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Risk analysis strategies in the water utility sector: an inventory of applications for better and more credible decision-making

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ABSTRACT

Financial pressures, regulatory reform and sectoral restructuring are requiring water utilities to move from technically inclined, risk-averse management approaches toward more commercial, business-oriented practices. Risk analysis strategies and techniques traditionally applied to public health protection are now seeing broader application for asset management, assessing competition risks and potential threats to the security of supplies. Water utility managers have to consider these risks alongside one another and employ a range of techniques and devise business plans that prioritise resources on the basis of risk. We present a comprehensive review of risk analysis and management strategies for application in the water utility sector at the strategic, programme, and operational levels of decision making.

Keywords: decision making, risk analysis, utilities, water safety plans.

INTRODUCTION

A. Background

Providing wholesome, affordable and safe drinking water that has the trust of customers are the overarching goals of the water utility sector. The sector has publicly stated[8] that achieving this requires, at a minimum, that water is safe in microbiological and chemical terms; that it is acceptable to consumers in terms of taste, odour and appearance; and that the supply is reliable in terms of quality and quantity. Delivering these objectives in the context of an increasingly demanding consumer and regulatory environment, under constraints imposed by ageing infrastructure and the trend towards financial self-sufficiency is challenging. Many within the industry, spurred on by developments in international regulation and guidance, are now promoting a business-wide approach to risk management as a means to ease and exploit this transition (*e.g.* Lifton and Smeaton[82]). In practice, water quality managers and internal audit functions within the sector are working more closely to address issues of business risk and many of the larger international water companies now have 'group risk managers' in place to manage business and consumer risks within a single portfolio. Implementation of this business-wide approach to risk management is not straightforward, however - it requires:[121]

(i) integrated frameworks for the management of internal risks (*e.g.* from ageing infrastructure) and external risks (*e.g.* from 'competitor' actions) to the utility;

(ii) the support of Board level, executive management and operational staff as well as that of external stakeholders; and

(iii) the effective communication of risk and engagement within decision-making processes both within companies and with external stakeholders.

Furthermore, as illustrated in this review, there are potential tensions between managing the risks of a commercial water business and the overarching public health goal of the water industry, stated above. Critically in this regard, the transition to an explicit risk management philosophy within the water utility sector is now reflected in recent revisions to the World Health Organisation's (WHO) Guidelines for Drinking Water Quality.[167,168,45] This is placing an emphasis on the development and implementation of 'water safety plans' for water quality management and, within these, the application of risk frameworks and risk tools such as the 'hazard analysis and critical control points' (HACCP)[34,64] approach as a basis for prioritising risk management measures within the water supply chain from catchment to tap. The risk management approach is becoming increasingly embedded within utilities and with it a maturing view of risk analysis, shifting from that of a one-off technique to 'placate' regulators towards that of a practical methodology to facilitate process control, optimisation and corporate decision-making within a cost-effective framework. Despite a growing consensus, there remain significant barriers to the implementation of risk management within utilities. These can be categorised as business-related, the challenge of integrating risk management within organisational cultures and decision-making processes (*e.g.* Pollard *et al.*[121]); and technical, relating to the selection and application of risk analysis tools. One of the key difficulties all organisations face in implementing risk management is managing the interfaces between high level corporate objectives, business plans and operational reality. Here then, we critically review the risk analysis strategies and tools and techniques available for risk analysis within the sector, with particular emphasis on decision-making at the corporate (strategic), business (programme level) and operational levels in water utilities. Necessarily the discussion requires excursions into the management and technical environmental literature. However, we view the juxtaposition of these aspects of risk management as central to providing a well-round examination of the prior art in the current context of its application within the sector.

B. Risk analysis and decision-making

Before entering a discussion on risk analysis, we must be clear in our terminology. In simple terms, risk is widely accepted to consist of a combination of probabilities and consequences. However, further clarity is required. Adapting Hrudey's[68] elaboration, we consider the notion of risk to be a prediction or expectation that involves:

- an agent with the potential to cause either harm and/or benefit (*e.g.* a chemical contaminant, or an investment opportunity);
- uncertainty of occurrence and outcomes (expressed by the probability or likelihood of occurrence);
- consequences (the possible outcomes);
- a specified time frame.

The exploration of these facets provides us with an analysis of risk (note that the authors consider the terms risk assessment and risk analysis to be interchangeable). Risk is inextricably linked to uncertainty. Thus uncertainty analysis plays a prominent role in many risk analysis strategies. Finally, and in a distinct business context, we consider risk management as the sum of the constituent sets of socio-technical decisions and actions taken by staff to optimise their organisation's exposure to risk.

Risk analysis plays a role alongside other decision tools for risk management.[121] Detailed risk analysis is not a prerequisite for effective risk management. In many industries there are accepted standards of performance and codes of practice (*e.g.* engineering standards; accepted best practice; Figure 1) that, if adhered to, provide high degrees of control. These are applied in familiar and well-characterised situations where uncertainties and system vulnerabilities are well understood. However, complex, uncertain and novel systems, that 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, thereby allowing management measures for the reduction of unacceptable risks to be targeted for greatest effect.[121] This principle extends beyond the operation of technical systems to embrace all aspects of managing a business. This said, risk analysis is, in many respects, a practitioner-driven discipline. Its application within water utilities has its roots firmly in the protection of public health from pathogens afforded by the multiple barrier approach to raw water treatment. Whilst the extension of risk analysis to asset management, water supply security and catchment (watershed) management is clearly evident, these applications and the use of risk-based techniques for optimising treatment plant performance, on-site energy use, maintenance programmes and compliance monitoring regimes can inadvertently but easily detract from and confuse the principal purpose of the water supply industry – to provide wholesome, affordable and safe drinking water that has the trust of customers. In all these applications this goal must remain paramount.

C. The risk hierarchy

The organisational hierarchy that exists even within ‘flat’ organisations requires that risks are actively managed at the strategic, programme and operational levels of an organisation (Figure 2). Typically, there are split accountabilities for these risks such that the chief financial officer / financial director and Board have overall responsibility, supported by an internal audit or control function for the management of strategic risks; executive and senior management address programme level risks (*e.g.* asset management, maintenance planning); and operational (*e.g.* site) managers bear responsibility for operational risks (*e.g.* treatment plant performance).[121] A range of strategies exist for assessing and managing these risks in a business context. The focus in this review is sector-specific, addressing ‘process’ risk analysis (*i.e.* risks at the operational and programme level), but in establishing a business-wide context for this activity we also draw upon the experiences of organisations assessing risk at the strategic level.

2. STRATEGIC RISK ANALYSIS

Within an overarching context of public health protection and the maintenance of process reliability, utility managers are increasingly concerned with managing the risks inherent to corporate level decision-making. Critical issues include decisions on outsourcing asset maintenance, billing and monitoring, the management of change, staff retention, the long-term viability of investment decisions, and the management of external interfaces with regulators and ‘competing’ utilities. Risk analysis tools are available to inform decisions on these issues (Table 1).

A. Regulatory risk

Throughout the 20th Century, the central role of water quality to the protection and preservation of public health encouraged governments to manage utilities within the public sector.[138] Regulation was historically self-imposed and limited in scope, and, by extension, posed relatively low risk to municipalities and utilities (in terms of both the likelihood of non-compliance and the associated penalties). In contrast, more recent (since the 1980s) regulatory pressures and drives to impose market discipline on the sector, whether directly (privatisation) or by proxy (*e.g.* corporitisation or required self-sufficiency), have externalised and broadened the role of regulatory scrutiny and intervention. Here our discussion is largely restricted to economic regulation.

A concept of regulatory risk is difficult to grasp. Parker[114,115] contends that it arises from the nature of the regulatory rules and practices, with rules determining the extent to which interventions are discretionary, and practices relating to the interpretation the regulators and others (particularly government) place on the rules. Kilpatrick and Lapsey[75] consider regulatory risk as the uncertain impact of regulatory decisions on regulated companies. Regulatory risk may best be considered as a combination of the above interpretations, encompassing both the uncertainty of the decision-making process and of its impact on utilities.

The core issues of regulatory risk are: regulatory independence; regulatory discretion; transparency and accountability. Independence is critical to minimising the risk of political interference in a regulatory regime. For example, in England and Wales, the economic regulator (the Office of Water Services; Ofwat), acting in the public interest, is vested with a high degree of autonomy from central government, ensuring that the regulatory process is not subject to direct political interference. In contrast, in South Australia (SA), the state government directly controls the tariff setting process, and as the dividend from SA Water is a significant contributor to the state budget, there is the danger that political considerations, as well as commercial ones, might be perceived to influence regulatory pricing.[7]

Regulatory discretion refers to the freedom afforded to regulators to interpret the importance of set duties and objectives and to determine how best to accomplish them.[114,75] In the UK, Ofwat's Director General is free to identify and change the importance attached to set objectives within the regulatory system, within broadly defined constraints.[114] Arguably, the greater the discretion afforded to the regulator, the greater the uncertainty related to future regulatory decisions. Ofwat's regulatory practices are characterised by high levels of transparency and accountability. In practice, utilities are fully engaged in regulatory decision-making, with avenues for consultation and appeal established should companies wish to challenge the outcome. Similarly, the New Jersey Board of Public Utilities, which regulates all investor-owned utilities in the State, publishes reports on its activities and is transparent and accountable in its decisions and processes.[7] These arrangements compare to the German system. Water and sewerage in Germany is the responsibility of the municipalities and the municipalities regulate and manage the water supply based on European, national, state and municipal legislation. Though many are satisfied with these relationships, there has been criticism in a recent report,[7] where regulatory decisions were viewed as being taken in a closed fashion with little clear accountability.

The nature of a regulatory system (*i.e.* its objectives and the systems in place for their achievement) represents a core strategic risk for water utilities. For example, in many developing countries, regulatory scrutiny is largely confined to ensuring a safe, secure water supply,[7] which, whilst introducing inherent operational risks, does not invoke strategic uncertainty. In contrast, main goal of Ofwat is to facilitate competition within the sector, an objective that introduces utilities to a range of hitherto unknown risks.

Quantitative treatments of regulatory risk within the literature are restricted to *ex-post* analyses of the relationship between utility share price volatility and the regulatory process. Buckland and Fraser[19] modelled variations in the systemic (market) risk, using a variable β (which measures the variability in returns of a stock relative to the variability of the broader market), of UK water utilities over time, examining the extent to which observed variations were associated with the regulatory process. A key finding was the surge in the market's assessment of the systemic risk to the industry accompanying the 'surprise' result of the 1992 general election. The authors' analysis illustrates the influence of politics in even the most independent of regulatory systems. Similarly, Morana and Sawkins[98] modelled the London stock market's response to the 1994 'periodic review' of water price setting in the England and Wales utility sector, finding a significant reduction in share price volatility, which they postulated to be a reflection of shareholder confidence in the credibility and sustainability of the settlement.

Ideally, for the active management of regulatory risk, analyses should extend to *ex-ante* treatments of risk. This is of particular relevance to the modern water utility sector, where widespread structural reforms are requiring utilities to operate under rapidly evolving regulatory systems – creating unprecedented uncertainty. In such a market, there has been no historical evolution and the participants, including the regulatory institutions, have a limited understanding of how it will operate in the short term and evolve in the future.[78] In such situations, analytical models may offer value in alerting utilities to unintended consequences of their actions that may trigger the regulator into reaction.[78] Larsen and Bunn[78] argue that system dynamics, which incorporates systems thinking into simulation modelling, is conducive to the dynamic, uncertain and subjective nature of assumptions inherent to strategic analysis. To illustrate, Bunn *et al.*[20] developed a system dynamics model to simulate regulatory problems in the restructured UK gas and electricity markets. Following problem definition and hypothesis formulation, the authors constructed a simulation model describing the main feedbacks involved in the exercise of 'latent' market power. Their analysis explored the relationship between corporate strategies designed to exercise this power and the risk of regulatory scrutiny. The authors concluded that market mechanisms were open to exploitation. Such analysis, and assessments of system sensitivity, could provide utility managers with *a priori* insights into opportunities for exploiting market 'imperfections', thus aiding the development of corporate strategies.

B. Competition risks

Comparative competition

On account of the water industry's inherent monopolistic nature, many governments and their regulators have sought to expand the role of sectoral competition. None more prominently perhaps than in the UK, where the concept of comparative competition underpins the regulatory regime.[137,135] The theory of comparative, or 'yardstick competition' may be traced to the work of Shleifer,[143] who proposed a regime in which the price (or financial rewards) received by a regulated firm depends not on its costs (as in traditional 'cost-of-service' or 'rate-of-return' regulation), but rather on the costs of 'identical' firms operating within the same sector. Shleifer reasoned that by breaking the dependence between the price a firm received and its own costs, and ensuring that the rewards for a given firm depended on its standing *vis-à-vis* a 'shadow firm' (a weighted average of other firms operating within the sector – an idealised benchmark), each firm would be forced to 'compete' with its shadow, providing incentives for cost efficiency (widely perceived as lacking from rate of return regulation). In practice, the inherent risks of this 'competition by proxy' pale in comparison to those found in fully liberalised markets because market share is not directly threatened.

