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Decision support for risk management in drinking water supply

Overview and framework

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Title
Decision support for risk management in drinking water supply: Overview and framework

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Summary

This current report is the first deliverable of WP4.4 and the objectives of the report are:

- to present a literature review on existing methods for decision support regarding risk management in the drinking water sector,
- to present an overview of the definition of risk tolerability in the water sector as a basis for decisions on risk-reduction measures,
- to perform a survey of how water utilities in some European countries currently make decisions regarding risk issues and the decision criteria they use, and
- to suggest a decision support framework for integration of risk management in asset management.

In a second deliverable and report of WP4.4 (see Lindhe et al., 2010a), specific methods developed in TECHNEAU for providing decision support and cost optimization are presented.

The literature review was carried out as a review of international academic and industry reports concerning decision support in the drinking water sector. The survey of decision-making at water utilities was made by interviews with water utility representatives in different countries to provide real world examples of decision problems as well as methods and criteria applied in the decision-making process. The framework for decision support was developed on a generic level and based on the TECHNEAU risk management framework and the literature review and survey. The work was carried out by Chalmers University of Technology, KWR and the University of Surrey.

It is concluded that efficient risk management, including proper risk assessments and decision analyses that support well-informed decision-making, is necessary to achieve and maintain a reliable supply of safe drinking water. Since not all risks can be eliminated, methods and tools for facilitating the task of balancing risks, cost and benefits are important. The framework and methods for integrated risk assessment and decision analysis presented in TECHNEAU provide useful decision support and facilitate efficient risk management of drinking water systems.

Contents

1 Introduction

1.1 Background

The main goal of the drinking water sector is to provide to customers an uninterrupted supply of water with a high aesthetic quality and with a minimal risk to human health. However, because of potential hazards in the raw water, treatment and distribution parts, water supply systems and consumers are exposed to a wide variety of risks. In addition, climate changes, societal evolution and emergence of new contaminants constantly create new risks to water supply systems. As a result, water companies have to continuously adapt to manage these risks and to fulfil their common goal.

End-product testing and water quality standards have been widely used around the world as a means of managing risks associated with the supply of drinking water. For example, USA has established maximum contaminant levels under provisions in its Safe Drinking Water Act (1996) which set the maximum permissible level of a contaminant in water supplied by a public water supply system (Rowe et al., 2007). The EU Drinking Water Directive (98/83/EC) sets minimum standards for common substances found in drinking water, specifying 48 microbiological and chemical parameters that must be monitored by member states (European Commission, 2003). Member states are free to set water quality standards higher than these minimum standards.

There is a general global trend to move away from water quality standards as a single means to ensure water safety. Instead, the use of risk assessment and management is being increasingly advocated, illustrated e.g. by the incorporation of this approach into the World Health Organization (WHO) guidelines (Howard et al., 2006). A major driver of this change is the recognition by organisations such as the WHO that detection of microbial or chemical substances in drinking water which are harmful to human health is generally slow, complex and costly, meaning that it is not practicable to test for all drinking water quality parameters. When high levels of sanitation are present, the loading of pathogens into a drinking water system in amounts sufficient to cause a disease outbreak will occur intermittently and infrequently. This results in extended periods without any problems but no guarantee of safety (Hrudey et al., 2006). The impracticability of effective monitoring limits the effectiveness of early warning systems and means that reliance on water quality standards alone is insufficient to ensure the protection of public health (WHO, 2006).

As part of the work to move away from water quality standards as the primary means of ensuring water safety, the European Commission began during 2007 to develop proposals to revise the Drinking Water Directive. The revision meant a move towards a risk based approach to drinking water safety in line with the WHO 2004 Guidelines for Drinking Water Quality (European Commission, 2008).

As a consequence of the gradually changed perspective, risk assessment and risk management is becoming an increasingly important aspect of drinking water production. In the 3rd edition of the Guidelines for Drinking-water Quality, the World Health Organisation (WHO, 2004; 2008) recommends preparation of risk-based Water Safety Plans (WSPs) with a holistic perspective, considering conditions in source waters, treatment systems and distribution networks comprehensively. WSPs are currently being implemented in several countries and are expected to become an increasingly important framework for water management in both developed and developing countries.

The TECHNEAU project initiates the rethinking of water supply options and the development of new technologies (Techneau, 2005). One of the work areas of TECHNEAU is *Risk Assessment and Risk Management*, which is directed at integrating risk assessments of the separate parts of a water supply chain into a comprehensive decision support framework for cost-efficient risk management in safe and sustainable drinking water supply. It also enables the integration of the project results into the practice of water companies. To reach this objective, WA4 is divided into five work packages (WP):

WP4.1: Basic risk management framework and hazard identification
WP4.2: Integrated risk assessment and risk evaluation
WP4.3: Risk reduction options
WP4.4: Framework for decision support
WP4.5: Training activities in risk assessment and risk management

WA4 provides different types of outputs for risk management: a generic framework, guiding reports and method descriptions and a toolbox. A schematic illustration of the outputs of WA4 is given in Figure 1.

An increasingly important aspect of risk management is how to prioritise between different risk reduction options. Given the limited resources of every organisation, prioritisations must be made on both operational and strategic levels. Efficient use of existing resources requires well-founded prioritisation methods and a clear view of the goals of the risk management. This means that the decision-maker must define the criterion or the set of criteria for the risk management decisions, e.g. cost-effectiveness or maximum expected utility. The risk tolerability of the consumers and regulatory agencies, e.g. specific performance targets in the supply of drinking water, must be considered when defining the decision criteria.

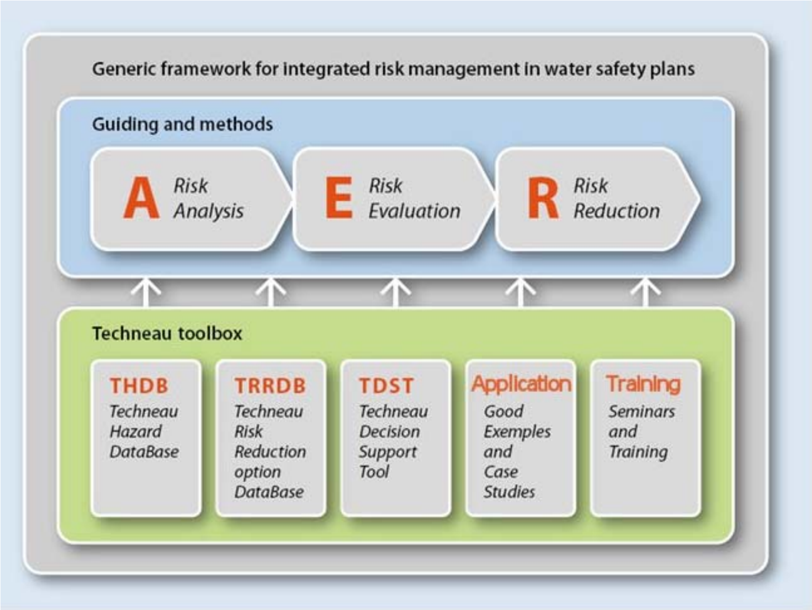

Figure 1. Schematic illustration of the outputs of WA4 in TECHNEAU.

The WP4.4 focuses on further developing a framework and methods for decision support in risk management. This work consists of two parts:

1. Integration of risk management in asset management.
2. Development of a framework for cost optimization.

1.2 Objectives

This current report is the first deliverable of WP4.4 and the objectives of the report are:

- to present a literature review on existing methods for decision support regarding risk management in the drinking water sector,
- to present an overview of the definition of risk tolerability in the water sector as a basis for decisions on risk-reduction measures,
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- to suggest a decision support framework for integration of risk management in asset management.

In a second deliverable and report (see Lindhe et al., 2010a), specific methods developed in TECHNEAU for providing decision support and cost optimization are presented.

1.3 Method

The literature review was carried out as a review of international academic and industry reports concerning decision support in the drinking water sector. The survey of decision-making at water utilities was made by interviews with water utility representatives in different countries to provide real world examples of decision problems as well as methods and criteria applied in the decision-making process. The framework for decision support was developed on a generic level and based on the TECHNEAU risk management framework (Rosén et al., 2007) and the literature review and survey. The work was carried out by Chalmers University of Technology, KWR and the University of Surrey.

1.4 Limitations

The review had to be limited to the literature accessible through e-journal services and branch-organisations. Reports made by various water companies could unfortunately not be included given the time restrictions of this work and confidentiality issues. The results of the interviews did not aim to represent all water utilities but to provide good examples from different types of systems in different countries.

1.5 Outline of the report

The outline of the report is as follows:

- A short overview of the risk management process, risk management in the drinking water sector, international frameworks and the generic framework for risk management suggested in the TECHNEAU project (Ch. 2).
- A review on existing literature concerning risk tolerability in the drinking water sector (Ch. 3).
- An overview of decision analysis and decision support methods (Ch. 4)
- A survey of important types of decisions in the drinking water sector (Ch. 5).
- Presentation of a generic framework for decision support for water utilities (Ch. 5).
- Conclusions and recommendations (Ch. 6).

1.6 What is decision support?

Decision support may be many different things. In this report, we use the term *decision support* as follows. Managing risk can be described as a process that in the end always aims to make decisions about risks. The decision may, for example, be to take a specific action or not to do anything. Hence, decision-making and risk management are closely linked to each other. Decision support may generally be described as being about how to use information from one or several sources to provide useful and accurate information that can facilitate the decision-making process. Decision support in managing risk issues can be provided by a wide variety of analyses, evaluations etc. In the present report, we focus on methods where risk analysis well as risk evaluation is explicitly performed. Thus, in this report *decision support* is mainly about providing information that facilitates selection between alternative risk-reduction options.

2 Risk management in the water sector

2.1 Introduction

Sound and effective support for decisions concerning risk issues requires a thorough understanding of risk and risk management. As a background to the subsequent chapters on decision support, we provide here descriptions of risk management in the water sector in general. We then give a brief description of the framework for risk management suggested in TECHNEAU, as described by Rosén et al. (2007).

2.2 Risk management and decision-making in the drinking water sector

The risk management process includes the entire process from the initial description of the scope and purpose of risk management, the identification of hazards, and the estimation of risks, through the evaluation of risk tolerability and identification of potential risk reduction options, to the selection and implementation of appropriate risk reduction measures. Risk management also includes risk monitoring and follow-up during operation. It must be emphasized that risk management is an iterative process of continuous updating as new information becomes available and as the preconditions change. Successful risk management also requires careful communication of risks between the various involved stakeholders.

The WHO (2004) defines safe drinking water as water that *does not represent any significant risk to health over a lifetime of consumption, including different sensitivities that may occur between life stages*. As noted by Hrudey et al. (2006), safe does not mean the absence of any risk since to demand an absolute standard would mean that no water would ever meet this standard and thus no water could ever be considered safe. This would render the concept of safe water meaningless. Rather, safety is a relative concept. Hrudey et al. (2006, p949) propose that a definition of safe might more appropriately be “a level of risk so negligible that a reasonable, well-informed individual need not be concerned about it, nor find any rational basis to change his/her behaviour to avoid such a small, but non-zero risk”. Specifically in the context of drinking water this definition implies that safe water refers to water that can be consumed without the expectation of death or serious illness. The definition by Hrudey et al. (2006) of safe implies that an expert definition of risk as “negligible” should also be categorised by a non-expert as acceptable, a somewhat problematic assumption. Savadori et al. (2004) note past experience and specialist technical knowledge can lead to very different judgments about risk and that quite a number of studies have documented significant differences between experts and the public in risk perception.

The International Water Association (IWA, 2004) points out that a reliable supply of safe drinking water is fundamental to public health and economic development. WHO (2004) concludes that a comprehensive risk assessment and risk management approach is the most effective way of ensuring the safety of a drinking water supply.

