Environment International, Volume 34, Issue 8, November 2008, Pages 1120-1131

What can water utilities do to improve risk management within their business functions? An improved tool and application of process benchmarking.

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Abstract

We present a model for benchmarking risk analysis and risk based decision making practice within organisations. It draws on behavioural and normative risk research, the principles of capability maturity modelling and our empirical observations. It codifies the processes of risk analysis and risk based decision making within a framework that distinguishes between different levels of maturity. Application of the model is detailed within the selected business functions of a water and wastewater utility. Observed risk analysis and risk based decision making practices are discussed, together with their maturity of implementation. The findings provide academics, utility professionals, and regulators a deeper understanding of the practical

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and theoretical underpinnings of risk management, and how distinctions can be made between organisational capabilities in this essential business process.

Keywords: risk analysis, management, decision theory, benchmarking, water utility.

1. Introduction

The provision of safe, reliable drinking water, the overarching goal of the water utility sector (AWWA *et al.* 2001), is within the bounds of the developed world's science, technology, and financial resources. Nevertheless, a nagging prevalence of water quality-related outbreaks remains in the developed world, with "causes" ranging from technical failures to institutional lapses and, in the extreme, negligence on the part of operating and managerial staff (Hrudey and Hrudey, 2004). Regardless of the manifestation of these incidents, one might argue that excepting "acts of God," they all derive, fundamentally, from a limited organisational capacity in learning how to prevent failures; in failures to proactively manage risk.

Conventionally, utilities manage risk through codifying standard design and operating procedures. Procedures develop with the introduction of improved methods and technologies (*e.g.* novel treatment processes) and by reflecting on past mishaps. From a risk management perspective, we are particularly concerned with the latter. A developmental cycle begins with a contamination event or near miss, following which incident analysis is undertaken to determine its root cause, concluding with a technical, operational or administrative solution (*e.g.* adapting design standards or operating procedures) designed to prevent its recurrence. This cycle exists at the individual utility and sector level, the latter reflected in changes to national or sector-wide codes, standards or regulations where learning is generalised; for example, regarding the pathogenic hazards associated with backwashing treatment filters. Whilst this retrospective approach to managing risk is necessary, it is a mistake to consider it sufficient for risk management. Procedures can proliferate to the point where resources are diverted towards preventing incidents that have happened, rather than those most likely to happen in the future (Lee, 1998). Further, a reliance on learning by trial and error, in isolation of more proactive strategies, is unsound where public health is at stake because it is not protective. Although illustrated in a water quality context, this argument extends to all aspects of the design, operation and management of utility systems (*e.g.* from process engineering to occupational health and safety management) and across many industrial (water, waste, energy, transport) sectors.

Recognition of the limitations of *post-hoc* analysis is shifting the water sector towards proactive risk management, wherein utilities identify potential weaknesses and eliminate root causes of problems before failure occurs (MacGillivray *et al.*, 2006; Hamilton *et al.*, 2006; Pollard *et al.*, 2004). Our research (Pollard *et al.*, 2004; 2006; Hrudey *et al.*, 2006; Pollard *et al.*, 2007; MacGillivray *et al.*, 2007a/b) has been concerned with how we can improve organisational competencies in risk management within the utility and related sectors. We have focussed on *implementation* rather than the technical aspects of the risk and decision analysis techniques employed and here, we introduce a model for benchmarking and improving the *processes* of risk analysis and risk based decision making within utilities. We describe its application within a water and wastewater utility, and end by reflecting on our theoretical and empirical contributions.

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2. Benchmarking risk analysis and risk based decision making

Capability maturity models (Paulk, 1993) are simplified representations of organisational disciplines (*e.g.* software design and engineering) that codify industry practice within a maturity framework. They allow distinctions to be made between organisational capabilities (*e.g.* the ability to manage risk) by reference to the maturity of the processes applied. We have published the design (MacGillivray *et al.*, 2007a) and application (MacGillivray *et al.*, 2007b) of a capability maturity model for benchmarking risk management practice within the utility sectors. This model contained eleven risk management processes at five maturity levels. The premise of the maturity levels was that once each process was enshrined in procedure, with staff trained in their application, roles and responsibilities assigned, necessary resources secured, and mechanisms in place to prevent deviations from requirements and to learn from the feedback obtained, then implementation of risk management should be of consistently high quality. The demonstrable *maturity* of risk management then becomes the benchmark of an organisation's capability to manage risk, rather than simply the presence of risk policies, techniques or champions.

We have since revised the model, responding to theoretical and empirical challenges derived from its application (see MacGillivray, 2007c). Our revision follows the spirit of the grounded theory approach (Glaser and Strauss, 1967; Straus and Corbin, 1994), drawing primarily upon:

(i) the capability maturity modelling and quality management literatures;

(ii) normative risk analysis and management frameworks, both specific to the water and wastewater sectors and beyond;

(iii) behavioural research on decision making under uncertainty; and

(iv) our recent empirical observations.

A revised model, described here, incorporates risk analysis and risk based decision making, which are comprised of distinct practices. Risk analysis (Fig. 1; Table 1) comprises the practices of system characterisation, hazard identification, exposure assessment, control evaluation, consequence evaluation, likelihood evaluation, and risk evaluation. Risk analysis looks to the future to determine what can go wrong and how, the potential consequences and the relative likelihood of this, and finally the overall level of risk. Risk analysis is always part of a decision context (Aven and Kørte, 2003). Risk based decision making (Fig. 1; Table 2) is concerned with the identification and evaluation of risk management options and a managerial review prior to selecting the optimal option(s). It is informed by criteria that establish the acceptability of risk and that set out stakeholder values and concerns, which are used to assess the relative merit of alternative options.

Both processes are presented in five maturity levels, from *ad hoc* to adaptive, characterised by the completeness of the process (*i.e.* whether all practices are undertaken) and attributes that reflect the maturity of implementation. Maturity levels codify the extent to which each process is repeatable (level 2; L2), defined (L3), controlled (L4) and adaptive (L5). Whilst the maturity attributes (Table 3) and levels (Table 4) are specific to risk analysis, the same principles apply to risk based decision making. Note, that to achieve a given maturity level, all positive requirements of that level and the preceding levels must first be satisfied.

3. Research methods

What can individual utilities learn about their organisational risk management maturity and how should they respond? How far should they go to improve risk management and what actions should they take? One water and wastewater utility participated in this case study. The provision of safe, reliable drinking water depends on a range of business functions spanning the design, operation and management of water supply, wastewater treatment systems. We view the integration of risk management across the breadth of these business functions as crucial to delivering a high level of competency in public health protection. Though the focus of our research is water quality, by the nature of the utility's organisation, it extended to aspects of their wastewater services. We critically assessed seven business functions: engineering; project management; drinking water quality management; network planning; asset management; emergency management; and occupational health and safety. The research methods included interview and document analysis, as described below.

Semi-structured interview templates were developed and applied by business function (*e.g.* asset management) and, where judged relevant, by functional discipline (*e.g.* dam safety management). Questions explored the practical form of risk management in each business function (*e.g.* "what is the process for identifying health and safety hazards within workplaces?") and its maturity of implementation (*e.g.* "are there mechanisms for quality control of risk analyses?"). Interviews (mean approx. 45 min.) were conducted face to face (n = 32) and by 'phone (n = 1), recorded, and transcribed *verbatim* (with two exceptions, where notes were taken). Transcripts were returned to each interviewee, for comment. Finally, relevant company documentation was obtained from interviewees, the corporate intranet and the public domain (*e.g.* internet, conference articles). This included risk management policies and frameworks, risk analysis procedures and methods, accident and incident statistics and reports, water safety plans and risk analysis outputs.

Each business function's process maturity was assessed according to the lead author's judgement based on the data obtained, by reference to our model. We consider the subjectivity of this to be unimportant, because the principal research objective was to refine the model and illustrate its application, not necessarily to derive a maturity assessment of auditable rigour. Mechanisms to validate our findings were adopted, including sample anonymity and triangulation. Anonymity removed the potential for conflicts with the goal of adding to the body of knowledge on risk management capability (as opposed to the participant's potential desire that findings reflected positively on their organisation). Triangulation was secured through interviewing a range of representatives from each business function and cross-checking for inconsistencies in accounts, cross-checking interviewee accounts with documented sources, and providing the interviewees an opportunity to comment on drafts of the research outlined in this paper. Of the seven functions evaluated, "emergency management" was excluded from the analysis due to contradictions in the data and the limited sample of interviewees (two, compared to a minimum of three elsewhere), whilst "network planning" was excluded because of limited documentation obtained.