Techniques for evaluating the 'explicit' risks posed by competitors have been well developed in the business and economic literature. A notable example is competitor analysis, with its potential to reduce the uncertainty of the price review process (as price setting is linked to competitor performance). Its application is helped by the tendency for regulatory bodies to disclose company performance data in the interests of transparency. In addition to reducing uncertainty, competitor analysis represents a strategic tool which assists managers in: evaluating competitors' strengths and weaknesses; identifying sources of competitive advantage; and assessing the implications of competitors' strategies on both the sector and their own utility.[38,133]

Capital market competition

As Cowan[27] contends, competition in the capital market can be thought of as a private-sector version of yardstick regulation, in that it derives from the ability of investors to make comparisons between different companies in the same sector. Littlechild,[85] in his report to the UK Department of the Environment on the prospects for water privatisation, emphasised that this would be an important incentive mechanism for utilities, as inefficient firms would be reflected in their share price and be vulnerable to take-over, in addition to facing higher costs of capital. Although Ofwat's restrictions on mergers within the UK water sector, in the interests of maintaining sufficient comparators, act as a constraint on capital market competition,[27] the growing internationalisation of the industry increases the risk of 'external' mergers, whilst firms looking to diversify remain a threat to existing utilities.

Furthermore, the quality and quantity of comparative information available under the 'yardstick' system assists predators in identifying and assessing potential take-over targets.[136] Singh and Harianto,[145] in reviewing the acquisition literature, surmised that profitability, size, leverage, and dividends were negatively correlated with the risk of being acquired. In contrast, profitability and liquidity were positively correlated with the probability of a firm acquiring, with leverage and dividends negatively so. In light of this information, the dynamic risk of take-over can be tracked both in real-time (*e.g.* with respect to the transfer of, for example, more than 5% of firm stocks to a potential acquirer and, in the US, the filing of 13D statements indicating investor intent) and pro-actively (by 'screening' the external environment for trends and potential hostile bodies). Of further interest to corporate strategists, recent research by Dickerson *et al.*[35] suggests that acquisition can be used as a strategy to reduce the risk of take-over. The researchers concluded this strategy allows firms to grow quickly, thus protecting them from subsequent take-over. For utilities considering expansion or diversification strategies, take-over represents not just a threat but also an opportunity.

Competition for the market

Another means of fostering competition is to encourage the private sector (perhaps along with the incumbent public utility) to bid competitively for a concession, lease, tender, or management contract.[27] The two key vehicles for doing so are franchising and, more conservatively, contracting out (not involving the transfer of assets). Numerous variants of these processes are adopted internationally, including: build, operate and transfer (BOT) arrangements; finance, operate and own (concession); and operate and provide working capital (*affermage*). The inherent complexity of many of these arrangements, the generally low equity in the project vehicle,[55] and the often significant investment obligations required of the sponsor, create a pressing need for comprehensive risk assessment.

The project and financial risks associated with public-private partnerships have been reviewed by Grimsey and Lewis.[55] Using the financing of Stirling Water, a Scottish design-build-operate contractor as an illustrative example, they discuss the complexity of the contractual arrangements within such partnerships and use a quantitative analysis of returns on investment to characterise the robustness of cash flows from each of the senior lenders to this joint public-private venture. From the procurer's perspective, project risks (*e.g.* delays and claims) are valued and incorporated within the NPV calculation, whilst the impact of financial risks (inflation and interest rate changes) are evaluated through sensitivity analysis. From the sponsor's perspective, risk analysis centres on simulating the effect of the underlying variables (*e.g.* operating performance) upon the equity return. Ranasinghe[128] uses water supply projects in Sri Lanka to outline a methodology based on financial risk analysis that a government or public utility can use to assess the viability of private sector participation in new infrastructure projects. The author links a commercially available simulation package to the financial model to analyse the uncertainty associated with the underlying variables (*e.g.* escalation in cost).

Product market competition

The traditional approach to introducing direct product market competition into utility services has been to separate the monopolistic component of the industry and regulate it, and to encourage competition in all other areas, *e.g.* the UK model of separating the gas, electricity and railway networks (monopolistic) from the supply of services over the network.[27] This so-called 'vertical disaggregation', although promoted by the World Bank,[172] has not been widely adopted in the water sector, the implicit assumption being that the industry is naturally monopolistic.[27,138] The UK has led the way in adopting alternative approaches to facilitate product market competition. This can be traced back to the 1991 Water Industry Act, which introduced the concept of 'Inset' appointments, whereby a utility can apply for an appointment to provide water to a 'large' customer located within the statutory area of an existing company, usually by seeking a bulk supply from the incumbent.[65] Sawkins[136] reports that the first Inset appointment was granted in May 1997, when Anglian replaced Essex and Suffolk Water (ESW) as the supplier to Buxted Chickens Ltd. Company licences were altered and a new pipe constructed linking the site with an Anglian water main.

In practice, various restrictions, recently eased, have meant that this form of competition has been slow to develop.[136] Similarly, although the 1992 Competition and Service Act allows for cross-border competition, the costs are prohibitive in the majority of cases. Perhaps the most significant recent development has been the introduction of the 1998 Competition Act, which created the possibility for common carriage agreements, or network sharing, in the water industry. Here, the shared use of an incumbent's infrastructure by a third party enables the latter to provide services within the incumbent's area. To aid this, Ofwat now requires that all water utilities publish 'Access Codes' that set out their terms and conditions for common carriage, and has published guidance on this procedure.[110] Hern[65] reports that under the Act, utilities risk infringement if they refuse access to any parts of their infrastructure deemed 'essential' without objective justification, or if their access terms are considered unreasonable. Although no successful applications for common carriage have resulted to date, the threat alone acts as a catalyst for performance improvements.

The authors were unable to uncover literature quantitatively addressing the risks of product market competition within the water utility sector, a reflection of its nascent development and descriptive nature. It seems appropriate here, however, to introduce an oft-neglected truism: quantitative risk analysis is not a prerequisite of effective risk management. This is apt in addressing the threats introduced by product-market competition, where competitor identification and analysis, in concert with a critical appraisal of self-performance and room for improvement, often provide an appropriate foundation for minimising competitive threats. In contrast, harnessing the opportunities presented by product-market competition requires more detailed analysis, and in the absence of a relevant body of literature, the authors suggest treating what are effectively, at least in the UK model, potential acquisitions of company operations in the manner of strategic investment decisions.

C. Business process re-engineering risks

Our discussion thus far has focused on the strategic approaches to risk management within the sector. The pressures described are having important impacts on the performance of the water sector. Structural changes to utility markets, an increasingly demanding political and consumer environment, and more stringent regulation are requiring utilities to improve financial and operational efficiencies. As Westerhoff[166] notes, water utilities are responding by rethinking their operations, finding new ways to address problems, and revamping traditional business models – in other words, re-engineering. According to Clemons,[23] major business process re-engineering (BPR) initiatives – which range from the redesign of existing processes for efficiency improvements, to the development of novel processes in support of a new corporate vision – require the commitment of substantial resources and often constitute a lasting legacy. If we define the risk of a project as the deviation in results from the established goals, then there is substantial empirical evidence marking BPR as a high risk endeavour. Many, if not most re-engineering efforts ultimately 'fail' (see Crowe *et al;*[28] Remenyi and Heafield[130]). Of particular relevance is the work of Dean *et al.*,[31] whose analysis of change programmes undertaken in the UK water industry suggests that re-engineering efforts, whilst often effective, produce highly variable outcomes. On account of this, project risk analysis should be an integral part of any re-engineering effort.

Clemons[23] considers the core determinants of the risk profiles associated with large scale BPR efforts to be: (a) functionality risk – the risk of making inadequate or incorrect changes to systems or processes; and (b) political risk – the risk that the organisation will not complete the project, either because of significant internal resistance to the proposed changes or due to a more gradual loss of will. Clemons promotes scenario planning – a strategic planning tool that embraces uncertainty – as a means for assessing and subsequently managing the risks associated with re-engineering efforts. Rather than determining a single 'correct' view of the future with its implicit single response, scenario planning acknowledges the key sources of uncertainty and incorporates these in developing a range of future scenarios and strategic responses for exploration. Clemons argues that its use is suited to the context of re-engineering efforts as it encourages the critical examination of potential futures and strategies, reduces functionality risk and helps ensure the need for change is internally addressed and accepted, thus reducing political risk. Scenario planning has been embraced by the majority of UK water utilities.[120] A 2001 study[120] explicitly linked the tool's use with improved financial performance on the part of utilities, although notably the authors suggest that scenario planning may implicitly encourage firms to focus on financial returns at the expense of customer service levels.

Recent work by Crowe *et al.*[28] has led to the development of a semi-quantitative tool for estimating the 'risk of failure' of companies about to undertake re-engineering efforts. The tool, developed through a survey of BRP-experienced organisations, is based on measures of the core success (*e.g.* egalitarian leadership; collaborative working environment; top management commitment; and change management systems) and failure (middle management fear of losing authority; fear of job loss; scepticism; discomfort of new working environment) factors of implementing change. Raw data is extracted by questionnaire (*e.g.* ''do managers usually share vision and information with their subordinates'' is used to mine information on the general leadership style), and refined *via* fuzzy mathematics. Crowe *et al.*'s model is intended to provide companies with an estimate of the likelihood of success or failure of proposed efforts prior to committing resources and to improve management's *a priori* insights into the potential outcomes of re-engineering. Similarly, Remenyi and Heafield[130] outline a methodology for evaluating the key risk issues relating to re-engineering efforts. The methodology centres on a risk matrix (Table 2) that groups a variety of potential BPR risks under the categories of business risk, financial risk, corporate structure, corporate culture, technology and human. Organisations identify, weight and rank what they consider to be the ten factors most pertinent to their proposed re-engineering efforts. The framework represents a succinct method for appraising and comparing the risks associated with BPR strategies. A perceived failure of much of the BPR literature is the limited emphasis placed on the risks introduced by adopting new technologies, an aspect critical to many re-engineering efforts.

Technological risk

Clark *et al.*[22] report that technology adoption is increasingly becoming a concern of strategic planners and policy makers within the water industry. The introduction of novel technology poses risks due to the inherent difficulty of preparing accurate estimates of the costs, performance and system-wide effects of new components and processes; and the long development cycles required for changes in regulations and consumer demands.[26] This has led many researchers to advocate the incorporation of risk management techniques for the effective implementation of new technologies (*e.g.* Colmer *et al.*[26]; Fitzpatrick[47]). This is highly relevant to the water sector, where, as Maxwell[91] notes, the advance of modern technology is illustrated by such trends as the replacement of traditional methods of water treatment with advanced oxidation and other novel physical and mechanical technologies; the broad use of membrane systems to desalinise seawater for human consumption; and the increasingly widespread use of recycling systems and technologies.

McGaughey *et al.*[92] describe a framework for viewing and comparing the risks inherent in the adoption of new technologies, specifically relating to IT. Initially, proposed projects are assessed, through value chain analysis, in terms of their potential positive and negative outcomes – these are then mapped onto a ‘speculative’ risk matrix to provide management with an initial screening of alternatives. In later stages of planning, specific threats and opportunities associated with the project are identified and ranked, by likelihood and consequence, for prioritisation purposes. Hartmann and Lakatos[62] drew on case studies monitoring the pace and quality of technology delivery within two product development programmes and generated an algorithm characterising the risk of each technology problem (Figure 3). The authors suggest that its use can aid in the refinement of technology development and implementation plans following risk identification. Hartmann and Lakatos define technology problems as those arising:

- from the application of a new process, material or subsystem before fully understanding parameters that control cost, latitudes and failure modes;
- when a previously commercialised technology is extended outside the known domains of the pertinent design rules; and
- from unexpected interactions arising from a new or unique combination of known subsystems of components.

Of further interest, the authors[62] developed a checklist to help technology and product developers audit technology progress, which we have adapted to serve as a tool for minimising the risk associated with introducing new technologies (*i.e.* beyond the development stage):

- Implementation goals confirmed
    - validate business assumptions and technology specifications for cost, performance and reliability
- Technology mastery demonstrated
    - critical parameters identified

  - failure modes identified
  - set risk tolerances relating to the critical parameters so as to avoid failure modes and deliver the required performance
  - performance demonstrated using a combination of hardware and mathematical simulation
  - manufacturing feasibility established
- System specifications re-established
  - system and subsystem financial and operational performance targets are re-established and re-assessed based on technology specifications
- Additional assessments completed
  - supporting assessments completed, such as safety and environmental impact study
- Contingency planning
  - develop contingency plans should critical risks materialise in spite of control procedures in place

Wildemann[170] describes a framework for guiding technology planning. Risk profiles are constructed displaying the relative importance of identified threats and opportunities, and thus the inherent 'attractiveness' of the technology, complemented by a strengths-weaknesses analysis that estimates the ability of the firm to successfully implement the technology. The author's aim was to provide an analytical basis upon which strategies may be developed for the introduction of new technologies.

D. Outsourcing risks

Our discussion of risk analysis strategies moves to one of the key features of the international water business – outsourcing. A significant feature of water utility management in recent years has been the growth in outsourcing, defined as the transfer of previously in house activities to a third party. Outsourcing allows utilities to focus on critical functions (core business), access economies of scale, minimise investment, increase quality of service, transfer risk, and reduce administrative burdens including regulatory compliance.[116,42,36] Common candidates for outsourcing include information technology, maintenance, distribution, manufacturing, and customer care and billing.[116] A widely held view is that the potential for outsourcing is far from exhausted. A holistic approach to risk being promoted in this review requires that in addition to the traditional review of legal and regulatory responsibilities following contractual agreement, the process of outsourcing should fall within the remit of corporate risk management. That is, outsourcing alters the boundaries of the firm, and the scope of risk analysis and risk management programmes should be extended to reflect this.