The drinking water sector faces risks as well as opportunities. At the same time, governments and regulators expect water utilities to adopt a management approach that focuses on avoiding losses and taking advantage of opportunities (Dalgleish and Cooper, 2005). Pollard et al. (2004) suggest that an enterprise-wide management approach should be used, which requires:

- integrated frameworks for the management of internal as well as external risks to the utility;
- support of board level, executive management and operational staff as well as that of external stakeholders; and
- effective communication of risk and engagement within decision-making processes both within companies and with external stakeholders.

Risks can be managed on different levels in an organisation depending on what kind of decision needs to be made. The different levels can be described as *strategic*, *programme* and *operational* (MacGillivray et al., 2006; Pollard et al., 2004). Pollard (2008) describes a three-level hierarchy of decisions in the water utility sector, see Figure 2. On the strategic level regulatory, commercial and financial risks are included while risks linked to, for example, asset and catchment management are considered at a programme level. Risks associated with specific operations, such as failure of process components, are managed at an operational level. Strategic decisions are supposed to be transferred into actions at a programme level and implemented at an operational level.

As a consequence of the variety of decisions, risk management of drinking water systems will often include different types of risks, such as public health, reputation, environmental, financial and legal risks (Pollard, 2008). Successful risk management will therefore need to include a variety of tools to support decisions. For example, strategic decisions may involve cost-benefit analysis, programme decisions may involve models of pathogen distributions in watersheds, and operational decisions may involve fault-tree analysis or qualitative risk classification methods for estimating system reliability. For all types of decisions, the decision-maker has to carefully evaluate risks and have an understanding of risk tolerability and the underlying criteria for making the decisions.

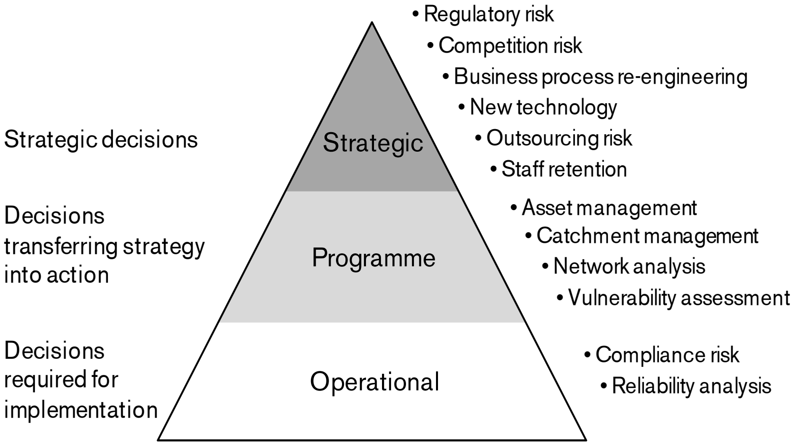

Figure 2. The hierarchy of decisions in risk management in the water utility sector (after Pollard, 2008)

According to Pollard et al. (2004) the drinking water sector is now formalising and making explicit approaches to risk management and decision-making that were formerly implicit. Furthermore, MacGillivray et al. (2007) emphasise that a significant shift in the drinking water sector's approach to risk management is ongoing. Risk management is becoming increasingly explicit and better integrated with other business processes compared to the historical implicit approach focused on treatment plant design and operation (Hrudey et al., 2006). One example is the increased use of the Hazard Analysis and Critical Control Point (HACCP) approach within the drinking water sector (Damikouka et al., 2007; Dewettinck et al., 2001; Gunnarsdóttir and Gissurarson, 2008; Hamilton et al., 2006; Howard, 2003; Jagals and Jagals, 2004; Mullenger et al., 2002; Yokoi et al., 2006). Principles and concepts of the HACCP approach in particular have been used by the WHO to develop the Water Safety Plan (WSP) approach (WHO, 2004), which is currently being implemented in many countries. MacGillivray et al. (2006) provide an extensive review of approaches to more credible and better decisions in the drinking water sector.

2.3 Water Safety Plans

In the 3rd edition of the *Guidelines for Safe Drinking-water Quality*, the WHO presented a *framework for safe drinking water* (WHO, 2004; 2008). The framework consists of health-based targets, Water Safety Plan (WSPs) and independent surveillance. The health-based targets should be based on evaluation of health concerns by a high-level authority and reflect what is considered to be an acceptable level of risk. The WHO (2004) defines safe drinking water as water which "does not represent any significant risk to health over a lifetime of consumption, including different sensitivities that may occur between life stages". The health-based targets are supposed to guide the WSPs and the independent surveillance aims to ensure the work is performed properly and also promotes improvement. The surveillance should be conducted by an independent agency and include all aspects of safety.

WSPs describe the development of comprehensive risk assessment and risk management procedures which encompasses all steps of the water supply system from catchment to consumer (WHO, 2006). This WSP approach was developed to organise and systematise a range of management practices, and thus draws upon a range of risk management approaches, including the multiple-barrier approach and the Hazard Analysis and Critical Control Points (HACCP) approach used in the food industry (WHO, 2006). WSPs vary in their complexity, being very simple in some situations. They are, however, a powerful tool for managing water supply safety.

The WSPs are a key element in the framework for drinking water quality and include:

- *system assessment:* to determine whether a water supply system can deliver water of sufficient quality to meet health-based targets. This assessment should include the entire system and consider interactions between elements.
- *operational control and monitoring* to control identified risks as well as monitor the system in order to detect any deviation from the required performance in a timely manner.
- *management plans* which describe actions to be taken under normal operating conditions and during incidents, and supporting programmes. (See Figure 3).

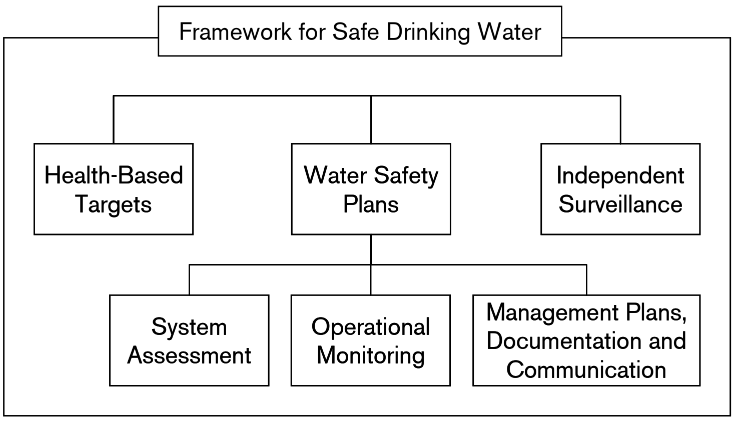

Figure 3. The framework for safe drinking water as presented by Davison et al. (2005).

The WSP approach is based on an integrated approach, i.e. the entire system from catchment to consumer should be considered, and includes principles and concepts from the multi-barrier approach and the Hazard Analysis and Critical Control Point (HACCP) system (described further below). A WSP should aim to minimise the contamination of water sources, reduce contamination of through treatment processes, and prevent contamination during storage, distribution and handling of drinking water, with these objectives applying equally to a large water supply system as well as household based supply systems (WHO, 2006). Effective control processes in the water supply system are the principal means of ensuring water safety in WSPs (Mahmud et al., 2007).

WSPs are currently being implemented in countries around the world and are thus an important part of risk management of drinking water systems (Breach and Williams, 2006; Garzon, 2006; McCann, 2005; Vieira, 2007). In October 2008, the WHO published a manual aimed at providing practical guidance to facilitate WSP development (WHO, 2008). The steps which need to be performed in a WSP are outlined in Figure 4.

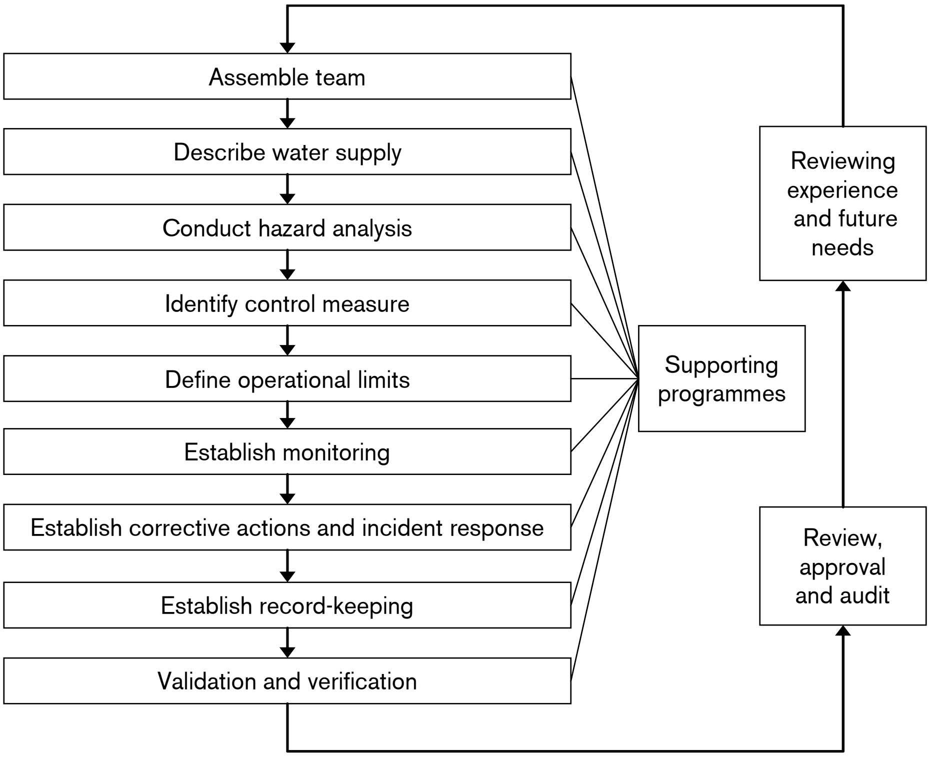

Figure 4. Key steps in developing a WSP (WHO, 2008; after Davison et al., 2005).

2.4 The TECHNEAU generic framework for risk management

A generic framework was developed in TECHENAU (Rosén et al., 2007), see Figure 5. The overall structure of the framework is based on the general risk management process as described by IEC (1995) but has been updated with important aspects of the WSP approach to link it more clearly to drinking water systems. The framework comprises three main parts: *risk analysis*, *risk evaluation* and *risk reduction/control*. *Risk assessment* comprises of risk analysis and risk evaluation. However, important tasks such as review, communication, collection of new information and updating are also emphasised in the framework.

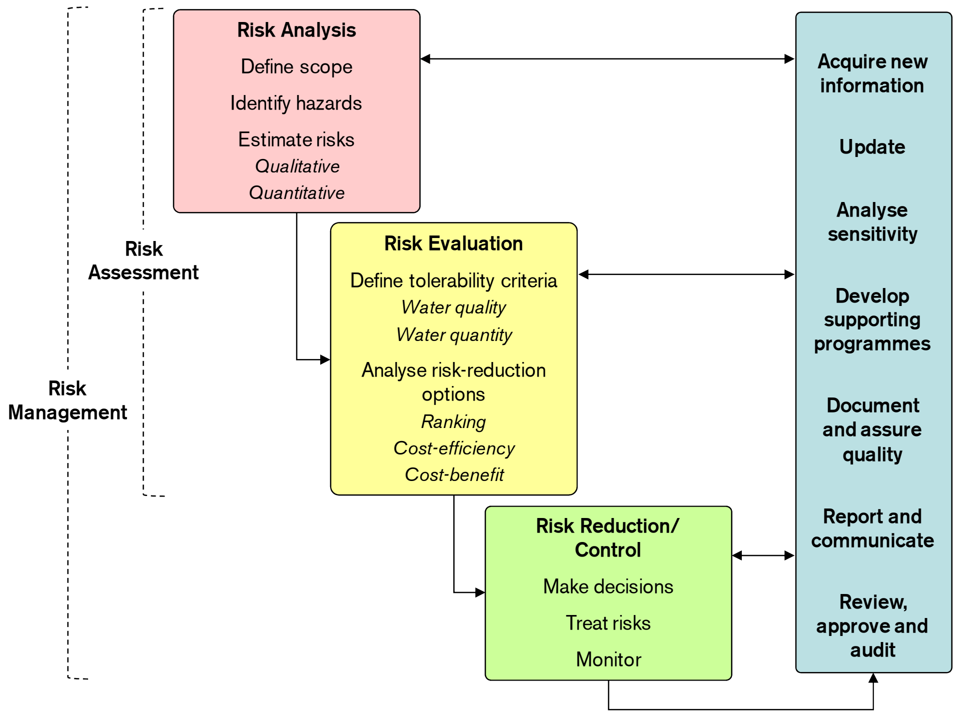

Figure 5. Schematic illustration of a framework for integrated risk management in WSP (after Rosén et al., 2007).