4. Results

We begin by summarising and discussing the observed risk analysis practices, before evaluating their relative maturity of implementation. We then turn to risk based decision making.

4.1. Risk analysis: observed practices

Table 5 summarises risk analysis practice within the sub-sample of business functions examined. Below, we provide a critical evaluation of the strengths and limitations of a selection of these practices.

4.1.1. Hazard identification

The business functions within this utility adopted a range of hazard identification methods, each with their own strengths, limitations and application contexts. In occupational health and safety management for example, hazard identification was concerned with identifying physical, chemical and biological threats. These were primarily identified using checklists linking known hazards with processes, equipment, workplaces, or operations, and supplemented with *“judgement formed from experience and knowledge of the work, past incident records, brainstorming, and system engineering techniques.”* The approach acknowledges the value of checklists in contexts where there is a significant body of knowledge or experience on the range and nature of potential hazards, and the notion that it is inappropriate to base hazard identification solely on lessons learned from the past, because hazards and the contexts in which they arise are fundamentally dynamic.

System engineering techniques were applied within the engineering function. Here, hazard identification was concerned with determining the root causes by which engineered systems may fail to operate within their design specifications. This was reflected in the utility’s use of hazard and operability studies (HAZOP). In brief, analysts examined a process (*e.g.* disinfection) subdivided into nodes. At each node, the analysts applied guidewords (*e.g.* low, high) to process parameters (*e.g.* temperature, pressure, flow) to identify ways in which the process may deviate from its design intention.

In contrast, neither prescription nor a definitive methodological structure was evident in project management’s approach to hazard identification, which was concerned with threats to the delivery of projects to time, to budget, and within the required quality parameters. Reflecting the unique nature of projects and their related hazards, this function adopted facilitated group brainstorming, informed by generic risk categories (*e.g. “economic / business risk: the risk of exceeding project budget due to, for example, the impact of unfavourable exchange rates on the cost of minerals”*) to stimulate dialogue and encourage a systematic and creative approach to hazard identification.

4.1.2. Exposure assessment

The existence of a hazard does not constitute a risk because each hazard requires a pathway (a sequence of events, actions, or processes) that, if available, leads to its realisation at a receptor. Whilst hazard identification is concerned with *what* can go wrong (*e.g.* introduction of hydrocarbons within a water supply system), exposure assessment examines the *how* and *why* (*e.g.* off-take water contaminated *via* oil emissions from inadequately maintained pumps or pipes, due to an absence of procedures or inadequate supervision and training of maintenance staff). It involves identifying possible routes to and causes of failure.

Consider the drinking water quality management function within our case study utility, where risk analysis was based on an adaptation of the hazard analysis and critical control points (HACCP) methodology. The method seeks to provide a basis for understanding and prioritising human health and aesthetic hazards within the water supply chain from catchment to tap. Within the function, knowledge of the environmental behaviour of hazards (*e.g.* the environmental fate and transport of pathogens) and the system under examination, technical judgement, incident reports, survey maps, and monitoring records was synthesised to link hazards within each subsystem (*e.g.* catchment: chlorine resistant pathogens) to their sources (*e.g.* dairy farming or grazing) and to the chain of events that may lead to their realisation (*e.g.* runoff or percolation from land based activities).

Whilst variable in rigour and method, a common theme was that each function's approach to exposure assessment – where evident – tended to focus on *how* failure events may arise, rather than addressing the in-depth root causes. They neglected to explore the reasons *why* human or technical systems fail. This is an important oversight in that easily predictable causes of failure are often manifestations of deeper, underlying weaknesses (Reason, 1997). An inability to understand causal paths to failure constrains the development of risk management options targeted at the root causes of risks. Indeed, this should be the guiding basis of HACCP – in that risk (rather than hazard) management should focus at the critical points of management control; that is on those processes whose failure is likely to drive the risk (Hrudey *et al.,* 2006).

4.1.3. Consequence evaluation

This practice involves identifying the nature of the consequences that follow a hazardous event (*e.g.* financial, environmental) and assessing the severity of impact. A range of techniques, from quantitative modelling to qualitative ranking were applied within our sub-sample of business functions. Applications of the former were restricted to asset management (*e.g.* event tree analysis, dam break modelling, inundation mapping, and economic impact evaluations in major dam risk analysis), with the majority of evaluations of the impact being single point estimates framed by risk ranking techniques. These techniques presented consequences according to the nature of their impact (*e.g.* financial, environmental), and a graded scale of severity expressed by descriptive benchmarks. Their application within the sub-sample of business functions was not typically underpinned by an analytical method, relying instead on the interpretation of limited data sets (*e.g.* in occupational health and safety: cost of claims, lost time due to incidents) to derive a credible consequence evaluation. Whilst this is often a practical necessity, the indeterminacy intrinsic to this approach provides scope for individuals to bias (inadvertently or not) consequence evaluations, often in subtle and difficult to detect ways such that risk analysis outcomes may reflect the desires of vested interests (*e.g.* to secure funds, or to divert attention from flaws) rather than the corporate good. Such concerns are not unique to consequence evaluation, and provide a powerful rationale for quality control of the risk analysis process, which we discuss in section 4.2.4 below.

4.1.4. Likelihood evaluation

This involves evaluating the probability that a hazardous event will occur and lead to a defined severity of consequence. In drinking water quality management, analysts sought to characterise the likelihood of hazardous events occurring and leading to a derogation of water quality standards or guidelines. Such judgements were informed by historic frequencies of exceedence (*e.g.* from turbidity monitoring data, *E. coli* concentrations). In some cases, these were supplemented by analysing critical variables. For example, evaluations of the likelihood of climatic and seasonal variations leading to excess levels of suspended solids in source waters were informed by analysis correlating the historic loadings of suspended solids with flow and rainfall data. However, whilst comprehensive monitoring of water quality parameters within catchments and at customer taps was routine, the absence of an overarching monitoring philosophy rooted in preventative risk management, at the treatment and disinfection plant level meant that the datasets characterising hazards within water supply systems were incomplete. As one interviewee noted, *"we do have online monitoring…but traditionally it's been a fairly ad hoc process…no-one has really taken a holistic view…and said – I think we should have online [pH] monitors here, chlorine residual analysers [here and]…for these reasons."*

A similar theme emerged in occupational health and safety, whose risk analysis procedure stated that likelihood evaluations *"may be determined using statistical analysis and calculations,"* but *"where no past data exists or is available, subjective estimates will be required to reflect an individual's or groups degree of belief"* that a particular severity of consequence will occur. It further specified that experiments and prototypes and economic, engineering or other models may be used to minimise subjective bias. Our observations revealed that modelling (*e.g.* event tree analysis) was restricted to isolated applications, whilst the availability of historic data (*e.g.* frequency rates by injury type, mechanism of injury, *etc.*) was paradoxically constrained by the organisation's good health and safety record. As one interviewee offered: *"the amount of information that we generate doesn't produce sufficient data for us to analyse…and that's not necessarily because of a lack of reporting, it's just that…we actually don't produce that many incidents."* This was offset, in part, by reference to external data sources (*e.g.* national health and safety databases). However, these fail to reflect the unique nature of the utility's design, construction, operation, and maintenance practices and, more broadly, their working culture.

4.2. Risk analysis: maturity of implementation

Having summarised (Table 5) and discussed the business functions' risk analysis practices, we now consider their maturity of implementation. Within each business function, the requirements of Level 2 maturity in risk analysis (Table 4) were satisfied (Fig. 2). A *repeatable* process was in place, characterised by explicit critical risk analysis practices. Level 2 is limited in two fundamental ways. One is that the key practices of exposure assessment and control evaluation may be absent or undertaken implicitly. With the exceptions of engineering and drinking water quality management, this was true across our sub-sample (see Table 5). This is significant because a knowledge of the pathways by which hazards are realised and of the weaknesses in the design, operation and management of existing controls, is a prerequisite to developing risk management options targeted at common and root causes of failures that are yet to arise. A further defining L2 characteristic is that the rigour and quality with which critical practices are performed depends in large part on individuals that execute and manage the work, and may therefore vary considerably. Additionally, the techniques adopted may be retrospective and historical, regardless of their applicability or currency. This is because they do not fully satisfy the requirements of a defined (L3), controlled (L4) or adaptive (L5) process. However, *fully* is the key word here, as we observed each function exhibiting some of the higher level maturity attributes and so our characterisation may be somewhat harsh. We now discuss specific attributes of their maturity in risk analysis.