Risks are inherent in the process of outsourcing, from the decision to outsource, to the management of agreed contracts. Received wisdom has been that companies should focus on ‘core competencies’ and outsource the remaining parts of the business (although the validity of this distinction has been questioned of late, notably by Heikkilä and Cordon[63]). The core risks discussed in the literature relating to decisions over what to outsource and who to outsource to include: the loss of key capabilities, developing dependence on the vendor, and risks linked to the service provider’s deficient capabilities. Each decision to outsource must be carefully assessed from a risks and benefits perspective.[36] Decision-making frameworks are available for this purpose. Lonsdale's[86] decision tree for outsourcing provides a framework for evaluating what constitutes an organisation's core competencies, and analysing market opportunities for outsourcing the remaining parts of the business. The framework seeks to ensure managers retain those resources responsible for competitive advantage, avoid monopolistic or oligopolistic supply markets, and effectively manage the risk of post-contractual dependency. A similar model, although focussed at the policy level, is provided by Quélin and Duhamel.[125] Of course, successful outsourcing further depends on managing supply risks, defined as the transpiration of failures with in-bound goods and services.[176] Core categories of supply risk discussed in the literature include: the financial stability of the supplier; cost fluctuations; capacity constraints of the market and specific suppliers; variations in quality; the ability of the supplier to adapt to required changes in design or technology; and natural disasters. Two diametrically opposed approaches to managing supply risk are the active management of risk interfaces with the intention of reducing vendor failures,[176] and the construction of barriers (*e.g.* safety stock, multiple sources) to buffer the effects of inherent uncertainties.[46,104] Tools in support of the former approach include qualitative assessments of the financial stability of potential suppliers; formal models for the demonstration of supplier capacity performance; 'what-if' scenario planning; and statistical process control to detect deviations from desired quality.[176]

E. Employee retention

Retaining valued employees has long been an implicit component of good utility management. The recent emphasis on people as *the* resource, along with the external realities of an increasingly dynamic and pressurised labour market, have led to the sector embracing employee retention as a critical risk issue – particularly in the technically specialised areas of the water business. This focus is exemplified in recent sectoral research initiatives (*e.g.* American Water Works Association Research Foundation (AwwaRF) project #2850 'Succession planning for a vital workforce in the information age'), and a recent (2001) policy statement from AWWA calling on utilities to establish formal employee retention plans.

Maintaining employee retention, thus managing the risk of losing organisation capacity, begins at the recruitment stage (*e.g.* Barney,[9] McNally,[94] Denton[33]). Empirical evidence suggests that ensuring a 'cultural match' between employees and the organisation plays a critical role in reducing staff turnover.[141] The tool applied by Sheridan[141] to 'measure' culture (beliefs and values) was the Organisational Culture Profile (OCP) instrument developed by O'Reilly *et al.*[109] The OCP assesses candidates by encouraging them to sort value statements on: norms regarding the completion of work tasks; norms regarding interpersonal relationships; and norms regarding individual actions. Utilising the OCP as a part of the recruitment process could provide utilities with a proactive tool for minimising staff turnover, by filtering those most likely to leave the organisation early from the selection process. Additionally, it enables the risk-based targeting of retention efforts, for example by focusing efforts on employees hired regardless of 'cultural misfit'.

This philosophy is mirrored in the work of McNally,[94] who promotes the use of more traditional tools such as personality assessments at the recruitment stage to ensure 'good fits' of personality and work ethic. As Denton[33] notes, whilst *''good recruitment is certainly important, it is what happens to recruits after joining an organisation that determines whether a company will retain them.''* In relation to this, McNally[94] encourages organisations to develop 'early warning systems' to identify employees at risk of leaving. Such a system requires the collection and analysis of retention data by subgroup (*e.g.* ethnicity, gender, function, organisational level, *etc.*) to facilitate identification of 'at-risk' groups. Following identification, tools such as employee surveys, employee reviews, mentor or manager feedback, local economic trends, head-hunter activity, and, crucially, the exit interview may be used to determine factors driving high rates of defection.[94] Adherence to such a system would provide utilities with comprehensive data on who is leaving and why, providing the foundation for developing effective, tailored retention strategies. A recurrent theme of the retention literature is that incentives (*e.g.* salaries and benefits) alone are not enough for achieving high levels of retention, the contention being that retention is related more closely to employee development and intrinsic benefits such as working relationships, job satisfaction and a sense of empowerment (*e.g.* Hagevik;[60] McNally;[94] Thompson;[158] Denton[33]). Accordingly, utilities may consider undertaking a gap analysis of their employee development schemes (interestingly, Brueck[18] reports that water utilities spend as little as 1% or less of their labour budget on nonmandatory employee training) and benefit programmes before remedying deficiencies in order to minimise turnover rates. An alternative approach to identifying the level of retention risk is to undertake an informal risk assessment[4] which is essentially a checklist addressing the core issues influencing turnover (*e.g.* employee-manager relationships, communication, job satisfaction, *etc.*).

The negative consequences of employee turnover are clearly emphasised throughout the literature, leading to the implicit assumption that organisations should 'pull out all the stops' to minimise defection rates. However, as Sigler[144] and Mowday[100] contend, the costs of reducing retention may, in some cases, exceed the benefits to be derived. It is thus incumbent on organisations to critically analyse the costs and benefits of implementing retention strategies; the cost-benefit analysis approach offers a promising framework for this purpose.

F. Assessing investment risks

Behind each strategic investment an organisation considers lies some calculation of the move's worth.[87] Following Rothstein and Kiyosaki,[134] we define strategic investments as those resource allocations that will yield substantial advances toward the achievement of a utility's strategic goals. Whether considering a joint venture, acquisition, or a major extension of an existing facility, how the utility estimates value is a critical determinant of how it allocates its resources, which is in turn a key driver of its overall performance.[87] Valuation methodologies range from the formal (comprising an appraisal model and a supporting theory) to the informal (based on heuristics).[87] However, since the 1970s there has been a trend towards applying valuation methods that are more formal, explicit, and institutionalised.[87] The most widely adopted framework is the Net Present Value (NPV) model, which estimates value by capitalising (discounting) future streams of cash flow that the investor expects to receive from an asset. The capitalisation rate is the minimum expected rate of return needed to induce an investor to acquire. Capitalisation is comprised of two components, the risk-free rate of return (accounting for the time value of money) and the risk premium (the additional compensation demanded by investors for assuming risk). Although issues have been raised regarding the applicability of conventional appraisal methodologies to the water industry, specifically relating to the long lifespans of many capital projects and the fact that they often do not generate revenues in the traditional sense (*e.g.* Tebbutt *et al.*[155]), they remain favoured by academics and industrialists. Our subsequent discussion focuses on three distinct investment problems: valuation of assets-in-place; valuation of ‘opportunities’; and the valuation of joint ventures.

Assets-in-place

The most basic valuation problem is valuing assets-in-place, *i.e.* the valuation of an ongoing business or some part of one, for the purposes of informing decisions ranging from a change in suppliers to an acquisition.[87] It is for such situations that Discounted Cash Flow (DCF) techniques (methodologies for determining the capitalisation rate) are suited.[87] In brief, the established DCF methodologies include the weighted-average cost of capital (WACC),[97] the capital asset pricing model (CAPM)[140] and the adjusted present value (APV).[102] The WACC, which establishes the risk premium on the basis of the ‘cost of capital’ financing the investment, remains the most commonly practised approach,[87] though is increasingly criticised in academic circles (*e.g.* Luehrman;[87] Gregory[54]). The fundamental idea behind CAPM is to use β, a measure of systemic (market) risk, to adjust cash flows. In contrast, APV seeks to unbundle the various components of value (*i.e.* cash flows), analyse them separately, and then add up the present values. For a fuller discussion of these and other DCF techniques see *e.g.* Modigliani and Miller,[97] Sharpe,[140] Myers,[102] Berry *et al.*,[12] Gregory,[54] Luehrman,[87] and Ye and Tiong.[173]

Regardless of the individual strengths and limitations of the above models, a common deficiency is that there is no indication of the confidence level on the determined capitalisation rates.[173] Following on from Hertz,[66] who highlighted the misleading nature of single-point estimates in investment analysis, most researchers advocate the appraisal of investments within a non-deterministic framework; the principle being that investment forecasts are, by definition, uncertain. Reflecting this uncertainty in model outputs lends some assurance to the decision-makers that the available information has been used with maximum efficiency.[66] This is reflected in Guidelines published (1999) by the Asian Development Bank[6] on the application of financial evaluation methodologies to water supply projects. Risk analysis, in the form of sensitivity analysis and stochastic simulation, is promoted as a means to examine the influence of changes in key underlying variables on forecast cash flows, and the probability that project NPV will fall below zero. Incorporating these principles, Barriex *et al.*[10] describe the application of the NPV framework to the proposed restructuring, privatisation and optimisation of water utility operations in Panama. The focus of their study is on the proposed rehabilitation of systems supplying water to Arraijan, Chorrera, Colon and Panama City, a 'holistic' programme entailing the upgrading of commercial, technical and operational aspects. Through stochastic simulation and sensitivity analysis of forecast financial returns, the authors confirmed the project's robustness from a financial standpoint, determining a 'zero' probability of negative NPV.

Thomas[157] uses an illustrative example to examine the role of CAPM in adjusting for the risk inherent to acquisition / diversification appraisals (using internal rate of return (IRR), an appraisal framework similar to NPV). Accounting for the unique nature of acquisition / diversification appraisals, the author provides a methodology for integrating expected financial and operational synergies (*e.g.* derived from financial and operating economies, or the pooling of functional areas) within the analysis. However, through applying a risk premium to projected cash flows (which by definition accounts for the increased returns investors demand for variable cash flows) and undertaking simulation of the variables influencing future cash flows (thus explicitly modelling the variability of returns), Thomas[157] is effectively 'double counting' for risk, introducing a bias against investment decisions. This criticism is supported in the work of Burchett and Tummala,[21] who apply Monte Carlo simulation to an NPV based appraisal of an infrastructure capital investment decision. These researchers argue that applying specific probability distributions to the relevant variables captures all potential risks relating to the investment, thus negating the requirement for incorporating a risk premium as part of the capitalisation rate.

Although it is widely accepted that a probabilistic approach to investment risk analysis is desirable, problems exist. As Songer *et al.*[148] assert, the failure to identify all significant risks (*i.e.* to apply appropriate probability distributions to all relevant underlying variables) quickly undermines model validity and output. A further pitfall is identified by Mosca *et al.*,[99] who in applying simulation methodologies to a proposed plant investment, found that the choice of frequency distribution chosen (often arbitrarily) for the independent variables can have a marked effect on the process outcome. These are important observations in that they highlight the biases inherent to all risk models, reminding of us of the need to use risk analysis output diagnostically rather than to over-invest belief in quantitative risk estimates.

In financial circles, recent times have seen an increasing adoption of tools that can perform economic evaluation and modelling on the combined entity of investments (portfolio) as well as for each individual project. This trend extends beyond the financial sphere, as is illustrated in the work of Rothstein and Kiyosaki,[134] who describe the application of portfolio management theory to water utility investment planning. The philosophy of their approach is to create a portfolio representing a balanced array of investments that mitigate uncertainties and that are likely to realise potential returns. Of particular interest is their use of multi-attribute analysis, which allows the risk-based prioritisation of monetary and non-monetary investment decisions within a single analytical framework.

Opportunities

It is relevant here to further discuss the work of Luerhman,[87] who categorises a second type of valuation problem – the valuation of opportunities (*i.e.* possible future operations) – as distinct from the valuation of operations (assets-in-place). The distinction is that with the former, the decision to invest may be deferred. In opportunity valuation, risk matters in two ways: the risk of the investment, and the risk that circumstances will change before a decision has to be made – such contingencies are not well handled by the traditional DCF approach.[87] Luerhman[87] states that a common approach in the valuation of opportunities is simply not to value them formally until they mature to the point where a decision can no longer be deferred, where they can then be valued, in effect, as assets-in-place. Critics have decried this practice, on the premise that it leads companies to undervalue the future and hence underinvest.[87] In response, Luerhman[87] discusses the potential of 'option-pricing theory'[14] - an analytical strategy that allows managers to handle the contingencies created by the time-dependant nature of opportunity valuation - as a supplement, not a replacement, for the valuation method for in place assets.

Joint-ventures

A further category of investment decisions is found where firms participate in joint ventures, partnerships, or strategic alliances. This takes on particular resonance in the water industry, where recent years have seen a proliferation in public / private partnerships. In such cases, where ownership is shared with other parties, managers need to understand both the value of the venture as a whole *and* the value of their company's interest in it.[87]

The investment risks associated with public-private partnerships have been reviewed by Grimsey and Lewis.[55] Using the financing of Stirling Water, a Scottish design-build-operate contractor as an illustrative example, apply quantitative analysis of returns on investment from the perspective of the private (sponsor) and public (procurer) sector entities.