The first part of the framework is risk analysis, which starts with an initial scope definition. Defining the scope is important in order to set the basis for the risk analysis. It should include a definition and description of the system as well as descriptions of concerns, assumptions and required output to support decision-making. As clearly pointed out in the WSP approach, a team of people should be put together to support the risk analysis. The team should include people with knowledge of the system being analysed as well as people with knowledge of risk analysis. Together the team should have sufficient knowledge to perform the analysis. Once the scope has been defined, hazards should be identified and the risk estimated. The risk analysis can be qualitative or quantitative, depending on its purpose.

The output from the risk analysis should be used as input in the risk evaluation, which supports decision-making regarding risk management options. To enable risk evaluation, tolerability criteria defining an acceptable level of risk are needed. The WSP approach includes health-based targets related to the water quality. However, targets related to water quantity and other stakeholder values are also needed in order to evaluate all the risks. Efficient risk management of drinking water systems must include risks related to both quantity and quality problems. If the risk is not acceptable, it needs to be reduced and/or controlled. Alternative options for risk reduction can be identified and evaluated by means of decision analysis methods, such as cost-effectiveness analysis, cost-benefit analysis and multi-criteria analysis (MCA).

Based on the information from the risk analysis and risk evaluation (together termed risk assessment) decisions are made and implemented. To evaluate the efficiency of the implemented safety measure monitoring may be used. The information from monitoring and reporting systems as well as other information sources should be used to update the risk analysis and the risk evaluation.

In addition to the analysis, evaluation and reduction/control steps, the framework in Figure 5 emphasises the importance of analysing and considering uncertainties related to all steps. Furthermore, supporting programmes, documentation, communication and review are highlighted as important tasks.

The purpose of the framework is to provide a structure and toolbox to assist water utilities in their risk management work. The framework supports integrated risk management in WSPs and facilitates transparency and rational decision-making. The framework stresses the importance of an iterative process of continuous updating as new information becomes available and as conditions change. Communication between stakeholders is emphasised as important since it facilitates increased awareness and knowledge regarding risk issues among, for example, decision-makers, water utility personnel and the generic public. Furthermore, the framework includes methods and tools to assist hazard identification, risk estimation and evaluation in order to provide cost-effective and sustainable prioritisation of safety measures (Rosén et al., 2007; Lindhe et al, 2009; Rosén et al., 2010, Lindhe et al., 2010a, Lindhe et al., 2010b, Lindhe et al., 2011).

3 Risk tolerability in the water sector

3.1 Introduction

The establishment of criteria for the acceptability and tolerability of risk in the water sector is one of the least understood aspects of risk management (MacGillivray et al., 2007). None the less, criteria, explicit or implicit, are used to define risk tolerability in relation to water supplies as the supply of drinking water inherently involves health risks generated from the quality of the water supplied and supply risks due to drought and other factors. Hence there is a need for a continuing shift from an implicit approach to risk management to a more explicit approach in the water industry (Hrudey et al., 2006) in order to make risk management in the water sector more transparent and in line with societal expectations.

According to Renn (2008), an activity may be considered tolerable when its benefits justify it as worth pursuing but its associated risks require reduction to bring them within reasonable limits. An activity may be considered acceptable when remaining risks are so low that further risk reduction effort is not seen as necessary (Renn, 2008). This distinction is applied in the ALARP model outlined in Section 2.6 and Figure 4, where risks are classified as "acceptable" and "unacceptable", or fall in between in the ALARP region where the risk is tolerable but must be managed in accordance with the "as low as reasonably practicable" principle (Renn, 2008). Determining where the line between intolerable, tolerable and acceptable should be drawn is one of the most difficult tasks of risk management.

3.2 Risk acceptability and tolerability criteria

While risk assessment can provide an appraisal of the level of risk, risk managers still have to determine what level of protection is required (Salgot et al., 2006). According to MacGillivray et al. (2007), the establishment of risk acceptance criteria is the least understood aspect of risk management. In some organisations risk acceptability is largely set with reference to regulations and standards. Risk acceptance criteria may also set be in some organisations within discrete organisational areas of the company without reference to risk management policy or strategy, thus out of the control of any corporate risk manager (MacGillivray et al., 2007).

The WHO (2006) argues that in setting water quality standards, governments must take into account environmental, social, cultural, economic, dietary and other factors which will affect individuals exposure to water contaminants, thus leading to varying standards in different countries; because of this range of factors, society as a whole has a role to play in the standards setting process, particularly, the communities served, together with the major water users. Presumably the WHO means that representatives from a wide range of the different groups within society should be encouraged to participate in the standards setting process rather than individual members. For the public, in addition to water characteristics, factors like equity, voluntariness and nature of the exposure are important when considering water related risks for society (Havelaar and Melse, 2003). Ideally a quantitative risk assessment process, which takes into account local conditions and hazards, should be used to set health based targets (WHO, 2006). The quantitative risk assessment process should feed into management decision making and aim to provide incremental improvement in water quality.

The WHO (2006) suggests that modest but realistic goals for a water supply system are potentially more useful than overambitious goals which are unachievable, with the cost of implementing water quality standards needing to be considered when setting standards (WHO, 2006). Due to varying local conditions, governments should focus upon factors of greatest significance for public health. In general priority should be given to ensuring that the drinking water supply is microbiologically safe and to discourage consumers from using potentially less safe drinking water sources (WHO, 2006). The next priority is to manage chemical contaminants with a known health risk, such as arsenic, nitrate and fluoride, and then finally attention should be given to managing other chemical contaminants.

Hunter and Fewtrell (2001) suggest a list of possible approaches for determining whether a risk is acceptable or tolerable:

The pre-defined probability approach: With this approach the level of risk must fall below an arbitrarily defined probability, such as a life-time risk of cancer resulting from the hazard having to be less than one in a million, and thus able to be considered negligible.

The "currently tolerated" approach: This approach is based on the principle that a level of risk must fall below a level that is already tolerated by society and thus seen as acceptable. While superficially appealing, this approach is problematic. People are willing to tolerate different levels of risk for different activities, thus while it may be possible to calculate the currently tolerated risk of bathing in marine waters, this cannot be used to calculate a wider societal "currently tolerated" acceptable level of risk for other activities. Additionally, as noted by Hunter and Fewtrell (2001) there is a difference between currently accepted and acceptable, with smoking being an example of an accepted activity but the level of risk it imposes being considered unacceptable. Furthermore, the level of risk tolerated by part of society will not necessarily be tolerated by society as a whole.

The disease burden approach: This approach requires that the level of risk from a specific hazard falls below an arbitrarily defined attributable fraction of total disease burden within society.

The economic approach: This approach suggests that the cost of reduction of a risk should not exceed the benefits of reduction; opportunity costs should be considered if resources could be better spent of other more pressing health problems. One problem with this approach is that the cost of reducing a water related risk in a society are frequently borne by different groups than would benefit from the risk reduction (Hunter and Fewtrell, 2001).

The public acceptance approach: With this approach the views of the public determine what level of risk is acceptable. This approach, while also superficially appealing is problematic because rarely will all sections of a society have full access to the all the information required to judge the tolerability of a risk and the whole of society may not have the skills required to interpret that information. People's judgements about risk can be distorted by a range of factors:

- Availability bias – how easily events related to the risk can be recalled.
- Confirmation bias – the idea that after a person has reached a view on something they ignore evidence to the contrary
- Framing bias – the idea that the way a risk is presented will have a significant effect on whether the public feel the risk is acceptable (Kahneman et al., 1982).
- Distribution bias – the more constant the losses resulting from the source of risk, the more likely its overall impact will be underestimated (Renn, 2008).

Furthermore, factors such as whether the risk is involuntary or inequitably distributed within society also play a role in determining public acceptance of the risk (Hunter and Fewtrell, 2001).

While risk tolerability may be determined by expert judgment using some of the approaches outlined above, Hunter and Fewtrell (2001) suggest that risk tolerability will frequently be determined through a political bargaining process that may not produce the (expert determined) optimum solution, but rather, a solution which is acceptable to most stakeholders. However, while expert judgment based on scientific processes may be superficially appealing, experts' opinions themselves are value laden (Hunter and Fewtrell, 2001).

Murphy and Gardoni (2008) suggest the five criteria that need to be met when choosing an approach to judge the tolerability and acceptability of risks:

- Relevant factors need to be taken into account in an appropriate way.
- Required data inputs must be accurate, available and accessible.
- Concrete, practicable and theoretically justified conclusions about the required actions must be possible.
- Value judgements and the methods used need to be transparent.
- An indication of the societal distribution of risks must be provided.

Renn (2008) also considers the role of values and evidence when forming judgements of the acceptability and tolerability of risk. The tolerability of a risk can never be determined on the basis of evidence alone, but likewise, evidence is essential in order to determine whether a societal value has been violated.

Murphy and Gardoni (2008) argue a capabilities-based approach is required for judging the acceptability and tolerability of societal risks. They argue that judgements about the acceptability of risks should be based on the expected impact of a hazard on individuals' capabilities, with capabilities referring to the functioning and activities of individuals given the resources available to them. Murphy and Gardoni's (2008) approach to determining risk tolerability of looking broadly at the aggregate effects of hazards on individuals within society is different to other approaches in the literature, such as outlined by Hunter and Fewtrell (2001) as these approaches focus more on determining individually the acceptability of risks posed to individuals by specific technologies.

When assessing the expected impact of a hazard on individuals' capabilities Murphy and Gardoni (2008) argue that two thresholds should be examined. The first threshold is the minimum level of capabilities attainment which is acceptable for individuals to have following a hazard event over a period of time and which ideally no individual should fall below. However, it may be acceptable for a small number of individuals to fall below this threshold temporarily. The second tolerability threshold is the absolute minimum level of capabilities attainment below which no individual should ever fall (Murphy and Gardoni, 2008). As capabilities themselves cannot be quantified directly indicators are needed to assess the level of individuals' capabilities. The acceptable risk threshold is calculated by summing the minimally acceptable level of selected capabilities measured by these indicators, and then the probably of a given hazard exceeding the acceptable threshold can be assessed (Murphy and Gardoni, 2008).

Although the capabilities-based approach may be simple in theory, in practice the difficulty lies in how you define and measure minimally acceptable levels of capability since these are generally not quantities but states of well-being. Getting agreement on capabilities these would be as difficult as with other methods for establishing risk tolerability. The applicability of this capabilities-based approach for some water quality risks is questionable as presumably the death of individuals within a society would result in a hazard being unacceptable since those individuals affected would clearly fall below the second threshold permanently.

3.3 Baselines of tolerable risk: Water quality risk

While recognising the complexity of the risk management process for drinking water supply, the WHO (2006) recommends the adoption of a baseline definition of tolerable risk for the development of water quality guidelines from which departure is possible in specific situations. As Havelaar and Melse (2003) argue, one potential problem with this approach is that the setting of risk reference values suggests that strict lines can be drawn between tolerable and intolerable, and between where action is required and when it is not.