4.2.1. Initiation criteria

Within many sectors, there are accepted standards of performance and codes of practice that, if adhered to, provide high degrees of control (UKOOA, 1999; Pollard *et al.*, 2004). These standards are applied in familiar and well-characterised situations where uncertainties and system vulnerabilities are well understood. Adhering to the historic basis for safe operations can be considered as discharging the risk management duty (Health and Safety Laboratory, 2003; UKOOA, 1999). Returning to our sample of business functions, this concept was reflected in an electrical engineer's comments: *"electricity is a dangerous thing, it's a source of high energy that can be released instantaneously. Obviously you need to be in control and protected satisfactorily to make sure that there's no risk to personnel or the property…because the technology is very mature…we have our own design guidelines [for electrical engineering] that actually emphasise…issues like lifecycle cost, security of operation, reliability, safety…[and so on] I don't think it is necessary to have a formalised [risk analysis] process [in electrical engineering], because it's part and parcel of the detailed design anyway."*

However, complex, uncertain and novel systems, with the potential to deviate from routine operation, may require risk analysis, so as to better understand what drives the risk from or to the plant, process or operation (UKOOA, 1999; Pollard *et al.*, 2004). This principle extends beyond technical systems to embrace all aspects of managing a water utility. As such, a L3 attribute is the existence of initiation criteria: criteria that *initiate* the application and revision of risk analysis. Criteria observed within our sub-sample included: undertaking project risk analyses prior to full financial approval depending on the cost, complexity and novelty of the project; undertaking manual handling risk analyses in occupational health and safety management for novel, altered or relocated processes or in response to high frequency injury records or employee requests; undertaking HAZOP studies within engineering for complex or costly processes at set stages of design completeness. Timescales for revising risk analyses of various asset classes were observed in asset management. These criteria acknowledge that risk analysis is not a one-off activity, but requires regular revision to reflect system changes and the improved understanding of risks, that inevitably develops over time (*e.g.* from monitoring data, increased operator experience). In a world becoming obsessed with "the risk management of everything" (Power, 2004), an absence of these initiation criteria may drain resources, as staff are tempted to conduct risk analysis without first considering whether adherence to good practice would serve for sound risk management. At the other extreme, analysis may be applied reactively, perhaps even to provide *ex post* justifications of investment decisions (*e.g.* Health and Safety Laboratory, 2003).

4.2.2. Stakeholder engagement

A further positive characteristic of the utility's approach to risk analysis was the reflection of a broad spectrum of knowledge, skills, experience and perspectives within each function's approach to risk analysis. One benefit of their primarily qualitative approach was that it ensured that non-specialists, or what one interviewee referred to as *"the people that use the systems, use the equipment and undertake the processes,"* could actively participate in and critically scrutinise the process. This is key, as engaging operational staff who have practical knowledge of the hazards under examination ensures a sense of ownership and engagement in the process, as opposed to accountabilities residing within a core set of head-office experts isolated from operational reality.

4.2.3. Competence

As Rosness (1998) notes, the accuracy of risk analyses depends to a large extent on the competency of analysts to critically evaluate information and integrate it with their own knowledge and assumptions. A need for education and training in risk analysis remains irrespective of the technical complexity of the methods adopted. Aside from the ubiquitous "on the job" training, two elementary programmes were observed within our sub-sample: (i) internally delivered training modules within occupational health and safety, comprising an overview of the relevant legislation, the risk analysis process, and some practical exercises; and (ii) voluntary external modules for HAZOP facilitators and project managers. However, formal definitions of the competencies required of risk analysts and metrics for assessing whether they had been imparted were absent, leading one to question on what basis education and training in risk analysis was targeted, assessed and improved. This critique is not restricted to our sub-sample; there is a broader need for research on (i) the attributes and characteristics of competent risk analysts; (ii) how they can be developed within staff; and (iii) how the vigilance secured can then be measured and retained.

4.2.4. Verification: quality control

The quality control of risk analyses is intended to enhance their credibility through addressing inherent uncertainties, both epistemic, due to lack of knowledge, and operational, derived from the use of knowledge (*e.g.* analyst bias, judgements, human error; see Faber and Stewart, 2003; Amendola, 2001). This aspect was perhaps a core weakness of the sub-sample. For example, peer reviews of risk analysis were executed in a largely informal and unsystematic manner, whilst the use of facilitators was restricted to project risk analysis and HAZOP studies. That said, the role of the latter should not be underplayed, as our interviews emphasised that they did *not* drive particular outcomes or provide specific technical input, but sought to guide analysts in the application of methods and focus on the quality of process execution (*e.g.* challenging outliers during consequence evaluation, ensuring all relevant risk categories were considered during hazard identification).

With formalised quality control mechanisms being the exception rather than the norm, there was an implicit reliance on analyst competencies, a presumed absence of bias, and an assumed validity of the methods adopted. In practice, all risk analyses have inherent limitations and are based on assumptions rarely made explicit, and arguably, their applications are not scientific in a classical sense, but rather draw on the accumulated experiences, knowledge and bias of analysts (Aven *et al.*, 2006). As such, ignorance, assumptions, value judgements, and local perspectives distort analysis outcomes from true objectivist ideals. Given this, the utility’s rescinding of the Delphi technique within their project risk analysis was disappointing. Historically, facilitated discussions and iterative anonymous voting had been used to generate consensus in risk evaluation. Characterised by group participation, anonymity and feedback loops, it minimised bias and dogma (*e.g.* reduced the reluctance of staff to abandon previously stated views). One interviewee suggested that since the approach had been abandoned, evaluations tended to reflect the subjective judgement of lone experts, which *"typically went unchallenged."* This may be viewed as a pyrrhic victory for those who railed against this symbol of "bureaucracy," and a timely warning that the much maligned concepts of due process, of checks and balances, can suppress greater evils.

4.3. Risk based decision making: observed practices

Table 6 summarises risk based decision making practice within the sub-sample. Below, we evaluate the strengths and limitations of a selection of these practices.

4.3.1. Establish criteria for evaluating alternative risk management options

A range of risk management measures may be considered for a particular decision. Consider drinking water quality management. Options for reducing risks to public health posed by waterborne pathogens include: enhancing the monitoring of indicator organisms in source waters (*e.g. E. coli*), catchment protection (*e.g.* fencing, or exclusion zones for livestock), infrastructure upgrades (*e.g.* filtration flow control), chlorine residual monitoring and operator training. The objective of each option is to reduce the risk to a level considered acceptable. The decision as to which option(s) is considered the best is influenced by many factors. Notwithstanding that all risk management decisions are value-laden, in best practice organisations these factors are reflected in explicit criteria used to evaluate the relative merit of alternative options.

As cost benefit analysis is linked to determining of whether risk management options satisfy the "as low as reasonably practicable" (ALARP) criteria adopted within the sub-sample, it is tempting to consider the balancing of costs and benefits as an evaluation criterion. However, we propose cost benefit analysis is best viewed as a methodology for evaluating the relative utility of a risk management option. It does not prescribe whether one should simply balance the financial expense of implementing an option with the benefits of the risk reduction, or whether one should incorporate less tangible aspects such as technical feasibility, social values such as equity and distribution, or political concerns. In other words, it leaves the evaluation criteria unspecified. Whilst our research revealed that a broad range of criteria guided the evaluation of risk management options within our sub-sample, they were only made explicit within asset management's risk-based approach to prioritising mains replacement and dam safety upgrades (Table 6). As such, one can expect what Arvai *et al.* (2001) termed "alternative focussed" decision making to predominate. This is characterised by an analysis of available alternatives followed by selection of the "optimal" option from a set of implied or poorly defined criteria. It is not desirable for a decision process to dictate or prescribe decisions, as an overly mechanical approach fails to recognise the human aspects of performing difficult value judgements under uncertainty (Aven *et al.*, 2006). However, expressing the criteria against which those judgements should be taken ensures that the rationale for decisions is constructed *a priori* in a deliberative manner, rather than rationalised *post hoc*. Aside from improving risk management, explicit criteria serve to better equip utilities to manage *risk issues*, as they (i) provide a mechanism for reflecting legitimate stakeholder concerns in utility decision making (*e.g.* by incorporating public values and preferences); and (ii) provide a documented, defensible rationale for decision on risk.