A common observation of the risk management literature is an all too obvious gap between theory and practice. Much of the highly theorized investment literature does not reflect standard industry practice, particularly that relating to the application of complex methodologies such as simulation and scenario analysis. The discrepancy is explained, in part, in that such techniques do not fit naturally into most companies' skill sets or capital-budgeting systems.[87] Despite this, there is a dearth of literature focussing on the practicalities of integrating such tools deep within company structures. To address this issue and as part of the research that has informed this review, the authors will be undertaking a benchmarking of risk management capabilities within the international water utility sector.

3. PROGRAMME RISK ANALYSIS

We turn to a more familiar discussion of the application of risk analysis to the water utility sector. The revised WHO guidelines[167] are promoting the implementation of water safety plans for water quality management from catchment management, through process control, distribution and on to the tap.[160] Application of risk analysis to these aspects of the water 'supply chain' extends to programmes of work as well as individual plant operations. A discussion of the latter, operational risk analysis follows, but here we are concerned with the analysis of risks associated with programmes of activity that are ‘rolled-out’ across organisations, such as asset management and maintenance planning. Here, managers are responsible for the implementation of strategies across company functions, multiple sites and geographic regions. They are concerned with: evaluating the risks posed by a similar hazard at a variety of locations (*e.g.* mains bursts, network intrusion – in asset management, for example); the risk-based appraisal of operational strategies and long-term planning in relation to the water supply-demand equilibrium; and the wide variety of risks existing within a catchment or watershed. Table 3 summarises the portfolio of analysis techniques available at the programme level.

A. Asset management

In line with Booth and Rogers,[16] we consider asset management as *‘‘managing infrastructure capital assets to optimise the total cost of owning and operating them while delivering the service levels customers desire.’’* Managing risk in the face of limited resources has long been an implicit component of asset management. Within the UK, pressure from the economic regulator has ensured that the explicit incorporation of risk analysis into asset management programmes has taken on added momentum. Water utilities are expected to:

‘‘demonstrate how the flow of services to customers can be maintained at least cost in terms of both capital maintenance and operating expenditure, recognising the

trade off between cost and risk, whilst ensuring compliance with statutory duties'' (Ofwat letter MD 161, April, 2000).

In addition to regulatory pressures, the global trend towards requiring financial self-sufficiency on the part of public and private utilities has created a climate in which management can no longer seek to 'over-engineer' facilities with the presumption of screening out technical risk. A recent (2004) report[163] to the US Senate cites ``*mounting evidence suggest[ing] that the integrity of the nation's [water] infrastructure is at risk without a concerted effort to improve the management of key assets…and a significant investment in maintaining, rehabilitating and replacing these assets*''. The report goes on to explicitly endorse the role of risk analysis in asset management. More than ever, utilities must now seek to balance spending with risk minimisation. A risk-based approach to asset management requires an integrated, systematic process drawing upon a broad range of methodologies for the identification, analysis and prioritisation of assets-at-risk, from the process to the component level (*e.g.* Lifton and Smeaton;[82] Booth and Rogers[16]).

On a national scale, the US Natural Resources Defence Council (NRDC)[106] recently (2003) reported on the risk to drinking water quality from ageing pipes and process plant across the US with individual city 'rankings' being informed by water quality data, USEPA compliance records and water utility annual reports. Many water companies have in place risk-ranking procedures to evaluate and rank potential risks across a variety of categories, and thus help inform and prioritise risk management procedures.[121] For example, Radovanovic and Marlin[126] describe the risk-based approach to water mains asset management in place at Sydney Water (Australia). Budgetary requirements are estimated through the application of KANEW, a statistically based survival model which aids the calculation of pipe rehabilitation and replacement needs for distribution networks. The identification of specific pipes requiring work is external to the model, with separate approaches for trunk and reticulation mains (the latter generally being run to failure). Critical trunk mains are identified by means of a checklist-aided screening approach, wherein preliminary assessments of failure likelihood and consequence are combined to create an overall risk score. This combined risk score is used to identify critical water mains deemed to require more detailed analysis (*e.g.* condition-based assessments). This methodology allows Sydney Water to identify and prioritise water mains in need of rehabilitation / renewal, and to proactively assess budgetary requirements.

Louisville Water Company (Kentucky) apply their Pipe Evaluation Model, which integrates data such as pipe age and maintenance history, as a tool for prioritising pipe and water mains for rehabilitation and replacement.[163] Utility managers report that this model, in combination with wider asset management practices, has helped reduce the frequency of water mains breaks from 26 to 22.7 per hundred miles and the frequency of joint leaks from 8.2 to 5.6 per hundred miles.[163] Seattle Public Utilities adopt a risk-based approach to asset management, considering likelihood and impact of pipe rupture with reference to such factors as age, material, location and historical cost of repair.[163] Drawing upon this analysis, utility officials were able to delineate their pipe network into areas of critical and non-critical risk, and allocate maintenance and rehabilitation resources accordingly. Through adopting this approach, officials believe that they are using staff resources more efficiently and that, over time, the programme will lead to a reduction in maintenance costs.[163]

Kent *et al.*[73] describe how risk analysis informs the prioritisation of investment strategies for trunk main maintenance at *Dwr Cymru* Welsh Water. The methodology is based on the available records of asset performance, condition and serviceability, which are stored on the company's WAM (Water Asset Management) database.

STRUMAP, a software-based mapping system, allows clustered failures to be considered separately from 'random' bursts, a task performed as the former are considered likely to be representative of underlying susceptibilities. For each location where a cluster is identified, specific failure rates are derived. For random bursts, failure data is separated according to pipe material and diameter, with failure likelihood determined by group. STRUMAP further enables consideration of failure consequences, in terms of the number of properties potentially affected by an event, taking into account service reservoir storage. Failure likelihood and consequence are then combined to derive an overall severity score, which in turn informs the derivation of investment requirements. The National Research Council of Canada are currently developing a prototype Water Mains Renewal Planner (WARP),[127] which is aimed at integrating the most promising breakage analysis models into one discrete decision support tool. At present, WARP consists of three modules: a) analysis of water main breakage patterns; b) short-term operational forecasting; and c) long-term renewal planning. A fourth module is to be added to enable prioritisation of individual water mains for renewal.

Foster *et al.*[50] detail a risk-ranking approach for estimating the relative likelihood of failure of embankment dams by piping. Failure likelihood is assessed by weighting the historical frequency of piping failure with respect to dam zoning, filters, dam age, core soil types, compaction, foundation geology, dam performance, and monitoring and surveillance. The methodology allows the prioritisation of dams-at-risk for more detailed analysis, and is further offered as a check on traditional event-tree methods (see also Seker *et al.*[139]).

Failure modes and effects analysis (FMEA), developed by the US military, is an engineering technique that tabulates failure modes of equipment and their effects on a system[1] (Table 4). The failure mode describes how equipment fails (open, closed, on, off, leaks, *etc.*). The failure effect is determined by the system's response to the equipment failure. When FMEA is extended by a criticality analysis, it is known as failure modes, effects and criticality analysis (FMECA).

Lifton and Smeaton[82] detail how Scottish Water apply source-to-tap FMECA studies across their water supply systems as part of their 'asset management toolkit'. This allows priority risks to be identified and subsequently compared across the utility portfolio (*e.g.* various mains, raw and treated reservoirs, treatment works *etc.*) in order to focus attention on the most serious threats to system performance. Infrastructure investment strategies are further informed by the HYSIM-AQUATOR supply-demand model. Of particular interest is their description of the asset risk and criticality scoring system implemented at Scottish Water. The system is designed to assess the relative 'total business impact' of asset failures across the company by reference to a 'common currency of risk' (one point equates to £1000 of business impact), facilitating a consistent approach to risk scoring across Scottish Water. Additionally, this scoring system guides the prioritisation of reliability studies at the operational level, which further informs asset management strategy.

Given the complexity inherent in describing modes of structural failure and assessing their likelihoods,[53] logic models (visual risk schematics, *e.g.* reliability block diagrams, fault tree analysis (FTA) and event tree analysis (ETA), see Figures 4 and 5) have found application in support of asset management. Parr and Cullen,[117] through examining the applicability of logic modelling techniques to dam failure analysis, illustrate how such an approach can inform the prioritisation of expenditure on monitoring, maintenance and remedial works. Similarly, Gray and Powell[53] promote the use of logic diagrams in aiding the development of risk-based strategies for maintaining asset security. The authors model the interactions leading to failure for each class of aqueduct structure. To this, historic data, or where data is deficient, engineering judgement, are applied in order to derive failure probabilities. A cautionary note is sounded by Latiffe,[79] who contends that risk analysis, specifically logic modelling, is not yet effective in modelling dam failure. The author cites insufficient statistical data on the deficiencies of structural components as the core drawback.

Spatial context of risk

Geographic Information System (GIS) technologies now play a critical role in asset management. At its most basic level, GIS allow utilities to convert data ordinarily displayed on paper maps into one single, easily accessible digital format, representing an excellent method for storing and collating data for future use.[49] The level of detail (*i.e.* the layers of spatial data) contained within such systems varies widely. Kaufman and Wurtz[72] describe the evolution of a GIS for a small utility (Beecher Water District, Michigan). An extensive inventory of asset condition records and failure and maintenance data is collated within the system, supporting the risk-based planning of capital improvement and maintenance works. Pertinently, the system took only three months and less than $3,000 to develop. Similarly, Booth and Rogers[16] illustrate how the implementation of GIS technologies within an asset management decision support system can allow for the visual tracking of infrastructure assets and their associated risk factors.

Although applications of GIS technologies in support of asset management have proven to be powerful risk-tracking, visualisation and communication tools,[16] they rarely utilise the capabilities of GIS to spatially analyse data in the classical sense.[49] Doyle and Grabinski[37] illustrate these capabilities through quantitatively relating Toronto's infrastructure deterioration to spatially variable corrosion risk factors, providing a basis for the identification of network areas most at risk from external corrosion. Such an approach may allow utility managers to better focus rehabilitation efforts through having a more complete understanding of the causative factors behind water main deterioration. Of further interest is the work of Ta,[153] who describes the application of a probability model for burst risk studies of water mains. Contributing factors (*e.g.* pipe number density, pipe age, material and diameter, soil corrosivity, *etc.*) are represented as GIS data layers and correlated with past failure data in order to deduce burst probability scores for each water main. The tool, developed for Thames Water Utilities Ltd. (UK), is not intended to predict the likelihood of pipe bursts, rather to aid utilities in sourcing the origin of an area burst (*i.e.* following a pipe burst in the area, the value of probability evaluated for a particular pipe section would indicate the likelihood that the burst actually occurred at that section).

While GIS represent powerful tools for spatial data analysis, their inherent capabilities for complex and dynamic analysis are limited.[152,43] In contrast, traditional simulation models are powerful tools for complex and dynamic situations, but often lack the intuitive visualisation and spatial-analysis functions that GIS offers.[152,43] Consequently, researchers have sought to couple these systems. Lindley and Buchberger[83] describe the integration of hydraulic modelling within a GIS for the purpose of assessing intrusion susceptibility in distribution systems. The holistic methodology enables the synthesis of multiple risk factors describing the three key (geographically variable) susceptibility conditions of adverse pressure gradient, intrusion pathway, and contaminant source, thus identifying areas susceptible to intrusion (accidental or intended). Susceptible locations are then prioritised for attention by considering how they are hydraulically connected to local sensitive populations. In addition to informing asset management programmes, this framework may also be applied in a reliability context at the design stage. Similarly, Besner *et* *al.*[13] illustrate *via* case study how the coupling of a GIS containing structural, operational and water quality parameters with simulation model EPANET facilitates the identification of key factors responsible for water degradation in the distribution network. Through identifying network areas presenting the greatest risk, this technique can inform the prioritisation of risk management strategies.

B. Catchment management

The concept of catchment (or watershed) management has gained widespread international support, representing a shift from the sole reliance on end-of-pipe treatment technologies for point sources towards the watershed-specific prioritisation of water quality problems and their integrated solution.[48] An outcome of this is that the assessment of hazards to the quality of water resources within a catchment is increasingly subject to formal risk assessment and can be expected as part of routine water safety plans.[160,161,167] In Europe, the DPSIR approach to identifying key hazards within a watershed, by reference to the driving forces (*e.g* population growth), pressures (sewer discharge), state (increased nutrient load), impacts (anthropogenic eutrophication) and policy response (discharge control) is being adopted under the European Water Framework Directive.[70] Here, risk assessments of activities posing a an actual or potential threat to the quality of water bodies in 'river basin districts' are intended to inform and help prioritise a programme of multi-agency action plans targeted at raising the overall ecological status of the watershed within statutory timescales. Given the plethora of potential catchment management issues in any improvement programme, there is a need to prioritise risk management efforts within the watershed by concentrating on those measures that reduce the significant likelihood of severe impacts being realised. Southern Water (UK) adopt a semi-quantitative ranking scheme in screening their groundwater sources for *Cryptosporidium* contamination risk, as described by Boak and Packman.[15] The methodology consists of ranking source waters across ten risk categories (*e.g.* land use) using pre-determined scoring hierarchies (*e.g.* occasional livestock grazing: 2), before combining these category rankings into an overall weighted risk score. Through this approach the utility identifies those sources deemed to be at significant risk of oocyst contamination, and which therefore require continuous monitoring (in line with regulations).