The reference level of risk used by the WHO in its guidelines is a 10^{-6} Disability Adjusted Life Years (DALYs). DALYs are a health impact measure which combines years of life lost with years of lived with a disability that is standardised by severity weighting (Havelaar and Melse, 2003). DALYs are calculated for a specific pathogen or pollutant by multiplying the number of people affected by average duration of the adverse health response and the severity of the adverse health response (Havelaar and Melse, 2003). The major advantage of using DALYs is that this system allows the comparison of very diverse health outcomes by the use of a common metric – time (WHO, 2006). The disadvantage of DALYs is that they are not very easy to interpret by non-experts, with alternative measures, such as mortality rates per million people, being easier to understand (Havelaar and Melse, 2003).

The WHO's reference level of risk of 10^{-6} DALYs equates for carcinogens as the equivalent of one excess cancer death per 100,000 people drinking water containing the carcinogenic substance over their lifetime; for a pathogen with a low fatality rate, this is the equivalent of a one in a thousand annual risk of disease or a one-tenth risk over a life time (WHO, 2006).

In the US the maximum permissible levels for pollutants in public water supply are set by the US Environment Protection Agency (EPA) as close as feasible to the maximum level of contamination at which no known or anticipated human effects occur (Rowe et al., 2007). The primary goal of the EPA in setting maximum permissible levels of pollutants is the protection of human health with the standards being based on information from peer-reviewed scientific journals (US EPA, 2005); in the absence of data to the contrary, the default position is to be health protective. Additionally, the US also has health based screening levels which are non-enforceable benchmark concentrations of contaminants which, if exceeded, may be of concern for human health (Rowe et al., 2007). For carcinogens, health based screening levels correspond to an increased lifetime cancer risk of one in a million to one in ten thousand; for non-carcinogens, health based screening levels indicate the maximum contaminant concentration in drinking water not expected to cause any adverse effects throughout a lifetime of exposure (Toccalino, 2007). This level of risk is calculated on the basis of a 70 kilogram adult drinking two litres of water per day over their lifetime, and for non-carcinogens it is also assumed that 20 percent of contaminant exposure comes from drinking water sources and the rest from other sources such as food or air (Toccalino, 2007).

California has set similar drinking water standards as those set nationally in the US, while simultaneously requiring regular testing of drinking water. A one in a million risk is the required standard for carcinogens while for non-carcinogen pollutants, the level is set such that no toxic effects are expected (Office of Environmental Health Hazard Assessment, 2003). The Californian Department of Health is required to set drinking water standards for chemical contaminants as close to this level of risk as possible.

3.4 Baselines of tolerable risk: Water quantity risk

3.4.1 Water scarcity risk

Much of the discussion so far has focused upon the management of water quality risk. However, water utilities equally have to manage water scarcity risk. Factors producing water scarcity risk include droughts, water quality concerns, lack of institutional capacity for effective water governance, political and regulatory conditions, cross-boundary issues, and stakeholder concerns (Emtairah et al., 2004).

Iglesias et al. (2007) outline a framework for the management of water scarcity risk made up of six components:

- Evaluate the data and information relevant for characterising and assessing water scarcity and which may be used to produce trigger indicators.
- Describe the institutional and legal frameworks that impact on reservoir inflows and drought preparedness.
- Identify stakeholders.
- Validate the understanding of the interactions between institutions, legislation, and stakeholders.
- Define thresholds for acceptable water scarcity risk and the indicators for identifying the risk level.
- Develop measures for managing the risk.

Hensher et al. (2006) note that all water supply systems are designed to deliver a specific level of security of supply, and to manage the risks associated with this water utilities regularly must make tradeoffs. Options open to water utilities for managing quantitative risk include the augmenting of supplies, and the adoption of demand-side measures, with each of these actions imposing a cost to society while at the same time reducing the probability of future water restrictions.

Hensher et al. (2006) suggest that willingness-to-pay studies with water users can be used to define risk tolerability relating to water scarcity (Hensher et al., 2006). What they are suggesting is essentially applying a public acceptance approach to determining risk tolerability. Given that the effects of water supply quantity problems on a population, except in extreme cases, tend to be economic and these impacts are generally understandable to the public, it is easier to make a case for applying a public acceptance approach for determining risk tolerability levels in this context than it is for water supply quality problems which may affect the health of only specific segments of the population and require the synthesis of complicated technical data.

According to Hensher et al. (2006) the water supply system for Canberra, Australia is managed to deliver an unrestricted water supply 95 percent of the time, thus water restrictions can be expected to occur for at most 12 months in every 20 years. Water restrictions are trigged when reservoirs reach pre-defined levels and there are five levels of restrictions, ranging from voluntary through to mandatory depending upon how serious the supply situation becomes.

3.4.2 *Supply interruptions*

In addition to dealing with water scarcity and managing the risk of climatic variation affecting the security of water supplies, water utilities also have to manage the risk of supply interruptions, such as the effects of a water mains bursting and thus cutting off supply to water consumers. MacDonald et al. (2005) investigated the effect of service interruptions on water consumers in Adelaide, Australia and the extent to which water consumers were willing to pay for a more reliable water supply. They conducted a survey in streets which had recently experienced supply interruptions, although not all respondents had actually been affected. The perceived inconvenience of supply interruptions varied widely, with 47% of respondents perceiving no or only minor inconvenience, 35% some inconvenience, and 12% significant inconvenience and only 5% extreme inconvenience (MacDonald et al., 2005). Choice modelling was used to assess the willingness to pay for improved reliability of supply and interruptions of supply of shorter duration. Respondents were given a choice of three options:

- Option A (Status quo): The likelihood of two supply interruptions of six hours in the next 12 months but water bills remaining unchanged.
- Option B: The likelihood of one supply interruption of four hours in the next 12 months but water bills increasing by $40
- Option C: The likelihood of no supply interruptions, but any supply interruptions that do occur likely to be of two hours duration, and water bills increasing by $80.

Fifty percent of respondents chose option A, 19% chose option B, 17% chose option C, and 14% didn't know. Recent experience of an interruption did not have a significant influence on results.

In many developing countries urban water supply systems are intermittent, with water consumers regularly receiving water less than 24 hours per day (Totsuka et al., 2004). Such intermittent supplies can create inequities within a water supply system for consumers as the large peak flow within a water network when pressure is restored will result in significant pressure loss furthest from supply points and so distant consumers will have less opportunity to refill roof-top storage tanks. Furthermore, intermittent supply systems lead to an increased risk of water quality problems due to low pressure or even vacuum conditions forming in pipes, with contamination entering through leakage points (Totsuka et al., 2004). Water quantity and water quality risk are interrelated and thus need to be considered together.

3.5 Conclusion

Defining risk tolerability in relation to the supply of drinking water is not a simple process, with the risk related literature providing few concrete answers on how to define risk tolerability. Risk assessment can never be a neutral scientific and fully objective process since risk itself is a subjective social construct and risk tolerability is very context specific. Thus, it is rarely possible to produce meaningful thresholds. Rather, many stakeholders need to be involved and the highly contested political processes need to be made as transparent as possible so that the tolerability criteria used and associated value judgements are explicit. It is also important that the distribution of risk within the society is considered in a transparent way.

The processes described here for defining water quality thresholds and standards are largely based on what is presented as rational scientific expert processes and the question for the general public then is whether these processes seem "reasonable". Risk managers need to employ best practice and the most rational methods for setting standards, transparent processes are required so that these processes are open to public scrutiny and risk managers need to ensure that they are seen as having the public's health as their primary motive.

4 Decision support

4.1 Introduction

As previously described, different types of decisions need to be made by water utilities in managing risks. MacGillivray et al. (2006), Pollard et al. (2004) and Pollard (2008) suggested that decisions can be categorised into *strategic*, *programme* and *operational decisions*, see also Figure 2. At the strategic level regulatory, commercial and financial risks are included while risks linked to, for example, asset and catchment management are considered at the programme level. Risks associated with specific operations, such as failure of process components, are managed at the operational level. Strategic decisions are supposed to be transferred into actions at the programme level and implemented at the operational level.

As a basis for the decisions, criteria need to be defined for how to decide between different alternative actions or risk-reduction options. Examples of decision criteria are:

- *Maximum expected utility:* In an economic context, choose the alternative associated with the maximum expected monetary outcome, considering the stream of costs and benefits over a given time horizon, including the economic value of risk reductions. A cost-benefit analysis may include people's willingness to pay for specific service levels.
- *Cost-effectiveness criterion*: Choose the alternative that achieves tolerable risk levels at the lowest cost. This criterion does not require a monetary valuation of the risk reduction.
- *Specific performance target criterion*: Choose the alternative that complies with set performance targets, such as a specified tolerable health risk level or specified component reliability.

What criterion to use depends of course on the type of decision. At the strategic and programme levels, the cost-benefit criterion may be relevant. Cost-effectiveness may be a relevant criterion at programme level and in some cases at the operational level. At the operational level the specific performance target criterion is probably applicable to many decisions. These criteria are all described as one-dimensional, whereas in reality the decision-maker, especially at strategic and programme levels, often has to acknowledge several criteria simultaneously, such as environmental, financial, reputation, public health and regulatory criteria. In addition, as described in Chapter 3, defining specific performance targets or risk tolerability levels is not an easy task and adds to the complexity of the decision-making process.

An obvious goal of decision-making appears to be to choose the alternative that maximises (or minimises) some specified criteria. However, for many factors of the decision problem, such as technical factors, environmental factors, economics, regulations and reputation, we do not know the outcomes. As a result, decision-making is almost always associated with uncertainties and we have to make decisions under uncertainty. In water management, there is a vast literature on uncertainty in decision-making. For example, Beck (1987) reviewed the role of uncertainty in identification of water quality models. Decision analysis is a systematic approach to support decision-making under uncertainty. Examples on decision analysis methods are cost-benefit analysis (CBA), cost-effectiveness analysis (CEA), Bayesian decision analysis, and multi-criteria analysis (MCA). Numerous examples of such methods applied to water and environmental decision problems are given in the literature, see e.g. Freeze et al. (1990), Wladis et al. (1999), Norrman (2004), Back (2006), Back et al. (2007), Burgman (2005), French et al. (2005), Xu & Tung (2006), Brower & De Blois (2008).

Given the inherent uncertainties in many decision problems, the challenge is according to Aven (2003) to establish relevant guidelines on how to handle uncertain situations so that we make *good* decisions. According to Aven (2003) there are two basic ways of thinking to reach a good decision:

1. Establish an optimization model of the decision-making process and choose the alternative that maximizes some criteria.
2. See decision-making as a process with formal risk and decision analyses to provide decision support.

Aven (2003) suggests that the second way is the most realistic and useful in most circumstances. He points out that a mathematical optimization model alone is typically not enough to provide the full basis for the decision-making. Risk and decision analysis methods should instead be seen as tools that can support the decision-maker with important input. It is then the responsibility of the decision-maker to perform relevant managerial review and judgment of factors that cannot be incorporated into a formalised model in order to reach a good decision. Aven (2003) suggests a basic structure for the decision-making process, see Figure 6.

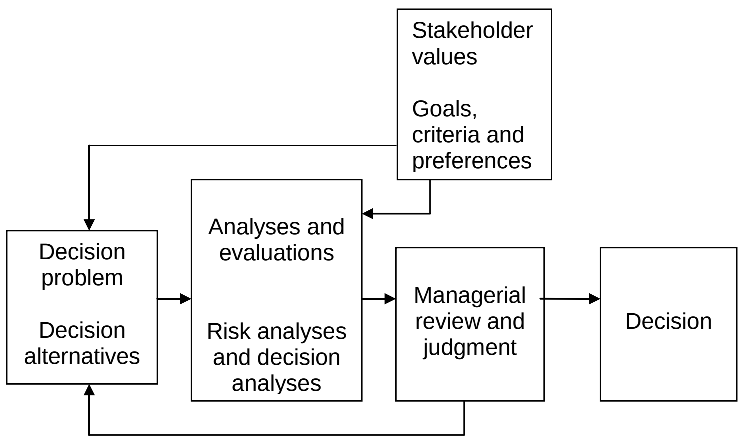

Figure 6 The basic structure of the decision-making process (Aven, 2003)

The decision problem concerns choosing among a set of decision alternatives. The set of alternatives is defined through an integrated process involving managers and experts. The development of alternatives is driven by the boundary conditions such as stakeholder values which provide criteria, goals and preferences. Moreover, managers and experts have knowledge and information which can influence the selection and design of alternatives.