4.3.2. Identify risk management options

This practice is concerned with generating alternative solutions for managing risk. Within the business functions, it was typically undertaken within creative workshops involving a diverse range of stakeholders. The value of brainstorming, which seeks to stimulate innovation through open interaction and feedback, was cited by various interviewees, one noting that it *"empowers people to think; the worst [thing] that you can do is take away people's creativity."* Furthermore, engaging stakeholders with diverse skills and backgrounds helps identify and address those assumptions, constraints and biases that can have a significant influence on the generation of alternatives (Aven and Kørte, 2003). Whilst primarily creative, within some functions this practice was informed by checklists of risk reduction alternatives. One example was occupational health and safety management's hierarchy of risk controls (control banding), which classified: engineering controls for hazard removal (*e.g.* substitution, isolation, modification to design, guarding and mechanical ventilation); administrative controls for preventing the occurrence of hazardous events (*e.g.* safe work practices, or procedures, training, supervision, nominating maximum exposure times); and personal protective equipment for minimising their severity of consequences.

Perhaps the most important factor was the depth and rigour of the risk analyses. Consider risk analysis within drinking water quality management. Recall that hazards identified within each subsystem (*e.g.* catchment: pathogens) were linked to their sources (*e.g.* dairy farming or grazing) and the events that may lead to their realisation (*e.g.* runoff or percolation from land based activities). Detailed surveys were undertaken exploring the adequacy of design, management and operation of those actions, activities and processes applied to mitigate the introduction or transport of said hazards from catchment to customer tap (*e.g.* catchment protection, pre-treatment, ozonation, *etc.*). We propose that systematically identifying the underlying mechanisms through which hazardous events may occur, *before* evaluating the latent and active weaknesses in their control mechanisms, is the normative approach to identifying risk management options. The overarching purpose of risk analysis should be to develop a better understanding of the factors governing system reliability, rather than a “numbers game” (*e.g.* to simply satisfy quantitative risk acceptance criteria; Faber and Stewart, 2003). When used diagnostically, risk analysis represents an efficient tool for improving system safety and performance.

4.3.3. Evaluate options

We now turn to the evaluation of risk management options. There are three elements to this practice: (i) forecasting the impact of options against each evaluation criteria (*e.g.* technical feasibility); (ii) determining the relative merit of each option; and (iii) determining the acceptability of the residual risk, post-implementation.

Methods for achieving the former within our sub-sample of business functions included applying professional judgement, stakeholder consultations, cost-estimations, and engineering studies (*e.g.* feasibility studies in major dam safety management). This said, recall that in most business functions evaluation criteria were not defined, and so this element often tended towards the informal or implicit. For the second element, the cost-benefit approach was widely adopted for assessing the relative merit of alternative risk management options. Formal mathematical analyses were restricted to risk management options that took the form of major capital projects (*e.g.* in major dam safety management). More commonly, managerial judgement was used to balance costs and benefits, at times informed by cost-effectiveness evaluations of risk reduction per unit (Euro) spent. Thus, the determination of whether risks satisfied the ALARP criteria was judgement-based, rather than informed by an explicit evaluation of the costs and benefits of reducing vs. maintaining risk levels.

We present two justifications for the variable rigour and formality that characterised this practice: (i) that the resources expended in decision analysis must be justified by the benefit of better decisions, and so detailed analysis is neither desirable nor justifiable for every decision; and (ii) that evaluation criteria incorporating intangible dimensions are difficult to incorporate within the analytic framework of cost benefit analysis.

4.4. Risk based decision making: maturity of implementation

The sub-sample's risk based decision making profile mirrors that of risk analysis (Fig. 2). However, the decision making processes were less mature, and characterised by a lesser degree of definition. One implication is that we may expect a lesser degree of rigour and formality in risk based decision making. Perhaps this reflects an organisational culture that values judgement, intuition, and creativity of decision above prescription. However, our model is intended to guide, not prescribe, decision making with the objective of encouraging a high degree of consistency, credibility, and confidence in the outcomes. In the absence of a clear framework, people struggle to identify their full range of values and concerns in a given decision context, and are ill-equipped to perform the complex trade-offs common to risk based decision making (Arvai *et al.*, 2001; Slovic *et al.*, 1977; Payne *et al.*, 1992; Slovic, 1995; Matheson and Matheson, 1998). It does not require a strong grasp of decision theory to conclude that an aversion to decision frameworks, however motivated, is not conducive to sound risk management.

5. Discussion

We now critically evaluate our contribution, which is three-fold. We have (a) synthesised empirical observations with prior behavioral and normative risk research to codify the processes of risk analysis and risk based decision making; (b) placed these processes within a maturity framework that distinguishes between levels of implementation, from *ad hoc* to adaptive; and (c) provided a comparative analysis of risk analysis and risk based decision making across a range of utility business functions.

5.1. Coding of risk analysis

Consider the codification of risk analysis (Fig. 1; Table 1), best described by reference to the prominent risk frameworks that adopt an organisation-wide focus (*e.g.* COSO, 2004; AS/NZS, 1999, 2004; FERMA, 2003) and those for drinking water quality management (NZMOH, 2001; NHMRC, 2001, 2004; WHO, 2002, 2004). Our inclusion of exposure assessment is distinctive because strategic risk management frameworks tend to focus on finding sources of potential harm, to the neglect of the underlying pathways that lead to their realisation (*i.e.* how and why hazardous events may occur). This focus on root causes is mirrored in our treatment of control evaluation, which involves identifying and assessing existing technical, physical and administrative controls. These are important advances, because the neglect of causal pathways to failure and latent weaknesses in system defences impedes the development of risk management measures targeted at the root causes, and therefore, promotes a focus on hazard, rather than risk, management.

We have placed consequence evaluation prior to likelihood evaluation. The majority of frameworks consider the order in which they are performed to be interchangeable, or at least make no explicit reference to the matter (*e.g.* COSO, 2004; AS/NZS, 1999, 2004; FERMA, 2003). Our reasoning is that the outcome(s) should be defined prior to any evaluation of the likelihood of occurrence. If these steps are performed in reverse, likelihood evaluation tends to be concerned only with the likelihood of a hazardous event occurring (*e.g.* the probability of asset failure), rather than with the likelihood of an event occurring *and* leading to a defined outcome (*e.g.*

the probability of an asset failing and leading to a given environmental impact). The former approach overestimates risk. This is not a purely theoretical danger; our research has revealed instances of its occurrence (MacGillivray *et al.*, 2007b).

5.2. Coding of risk based decision making

Strategic risk management frameworks (*e.g.* COSO, 2004; AS/NZS, 1999, 2004; FERMA, 2003) conventionally treat risk based decision making, namely the identification, evaluation and selection of options to manage risks, in a somewhat cursory manner. And so the novelty of our coding (Fig. 1; Table 2) is best illustrated with reference to the decision theory literature. Notably, we have separated “evaluate options” into three elements: (i) forecasting the impact of options against each evaluation criteria (*e.g.* technical feasibility); (ii) determining the relative merit of each option; and (iii) determining the acceptability of the residual risk associated with each option. We believe this provides an important advance to option evaluation, moving beyond the notion that the acceptability of a risk can be determined without considering the costs and benefits of maintaining vs. reducing risk levels (*e.g.* in using measures of risk as proxies for risk acceptability).