Given the improved capabilities and functionality of modern GIS and their inherent ability to map and analyse data that is spatially variable in nature, many catchment-level ranking methodologies have sought to incorporate their benefits. Various authors [88,146,169,49,111,51] describe the use of map overlay techniques (which essentially combine the attributes of two or more data layers across geographic space) in the identification and mapping of areas critical to catchment water quality. These risk-mapping (essentially spatial risk-ranking) methodologies centre on the analysis of those spatial attributes considered to play a significant role in pollutant transport (*e.g.* geology, rainfall, soil type, agricultural activities *etc.*) according to pre-defined formulae (*e.g.* a weighted runoff-potential index). Their focus may be generic or targeted towards specific hazards (*e.g.* animal feeding operations) or pollutants (*e.g.* through incorporating measures of their leaching potential).

Risk-ranking methods are applied to help target more detailed analysis towards critical risks and to inform the prioritisation of catchment management activities, specifically monitoring programmes. Of course, the potential exists that as the costs of planned monitoring decrease on the one hand, the risks may increase on the other. When designed well, piloted and implemented with feedback, risk-based resourcing strategies (Figure 6) can provide a sound basis for distinguishing greater risks from lesser ones, and for investing resources in risk management that are proportional to the risks posed.[122]

Most critically, however, these risk-based optimisation tools, whether intended to drive monitoring regimes, maintenance schedules or workforce planning, may themselves incur significant risk unless the consequences of resource trade-offs are themselves assessed. Consider the actions of the Saskatchewan Department of Environment and Resource Management (SERM) prior to the North Battleford *cryptosporidiosis* outbreak in April 2001.[121] SERM held legislative responsibility for the Saskatchewan drinking water programme and, partly in response to budget cuts in the mid 1990s, drastically reduced the already limited field inspection and enforcement of municipal utilities. This culminated in SERM proposing to eliminate its drinking water programme altogether, a motion tentatively approved by the Treasury Board in 2000/01 and justified as being ‘risk-based’. The subsequent North Battleford outbreak, infecting between 5800 to 7100 persons in the immediate community plus a large number of visitors from three other provinces, led to a public inquiry into the outbreak and the provincial drinking water regulatory system. Justice Laing[76] concluded in his Inquiry report: “*that the current risk-based model employed by SERM since 1996 is arrived at on the basis of economics, and has nothing to do with how best to safeguard the health of the population, all of whom consume water*”. The example aptly illustrates the inappropriate use of risk analysis as a justification for the removal of processes critical to public health protection. Tensions that arise between those seeking economic efficiencies and preservation of the principal goal of providing safe drinking water are often played out in the conflicting expectations and presumed purposes of risk analysis made by different professionals. The real consequences of stripping away levels of safety, precaution and protection using ‘risk analysis' as a justification can be to render the system as a whole less safe, more precarious and more susceptible to catastrophic failure and so optimisation programmes, maintenance schedules and risk-based monitoring require special scrutiny as to the balance between risk and the full cost of implementing these programmes.

Where more detailed analysis is deemed necessary, a common recourse is to model-based approaches. Water quality and flow / transport models represent core tools for this purpose, due to their combined ability to model the dispersal of pollutants and predict the resultant deterioration of water quality. Aside from the inherent value of fostering an increased understanding of catchment water quality issues, the core benefits of model-based analysis stems from their ability to test management scenarios (through *e.g.* sensitivity and scenario analysis), thus enabling informed decisions on how best to manage the resource. A range of models are available that apply to catchment risk analysis, from micro to landscape scales, from deterministic to stochastic approaches (Table 3).

Common practices of hydrological and water quality modelling have been based mostly on deterministic analysis, producing single point estimates that neglect prediction uncertainty.[2] Determinism has been embraced by many risk analysts, for example, Gündüz *et al.*[56] describe the use of the combined hydrodynamic and water quality model CE-QUAL-W2 in projecting potential water quality degradation patterns under different pollution loads. The tool is intended to aid management in the development of appropriate strategies for the management of water quality. Similarly deterministic approaches to catchment analysis are described by various other researchers (*e.g.* Cole *et al.*[25]). The limitations of determinism in risk analysis, discussed earlier, are particularly relevant in the context of hydrological and water quality modelling, considering the often scarce or incomplete data available.[89] This uncertainty takes on particular importance from the utility standpoint, as their assessments of catchment water quality are performed with regard to set regulatory standards. To illustrate this point, the uncertainties inherent in flow and contaminant transport modelling (from *e.g.* spatial variability, data scarcity, model imperfections) imply that there will always be a risk of exceeding a given standard at some point over space or time following a pollution event, regardless of the estimated single-point (mean) contaminant levels.[2]

An argument can thus be forwarded for the explicit consideration of prediction uncertainties in catchment level risk modelling. There exist two dominant approaches towards this task: stochastic modelling; and deterministic modelling allied with uncertainty analysis of the output. Adopting the former approach, Andersson and Destouni[2] outline the application of stochastic transport modelling to quantify the risk of exceeding regulatory standards for groundwater at any point on the compliance boundary. This quantification is coupled with an analysis of the abatement costs required to attain an 'acceptable' risk level. Halfacree,[61] for example, describes the use of PRAIRIE, an aquatic dispersion modelling tool for assessing chemical pollution risks to water bodies. The main elements are an aquatic dispersion model; hydrological, substance and standards databases; and a tabular / graphical output facility. The model has a deterministic mode used to 'screen out' low risk sites, and a probabilistic mode for more detailed analysis of high risk sites. The output results (*e.g.* frequency versus concentration curves) are compared with pre-determined criteria to inform regulatory actions on risk management from hazardous activities within a sensitive catchment. An advantage of the stochastic approach is that uncertainty is interwoven within the model.[175] However, the solution of stochastic equations is often impractical for complex problems.[81] This explains, in part, the preference for deterministic approaches to water quality / hydrological modelling, creating the subsequent need for external consideration of output uncertainty.

In this context, uncertainty analysis is performed to estimate the probability of obtaining a given output value when uncertainties on input variables and parameters are known.[89] Liou and Yeh[84] outline the use of a groundwater transport model in deriving the risk of contaminant concentration exceeding a maximum acceptable upper limit (*e.g.* regulatory standard). The analytical uncertainty of the predicted contaminant concentration is derived by first-order mean-centred uncertainty analysis, prior to the application of Monte Carlo simulation in order to compute the mean risk and associated confidence interval of exceeding standards. For detailed discussions of the forms of uncertainty in water quality modelling and the techniques for their analysis, see Mailhot and Villeneuve;[89] Portielje *et al.*;[123] and Beck.[11]

In the event of pollution leading to a violation of water quality standards, remediation may be required. Researchers have developed methodologies for optimising remediation strategies (*e.g.* Rogers *et al.*[132]). However, as Latinopoulos *et al.*[80] contend, if the inability to meet the constraints of a groundwater quality programme is considered a significant risk, then quantifying the risk of remediation failure in terms of failure to comply with regulatory standards is a primary task. In relation to this, Latinopoulos *et al*, through coupling stochastic flow and transport simulations with a risk-cost-benefit objective function, have developed a methodology facilitating the risk-based evaluation of remediation strategies (costing the risk of failure in terms of regulatory fines and the need to import / develop alternative supplies).

An alternative approach to characterising the extent and severity of source contamination is that of geostatistical inference (*e.g.* Passarella *et al.;*[118] Wingle *et al.*;[171] Rautman and Istok[129]). These kriging methods – essentially a form of least squares linear regression – focus on providing an estimate of a spatially distributed variable (*e.g.* contaminant concentration) at unsampled locations as a function of a limited set of sample values taken from surrounding locations.[129] As such, they are ideally suited to groundwater quality issues, where data collection is limited by expense and access. Of particular relevance to risk analysis is the discipline of geostatistical simulation, where multiple, unique estimates of site conditions that mimic the random variability of the parameter(s) of concern are produced.[171] Various authors[118,171,129] have illustrated how such an approach may answer the following questions: what is the probability that contaminant levels exceed regulatory standards; where are the compliance boundaries (and what is the associated level of confidence); and how much contaminant is present (and hence, how much must be removed)? Although the principles of geostatistical simulation are well established, the technique has yet to be widely applied to problems of groundwater contamination.[129]

Applications of GIS to catchment risk analysis were discussed earlier in the context of risk-mapping. Although representing efficient risk screening tools, their ability to quantify risk over space *and* time is limited. To counter this, researchers have sought to integrate these systems with simulation models. Feijtel *et al.*[44] illustrate that the embedding of chemical fate prediction models within a GIS allows for calculation of the distribution of predicted environmental concentrations, both in space and time, of ‘down-the-drain’ chemicals in catchment surface waters. Similar approaches are adopted by Dabrowski *et al.*[30] and Verro *et al.*[164] to assess surface water pesticide loading.

C. Network analysis

A water distribution system may be viewed as an interconnected collection of sources, pipes, and hydraulic control elements (*e.g.* pumps, valves, regulators, tanks) delivering water to consumers in prescribed quantities and at desired pressures.[112] System behaviour, which is governed by hydraulics, supply, demand, and system layout, may be described mathematically.[112] This description forms the basis of water supply and distribution modelling (network analysis), a discipline practised in the water industry for many years, particularly to inform the development of operational strategies.[154,17] Water utilities routinely apply network analysis in order to assess their 'security of supply', defined as the probability of being able to meet consumer demands (*i.e.* network reliability). 'Best practice' utilities extend their analysis beyond routine operating conditions to examine network performance under various supply-demand scenarios, thus reflecting the inherent uncertainty of the supply-demand balance. The standard Scottish Water methodology of yield assessment uses the software tool HYSIM-AQUATOR.[82] HYSIM, a hydrological rainfall-runoff simulation model, is used to derive historic inflow series, based on historic rainfall, potential evapotranspiration, and if necessary any artificial influences (*e.g.* abstractions). AQUATOR, a water resource system model, uses the output from HYSIM to simulate reservoir storage based on system demands and compensation flows. The model assists Scottish Water in understanding the level of supply availability risk in the current system and in determining the impact of prospective investment strategies to mitigate this risk.

Stevens and Lloyd[150] describe the application of the resource modelling package WRAPsim, with reference to the Yorkshire Water (UK) Grid. The model contains over 1200 components including all river and reservoir sources, boreholes, water treatment works, pipelines and demand centres. Through simulation of the conjunctive use of Yorkshire Water's sources over a given time period, model output provides the decision-maker with an accurate assessment of the behaviour of each source, its ability to meet demand, and the frequency of restrictions that would need to be imposed. Further insights are gleaned through the application of scenario analysis, wherein the supply-demand balance for each zone under variable scenarios (*e.g.* average year, dry year, peak week, *etc.*) allows an assessment of security of supply over a range of timescales and operating conditions. The authors report that WRAPsim's ability to predict future supply conditions, to optimise allocation of water resources, and to rebalance stocks, has significantly increased the yield and reliability of Yorkshire Water's supply system.[150]

Stahl and Elliott[149] discuss Essex and Suffolk Water (ESW)'s use of the risk-based resource planning and operational support model DROP (Drought Reliable Output Programme), an adaptation of WRAPsim designed to accommodate the utility's specific technical requirements. The model has been applied in a variety of areas, particularly in support of investment planning and the determination of operational strategies. The authors state that DROP has enabled ESW to improve their understanding of system performance, identify new schemes or short term options to improve reliability of supply, and to more accurately determine future operating costs associated with new developments. Such methodologies, although able to examine system reliability under a range of operating conditions, do not adequately address whether the system is *sufficiently* reliable, as this requires the definition and quantification of appropriate and meaningful reliability measures, a computationally difficult task.[113] Harnessing developments in computer processing power and operability, Ostfeld[113] has developed a methodology for the explicit reliability analysis of water distribution networks, with reliability defined, quantified and measured as the probability of zero annual shortfalls. The methodology, whose development was funded with the intention of practical application by the Israeli

Water Commission, is comprised of two interconnected stages: (i) analysis of the storage-conveyance properties of the system; and (ii) implementation of stochastic simulation through use of RAPTOR (Rapid Availability Prototyping for Testing Operational Readiness) software.

However, researchers in the field of network analysis are increasingly aware of the need to take account of both the frequency and severity of modelled failures, and as a result analyses are often suggested to extend beyond measures of reliability to incorporate resiliency (*e.g.* the capacity of a system to recover to a satisfactory state from a state of failure) and vulnerability (*e.g.* a measure of failure significance).[165, 71] Adopting this paradigm, Zongxue *et al.*[174] describe the coupling of a risk model (comprising measures of reliability, resiliency and vulnerability), which incorporates predictions of water demand, with a traditional network simulation model. The approach aids the identification of operational strategies of minimum risk under given supply and demand scenarios, and is illustrated by application to Fukuoka Water Supply System, Japan (see also Jinno *et al.*[71]). Similar methodologies are described by Wang *et al.*;[165] Merabtene *et al.*;[96] and Andreu *et al.*[3] though supplemented with formal optimisation procedures to assist derivation of the most appropriate operational policies of minimum risk.

To summarise, network analysis can: (a) allow utilities to assess their susceptibility to various supply-demand scenarios (*e.g.* drought or increases in demand); (b) aid decision-makers in determining ‘optimal’ supply strategies and policies; (c) assist in the design phase of distribution networks; and (d) inform the need for capital expenditure.

