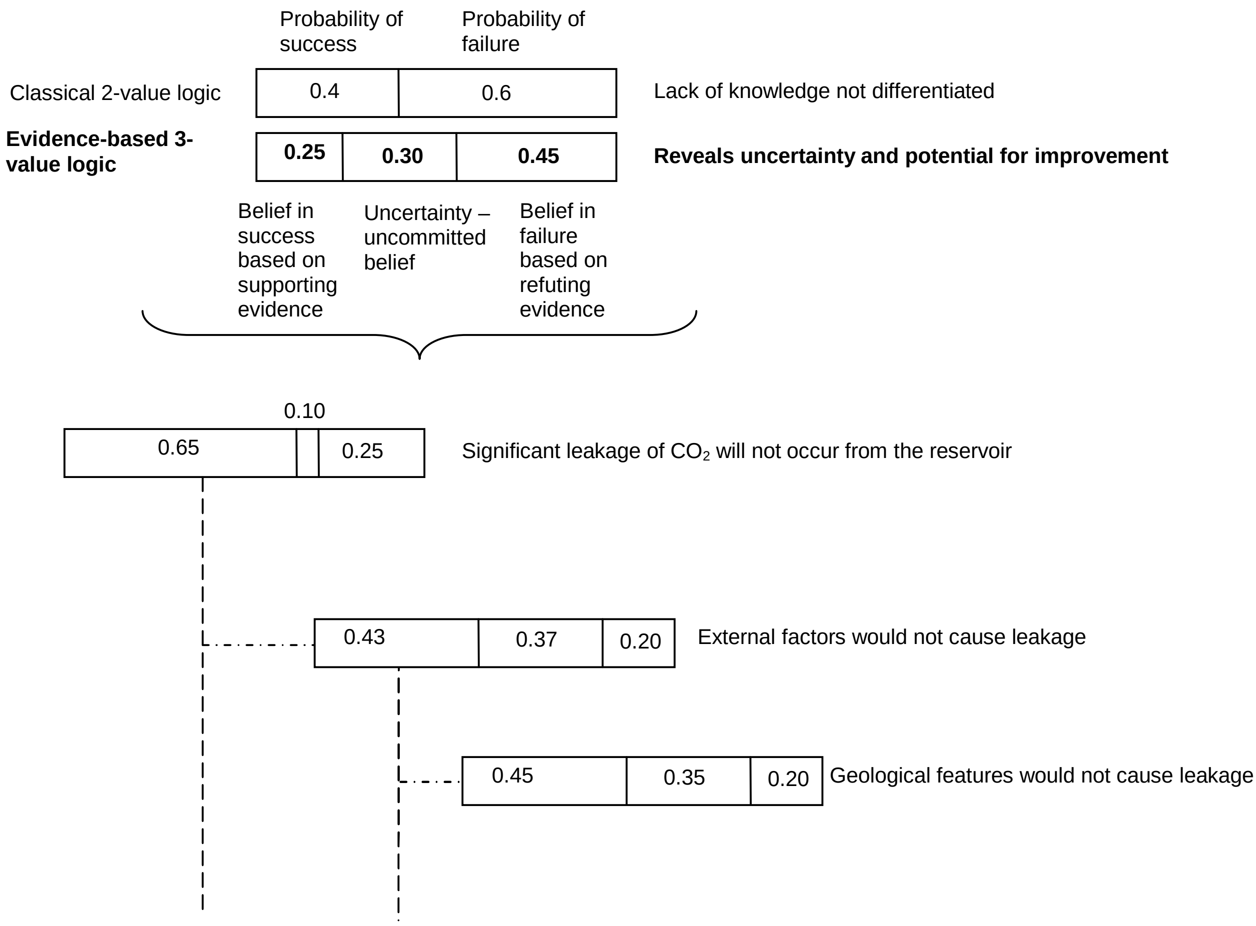

Figure 5. Basis for, and application of, evidence based (3-value) logic to carbon storage and capture decisions (partial tree for illustration; after Benbow *et al.*, 2006)

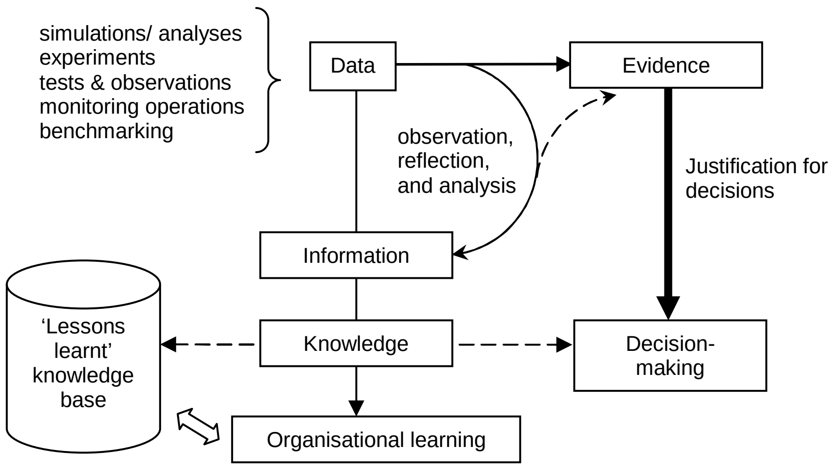

Figure 6. Managing risk knowledge is central to effective risk management.

Table 1 Quality indicators for scientific evidence (after Bowden, 2004)

Indicators of evidence quality							
Quality rank		Theoretical basis	Scientific method	Auditability	Calibration	Validation	Objectivity
	Very high (1)	Well established theory	Best available practice; large sample; direct measure	Well documented trace to data	An exact fit to data	Independent measurement of same variable	No discernable bias
	High	Accepted theory; high degree of consensus	Accepted reliable method; small sample; direct measure	Poor documented but traceable to data	Good fit to data	Independent measurement of high correlation variable	Weak bias
	Moderate	Accepted theory; low consensus	Accepted method; derived or surrogate data; analogue; limited reliability	Traceable to data with difficulty	Moderately well correlated with data	Validation measure not truly independent	Moderate bias
	Low	Preliminary theory	Preliminary method of unknown reliability	Weak and obscure link to data	Weak correlation to data	Weak indirect validation	Strong bias
	Very low (0)	Crude speculation	No discernable rigour	No link back to data	No apparent correlation with data	No validation presented	Obvious bias