We also highlight our inclusion of managerial review and option selection prior to the final risk management decision. Whilst not novel (*e.g.* Aven *et al.*, 2006), it is crucial because it highlights our view that decision analysis should compliment, but not replace, the knowledge, intuitions and judgement of decision makers (Mintzberg, 1994). Further, risk based decisions should not reflect theoretically or analytically derived perspectives that run counter to sound professional judgement (Hrudey and Hrudey, 2003). More specifically, it emphasises that because risk is at heart, an expression of uncertainty (Amendola, 2001), the outputs of a decision analysis must be treated diagnostically rather than deterministically, *i.e.*, they should provide decision support, not carte blanche decisions.

5.3. Coding of maturity

Our research applies capability maturity modelling principles to the processes of risk analysis and risk based decision making (Tables 3 and 4). It allows users to distinguish the relative maturity of implementation of risk analysis and risk based decision making, presumed to correlate this with performance in managing risk. The origins and logic of the hierarchy of maturity levels, particularly regarding the selection and definition of attributes used to define process maturity, are summarised in Table 3 (for more detail, see MacGillivray, 2007c). This hierarchy is the heart of our model, and the most valuable contribution by virtue of its usefulness as discussed below.

5.4. Utility of the model for benchmarking

Throughout our work we have been concerned with improving risk management practice and we are interested in vigilance on the ground. Hence we ask, who may use the model we have developed, and what will it enable them to do that they were previously unable to? The most obvious function of the model is as a tool for research on the form and, crucially, *implementation* of risk management within industry. At a basic level, this is valuable, because published investigations of the latter tend towards the anecdotal rather than methodologically rigorous (*e.g.* Dalgleish and Cooper, 2005; Aabo *et al.*, 2005). From an organisational perspective, its principal function is benchmarking, which enables organisations to compare themselves against others in their sector and beyond, and to identify and incorporate best practices. This is crucial because risk management remains ethereal to many in terms of practice on the ground, creating a need for the systematic evaluation of strengths and weaknesses and the sharing of best practice. It may also be used to drive improvements in the capabilities of key suppliers and partners (*e.g.* through using maturity evaluations to inform supplier selection). Finally, we consider its potential within regulation, envisaging that it may facilitate a step-change in the approach to regulating risk within utility sectors from its current focus on reactive, outcome based approaches (*e.g.* water quality standards) and prescriptions (*e.g.* codes and regulations), towards a proactive, capability based approach.

5.5. Empirical findings

Finally, we consider the contribution of our case study observations in their own right. Three observations bear emphasising: descriptive risk research; a focus on the implementation of risk management; and a cross-functional perspective. We highlight the first due to the lack of theoretically informed descriptive risk research within the water utility sector. The importance of the second is borne out by casting our eyes beyond this sector, where one observes that academic treatments of risk management tend to focus on technical and normative aspects, rather than institutional, behavioural, or descriptive facets, which our findings stress. Finally, our function-specific approach counters the concept of “enterprise wide risk management,” which appears to have created a majority opinion amongst its practitioners that risk management is an over-arching strategic discipline rather than a devolved process with variations and nuances of application within individual business functions.

6. Conclusions

We present a capability maturity model for benchmarking and improving risk analysis and risk based decision making, and illustrate its application to a cross-section of water and wastewater utility functions within a single utility. The insight offered is three-fold:

- a synthesis of empirical observations with behavioral and normative risk research to codify the processes of risk analysis and risk based decision making;
- an arrangement of these processes within a maturity framework that distinguishes their relative maturity of implementation from *ad hoc* to adaptive;
- a critical evaluation of the methods, techniques and maturity of risk analysis and risk based decision making across a range of utility functions.

These findings provide researchers, utility managers, engineers, asset managers, occupational health and safety representatives, public health officials, project managers, chief finance officers and regulators a deeper understanding of the practical form and theoretical underpinnings of risk management, and how distinctions can be made between organisational capabilities. This addresses an important gap in the literature because, although the premise that institutional capacities rather than technical aspects are the fundamental limiting factor in implementing risk management has earlier origins (*e.g.* Garrick, 1988; Luehrman, 1997; Strutt, 2006), there remains a dearth of descriptive research on the practical form of risk management within the utility sectors and, particularly, how it may be embedded. The latter is the subject of our ongoing research.

Acknowledgements

This work has been part funded by the AWWA Research Foundation (AWWARF project RFP2939) and a consortium of international water utilities. The authors are particularly grateful to the case study utility and the lead individuals for their contributions, peer review and permission to publish. The comments and views herein, however, are the authors' alone. BHM is co-funded by a UK Engineering and Physical Sciences Research Council (EPSRC) Doctoral training account.

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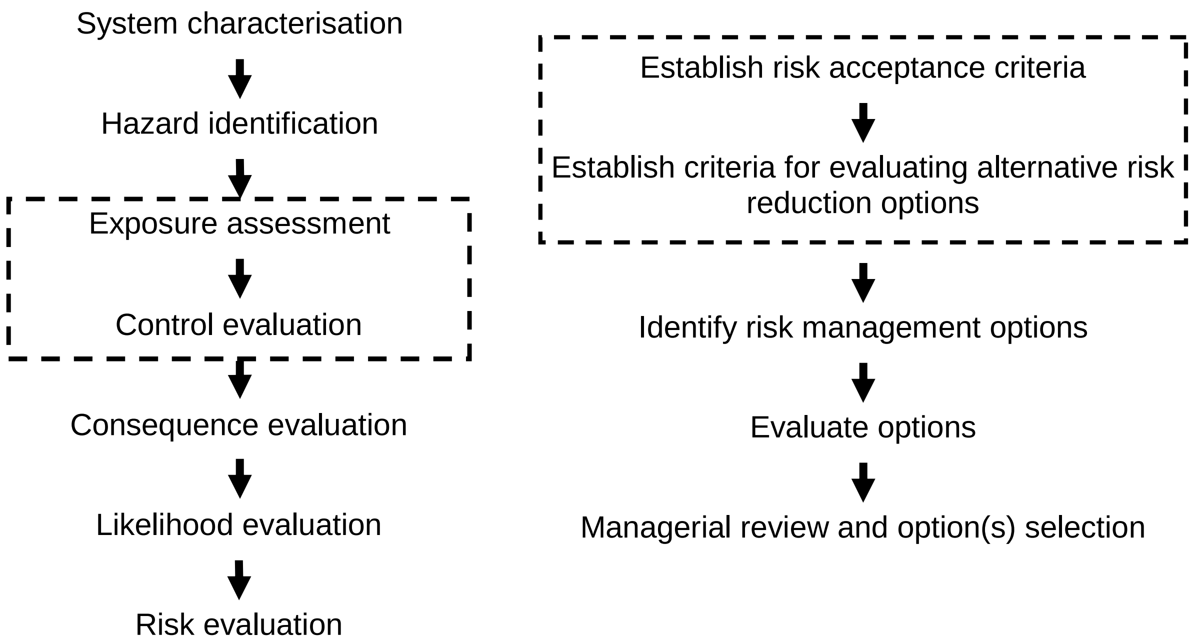
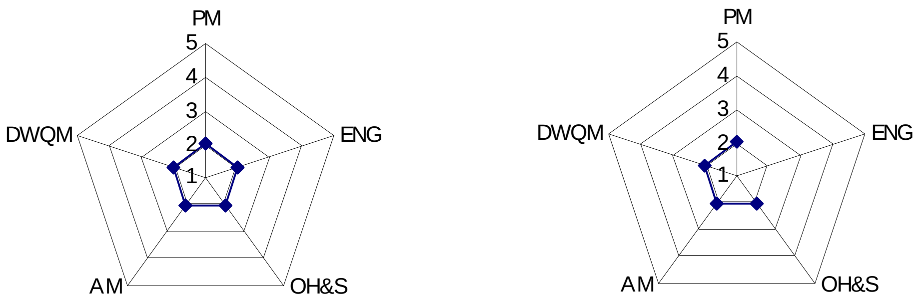


Fig. 1. Risk analysis (left) and risk based decision making practices (right). Those encased are considered key rather than critical, an important distinction in evaluating process maturity.



Key: DWQM: drinking water quality management; AM: asset management; OH&S: occupational health and safety management; ENG: engineering; PM: project management.

Fig. 2. Spider diagram illustrating the maturity of implementation of risk analysis (left) and risk based decision making (right) within the sub-sample (insufficient data was obtained to evaluate the latter within engineering).