D. Vulnerability assessments

Operational disruptions are the inevitable result of large-scale disasters (*e.g.* flooding, drought, earthquakes, terrorism). To minimise the risks posed by such 'uncontrollable' events, utilities must seek to eliminate or reduce their potential consequences – this is best achieved through contingency and emergency planning.[142] The role of formal risk analysis in emergency planning, long restricted to drought management, is now being widely adopted to address security risks. This is largely in response to the events of September 11th, 2001. In relation to this, a methodology for vulnerability assessments has been developed by Sandia National Laboratories (SNL) – known as Risk Assessment Methodology for Water Utilities (RAM-W). The methodology allows utilities to conduct a detailed assessment of their system vulnerabilities and to develop measures to reduce the risks and mitigate the consequences of terrorist or other criminal attacks.[147] The assessment comprises three steps:[147]

1) determine how well the system detects a problem, which involves surveying all security and monitoring features (*e.g.* how quickly could it detect an undesired chemical being introduced to the supply);
2) measure delay capabilities in order to determine how well a system can stop undesired events (*e.g.* security in place, length of storage time); and
3) measure the capacity of private guard forces and local, state and federal authorities to respond to an event.

Perhaps a more pragmatic approach, particularly for smaller utilities, is found in the questionnaire-based self-assessment developed by the National Rural Water Association.[107]

4. OPERATIONAL RISK ANALYSIS

Our review now progresses to the analysis of individual plant. Operational risk managers are responsible for the risks associated with specific operations at plant level – for example, the risk of failure of a device or process component, or the risk of exceeding a particular water quality standard and they are increasingly responsible for the health and safety of plant operatives. Analysis at this level is largely concerned with the 'classic' risk analysis methodologies developed and established within other process industries, most notably the oil and chemical sectors (Table 5).

A. Public health and compliance risk

Here, we are primarily concerned with the risk posed by specific contaminants at the plant and distribution system level, particularly relating to the hazards posed to human health and the related risk of exceeding regulatory standards. The multiple barrier approach to water treatment has been the central tenet of modern water treatment systems and relies upon the use of 'in-series' water treatment processes to remove hazardous agents from the public water supply. Failure or inadequacy of the treatment and distribution process can result in an interruption of supply and / or derogation in water quality (microbiological or chemical) with potential impacts on public health. The underlying causes may include source contamination, human error, mechanical failure or network intrusion. The consequences of process failure can be immediate, there is very little time if any to reduce exposure because of the lag in securing monitoring data and the impacts can affect a large number of people simultaneously.[121] Beyond the paramount impacts on public health through the direct ingestion of contaminated drinking water, financial and consumer confidence impacts invariably ensue. The financial costs to the community of the fatal Walkerton outbreak for example, were in excess of Cdn$65 million, with one time costs to Ontario estimated at more than Cdn$100 million.[108] Compounding this, the loss of consumer confidence following disease outbreaks is often enormous.[67] Even when there is no legislation covering certain aspects there can be claims of negligence against operating companies. Litigation for civil damages have been prominent features following both the Walkerton outbreak (settled out of court) and the Sydney Water crisis (largely dismissed, costs still incurred).[121]

Conventionally, the public health impacts of drinking water consumption have been assessed retrospectively using epidemiological studies.[69] Recognition of the need for a preventative approach to managing risk and providing safe drinking water, however, has driven international interest in the application of risk assessment methodologies within the sector, for both chemical and microbiological hazards.[5, 59] The generic approach is based on the risk assessment framework developed by the National Academy of Sciences (NAS),[103] which consists of four key steps:[59]

- problem formulation and hazard identification – to describe the human health effects derived from any particular hazard (e.g. infection, carcinogenicity, etc.)
- exposure assessment – to determine the size and characteristics of the population exposed and the route, amount, and duration of exposure

- dose-response assessment – to characterize the relationship between the dose exposure and the incidence of the health effects
- risk characterization – to integrate the information from exposure, dose-response, and health interventions in order to estimate the magnitude of the public health problem and to evaluate variability and uncertainty

Several substantive differences exist between assessment of risk of microbial agents and assessment of risk of chemicals.[58] Accordingly, the NAS approach has been adapted to account for the dynamic and epidemiologic characteristics of infectious disease processes,[45] to form what is known as quantitative microbial risk assessment (QMRA). The application of these models has long been the basis for the derivation of water quality guidelines for drinking water.[168] The substance-specific health risk assessments that have historically informed the guidelines may, however, be somewhat distanced from the immediate operational context of individual utilities.[121] However, recent work has extended the application of these models to the operational (plant-specific) context. For example, Medema *et al.*,[95] Masago *et al.*,[90] and Teunis *et al.*[156] describe the application of QMRA in determining the public health risks posed by the presence of microbial contaminants in treated water. The first step in the process is to define the relationship between measured pathogen source levels and the consumed dose (incorporating analytical detection levels, treatment removal efficiencies, drinking water consumption), followed by the construction of a deterministic model mathematically describing this relationship. Monte Carlo simulation (a method of uncertainty analysis) is then applied to the output of the deterministic model to determine the distribution of the daily consumed dose, to which the relevant dose response relationship is applied in order to determine the cumulative distribution of the probability of infection. From this, the mean annual individual risk of infection may be determined. Such approaches are of particular relevance in areas, such as the Netherlands, where water supply legislation expresses acceptable health risks in terms of infections per year.[95] Of course, core microbial standards generally refer to a maximum level of organisms in the treated water, and so consideration of consumption levels and the dose-response relationship is superfluous to compliance risk assessment. The approach perhaps has most utility in 'what-if' mode to answer questions such as: "*what are the public health implications of a failure of part of the treatment process or of a re-designing of the treatment process*".[52]

Tools are available to assess the risk of exceeding water quality standards relating to physical or chemical parameters. For example, Demotier *et al.*[32] describe an integrated FTA / FMEA approach to determining the risk of producing non-compliant drinking water across a range of parameters, taking into account the quality parameters of raw water and the removal efficiencies and reliability of the full set of treatment processes. Similar methodologies are described by Eisenberg *et al.*[41] and Haas and Trussell[57] in assessing the reliability of multiple, independent barriers in water treatment. These three pieces of research explicitly consider the performance variability of individual processes along the treatment line, an approach rarely described in operational QMRA. Not only does this offer a more realistic appraisal of compliance risk, it is in line with recent proposals from regulatory bodies (*e.g.* National Health and Medical Research Council (NHMRC))[105] calling on utilities to formally adopt the multiple barrier approach to risk management to ensure multiple levels of protection are afforded against specific contamination threats (see Rizak *et al.*[131]).

Of course, limitations in resources (human and financial) and in the data to underpin such sophisticated analyses often restrict the practical application of these more advanced methodologies within the sector. A more pragmatic analysis of the risks of process failure is commonly undertaken using a semi-quantitative risk-ranking of hazards according to their likelihood and consequence. Egerton[40] describes the application of ranking techniques for the prioritisation of contamination risks at a water treatment plant. Risks are scored according to the frequency with which they may occur, the ability to take action to contain the event, and the consequence of subsequent contamination. The methodology is intended to aid the targeting and prioritisation of remedial actions. Such approaches rely heavily on the experience and judgement of the assessment team, and depending on the level of guidance provided for scoring within these criteria, remain open to bias especially from unforeseen circumstances that often fall beyond the process boundary, *e.g.* deliberate or accidental human error.

Finished water can undergo a variety of physical, chemical, and biological changes during transportation through a distribution system.[13] Understanding the nature and likelihood of these risks has become a priority for water producers,[13] in part due to research linking such degradation to the incidence of gastrointestinal illnesses (*e.g.* Payment *et al.*[119]). Application of the methodologies developed by Lindley and Buchberger[83] and Besner *et al.*,[13] described earlier (see *Asset management)*, would provide utilities with a means to distinguish areas of the distribution system at greatest risk of degradation, providing a framework for prioritising risk management activities.

B. Reliability analysis

It is implicit in the planning, design and operation of water utilities that risk analysis is a qualitative component of the intellectual process of the experienced engineer / operator. Reliability analysis seeks to formalise, systemise, and, where necessary, quantify this process. Assessments of operational reliability range from component (*e.g.* risk of valve failure), process (*e.g.* risk of failure of treatment step) to network (*e.g.* network reliability under drought conditions, see *Network analysis*) level analysis. Regardless of focus, the aim is to identify the potential failures that may occur in a system, their effects and their likelihood, thus aiding the identification of critical components and processes where design and operational changes are required to meet safety and / or production targets.[151] Analysis may be summarised as follows:[151]

- system definition – defining the level of analysis;
- failure identification – identifying potential hazards (*e.g.* HACCP, hazard and operability studies, FMEA / FMECA);
- reliability modelling – to describe failure behaviour of system as a whole (*e.g.* FTA, ETA, reliability block diagrams); and
- sensitivity analysis

The National Health and Medical Research Council (NHMRC), the body responsible for issuing drinking water guidelines to Australian water utilities, in their 'Framework for Management of Drinking Water Quality'[131,105] advocated the application of a HACCP (hazard analysis critical control points) methodology, namely the determination of 'critical control points' whereupon risks can be monitored and reduced.[24] Hellier[64] describes the implementation of this approach within Melbourne Water (Australia). The process begins with the division of the water system into four discrete subsystems: catchment, treatment, distribution and customer premises. Across each subsystem (*e.g.* catchment) the sources of risk to water quality (*e.g.* native animals) and the associated hazards (*e.g.* bacteria, viruses) are identified and plotted on a simple risk matrix; those risks deemed to be significant are evaluated further for their critical control points. Assessors then identify the critical limits, monitoring systems and corrective actions for each CCP. The application of HACCP to South East Water Ltd.'s (Australia) distribution and reticulation systems is described in Mullenger *et al.*[101] Through implementing their HACCP plan, the company has developed a greater understanding of water quality issues, refined and optimised operating procedures, and observed a net decrease in customer complaints. These benefits stem from an increased knowledge and understanding of the water supply system and an improved ability to identify potential risks to water supply / quality.[101] Beyond managing existing process control, HACCP may also be used to assess and manage the risks from proposed operational changes, such as the integration of treated domestic wastewater to an existing potable production process (*e.g.* Dewettinck *et al.*[34]).

HAZOP (hazard and operability study), a technique developed by Imperial Chemical Industries Ltd., systematically evaluates the process and engineering intentions of new or existing facilities in order to identify the hazards that may arise due to deviations from design specifications.[1] Typically, a carefully selected team examines a process (*e.g.* disinfection) subdivided into 'nodes', at each node, the team applies guidewords (*e.g.* low) to process parameters (*e.g.* ozone levels) to identify ways in which the process may deviate from its design intention, before evaluating the causes and consequences of the deviation. A technical document published by the US Department of Energy[162] describes the undertaking of a HAZOP study on the partially installed chlorination process of a water treatment facility. The analysis, conducted in response to regulatory requirements, identified the key areas of uncertainty (*e.g.* chlorine cylinder received overfilled). 'Action items' and recommendations were formulated to clarify these uncertainties and to verify process conditions (*e.g.* check pressure potential from the chlorine cylinder and the system response).

The practical implementation of many of these techniques is often constrained by the institutional capacity of organisations and the skill sets available at the operational level. Risk analysis remains an expert discipline and many organisations are more comfortable with the historic and proven implicit approach to risk management. Nevertheless, we are witnessing a growing number of utilities making their analysis more explicit and using these tools for better decision-making, identifying risk issues early rather than later, when their ability to respond may be compromised. At Scottish Water, for example, FMECA-based studies are performed at the operational level. Targeted by a risk criticality scoring system, the analysis systematically considers various components of the water supply system and their respective failure modes.[82] As the scoring system is 'pseudo-economic', decision-makers are empowered to assess the costs and benefits in terms of risk reduction per pound of mitigation efforts through undertaking simple scenario modelling.[82] Where identified failure modes are traced to specific mechanical or electrical equipment, the equipment is subject to reliability centred maintenance – the risk-based prioritisation of maintenance activities. In recognition of the dangers of ill-informed risk-based resourcing, select critical-risk assets undergo formal optimisation of maintenance task cost-risk-performance using a suite of asset performance tools (APT).

These methodologies represent an informed and structured, if time-consuming, framework for pinpointing weaknesses in utility design and operation. Applied effectively using personnel with appropriate skills, experience and resources, they provide operational management with a basis for improving process reliability and identifying issues early. Ineffectively applied, they become little more than acronyms for complacency. As discussed, reliability analysis may require a quantitative treatment of the effect of identified risks at the system level. The importance and complexity of this task has increased in recent years, due in part to the increased range of available technologies and the tighter operational margins imposed by regulators.[41]

For unreliable or heavily used equipment, an analysis of historic data may be sufficient for this purpose. In the absence of such data, there is a requirement for the formal modelling of risk consequences. There exist a range of techniques for this task, including logic modelling (*e.g.* Demotier *et al.*;[32] Cyna[29]), 'quantitative' FMECA (*e.g.* Cyna), and multiple barrier approaches to treatment reliability (*e.g.* Demotier *et al.*; Eisenberg *et al.*[41]; Haas and Trussell[57]). An illustration of an integrated approach to evaluating plant reliability is provided by Cyna, who describes the methodology developed and applied by the *Compagnie Generale des Eaux* (France) (Figure 7). Following system definition and modelling (*via* reliability block diagrams), risks are identified and classified using HAZOP. Risk consequences are subsequently quantified *via* FMECA, allowing the computation of system availability (the probability of the system to be found operative at a given time). Cyna describes how the methodology was applied to a proposed post-chlorination system in *Neuilly-sur-Marne* plant, arguing that its employment helped conceive a reliable system and verified the adequacy of plant availability. The author concludes that reliability analysis is an essential tool at 'conception', which allows the adjustment of project design, and thus cost, to the level of reliability required, and, when associated with maintenance procedures, can provide insurance of design quality.