Before making a decision, managers need to know the consequences and performance of choosing an alternative instead of another. Here, decision support tools like risk analysis and decision analysis facilitate a structured evaluation of factors such as costs, risk reduction and environmental impacts.

Decision support in managing risk issues can be provided by a wide variety of risk analysis and decision analysis methods. Pollard et al. (2004) provide an overview of various methods applicable to different types of decisions in the water utility sector. They compiled information on a number of studies where primarily different risk analysis methods had been used for decision support, see Table 1.

Table 1. *Risk analysis strategies for operational, programme level and strategic risks in the water utility sector (Pollard et al., 2004).*

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

Important decision support tool in the water utility sector is provided by risk analysis methods. Numerous examples of the use of risk analysis tools exist in the literature, see e.g. Pollard et al. (2004) and Hokstad et al. (2008). However, in the present report, we focus on methods where risk evaluation is explicitly performed. Below, we therefore give a presentation of the principles of decision analysis and decision analysis methods.

4.2 Decision analysis

To analyse a decision problem can be compared to solving a puzzle (Figure 7). The problem can be simple, i.e. a puzzle with a few pieces, or complex, i.e.

a puzzle with many pieces. You may have little knowledge or be quite sure about what the puzzle will look like in the end, just like you may have different amounts of information about the alternative actions before the analysis is started. In the end you may have the full picture of the problem or there may be parts missing and these pieces may be difficult or impossible to find. Hence, subjective information, e.g. expert judgements, may be needed to fill in the missing gaps. The overall aim of solving a puzzle/analysing a decision problem is to put the pieces/the information together correctly.

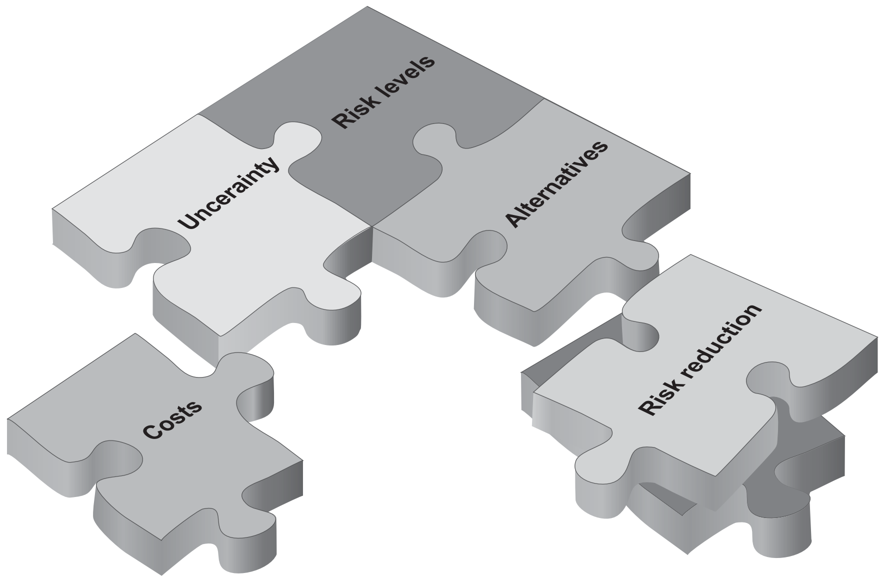

Figure 7 Illustration of a decision problem as a puzzle. The pieces represent information relevant to the decision problem (Lindhe, 2010).

The context of decision problems may look very different. However, Keeney (1982) lists five generic aspects relevant to decision problems:

- A perceived need to accomplish some objectives.
- Several alternatives, one of which must be selected.
- The consequences associated with alternatives are different.
- Uncertainty, usually about the consequences of each alternative.
- The possible consequences are not valued equally.

To deal with the above five aspects Keeney (1982) describes decision analysis based on the four steps: (1) structure the decision problem; (2) assess the possible impacts of each alternative; (3) determine the preference (values) of decision-makers; and (4) evaluate and compare the alternatives. This structure is very much in line with the decision-making process as presented by Aven (2003), see Figure 6. Different decision criteria can be used to evaluate alternatives and one of the most common is to maximise expected utility.

There are basically three disciplines of decision theory: (1) descriptive, (2) normative and (3) prescriptive. Descriptive decision models aim to describe *how decisions are made* by people. The purpose of normative models, in contrast, is to describe *how decisions should be made* to be rational according to predefined rules. The prescriptive models aim to support decision-making by providing a structure that avoids typical pitfalls and makes sure the decision-maker considers aspects identified as relevant. Prescriptive models can be seen as an aid to make decisions more in line with the normative theory. The decision models presented in this thesis are of a prescriptive nature and decision analysis here is used to refer to normative/prescriptive decision analysis.

A pitfall common to decision analysis is the misconception that it provides a solution to the decision problem. However, it should be understood that decision analysis, like any type of analysis, only focuses on part of a problem (Keeney, 1982). Instead, its purpose is to produce insight to help decision-makers to make better decisions (Aven, 2003).

Decision analysis methods provide different methods and tools for structuring decision problems and for providing decision support. The tools and methods need to be applied according to framework for decision-support that is clear and agreed upon within the water utility and at affected stakeholders. A suggestion to a generic framework for decision support is presented in Chapter 6, together with descriptions of some specific methods. More detailed descriptions of these methods and their applications in TECHNEAU are given in Lindhe et al. (2009), Lindhe (2010), Lindhe et al. (2010a), Lindhe et al. (2010b), Rosén et al. (2010) and Lindhe et al. (2011).

5 Survey on decision-making at water utilities

5.1 Aims, background and rationale

As noted by the World Health Organisation (WHO, 2006) water is essential for life and therefore every effort must be made to ensure that drinking water supply is as safe as practicable. Safe drinking water is defined by the WHO as water which "does not represent any significant risk to health over a lifetime of consumption, including different sensitivities that may occur between life stages"(WHO, 2006, p1). Achieving the supply of safe drinking water depends upon the effective management of risk by the water utilities which are tasked with the management of water supply networks. Risk assessment is part of an iterative cycle used to drive management decisions whose purpose is to achieve incremental improvements in water quality (WHO, 2006).

TECHNEAU's *Generic Framework and Methods for Integrated Risk Management in Water Safety Plans* report (Rosén et al., 2007) noted that although there are lot of risk models and theoretical approaches to risk management available, the use of these techniques may be limited.

The aim of this survey is to evaluate how different water companies actually make decisions about risk management and major changes to the water supply. As such, this survey documents risk management and investment approaches as implemented in a range of water companies in order to ascertain the extent to which any of the theoretical approaches identified elsewhere in WA4 are applied in practice.

5.2 Method

Representatives from water utilities in six European countries were interviewed about how they make decisions relating to risk management and major changes to their water supply systems. Water utilities were selected in order to provide a range of background conditions, such as the size of population served, whether they were predominantly urban or rural, known use of different risk management approaches, etc. Interviews were carried out in the Czech republic, Netherlands, Belgium, Norway, Sweden and the UK. Interviews were carried out by researchers from local universities or research institutes at the end of 2009 and beginning of 2010. See Table 2 for a list of the number of interviews conducted in each country, and Box 1 for a list of the interview questions. Names of utilities have not been used in the text as annonimity was requested by some utilities.

Table 2 List of countries, number of water utilities surveyed and organisation conducting the surveying / interviewing

Country	Number of water utilities interviewed / surveyed	Interviews conducted by researchers from
Czech Republic	3	Státního Zdravotního Ustavu (National Institute of Public Health)
Netherlands	9	KWR Watercycle Research Institute
Belgium	2	KWR Watercycle Research Institute
Norway	1	SINTEF
Sweden	4	Chalmers University
United Kingdom	3	University of Surrey

Box 1: Interview Schedule.

1) Thinking about the major infrastructure investment decisions your company has made in the last 5 years what were these?

- At what level of the organisation were the decisions made? Were the decision made in steps at different levels?

- When you made these decisions *how* did you decide between the options available?

- Did you use the same decision making process on each occasion? If not, how did they differ?

- Do you think that the best possible decisions were arrived at in each case?

- Did you consciously consider other ways of making this decision e.*g. CBA, MCA, CEA*? - If so, what were these ways and why did you chose not to use them?

2) Thinking about the next 5 years, what are the major decisions involving risks that you will have to make?

- How do you think you will make a decision between options?

- At what level of the organisation will these decisions be made this time?

- Will the decision be made in steps at different levels?

- Will you use the same decision making process in each case?

- Why have you chosen that way to do it?

5.3 Results

5.3.1 *Czech Republic*

In the Czech Republic interviews were conducted with three organizations involved in the supply of water and sanitation services. The smallest of these serves approximately 80,000 customers in a predominantly rural region, and while being a private company in majority foreign ownership, it is both the owner and operator of water services across the majority of the region it serves. The second of the organizations interviewed was a municipal water supply and sanitation department which serves a population of approximately 110,000 and owns but does not operate the water infrastructure across its region. The third organisation was a regional water company which operates the water supply and sewage infrastructure owned by the more than 600 municipalities of the predominantly rural region that it serves.

5.3.1.1 *Previous Investment Decisions*

The spokespersons for the organizations interviewed noted a range of investment decisions had been made during the previous five years, including:

- Creation of ten-year renewal plan, which includes selected parts of the water supply network, some water reservoirs, and some water treatment plants.
- Replacement of water mains.
- Reconstruction or partial reconstruction of water treatment plants, building of new conduits and building new pumping stations.
- Reconstruction of waste water treatment plants and two sewerage systems.

5.3.1.2 *How are decisions made?*

Water system investment decisions in the Czech Republic often start at a technical level when suggestions are made for investments. Decisions are taken at a board level and then recommendations from the board are submitted for approval to general shareholder meetings, with such meetings generally approving the suggested plans. If a subsidy is required for the investment to go ahead, the body providing the subsidy must give final approval of the decision.

5.3.1.3 *What criteria are used?*

A range of investment criteria are used, including:

- Cost of the investment
- Securing compliance with drinking water quality standards and compliance with the requirement to provide a continuous supply of water.
- Failure rate in the network
- Minimization of risk to consumers
- Minimization of operational costs

- Community and political views.

Other factors may be considered when relevant, such as for investments in existing technology, experience with such technology may be taken into account and evaluated.

5.3.1.4 *What decision making processes are used?*

The Czech water companies report using their own decision methods which are based on experience and while are not formalized methods such as Multi-Criteria Analysis (MCA), are essentially the same but are less formalized and therefore less time consuming and cheaper to implement.

The spokesperson for one of the companies stated that they are considering the use of formal techniques such as CBA, MCA and CEA for the future. Another of the companies said that they are using a MCA approach for the creation of long-term plans of renewal (ten years).

5.3.1.5 *Future Investment Decisions*

The Czech water companies interviewed expect to continue their current decision making processes. The process of having investment proposals initiated at the technical level of the organisation, an investment decision being taken at the board level, and then approved by shareholders and funders if a subsidy is required was seen as allowing an inclusive process which involving technical input as well as input from medium and high level management.

In terms of how decisions are made, compliance with legal requirements has priority in comparison with economic advantage. However, if two options are comparable for consumers with regard to water quality and reliability of operation, the key factor will be cost – initial investment and cost of operation during lifetime – in order to help ensure sufficient finances for system renewal and the building of new water supply and sewerage systems.

5.3.2 *Netherlands & Belgium*

A questionnaire was sent to nine water companies in the Netherlands and two in Belgium. Additionally, five face-to-face interviews were conducted with representatives of some of these water companies.

5.3.2.1 *How are decisions made?*

Decisions are made at different levels of the organisations, mostly depending on the associated costs. When decisions are within the yearly budget and are for more standard work, decisions are taken at a lower level. Larger decisions are made at the highest level. Since water companies are autonomous, there is no political involvement in making decisions.