Table 1 Descriptions of the risk analysis practices and of the rationale for their inclusion in our model

Risk analysis practice	**Description**	**Rationale**
System characterisation	To establish and describe the system with which risk analysis is concerned (*e.g.* workplace, engineering process, project).	A comprehensive system understanding is a *sine qua non* for generating risk analysis outcomes that are valid and accepted by stakeholders.
Hazard identification	Identifying situations, events, or substances with the potential for causing adverse consequences, *i.e.* sources of harm or threats to the system.	A hazard left unidentified is excluded from subsequent analysis.
Exposure assessment	Whilst hazard identification is concerned with *what* can go wrong,	The potential existence of a hazard does not in itself constitute a risk, as each hazard

	precursor identification focuses on *how* and *why* things can go wrong, in other words identifying possible routes to and causes of failure.	requires a process or pathway (precursor) to lead to its realisation. Thus, the value of this practice lies in both confirming the existence of pathways to failure (and therefore that a risk exists) and informing the development of risk management options focussed at root causes.
Control evaluation	The identification and assessment of existing technical, physical and administrative controls which may either reduce the likelihood of a hazardous event occurring, or serve to mitigate its severity of consequences. Assessment should address both the criticality of the controls (*e.g.* based on their inherent capacity to reduce risk, whether they are proactive or reactive, *etc.*) and their adequacy of design, management and operation.	An evaluation of existing controls: informs the evaluation of associated risk levels; serves to inform the development of risk management options through identifying latent and active control weaknesses (*i.e.* through serving as a gap analysis of existing risk management measures); and captures the historic basis for safe, reliable system operation.
Consequence evaluation	Identifying the nature of the consequences of a hazardous event occurring (*e.g.* financial, environmental) and assessing their severity of impact.	Deriving and combining measures of consequence and likelihood are required to establish the overall level of risk associated with a given hazard, so that management resources may be allocated accordingly and to assess the desirability of potential risk management measures (*e.g.* to see if they satisfy the ALARP criteria).
Likelihood evaluation	The evaluation of the likelihood (*i.e.* frequency or probability) that a hazardous event will occur and lead to a defined severity of consequence.	
Risk evaluation	Combining measures of likelihood and consequence severity to derive an overall measure of risk, either qualitative (*e.g.* high, low) or quantitative (*e.g.* expected loss of life, value at risk).	

Table 2 Descriptions of the risk based decision making practices and of the rationale for their inclusion in our model

Risk based decision making practice	**Description**	**Rationale**
Establish risk acceptance criteria	Establishing criteria for evaluating the acceptability of risk.	In the absence of such criteria, on what basis are decisions taken on whether to mitigate or accept risk?
Establish criteria for evaluating alternative risk management options	Establishing criteria used to evaluate the relative merit of alternative risk management options (*e.g.* forecast risk reduction, technical feasibility, cost of implementation, latency of effects, environmental impacts, *etc.*) and, where deemed appropriate (*e.g.* where multi-attribute analysis is subsequently undertaken), weightings to establish their relative importance.	A range of risk management options may be considered for a particular decision context; the decision as to which is considered the best option is influenced by many factors. Different concerns and values often need to be considered simultaneously, and their relative importance may be valued differently by various stakeholders (Faber and Stewart, 2003). Making this explicit in the form of criteria can improve the credibility and defensibility of decision making, minimise the possibility that decisions will be second guessed or that their rationale be forgotten, remove barriers to stakeholder buy-in, and ensure the existence of an audit trail (SEI, 2002). More broadly, it enables value rather than "alternative focussed" decision making, the latter being characterised by the selection of an "optimal" option from a set of implied or poorly defined criteria (Arvai *et al.*, 2001).
Identify risk management options	Generating alternative solutions for the decision problem.	Options not generated are excluded from subsequent evaluation and, ultimately, implementation.

Evaluate options	There are three elements to this: forecasting the impact of each option against the individual evaluation criteria; determining the relative merit of each option (*e.g.* via cost-benefit analysis, multi-attribute analysis); and determining risk acceptability.	Systematically evaluating the individual and cumulative merits of alternative options should provide for more credible, defensible and rational risk based decision making. Determining risk acceptability follows as it is risk management options, not risks, which are unacceptable or acceptable (Fischoff *et al.*, 1981), *i.e.* the acceptability of risk cannot be determined without considering the costs and benefits of maintaining vs. reducing current risk levels.
Managerial review and option(s) selection	The application of managerial judgement in reviewing the premises, assumptions, and limitations of analyses, prior to the final decision (after Aven *et al.*, 2006).	In line with Mintzberg (1994), we consider that decision analysis should compliment, but not replace, the knowledge, intuitions and judgement of decision makers, and further, that risk based decisions should not reflect theoretically or analytically derived perspectives that run counter to sound professional judgement (Hrudey and Hrudey, 2003). More specifically, given that risk is, at a fundamental level, an expression of uncertainty, and that the analysis of risk and decision alternatives is further subject to aleatory, epistemic and operational uncertainty (Amendola, 2001), the outputs must be treated diagnostically rather than deterministically, *i.e.*, they should provide decision support, not decisions.

806

Table 3 Descriptions of the risk analysis process maturity attributes and their rationale for inclusion within our model

Attribute	**Description**	**Rationale**	**Key aspects**
Procedures	The rules guiding the execution of risk analysis.	Procedures serve to capture and disseminate knowledge of the optimal conduct of risk analysis so that it is maintained within the organisational memory rather than as hidden expert knowledge (NEA/CSNI, 1999), and so ensure its consistent, efficient conduct.	Appropriate standardisation and formalisation of procedures taking into account personnel experience and knowledge; participation of end users (*e.g.* risk analysts) in their development; matching detail with complexity of work; making explicit the rationale for conducting risk analyses; being based on an analysis of the tasks required (NEA/CSNI, 1999; Health and Safety Laboratory, 2003).
Roles and responsibilities	Assignment of personnel to risk analysis roles and responsibilities.	To avoid the "not my job" phenomenon (Joy and Griffiths, 2005), and ensure risk analysis receives appropriate focus and resource allocations.	Matching role descriptions and assignment of responsibilities with personnel competencies and authorities (NEA/CSNI, 1999). Supporting well meaning statements that "risk management is everyone's job" with specific requirements.
Initiation criteria	Stages or conditions which initiate risk analysis.	To ensure risk analyses is undertaken as required, rather than being initiated on an *ad hoc*, over zealous, or reactive basis, or marginalised as "make work."	Identifying where risk analysis is necessary vs. where adherence to codes and standards can be said to discharge the duty (Health and Safety Laboratory, 2003; UKOOA, 1999), and making this explicit in cyclical and event-based criteria.
Resource management	The planning, acquisition, and deployment of funds, techniques and staff in support of risk analysis.	Resourcing of risk analysis is particularly critical during periods of reduced budgets and downsizing, which may bring an emphasis on economic rather than safe operation (NEA/CSNI, 1999).	Sufficiency and availability of financial resources; access to sufficiently competent human resources; and a range of risk analysis techniques which reflect the complexity of the organisation's activities and working environment (Health and Safety Laboratory, 2003).
Input data management	The identification, collection, and storage of risk analysis data inputs.	The systematic identification and capture of data requirements serves to ensure analyses are underpinned by objective data evaluation, rather than reflecting best guesses in the guise of "expert judgement."	The definition of data requirements / data sources for risk analysis, either at the process level or, where not practical, on a case by case basis, and mapping these to data collection and storage systems.