5. CONCLUSION

Risk management for water utilities is fast becoming an explicitly-stated paradigm, recognising the implicit approach performed over the last 150 years. With increasing globalisation, outsourcing and increased regulation of the industry, tools that allow system vulnerabilities to be identified before failures occur are essential. In many ways, however, the industry is discovering risk analysis afresh and there is a learning curve to climb in terms of the capabilities and limitations of these tools and techniques. The international water sector has helpfully restated its overarching goal reminding us that even in the face of rationalisation and economic pressure, public health protection[8] is the principal business of the water industry. Risk analysis has a part to play in focussing effort in the right places, but should not be treated as a panacea or substitute for managing risk and neither allowed to dictate the outcome of decisions without recourse to the fundamental goal of the business. Flexibility of approach is key to the successful application of these tools, as is their appropriate selection within the organisational context and legal framework. For large multi-utilities, one can expect high developed business risk capabilities, whereas for smaller and single utilities, an approach based on accepted codes and standards may be more suitable. Our analysis provide a comprehensive inventory of the current state-of-the-art as a reference for developing a risk analysis strategy that is fit for purpose.

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Figure Captions

Figure 1. Decision Framework for the Offshore Oil Industry (UK Oil Operators Association[159] with permission).

Figure 2. The risk hierarchy (adapted from Prime Minister's Strategy Unit[124]).

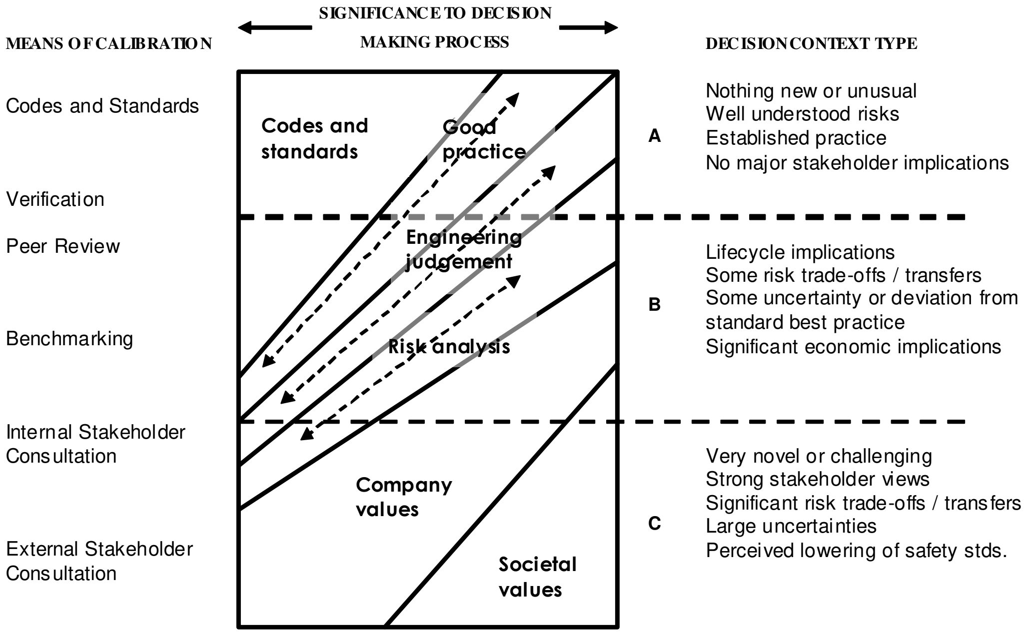
Figure 3. Technology risk algorithm (Hartmann and Lakatos[62]).

Figure 4. Illustrative fault tree for turbidity non-compliance (Demotier *et al.*[31]).

Figure 5. Reliability block diagrams (Cyna[29]).

Figure 6. Risk-based workforce planning (after Pollard *et al.*[122]).

Figure 7. Methodology for reliability analysis of a water treatment plant (Cyna[29]).



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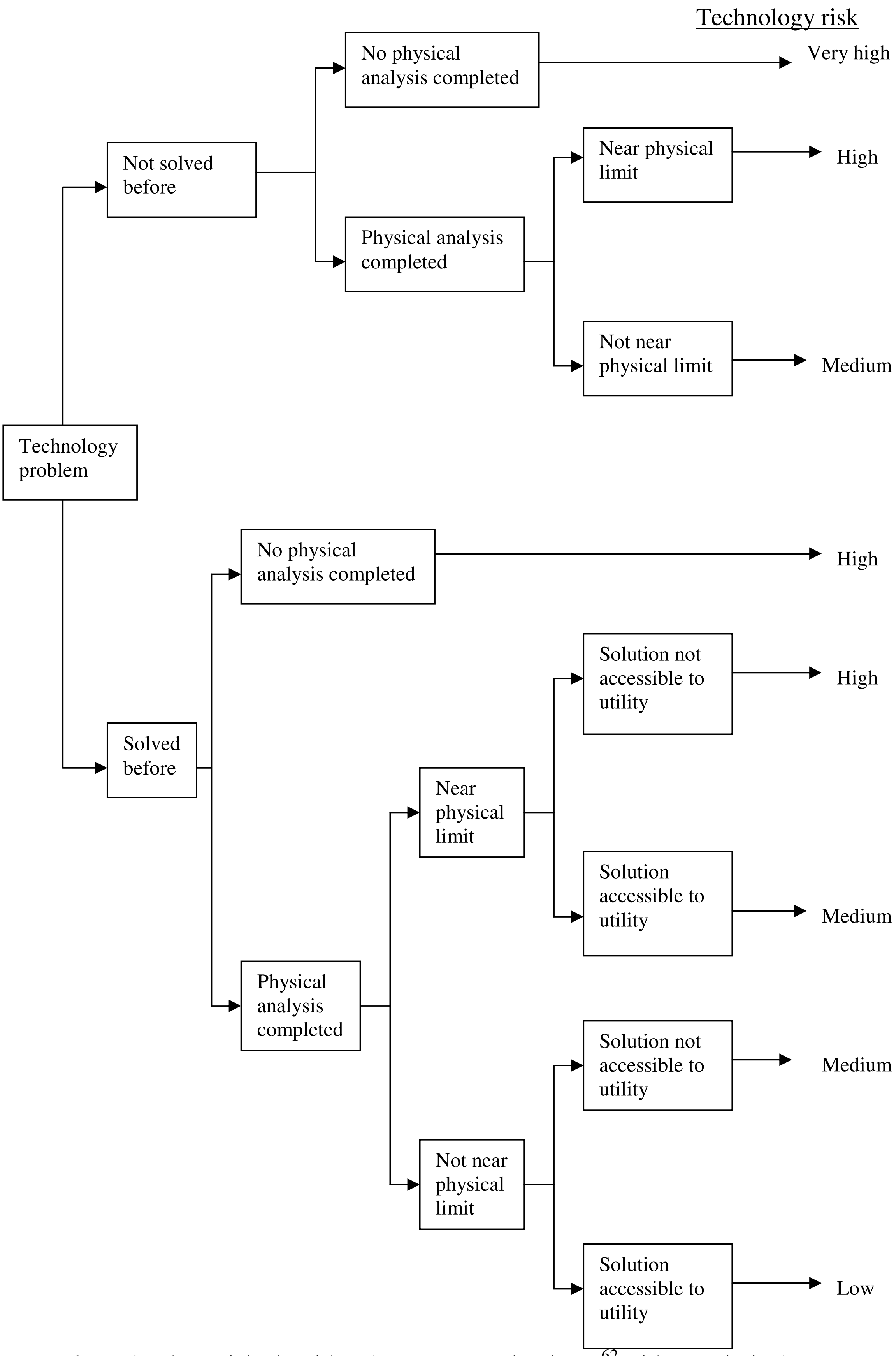

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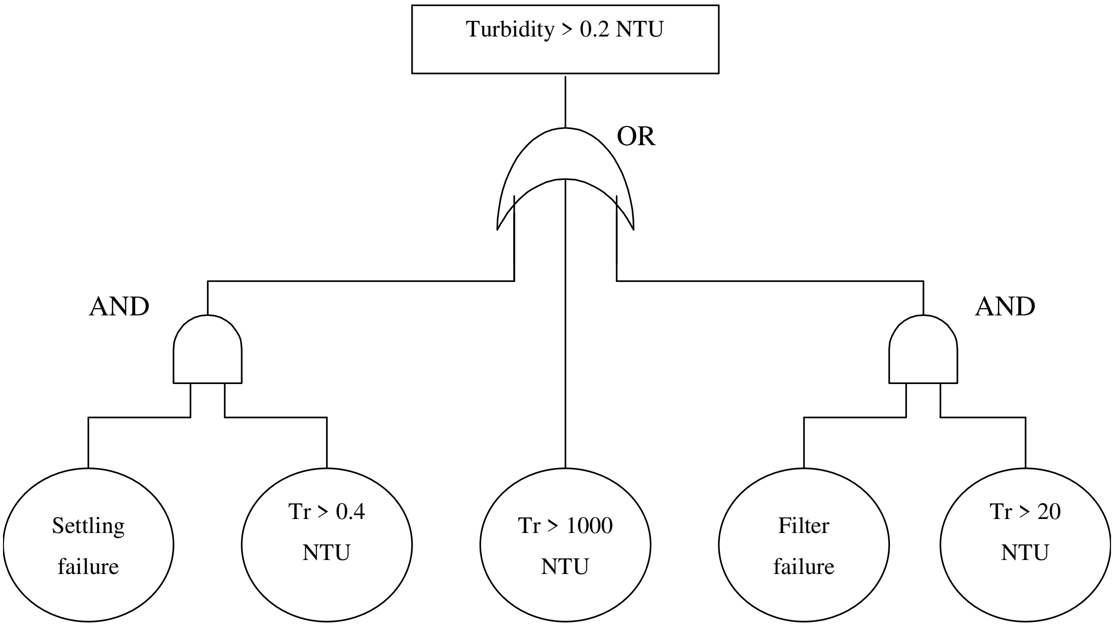
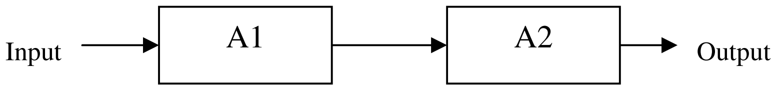


Tr = resource turbidity

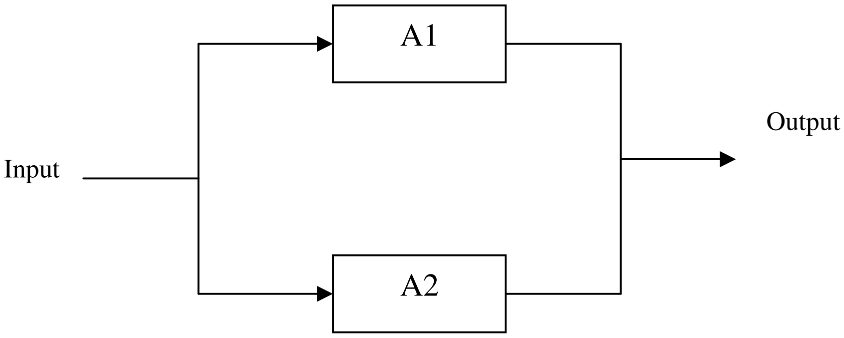
The probability of the top-event may be calculated if the probabilities of the sub-events are known or estimable.

Figure 4. Illustrative fault tree for turbidity non-compliance (after Demotier *et al*.[31]).

a) Series diagram – here, the system / process is working if A1 and A2 are working



b) Parallel diagram – here, the system / process is working if A1 or A2 are working



c) Redundancy diagram – here, the system / process is working if at least r elements among n are working

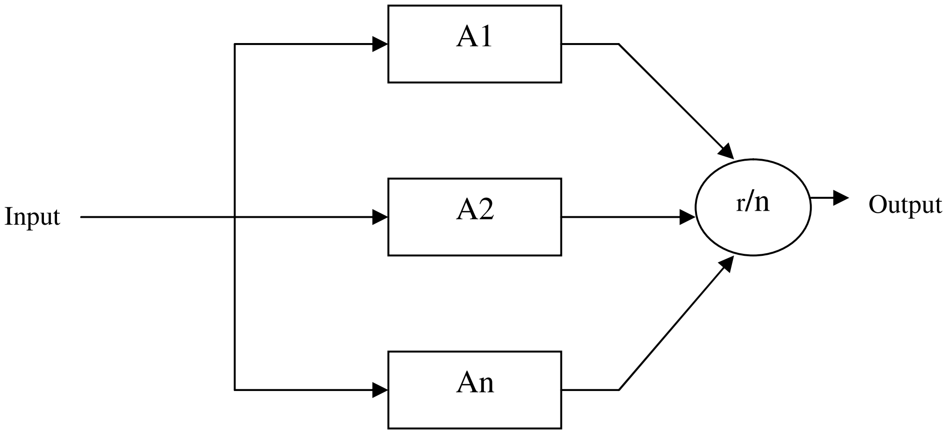


Figure 5. Reliability block diagrams (after Cyna[29]).