5.3.2.2 *What criteria are used?*

As part of this research with Dutch and Flemish water companies, a workshop was used to assess decision making criteria for mains replacement. A number of criteria for mains replacement were identified:

- Likelihood of failure: defined by burst frequency, main inspections or a decision support model.
- Consequence of a burst: defined by effects on direct supply, robustness of the system, risky elements in the vicinity of the main (roads, dykes, buildings).
- Future developments: planned works of third parties or based on a master plan for city development
- Cost-effectiveness

5.3.2.3 *What decision making processes are used?*

The companies all have their own standardised ways of making decisions, and claim that they make the best possible decisions. Although they state that formal procedures such as Cost-Benefit Analysis (CBA), Cost Effectiveness Analysis (CEA) or MCA are not performed, the option that meets the criteria to the lowest cost is selected, therefore a CEA approach is essentially used. Often many different criteria are considered, so the decision analysis is in some sense a MCA.

The concept of CBA was thought not to be relevant for water companies in the Netherlands and Flanders. Prices are set and the quality of supply is good so for customers there is no reason to pay more and companies do not calculate benefits.

In the first phase a problem is defined and analyzed. This results in a list of options, for which the best solution is chosen, mostly by comparing a number of alternatives for construction. In some cases an informal MCA approach is used. Water companies do not make a company wide analysis of risks; rather a general ranking of the most appropriate reduction method (by weighing risk reduction to costs) is used. Risk assessment can overlap with risk management decisions. Rather than follow a comprehensive theoretical framework for decision making, in practice water companies take decisions on risk in a more organic way, with an extensive risk analysis seldom being made. More commonly, the critical elements are defined, mostly based on experience, and informal risk management measures are taken. Due to the complexity of the network structure risk, quantitative risk assessment for water distribution this is not used extensively.

5.3.2.4 *Future Investment Decisions*

Water companies were asked if formal methods such as CBA, CEA, and MCA will be used in decision making within the next five years. From the ten interviewees, nine claimed that they would use these methods. They stated that in the future, more formalised decisions will be taken, because of:

- the increasing complexity of decisions

- stakeholders are asking for better founded decisions
- requirements for more uniform and reproducible decision making (PAS55)
- more focus on costs-efficiency
- the availability of better decision support models

5.3.3 *Norway*

The Norwegian component of the study involved one interview with a senior adviser of a municipal water and sewage company that serves a population of approximately one-quarter of a million people.

5.3.3.1 *Previous Investment Decisions*

The spokesperson said that some of the major decisions in previous years have related to the updating of the water treatment plants (WTPs) in order to fulfil the national drinking water regulations. The city served has 5 different WTPs which are connected into the same wastewater transport system making it a flexible and robust system. Each of the different WTPs can be closed down and all customers will still receive wastewater treatment services. All of the WTPs has been upgraded in the last 5-10 years with hygienic barriers, and four of the five WTPs have two hygienic barriers against parasites. Thus, a multiple barrier approach was adopted as a result of decision making within the last five years.

5.3.3.2 *How are decisions made?*

Considering key decisions that have been made, such as the updating of hygienic barriers for the treatment plants, decision making is based on the need to fulfil national legislative and regulatory requirements while considering alternative approaches.

Whilst the spokesperson acknowledges that a good and well established working procedure has been developed between the administration in the water company and the politicians. Acceptance criteria with thresholds for frequencies for different hazards, however, are not presented to politicians as more established and developed plans that are less technically detailed have been found to be more useful for political decision makers.

All the larger Norwegian water companies are public and follow a full cost recovery system where all cost related to water (and wastewater) are met by water tariffs. This also influences the way decisions are made. Available funds from water and wastewater utilities cannot be moved to other public sectors (like health care, the roads department, etc). The full cost recovery system implies that the water utilities can make investments if they are necessary and important. However, the water industry should still act as efficiently as possible, and different types of benchmarking are carried out for evaluative purposes.

5.3.3.3 What criteria are used in decision-making?

The main criteria and ranking in terms of relative importance are listed below:

1. Fulfilling water quality and quantity requirements according to regulatory and legislative requirements
2. Service level to the customers (i.e. providing redundancy in water supply to the customers to avoid supply disruptions)
3. Risk
4. Cost

The spokesperson stated that cost has become less important. Ten to twenty years ago cost was ranked higher, however, the understanding of water supply as critical infrastructure has evolved, even before the case of the water borne outbreak of giardiasis in Bergen in 2004.

5.3.3.4 What decision making processes are used?

The water and sewage company tries to achieve a good balance between the different decision making criteria. Evaluations are not carried out using formalized methods such as CBA, MCA CEA, however, quantitative evaluation of the criteria is carried out. For all projects estimates of planned investment costs are also calculated and implemented in the master plans. One of the reasons cited for not using formalized procedures such as CBA is that the use of discount rates in cost benefit analysis is not well suited for water and wastewater investment since infrastructure in this sector has a very long time horizon.

5.3.3.5 Future Investment Decisions

Within the next 5 years, major decisions involving the characterization of risks will include:

- Increasing the rehabilitation rate of the water network
- Network improvements leading to redundancy in specific areas of the water supply system in order to improve the reliability of the system.

Decision making approaches will involve a semi quantitative /qualitative approach which will be applied by comparing costs and listing 'pros and cons' with the different options. The spokesperson provided an example of the case of improving network reliability in a particular area of their jurisdiction, where a hazardous event could involve a major pipe break or pump failure on the main pipeline feeding the area. In such an event the existing water tank in the zone would only be able to feed the system for a few days. In order to deal with this problem there are different risk reduction options, mostly related to building new infrastructure. Intuitively there is one good solution to the problem which also has many positive side effects. Other possible technical solutions / alternatives may also exist which increase the system reliability, however, these lack as many additional positive effects.

5.3.4 *Sweden*

Four water companies in Sweden participated in this survey. Two of these were large water companies (here after referred to as Companies A and B) serve populations of several hundred thound, and two were smaller companies (here after referred to as Companies C and D) serve populations of less than 60,000.

5.3.4.1 *Previous Investment Decisions*

Examples of recent investments that have been made by the Swedish water utilities interviewed included:

- New electrical switch-gear plants and the upgrading perimeter protection (surveillance cameras etc.)
- New water treatment facilities or improvement to existing water treatment facilities
- New water protection areas
- Enhanced supply from reserve water sources
- Enhanced ability to handle "new contaminants"
- Connection of existing water distribution systems in order to increase the water supply safety and environmental benefits.

5.3.4.2 *How are decisions made?*

The spokesperson of one of the large utilities interviewed (Company A) said that decisions are made in steps at different levels in the organisation. Depending on the type of decision (mainly related to the cost) the decision is made at different levels in the water utility organisation, however, if costs are high the politicians in the city have to make the decision. In cases where the municipality has a range of options, an assessment of alternative options are prepared by the water utility and most of the time the option meeting the predefined criteria to the lowest cost is selected. Making a decision requires an analysis of the advantages and limitations of the different options.

The spokesperson of the other large Swedish utility interviewed (Company B) To provide an overview of relevant risks, each year the organisation identifies and assesses the probability and consequence for possible hazards. This is not a detailed risk assessment but is part of a screening process where the most severe risks are identified and further analysed later. The results are summarised and recommendations are provided by a safety team. The utility also consider the environmental and quality management systems to be parts of their risk management work.

In terms of how decisions are made, each department of the water utility writes proposals (for investments related the specific department, e.g. the distribution network) which are submitted to a committee. The committee includes representatives from different parts of the utility and the aim of their work is to prioritise between all suggested investments based on an understanding of the entire system. Depending on the total cost, the final decision has to be made at different levels in the organisation. A long-term plan has been compiled that aims to guide the decision-makers when deciding between alternative actions. Furthermore, the ability of the organisation to manage a specific project is considered when making a decision.

The spokesperson for the one of the small Swedish utilities interviewed (Company C) said that decisions are made in steps, whereby water utility personnel discuss suggested investments/actions with the politicians based on risk assessments (depending on the context, this may be simple or detailed) and a budget in then developed. Large investments are decided by the politicians and smaller ones by the water utility.

The spokesperson for the other small Swedish utility interviewed (Company D) said that decision making in Uddevalla regarding detailed water safety improvements are taken at the operational level. More strategic decisions on larger investments are made at a political level. The large investments are typically suggestions from the leadership of the operations, but the final decisions are made by the political boards. Decisions regarding the largest investments are made by the highest political board of the municipality. All costs for water and waste water services are financed by tariffs and fees. No costs are financed by taxes. In terms of how decisions are made between different options the details of the alternatives are evaluated from engineering and economical standpoints.

5.3.4.3 *What criteria are used?*

With Company A, the overall aim has been to reduce the risk to an acceptable level. Politically established goals / performance targets have been defined, which are based on what is considered to be acceptable risk levels. Alternative actions that meet the performance targets are identified and the one that is considered to be most cost-efficient is selected. The goals / performance targets are presented in an 'action plan' that also includes possible actions to reduce the risk. The document is prepared by the water utility and the goals/performance targets are approved / decided upon by the politicians. The suggested actions are however, not approved and have to be further analysed and discussed before they can be decided. One action can affect several goals and several actions may be required to meet one goal.

In Company B the two main types of risk that are considered are those related to interruptions in the supply and those related to human health. The aim is to minimise the risks. First of all, legislative requirements have to be fulfilled. Additional investments should be profitable for the utility. Also environmental criteria (related to raw water sources etc.) are also seen as important. Economic analyses are carried out and sometimes also cost-benefit analyses are used to ascertain if the investments are profitable for the society as a whole.

With Company C the spokesperson stated that the goal is always to:

- Select actions that are efficient from an economic point of view

- Reduce the environmental impact
- Provide safe drinking water

Sometimes actions are not strictly economically profitable but are performed since they have other important benefits. For example, households not connected to the municipal wastewater treatment plants have in some areas large negative effects on the environment. The cost for the municipality for connecting these households to the municipal wastewater treatment plant is large, but it is done due to the reduced environmental effects.

In Company D criteria used include, increasing the water supply safety (both quality and availability), costs and environmental benefits. Only the costs are evaluated quantitatively.

5.3.4.4 *What decision making processes are used?*

With Company A decision making processes are context specific, and depending on the specific problem different analyses are performed. Formal decision making procedures are not utilized, however, since the option that meets the criteria at the lowest cost is selected essentially a CEA approach is being used. Often many different criteria are considered, so the decision analysis is in some sense also an MCA.

In Company B overall decision making processes are similar. Proposals are submitted to the relevant committee, decisions are made by the committee, necessary further analyses and planning are made and finally the specific investment is implemented. Depending on the costs and other requirements the decision has to be made at different levels in the organisation and also the need for analyses and planning differs. Simplified types of CEA and CBA are performed. The spokesperson stated that the quality of these analyses could be improved.

The spokesperson from Company C stated that economic analyses are made which can be a kind of CEA. No detailed MCAs or CBAs have been performed, probably due to lack of knowledge and resources.

In Company D for all decisions the decision making process is similar, but with some small differences depending on the type of decision, such as the nature of the background studies which are required. In terms of procedures, formal CBA, CEA or MCA are not generally performed but these methods could be used more in the future. As an example, the spokesperson stated they conducted a CBA of finding new raw water in Ljungskile and treating this water compared to building a connection to Uddevalla together with increasing the capacity of the system there, but they compared the costs and benefits in a qualitative way. He stated that they do very detailed cost-calculations and also environmental impact assessments, for example conducting environmental risk analysis for investigating where environmental improvements due to improved waste water connections should be prioritized. The company use consultants for comparing the different alternatives. The most important aspects are the costs and the different types of benefits that can be identified.

5.3.4.5 *Future Investment Decisions*

In Company A it is expected that decision will be made in the same way as previously: analyses by the water utility, decisions at different levels in the organisation, seeking additional information, etc. Decisions involving high costs will be taken at a high level in the organisation or by politicians in the city, and with some decisions politicians may insist that a CBA is performed with some investment decisions to ensure that they are socially profitable. The way an investment is analysed will differ depending on the nature of the investment.