Output data management	The collection, storage and dissemination of risk analysis outputs.	Risk analysis outputs must be systematically recorded to inform decision makers, for audit and training purposes, and to facilitate future reviews (COSO, 2004; CSA, 2004). Further, this ensures staff have current knowledge of the human, technical, organisational and environmental factors that govern system safety (Reason, 1997).	Documenting in-depth the risk analysis outcomes, not simply the overall level of risk (*e.g.* sources of data, assumptions used, methods followed, *etc.*). Although in theory the storage media is unimportant as long as the outputs are easily retrievable (Health and Safety Laboratory, 2003), IT-based data systems (risk registers) have significant advantages, particularly in facilitating information flow between and across layers and boundaries of the organisation (COSO, 2004).
Verification	Ensuring compliance with risk analysis procedures, and providing quality control of the execution of risk analysis.	The mere existence of procedures is not in itself enough to ensure that staff actions will be consistent with them (Hoyle, 2001; ISO, 2000). Errors of omission or commission (*e.g.* due to misunderstanding instructions, carelessness, fatigue or management override), may cause deviations. Similarly, procedural compliance does not ensure the quality of execution of risk analysis.	Implementation of mechanisms to ensure adherence to procedures (*e.g.* auditing, "sign offs") and to sanction non-compliance. Quality control mechanisms (*e.g.* peer reviews, Delphi panels) should be implemented with explicit methods for controlling (*e.g.* establishing group consensus iteratively) or evaluating (*e.g.* quality criteria) the quality of analyses. An appropriate balance between the resources required, the constraints of bureaucracy, and the benefits of process control should be struck.
Validation	Assessing the fundamental correctness of the risk analysis process design (*e.g.* that the correct techniques are being applied, that the correct initiation criteria are in place).	The willingness and means to question the validity of current risk analysis practices is required to show due diligence and ensure that current practices are legitimate, and is further a prerequisite to the continual improvement of risk analysis.	Formalised approaches to validation include: statistical or mathematical approaches to validating technical methodologies, independent peer reviews, and benchmarking surveys; and informally may draw upon: professional networks, trade and scientific literature, *etc.*

Organisational learning	The manner in which the organisation identifies, evaluates and implements improvements to the design and execution of risk analysis.	Mechanisms for verification and validation are mere panaceas if their findings are not acted upon, *i.e.*, if they are not used to rectify deficiencies in the design and execution of risk analysis.	Reviews should: be undertaken at specified intervals and on an event driven-basis; consider a broad range of internal and external feedback; focus on improving the validity of the risk analysis process and the effectiveness of its execution, not on ensuring it complies with a given standard; treat errors of omission or commission in the execution of risk analysis not as isolated lapses requiring sanction to prevent their re-occurrence, but as opportunities to identify and resolve root and common causes of error; and be supported by a learning culture, wherein current methods and approaches to risk analysis, and their underlying assumptions, are open to question and critical evaluation.
Stakeholder engagement	The engagement of stakeholders, both internal and external to the utility, for the purpose of harnessing a broad range of perspectives, knowledge, skills and experience.	The legitimacy of risk analysis outputs depends upon appropriately broad stakeholder engagement, as risk is an intrinsically multi-faceted construct, whose comprehensive understanding is often beyond the capabilities of individuals or small groups.	A team approach to risk analysis which pools the knowledge, skills, expertise and experience of a range of perspectives is preferable (Health and Safety Laboratory, 2003; MHU, 2003; Joy and Griffiths, 2005). External stakeholders may be engaged to: capture expertise (*e.g.* consultants); confer additional legitimacy on the analyses; communicate due diligence (*e.g.* regulators); and capture community values and ensure they are incorporated within the analysis.
Competence	The ability to demonstrate knowledge, skills, and experience in risk analysis to the level required (Health and Safety Laboratory, 2003).	The legitimacy of risk analyses outcomes depends to a large extent on the capacity of staff to critically evaluate available information and to supplement it with their own knowledge and plausible assumptions (Rosness, 1998) , *i.e.* on staff competencies.	Definition of required staff competencies in risk analysis; evaluation and implementation of appropriate education and training vehicles to develop / maintain those competencies (*e.g.* class room learning, external workshops); providing "on the job" training under adequate supervision; designing and implementing methods for evaluating the efficacy of educating and training (*e.g.* for measuring that the required competencies have been imparted).

Table 4 Descriptions of the risk analysis process maturity hierarchy, from ad hoc to adaptive

LEVEL 5: *Adaptive*	Validation	A broad range of mechanisms are in place to capture feedback potentially challenging the validity of the risk analysis process (*e.g.* benchmarking surveys, professional networks, external peer reviews, mathematical validation of technical methodologies).
	Organisational learning	Norms and assumptions underpinning the design of the risk analysis process are openly questioned, critically evaluated and, where appropriate, revised in light of validation findings (*i.e.* double loop learning).
LEVEL 4: *Controlled*	Verification	Verification extends beyond rigorous mechanisms to ensure procedural compliance (*e.g.* sign offs supplemented by in-depth audits) to provide formal quality control of risk analyses (*e.g.* peer reviews, challenge procedures, external facilitation, Delphi technique, *etc.*).
	Organisational learning	Root and common causes of errors in the execution of risk analysis (*e.g.* deficient communication, overly complex procedures, lack of education and training) are identified and resolved. Modifications to the design of the process are identified, evaluated and implemented within periodic and event-driven reviews, but remain largely reactive and externally driven (*i.e.* mirroring changes to codes, standards, guidelines, *etc.*).
LEVEL 3: *Defined*	**The critical and key risk analysis practices are explicitly undertaken.**	
	Procedures	Procedures exist to guide the execution of risk analysis, with an appropriate degree of standardisation, detail, and complexity.
	Roles and responsibilities	Risk analysis roles and responsibilities are allocated with sufficient regard for staff competencies and authorities.
	Initiation Criteria	Cyclical and event-based criteria are in place to guide the initiation of risk analyses.
	Resource management	The requisite monetary, human and technical resources are identified, acquired and deployed in support of risk analysis.
	Input data management	The requisite data inputs are identified, acquired and deployed in support of risk analysis.
	Output data management	Risk analysis outputs are collected, stored and disseminated in a manner that supports decision-making, satisfies audit requirements, and facilitates organisational learning.
	Verification	Basic mechanisms are in place to ensure compliance with risk analysis procedures, focussing on outputs rather than tasks performed (*e.g.* sign offs on receipt of completed risk analyses).
	Validation	The validity of the risk analysis process is questioned in light of changes to regulations, codes and standards.
	Organisational learning	Non-compliances with risk analysis procedures are resolved on a case by case basis (*i.e.* treated as isolated errors requiring sanction to prevent their recurrence). Improvements to the design of the risk analysis process are implemented in a reactive, *ad hoc* manner (*e.g.* in response to changes in codes or regulations).
	Stakeholder engagement	A broad cross section of internal and external knowledge, experience, skills and perspectives is reflected within risk analysis, based on explicit guidelines or criteria for stakeholder engagement.
	Competence	Staff exhibit adequate knowledge, skills and experience in risk analysis. Education and training in risk analysis is planned and executed based on established competency requirements.
LEVEL 2: *Repeatable*	**The critical risk analysis practices are explicitly undertaken.**	
LEVEL 1: *Ad hoc*	**Risk analysis is absent; or the critical practices are implicitly or incompletely performed.**	

Table 5 Summary of the undertaking of each risk analysis practice within the sub-sample

	Drinking water quality management	Occupational health and safety management	Asset management		Project management	Engineering
			Treatment plants	Major dams*		
System characterisation	Schematics of water supply systems were produced. Data was obtained to characterise the following system elements: catchment (*e.g.* geomorphology, climate, land uses); source water (*e.g.* surface or ground water, flow and reliability, seasonal changes); storage tanks, reservoirs and intakes (*e.g.* detention times, design); treatment and distribution systems (*e.g.* processes, configuration, monitoring); current operational procedures; point sources of pollution; and consumers (*e.g.* population, demand patterns).	Checklists were used to interrogate characteristics of the work spaces and the type and methods of work to be undertaken (*e.g.* existence / location of pits, shafts, ducts, pressure vessels, access and egress routes, ventilation, isolation and lockout procedures, substances used, *etc.*).	Plant components were identified, their condition and performance evaluated through asset inspections, and current operating and maintenance regimes detailed.	Engineering assessments of dams were undertaken, drawing on technical reports, site visits, flood and earthquake loadings, dam safety standards, *etc.*	Project options were characterised through scope development and value management workshops. These detailed the project need and relevant assumptions and constraints, before characterising each option in terms including their: functional specifications, capacities, required inputs and outputs, and relative costs and benefits.	Prior to the application of HAZOP studies, process and instrumentation diagrams – which show the interconnection of process equipment and the instrumentation used for process control – were created.
Hazard identification	Chemical, microbiological, physical and radiological water quality hazards (*e.g.* chlorine sensitive pathogens) were identified on a	Hazards were identified via the use of task, substance and workplace specific checklists. Where deemed relevant, this	A FMECA-type approach linked potential hazards (*e.g.* supernatant	Significant failure modes (flood, earthquake, and static loading) were	Hazards threatening the delivery of the project option(s) on time, to budget, and within the	HAZOP studies identified potential deviations from process design intent (*i.e.*