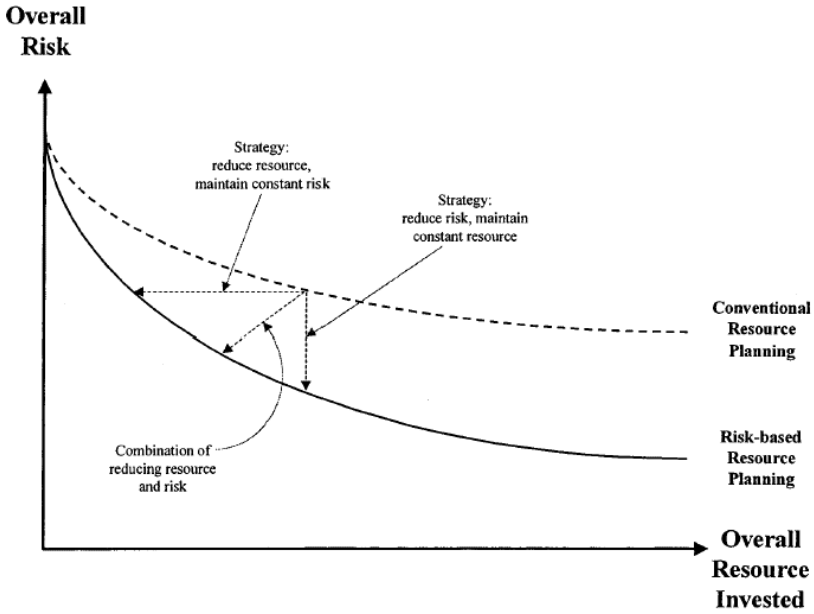


Figure 6. Risk-based workforce planning (after Pollard *et al.*[122]).

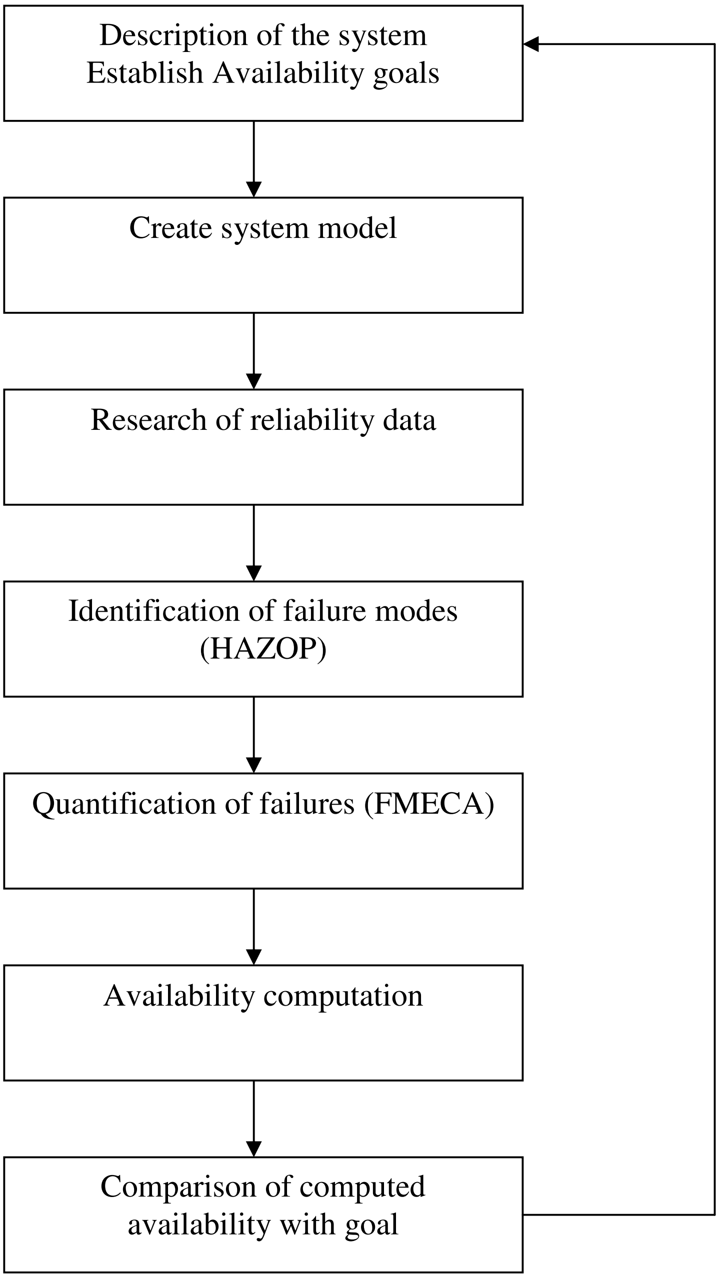


Figure 7. Methodology for reliability analysis of a water treatment plant (after Cyna[29]).

Table 1. Strategic risk portfolio.

Context	*Tool / Technique*	*Application*	*Reference*
Regulatory risk	*Ex-post* modelling	Interpreting / evaluating the relationship between stock risk and regulatory events	Buckland and Fraser,[19] Morana and Sawkins.[98]
	Ex-ante modelling	Modelling evolution of regulatory environment	Larssen and Bunn,[78] Bunn *et al.*.[20]
Competition risks			
1) Comparative	Competitor analysis	Reducing price review uncertainty (and conventional benefits)	Drohan and O' Connor,[38] Rothschild.[133]
2) Capital market	Screening	Tracking take-over risk	
	Investment analysis	Evaluating take-over opportunity	Thomas.[157]
3) For the market	Investment analysis	Evaluating joint venture	Ranasinghe,[128] Grimsey and Lewis.[55]
4) Product market	Competitor identification / analysis	Minimising competitive threats	Rothschild,[133] Drohan and O' Connor.[38]
	Investment analysis	Evaluating *de facto* take-over	
BPR risks	Scenario planning	Exploring potential BPR outcomes	Clemons.[23]
	Quantitative 'risk of failure'	Evaluating success likelihood of BPR efforts	Crowe *et al.*[28]
	Risk matrix	Appraising and comparing risks of BPR strategies	Remeyi and Heafield.[130]
1) New technology	Risk matrix	Appraising and comparing risks of new technology projects	McGaughey *et al.*[92]
	Risk algorithm	Characterising risk of new technology 'problems'	Hartmann and Lakatos.[62]
	Checklist	Minimising risk of new technology introduction	Hartmann and Lakatos.[62]
	Profile	Guiding strategic technology planning	Wildemann.[170]
Outsourcing	Outsourcing decision models	Evaluating core competencies and appraising market opportunities for outsourcing candidates	Quélin and Duhamel,[125] Lonsdale.[86]
	Scenario planning	Exploring 'what-if' scenarios	Zsidisin *et al.*[176]
Employee retention	OCP	Evaluating 'cultural fit' of prospective employees	Sheridan,[141] O'Reilly *et al.*[109]
	Early warning system	Identification of 'at-risk' employee groups	McNally.[94]
	Gap analysis	To assess employee development and benefit schemes	
	Checklist	Informal assessment of retention risk	Anon.[4]
Investment analysis			
1) Assets-in-place	NPV / IRR	Valuation of an ongoing business or some part of one	Barriex *et al.*,[10] Mosca *et al.*,[99] ADB,[6] Burchett and Tummala,[21] Luehrman,[87] Thomas.[157]
	Strategic portfolio planning	Creating a balanced utility investment portfolio	Rothstein and Kiyosaki.[134]
2) Opportunities	Option pricing theory	Valuation of possible future operations	Luehrman,[87] Black and Scholes.[14]
3) Joint Ventures	NPV / IRR	Valuation of prospective partnerships, strategic alliances	Grimsey and Lewis,[55] Ranasinghe,[128] Luehrman.[87]

Table 2. BPR risk matrix (after Remenyi and Heafield[130]).

Indicate the 10 most relevant factors

FACTORS

BUSINESS RISKS

Change to business scope (*e.g.* from diversifying)

Change to market structures

Change of regulatory relationship

Change of supplier relationship

Impact on (potential) ‘competitors’

FINANCIAL RISKS

Funded from current cash flow

Funded from new equity

Funded from long term debt

Funded from short term debt

CORPORATE STRUCTURE

Bureaucratic structure

Outsourcing utilisation

Flexibility of job positions

FACTORS

CORPORATE CULTURE

Staff attitude to technology

Staff attitude to changes

Staff attitude to senior managers

Managerial style

Positive shared vision

TECHNOLOGY

Size of project

Structuredness of project

Complexity of technology

Complexity of application

Novelty of technology

Novelty of application

Impact on technical infrastructure

HUMAN

Skills base

Table 3. Programme level risk portfolio.

Context	*Tool / Technique*	*Application*	*Reference*
Asset management	Risk ranking	Prioritisation of remedial work on infrastructure assets	Kent *et al.*,[73] Radovanovic and Marlin,[126] Foster *et al.*[50]
	FMECA	'Source to tap' risk identification and prioritisation	Lifton and Smeaton.[82]
	Logic models	Evaluating structural failure modes	Gray and Powell,[53] Parr and Cullen.[117]
	GIS risk tracking	Infrastructure risk-tracking, visualisation and communication	Kaufman and Wurtz.[72]
	GIS spatial analysis	Risk-mapping of infrastructure	Doyle and Grabinski,[37] Ta.[153]
	GIS risk simulation	Evaluating degradation risk	Lindley and Buchberger,[83]Besner *et al.*[13]
Catchment management	Risk ranking	Prioritisation of monitoring strategies	Dabrowski *et al.*,[30] Verro *et al.*,[164] Boak and Packman,[15] Feijtel *et al.*[44]
	GIS risk mapping	Mapping areas of catchment critical to water quality	Lytton *et al.*,[88] Sivertun and Prange,[146] Wickham and Wade,[169] Foster and McDonald,[49] Osowski *et al.*,[111] Fuest *et al.*,[51] Lantzy.[77]
	Contaminant flow / transport modelling	Projecting degradation patterns / assessing risk of water quality violation	Anderson and Destouni,[2] Gündüz *et al.*,[56] Halfacree,[61] Liou and Yeh,[84] Cole *et al.*[25]
	Kriging	Projecting degradation patterns with limited sample data (*e.g.* groundwater)	Passarella *et al.*,[118] Wingle *et al.*,[171] Rautman and Istok.[129]
	GIS risk simulation	Quantified risk mapping over space *and* time	Dabrowski *et al.*,[30] Verro *et al.*,[164] Feijtel *et al.*[44]
Network analysis	Network reliability modelling	a) Assess susceptibility to supply-demand scenarios; b) aid development of supply strategies and policies; c) assist design of distribution networks; and d) inform the need for capital expenditure.	Stevens and Lloyd,[150]Lifton and Smeaton,[82] Wang *et al.*,[165] Merabtene *et al.*,[96] Ostfeld,[113] Stahl and Elliot,[149] Zongxue *et al.*,[174] Andreu *et al.*,[3] Jinno *et al.*[71]
Vulnerability assessment	RAM-W	To assess system vulnerabilities and develop measures to reduce risks of attack.	SNL news release.[147]
	Questionnaire-based self assessment	As above	NRWA.[107]

Table 4. Component FMEA for chlorine cylinder and outlet valve (Egerton[39] with permission of Egerton Consulting Ltd.).

Failure mode	Failure effect on process	Failure effect on system	Methods of Detection	Comments
Fail to open / Reduced output / No output	Loss of adequate chlorination	Non-potable water will leave plant	Changeover should detect loss of supply	System failure would require combination of loss of flow and failure of changeover
Fail to close	None – changeover should transfer to standby cylinders	None	None	
Excess output	Excess chlorination	Possible taste and odour complaints. No serious consequences	Changeover should detect excess chlorine flow	
Outside specification (wrong or contaminated gas)	Outside specification (wrong or contaminated gas)	Non-potable water will leave plant. POTENTIAL FOR MAJOR SAFETY HAZARD	QA checks on delivery. Low chlorine residual readings and alarm	

Table 5. Operational level risk portfolio.

Context	Tool / Technique	Application	Reference
Compliance risk	Risk ranking	Prioritisation of plant contamination risks	Egerton.[40]
	QMRA	Assessing public health risk from microbial source contamination	Medema *et al*.,[95] Teunis *et al.*[156]
	End-of-pipe compliance models	Assessing risk of exceeding water quality standards	Demotier *et al*.,[31] Trussell.[57]
	GIS simulation	Assessing risk of distribution system water quality degradation	Lindley and Buc *et al.*[13]
Reliability analysis	HACCP	Identifying ‘critical control points’	Mullenger *et al*., *al*.,[34] Hellier.[64]
	HAZOP	Evaluating deviations from design intent	US Department and Abassi.[74]
	FMECA	Evaluating component failures	Lifton and Smea
	Logic modelling	Modelling process risk interactions	Demotier *et al*.,[31]
	Multiple barrier approach	Assessing the reliability of multiple barrier treatment processes	Demotier *et al*.,[31] Haas and Trussel