In Company B the decision making processes will involve the same procedures as currently used, differring according to the type of investment (cost, technical demanding or not, etc.). An expensive investment, such as reconstructing a treatment plant, requires much more detailed planning and analysis compared to smaller investment. The spokesperson stated that the applied decision making process used is based on many years of experience and seen to be effective.

Future investment decisions in Company C are expected to follow the same processes that have been used previously. Hence, the water utility personnel will analyse the alternatives and provide the decision-makers with relevant information about the specific problems and actions. Large investments are decided by the politicians and smaller investments by the water utility. The water utility personnel will identify possible actions, analyse them and finally have a discussion with the politicians. This is the common way of working within the municipality and it has so far been regarded as successful

When considering future decision making, the spokesperson from Company D stated that decisions will be made in a similar way as previously, but will require more detailed studies and decisions support methods, like CBA, may be used. A very important aspect is to cooperate and communicate with other stakeholders and politicians to form support for the alternatives. In this process, it is very important to identify distinct alternatives and to objectively compare these. More detailed studies and probably more structured methods for comparisons will be used. The spokesperson states that the reason for such an approach lies in the core organizational aims: the community being the responsible party and the politicians being the major decision makers.

5.3.5 *United Kingdom*

Three water companies in the United Kingdom participated in this study: one was a company serving approximately 1.5 million customers and two were companies serving more than three million customers. In each case the director of asset management was interviewed, with interviewees requesting annonimity.

5.3.5.1 *Previous Investment Decisions*

Recent previous investment decisions cited by the water companies have related to improving water quality in order to meet new water standards – for example standards relating to pesticides, cryptosporidium, nitrates and aesthetic water quality. Thus many decisions have been around water treatment issues. A further issue which has led to investment decisions which was mentioned by one of the company spokesperson related to improving security of supply, stemming from concern about having large populations served from single water treatment sources and the effect that an event like flooding could have on the water source nd thus the water supply system.

5.3.5.2 *How are decisions made?*

In the context of drinking water, attention is focused on guaranteeing the safety of drinking water by using a source to tap approach which is largely informed by the Drinking Water Inspectorate. Decisions are taken through a risk-based approach, taking into account barriers, benefits, etc.

Many of the tasks and decision making practices required by UK water companies, such CBA, are mandatory, and informed by regulators. Classic CBA is used to decide whether a non-statutory improvement (one that is not driven by a legal requirement) is valued by customers. When there are a range of options available, the views of different stakeholders are taken into account, depending on the context.

One of the spokespersons interviewed stated that he did not think the best decisions are always arrived at. For example, in the context of wastewater and investment, the industry has been required to make CBA justified decisions, however the spokesperson thought that attention should be focussed on using more robust methods for taking into account a broader range of issues, such as broader sustainability issues not currently considered within the CBA approach used.

5.3.5.3 *What criteria are used?*

Minimisation of risk and the meeting of drinking water standards were the key criteria used by the water companies which were outlined by the water company spokespersons. In addition, other parameters are considered such as environmental considerations and customer perceptions and other stakeholder views.

5.3.5.4 *What decision making processes are used?*

CBA, MCA and CEA are all used to varying extents by the UK water companies interviewed. While CBA may be currently used, the difficulty is valuing all the benefits that customers will receive. MCA is used in some contexts, such as deciding between different investment options to water demand requirements. However, as the use of MCA has not been formalised in the water industry, there have been issues with the regulators about its use.

It can be challenging gaining acceptance of new tools and decision making methods.

Some of the companies discused using decision making tools which are specific to their company. However, it was suggest that taking what has been learnt across the industry in terms of decision making processes for meeting the regulator's requirements in order to develop common decision making proccess and tools could be useful.

5.3.5.5 *Future Investment Decisions*

The water companies indicated that decision making processes and tools relating to water quality are prescribed. One of the spokespersons interviewed noted that while decisions at present are based on CBA and the cost of providing water, it is hoped that in the future a broader perspective would be taken which would consider other issues, such as water scarcity.

5.4 Conclusions

Decision making relating to risk management in different water utilities varies between countries, most probably due to differences in the local legislative environment in which they operate. While in the UK more formalised decision making processes using CBA are required by the regulators, elsewhere processes are in place which are effective less formalised forms of MCA and CEA. Some of the utilities stated that the plan is to use more formalised processes due to the growing complexity of decision making.

One of the biggest differences between the different water utilities surveyed was the degree of political involvement in decision making relating to risk management. Whereas in some countries, such as the UK, Belgium and the Netherlands, there was no direct political involvement in decision making, in Sweden and to a lesser extent Norway, politicians are involved in decision making, particularly those involving significant investment. This difference relating to political involvement does not appear to be due whether or not utilities are privatised as in the Netherlands water utilities are public while in the UK they are fully privatised. See Table 3 for a comparison of decision making processes in each of the interview countries .

Table 3 Comparison of decision making drivers, criteria and methods of the different water utilities interviewed.

		Czech Republic	Nether-lands	Norway	Sweden	United Kingdom
Decision Making Drivers	**Legislation & Regulations**	●	●	●	●	●
	Funding	●				
	Technical Status of Facilities	●	●	●	●	●
	Broader Regional Plans (e.g. third party plans)	●	●	●	●	●
	Optimising Operations	●	●	●	●	●
Decision Making Criteria	**Consumer Needs, Expectations**					●
	Cost Effectiveness	●	●	●	●	●
	Safety for Consumers	●	●	●	●	●
	Compliance with Legislation	●	●	●	●	●
	Long-term Company Objectives	●	●	●	●	●
	Compliance with other Stakeholder Views	●	●	●	●	●
	Compliance with Funding Procedures	●				
	Risk-based Assessments (likelihood x impact)		●	●	●	●
	Environmental Impact				●	●
	Shareholder Value					●
Methods Used	**CBA**	●			●	●
	MCA	●	●		●	●
	CSE		●		●	●
	Non-Formalised Methods (Quantitative)	●	●	●	●	

6 A generic framework for decision support

6.1 The framework

The framework in Figure 8 was devised to provide a combined structure and a generic description of risk management and decision-making in the context of drinking water supply. The framework is based on the descriptions of risk management produced by the International Electrotechnical Commission (IEC, 1995), the generic framework for risk management (Rosén et al., 2007) and the concepts of decision-making described by Aven (2003), see Section 4.

The purpose is not to describe a *new* framework but rather to stress the close link between risk amangement and decision-making and clearly illustrate the role of risk assessment results as decision support. Additional components and aspects have been added to the original descriptions to stress, for example, the importance of considering uncertainties, to acquire new information when available, to update models and analyses and to communicate results to the consumers and other stakeholders.

The framework (Figure 8) outlines risk management and decision-making as a proactive process where an underlying decision problem initiates a risk assessment and the results are reviewed by the decision-maker before a decision is made. Decision problems initiating risk assessments are often based on the need to prioritise possible alternatives such as risk-reduction measures. A drinking water utility may, for example, want to know the risk a new chemical facility within the watershed would pose to the water source and in the end to the consumers. Questions linked to such a problem could be wheter the risk is acceptable or not, and if not what measure should be taken to reduce the risk? When managing a drinking water system it is important to consider risk related to both water quantity, i.e. supply interruptions, and water quality, i.e. health problems. There may of course also be other risk types important to consider.

As illustrated in the framework, stakeholder values reflected in goals, criteria and preferences affect the decision problems as well as the risk assessment and the subsequent review. Examples of stakeholders are the water utility, the consumers, industries located within the watershed and government authorities. A typical example of criteria used within the drinking water sector is health-based targets defined by authorities. However, water utilities may also define their own performance targets and similar criteria that affect how prioritisations are made. Furthermore, there may be competing interests in society that affect the use of water sources. For example, new roads and railroads within the watershed of a groundwater source may be needed for improved transport, although this also introduces new risks to the water supply due to possible accidents, including hazardous goods.

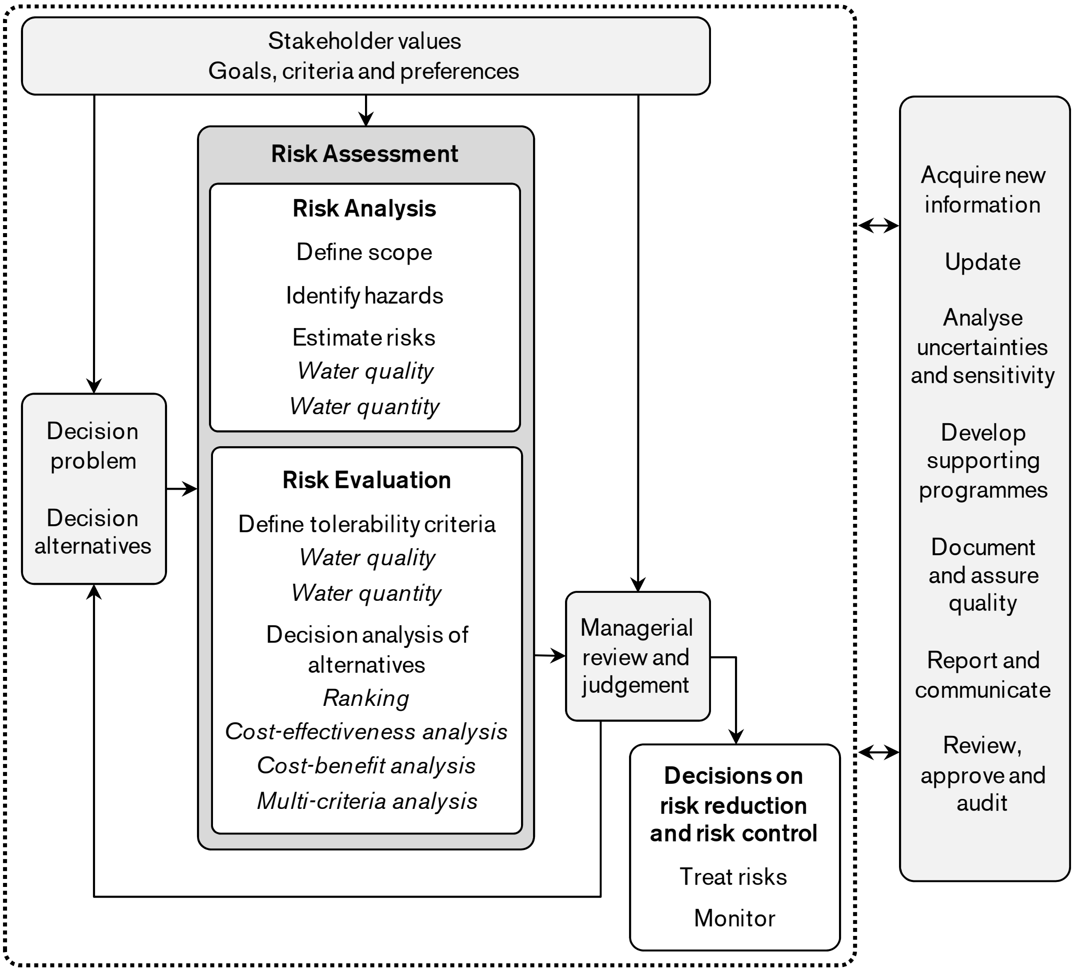

Figure 8 A generic framework illustrating the main steps in risk management and how it is interconnected with decision-making.

Based on the decision problem, suitable methods and tools should be selected and used in the risk assessment to provide useful results that can support decision-making. A decision problem includes a vast number of different dimensions that can be perceived in different ways. In most cases it is not possible to consider all these aspects in a risk assessment. Hence, the risk assessment results provide decision support although a subsequent managerial review and judgement is necessary to consider aspects not possible to include in the risk assessment.

To support the performance of a risk assessment a team of people should be put together. The team should include people with knowledge of the system being analysed as well as people with knowledge of risk assessment and other aspects that may be relevant.