	system and sub-system (*e.g.* catchment, treatment) specific basis through a checklist-based approach.	was supplemented by systems engineering techniques, incident and near miss records, and brainstorming.	overflows to surroundings or temporary pipework pumps) to their direct causes (*e.g.* not enough capacity to hold or evaporate sludge received) for each component and for the plant as a whole. Informed by site visits, incident records, and feedback from operating and maintenance staff.	identified.	required quality parameters, were identified through facilitated brainstorming, structured with reference to generic hazard categories.	hazards) through the application of guide words (*e.g.* low, high, none) to process parameters (*e.g.* ozone flow).
Exposure assessment	Knowledge of the environmental behaviour of hazards and the system under examination, technical judgement, incident reports, survey maps, and monitoring records were synthesised to link hazards (*e.g.* chlorine sensitive pathogens) to their sources (*e.g.* dairy farming or grazing) and to the events which may lead to their realisation (*e.g.* runoff or percolation from land based activities).	There was an absence of explicit provisions for identifying the precursors to identified hazards, one exception being for hazards arising from manual handling activities, where checklists examined which aspects of the actions and movements, workplace layout, and working posture generated said hazards.		No inference possible.	Hazards (*e.g.* aqueduct erosion) were linked to their direct causes (*e.g.* major storm runoff; water release from failed stormwater dams).	Engineering judgement was applied to identify potential causes of deviations from design intent (*e.g.* human error: acts of omission or commission; equipment failure; and external events).
Control evaluation	Actions, activities and processes applied to mitigate the introduction or transport of hazards from catchment to customer tap (*e.g.* catchment protection, pre-treatment,	Health and safety risk controls were identified with reference to a control hierarchy which established their relative criticality: engineering (*e.g.*	Not observed to have been explicitly undertaken.	The influence of structural and non-structural (*e.g.* early warning systems) controls was	Not observed to have been explicitly undertaken.	Systems or procedures designed to prevent, detect, provide early warning, or mitigate the consequences of a

	ozonation) were identified via a checklist-type approach applied to system schematics. Critical controls were identified via set criteria. Technical data, consultations with operators, and site visits informed survey-based evaluations of their adequacy of design, management and operation with reference to key attributes (*e.g.* infrastructure; planning, procedures and legislation; monitoring; and auditing).	substitution, isolation, design modification, guarding), administrative (*e.g.* training, supervision, procedures), and personal protective equipment. No explicit provision for evaluating their adequacy of design, management or operation.		incorporated within the modelling of failure scenarios (*i.e.* within event trees, dam break modelling, *etc.*).		deviation (*i.e.* safeguards) were identified. No explicit provision for evaluating their adequacy of design, management or operation.
Consequence evaluation	This may be generalised as the judgement-based interpretation of limited data sets describing the nature and severity of consequences of past hazardous events (*e.g.* in occupational health and safety: cost of claims, lost time due to incidents) to derive a credible evaluation of the potential consequence(s) of uncertain future events. Evaluations were near uniformly characterised with reference to descriptors of the nature (*e.g.* environmental, financial) and severity of consequences of events enshrined within the utility's portfolio of risk ranking techniques. However, isolated applications of mathematical modelling (*e.g.* event tree analysis, dam break modelling, inundation mapping, and economic impact evaluations in major dam risk analysis; event tree analysis in one occupational health and safety risk analysis application) were observed.					
Likelihood evaluation	May be generalised as the judgement-based interpretation of data pertaining to the frequency of past hazardous events (*e.g.* water quality exceedence frequencies) in light of analyst(s) knowledge, experience, and assumptions. Evaluations were near uniformly characterised with reference to likelihood benchmarks within risk ranking techniques. However, isolated applications of mathematical modelling were observed (*e.g.* in major dam risk analysis, network reliability analysis, *etc.*).					
Risk evaluation	Outside of isolated risk analyses driven by consultants (*e.g.* notional costs of risk and statistical lives lost were derived in major dam risk analysis), risk was expressed in qualitative terms (extreme, high, medium or low) derived by combining estimates of consequence severity and likelihood on a risk matrix.					

Table 6 Summary of the undertaking of each risk based decision making practice within the sub-sample

	Drinking water quality management	Occupational health and safety management	Asset management	Project management
Establish risk acceptance criteria	Corporate policy was to reduce risks to a level "as low as reasonably practicable (ALARP)." The ALARP principle recognises that it would be possible to spend infinite time, effort and money attempting to reduce a risk to zero, and reflects the idea that the benefits of risk reduction should be balanced with the practicality of implementation. However, ALARP was not referred to within individual functions' risk management procedures, with the exception of OH&S and in major dam safety management. In the latter, risk acceptability considered three criteria: life safety criteria; ALARP, and the *de minimis* risk concept, in order of stringency.			
Establish criteria for evaluating alternative risk management options	Not explicitly defined. Interviewees referred to cost, time and effort required for implementation; forecast risk reduction; regulatory compliance; risks introduced (*e.g.* disinfection by-products); geographical and technical feasibility (*e.g.* site constraints); operability; manpower required; and social and political concerns.	Not explicitly defined. Forecast risk reduction, cost of implementation, and technical feasibility were referred to by one interviewee.	Defined for below ground major water mains: qualitative risk reduction, cost of implementation, and latency of effects; for major dams: cost of implementation, and forecast reduction in statistical lives lost and economic losses from dam failure events (weighted to ensure preference for reducing lives lost).	Not explicitly defined. Although project managers were explicitly required to take a cost-benefit approach in evaluating risk management options, the scope of these considerations, *i.e.* the criteria with which costs and benefits were determined with reference to, was not defined.
Identify risk management options	Options (*e.g.* infrastructure upgrades, fencing off sensitive catchments, educating and training operators) were	Options (*e.g.* introducing standard work practices) were typically generated in	Options (*e.g.* for wastewater treatment plants: capital projects, alterations to operating or maintenance regimes, contingency plans; for dams: structural	Options were typically generated by the project manager in consultation with relevant stakeholders (*e.g.* engineering staff, environmental representatives), or

		generated by groups responsible for the risk analysis of each sub-system (*e.g.* catchment) in consultation with relevant specialists (*e.g.* engineering, operations).	brainstorming sessions involving a broad cross-section of regional / departmental staff, and, where relevant, OH&S staff.	and non structural measures, such as installing external back up seals on concrete faced rockfill dams, or early warning systems, respectively) were generated by those groups responsible for the risk analysis of each asset class in consultation with operating and maintenance staff.	within the risk analysis workshops through group brainstorming. This was informed by predefined measures for: reducing likelihood of occurrence (*e.g.* audit and compliance programs, training, preventative maintenance); reducing impact of occurrence (*e.g.* contingency planning, engineering and structural barriers, early warning devices); and risk transfer (*e.g.* contracts; insurance arrangements).
Evaluate options	The impact of options against individual evaluation criteria	Methods ranged from the application of professional judgement, to the revision of risk analyses (*i.e.* to derive the forecast risk reduction), to stakeholder consultations, cost-estimations, and engineering studies (*e.g.* feasibility studies in major dam safety management). However, given that in most cases the evaluation criteria were not explicitly defined, the undertaking of this tended towards the informal or implicit.			
	Determining relative merit of options	Largely informal and judgement-based, although the use of formal cost-benefit analysis was observed within asset management's approach to prioritising major dam safety upgrades, whilst cost effectiveness evaluations informed prioritisations of the replacement of below ground major water mains. Furthermore, risk management options that took the form of capital projects valued in excess of approx. $150,000 (US) underwent formal cost-benefit analysis as part of the capital approval process.			
	The acceptability of risk	The limited application of cost-benefit analysis in the context of evaluating risk management options meant that the determination of risk acceptability was typically judgement-based.			
Managerial review and option(s) selection		Whilst our interviewees referred to peer reviews of varying formality as helping to shape the final option(s) selection across our sub-sample, the data does not allow for a meaningful analysis of the roles of judgement, experience, bias, power structures, *etc.* in shaping decision outcomes.			