The arrows in Figure 8 illustrate the exchange of information between different steps as well as communication with relevant stakeholders. The task of communicating risk is important and carefully performed risk assessments may provide useful results that facilitate communication with decision-makers, consumers and other stakeholders. It is important to emphasise that risk assessment and decision-making should be a continuous and iterative process that is updated when new information becomes available and preconditions change. Furthermore, the framework emphasises that risk assessments and other work need to be reviewed in order to assure the quality.

6.2 Applications in TECHNEAU

In addition to the framework (Figure 8), tools and guidance documents to support water utilities have been developed within the part of the Techneau project dealing with risk assessment and risk management. Reports have been prepared describing risk management in general and more specifically risk assessment and decision-making (Hokstad et al., 2009; Rosén et al., 2007). Furthermore, tools for identifying and analysing risks have been developed, such as databases that include possible hazards and risk-reduction measures (Beuken et al., 2008; Pettersson et al., 2010).

Based on the approach to risk management and decision-making presented in Figure 8, risk assessment case studies were performed in South Africa, the Czech Republic, Germany, the Netherlands, Norway and Sweden (Lindhe et al., 2010c). The aim of the case studies was to evaluate the methods and tools that had been developed and to provide good examples.

Below, we present general descriptions of the following decision support approaches: cost-benefit analysis (CBA), cost-effectivenss analysis (CEA) and multi-criteria analysis (MCA). These approaches have been combined with risk analysis methods developed in TECHNEAU and applied on real-world problems. For detailed descriptions of these methods and applications the interested reader is directed to Lindhe et al. (2009; 2010a; 2010b; 2010c; 2011) and Rosén et al. (2010).

6.3 Decision support approaches

6.3.1 Cost-Benefit analysis (CBA)

For assessing if alternative actions are economically beneficial for society, a cost-benefit analysis (CBA) can be conducted. In a CBA the total benefits and the total costs are compared in monetary units to determine if the alternatives provide a positive net benefit or not (e.g. Johansson, 1993; Nas, 1996; Hanley and Barber, 2009). Although mainly directed at determining if alternatives are desirable for society, CBA can also be applied to decisions problems in the private sector, although when applied to the private sector CBA is commonly limited to the financial costs and benefits accruing to the private sector company rather than the full costs and benefits to society as a whole. In the drinking water sector, CBA is extensively used in the UK by the privatised water utilities. The applications by Yorkshire Water (Smith, 2005) are often referred to as a successful example.

CBA can be described as an analytical framework for assessing alternatives' costs and benefits to all members of society. Nas (1996) describes the CBA procedure based on four essential steps: (i) identification of relevant costs and benefits, (ii) measurement of costs and benefits, (iii) comparison of cost and benefit streams accruing during the lifetime of a project, and (iv) project selection. The identification of possible benefits and costs should be made with a *no action* alternative as baseline. In the end, it may be decided that the no action alternative is most beneficial. The valuation of costs and benefits may be a demanding task since both market and non-marked goods have to be monetised. Intangible elements, such as, human life and the aesthetic quality of water may not easily be valued. A set of alternative techniques exist that can be used to value non-marked goods, e.g. revealed preference methods, stated preference methods and methods that are less strongly founded in economic theory (e.g. Rosén et al., 2006; Hanley and Barber, 2009). When both costs and benefits are estimated the net benefit may be calculated as

$$\Phi = \sum_{t=1}^{T} \frac{1}{(1+r)^t} (B_t - C_t)$$

where Φ is the objective function representing the net present benefit value, B_t and C_t are the benefit and cost respectively occurring in time period t, r is the discount rate and T the analysed time period. Since costs and benefits occur over several years the present values have to be calculated using a discount rate.

A positive net benefit implies the alternative is desirable, since the total benefits exceed the total costs. In addition to the net benefit, alternatives may also be evaluated based on the cost-benefit ratios and the internal rate of return. Another important aspect form a societal perspective is to perform a distributional analysis in order to assure that stakeholders are not unfairly affected by the decision.

An example of decision support using CBA in the drinking water sector is given by Lindhe et al. (2010a) and Lindhe et al. (2011).

6.3.2 *Cost-effectiveness analysis (CEA)*

The aim of a cost-effectiveness analysis (CEA) can be described as to identify the alternative that provides a given level of effectiveness for the least cost, or the highest level of effectiveness for a given cost (Levin and McEwan, 2001). Depending on the specific study the aim of a CEA may differ but the purpose is always to provide a combined, not separate, and proper assessment of both the costs and effectiveness.

The effectiveness of an alternative corresponds to, for example, the reduced level of risk or other achieved outcome. The effectiveness is quantified using different measures depending on the analysed outcome. However, the benefits are not monetised as in a CBA. Thus, CEA is an applicable tool when one or several benefits cannot be monetised. The total cost of each alternative is calculated by including costs related to planning, construction, maintenance etc. If costs occur over several years the present value has to be calculated.

Based on the cost and effectiveness a cost-effectiveness ratio (CER) can be calculated as

$$CER = \frac{C}{E}$$

where *C* is the cost and *E* the effectiveness. The ratio corresponds to the cost required to obtain a single unit of effectiveness. Consequently, a low CER value indicates the alternative is cost-effective. If preferable the effectiveness-cost ratio can be calculated instead of the CER. Although an alternative has a high cost-effectiveness, it cannot be accepted if a predefined effectiveness criterion is not achieved. In most cases it is not reasonable to only rank the alternatives based on the CER. Instead the effectiveness, cost and CER for each alternative should be included when evaluating the alternatives. As stated by Levin & McEvan (2001) one has to pay attention to the scale of the alternatives when performing CERs. For example, based on the CER an alternative with a low cost and effectiveness not fulfilling the criterion may seem more beneficial than an alternative with a high cost and effectiveness fulfilling the criterion.

As emphasised by US EPA (2000), CEA is a useful tool to apply when many benefits cannot easily be monetised. Furthermore, CEA is practical when predefined levels of acceptable risk, effectiveness or similar exist. In these cases the aim is to identify what alternative fulfils the target value to the lowest cost. The main limitation with CEA is that we cannot determine if the total benefits of an alternative exceed the total costs, then a CBA is required. It should be emphasised that CEA is not only the calculation of CER values but the entire process of determining costs, effectiveness and comparing the alternatives.

An example of decision support using CBA in the drinking water sector is given by Lindhe et al. (2010a) and Lindhe et al. (2011).

6.3.3 *Multi-criteria analysis (MCA)*

Methods supporting multi-criteria decisions are designed to take several aspects into consideration and to identify alternatives that best comply with a specified array of criteria. A large number of methods for multi-criteria analysis (MCA), sometimes also denoted multi-criteria decision analysis (MCDA), exist and they apply different approaches for combining information relevant for the decision. Different methods can, for example, be used to identify the most preferable alternative, provide a ranked list of alternative options or only identify what alternatives are acceptable. The purpose is to help decision-makers make sense of a large amount of data. A comprehensive description of MCA/MCDA is provided by the Department of Communities and Local Government in UK (Communities and Local Government, 2009).

The basis of MCA is a set of objectives and measurable criteria defined by the decision-maker(s). The criteria are used to measure to what extent the analysed options fulfil each objective. Hence, MCA is based on judgments by decision-makers regarding what objectives and criteria to use. An advantage of MCA is that it provides transparency so that applied objectives and criteria as well as the way information is merged can be scrutinised and updated when necessary.

A common and easy way of conducting MCA is to use a performance matrix. In such a matrix the performance of each option with respect to a set of criteria is presented in a table. Depending on how well an option fulfils a criterion a score between, for example, 0-100 can be assigned. Based on the set of scores a weighted score may be calculated and used to compare the alternative options. Examples of other methods for MCA are:

- Analytical Hierarchy Process (AHP)
- Outranking methods
- Non-compensatory methods

The performance for different criteria in respect of an alternative may be measured either qualitatively or quantitatively. To be able to compare the different performances and combine them into a common unit, scales representing relative preference are used. For each criterion the performance is translated into a scale, for example from 0 to 1, where 0 represents the least preferable and 1 the most preferable outcome. Based on a linear additive approach an overall score, a weighted sum, of an alternative (s_j) can be calculated as

$$s_j = \sum_m s_{jm} w_m$$

where s_{jm} is the alternative's (j) performance score for each criterion (m) and $w_{jm} \geq 0$ are weighting factors that determine the relative importance of each criterion. The weighted sum is calculated based on the assumption that the criteria are mutually preference independent. This means that the preference scores assigned to the measures for one criterion do not depend on the preference scores for the other criteria (Keeney and Raiffa, 1993).

The results of an MCA model can be presented in different ways and can also be evaluated based on different approaches. An important aspect to consider is whether or not strong performance for one criterion may compensate for weak performance for other criteria. Hence, a compensatory or non-compensatory approach can be used. In a non-compensatory mode, critical performance levels can be defined and alternatives that do not meet this level are disqualified.

An advantage of MCA is that it provides transparency so that applied objectives and criteria, as well as the way information is merged, can be scrutinised and updated when necessary. MCA applications related to drinking water supply are frequently found in the literature (e.g. Bouchard *et al.*, 2010; Joerin *et al.*, 2009). A review of MCA-related techniques for water resource management was performed by Cohon and Marks (1975) and more recently by Hajkowicz and Collins (2007). In the latter study, the main challenges for water resource MCA research were identified. One of the main conclusions was that there is a need for improved handling of risk and uncertainty in MCA models. It was also concluded that there is a need of better means for incorporating risk preferences of decision-makers in MCA models.

Two different models for MCA were developed in TECHNEAU. Detailed descriptions of these models and their applications are given by Lindhe et al. (2010a; 2010b).

7 Conclusions

Although risks have been managed by water utilities in the past, the more integrated and proactive approach emphasised today requires new methods. The risk-based water safety plans (WSPs) suggested by the WHO address the importance of considering the entire system in an integrated way, from source to tap. By analysing the entire system and studying interactions between subsystems it is easier to see where risk-reduction measures are needed most and where they should be implemented to be most effective.

The fact that we cannot eliminate every risk and that resources for risk reduction are limited makes correct prioritisation of risk-reduction measures important when balancing risks, costs and benefits. An efficient use of available resources for managing risks requires a well-founded framework for supporting decision-making.

The generic framework for decision support described in this report is based on current knowledge of risk and decision theory. It has been shown how this framework can be effectively incorporated in the risk and asset management of water utilitiies by the development and practical applications of risk analysis and decision support methods performed in TECHNEAU.

The survey on decision-making in water utilities identified the most important criteria in decision-making among utilities participating in the survey. The survey showed that decision making relating to risk management in different water utilities varies between countries, most probably due to differences in the local legislative environment in which they operate. While in the UK more formalised decision making processes using CBA are required by the regulators, elsewhere processes are in place which are effective less formalised forms of MCA and CEA. Some of the utilities stated that the plan is to use more formalised processes due to the growing complexity of decision making.

One of the biggest differences between the different water utilities surveyed was the degree of political involvement in decision making relating to risk management. Whereas in some countries, such as the UK, Belgium and the Netherlands, there was no direct political involvement in decision making, in Sweden and to a lesser extent Norway, politicians are involved in decision making, particularly those involving significant investment. This difference relating to political involvement does not appear to be due whether or not utilities are privatised as in the Netherlands water utilities are public while in the UK they are fully privatised.

The generic framework presented here illustrates the basic steps involved in, and aspects affecting, risk management and decision-making in the context of drinking water supply. The close link between risk assessment and decision-making is shown and it is emphasised that risk assessments do not provide answers but rather necessary decision support for making well-informed decisions.

Efficient risk management, including proper risk assessments and decision analyses that enable well-informed decision-making, is necessary to achieve and maintain a reliable supply of safe drinking water. Research focused on developing theoretically well-founded methods that can be applied in practice contributes to the knowledge and the ability to assess risks. Since not all risks can be eliminated, methods and tools for facilitating the task of balancing risks, cost and benefits are important. The methods for integrated risk assessment and decision analysis presented in TECHNEAU provide useful decision support and facilitate efficient risk management of drinking water systems.

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