CHALMERS

Decision Support on Risk Reduction Alternatives in Drinking Water Systems

A multi-criteria analysis for making risk management decisions

Master of Science Thesis in the Master's Programme Geo and Water Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
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ABSTRACT

The World Health Organization (WHO) has emphasized the need for an integrated and holistic risk management approach for ensuring safe supply of drinking water. They presented the concept of Water Safety Plans (WSP) in order to facilitate the risk management work. Although the guidance on WSPs provides a suggestion for qualitative risk assessment by using a risk ranking method with a risk matrix approach, it lacks guidance for the selection process of a suitable control measure. Within TECHNEAU, a project funded by the European Commission, the current and future challenges of the water supply sector is addressed. One work area of the project is focused on integrating risk assessments of the different parts of a drinking water system into a comprehensive decision support framework. Within TECHNEAU, six risk assessment case studies were carried out at different drinking water systems during 2007-2008, including the systems in Bergen (Norway) and Březnice (the Czech Republic). The primary aim of this study is to develop a method for decision analysis based on risk ranking and multi-criteria analysis (MCA). An eight-step decision analysis procedure is proposed and applied to the systems in Bergen and Březnice. A MCA approach is used to integrate risk reduction and other key criteria in order to provide decision support on the selection of risk reduction alternatives. The method facilitates prioritization of risk reduction alternatives as well as provides sufficient information for the decision makers to make well informed decisions. Advantages and limitations of the suggested eight step procedure is also identified and discussed in the thesis. Moreover, the applied procedure to the case studies has ranked the alternatives based on their overall performances. The results are obtained both in bar diagrams and in values, therefore can be further analysed before making the final decision. It also provides flexibility to the decision makers to change when necessary until a balanced decision is obtained.

Key words: Decision analysis, Risk assessment, Drinking water, risk reduction, Water safety plan

Contents

Preface

The study has been carried out as a master's thesis work within the department of Civil and Environmental Engineering at Chalmers University of Technology, Sweden. It carries 30 hec and has taken the whole spring semester in 2010 to be completed. Additionally, it is also a part of the research project TECHNEAU, the largest of its kind, funded by the European Union. A method for decision analysis has been developed and applied, as examples, to the Bergen and Březnice drinking water systems in order to facilitate the risk management work.

The thesis work is carried out with Professor Lars Rosén and Licentiate of Engineering Andreas Lindhe as supervisor and co-supervisor respectively. I specially thank both of them for their continuous support during the work. I am also thankful to other partners of TECHNEAU who have provided a lot of information for the case studies. Opponent, Arezou Baba Ahmadi, has provided valuable comments on the report that are not only being appreciated but also have been considered during production of the final version of it. Finally, I thank my friends who have encouraged continuously and helped me in different ways during the work.

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Mahbub Alam

Notations

Following notations are used in the main text of the thesis:

ALARP	As Low As Reasonably Practicable
CRA	Coarse Risk Analysis
FMEA	Failure Mode and Effects Analysis
HACCP	Hazard Analysis and Critical Control Point
IEC	International Electrotechnical Commission
MCA	Multi-Criteria Analysis
NOM	Natural Organic Matter
RAC	Risk Acceptance Criteria
RVA	Risk and Vulnerability Analysis
TECHNEAU	A drinking water project funded by the European Commission (Technology Enabled Universal Access to Safe Water)
UK	United Kingdom
UV	Ultraviolet
WA4	Work Area 4
Web-HIPRE	HIerarchichal PREference analysis in the World Wide Web
WHO	World Health Organisation
WSP	Water Safety Plans
p	Probability
C	Consequence
E_j	Risk reduction effectiveness of an alternative
R_0	Current Risk Level
R_j	Risk level after implementation of an alternative to reduce the risk
Units	
l	Litre
s	Second
mJ	Milli Joule
cm^2	Cubic centimeter
m^3	Cubic meter

1 Introduction

1.1 Background

The World Health Organization (WHO), in their third edition of *Guidelines for Drinking Water quality* (WHO, 2004), has emphasized the need for an integrated and holistic risk management approach in order to ensure safe supply of drinking water. The risk management process incorporates many different elements from the initial identification and analysis of risk, to the evaluation of its tolerability and identification of potential risk reduction options, through to the selection, implementation and monitoring of appropriate control and reduction measures (IEC, 1995). In order to support risk management work in drinking water systems, the WHO has proposed the development of Water Safety Plans (WSP). WSP provides an approach for qualitative risk assessment by using a risk matrix for ranking of risks with respect to established tolerability criteria. Risks that are identified unacceptable in the risk assessment must be controlled or reduced to an acceptable level. Upon selecting a suitable measure, initially, a number of control measures might be at hand for managing a particular risk. Finally, a decision needs to be made by choosing an option that ensures the best utilization of society's resources and satisfies most of the criteria addressed by the utility's stakeholders, e.g. cost, environmental impacts, supply reliability etc. Although the WHO emphasized on water quality risks, risks associated with drinking water utilities are not limited to water quality. In addition to regulatory obligations on water quality and water quantity, utilities are equally concerned about their operational excellence for building and maintaining trust and confidence among its consumers. Selection of an optimal solution for managing risks effectively requires a well-structured method that takes into account all the aspects important for the utilities. Although the WHO guidelines provide a suggestion on risk assessment, it lacks guidance regarding the selection process of a suitable control measure that is expected to undergo stakeholder criticism (Rosén et al., 2007).

TECHNEAU (www.techneau.eu), a European Commission funded project, is addressing current and potential challenges of the water supply sector and is developing solutions to meet these challenges in a cost-effective and sustainable way. To meet the project aims, eight activity work areas have been defined where work area 4 (WA4) is *Risk assessment and risk management* with the primary objective to integrate risk assessments of different parts of a system into a comprehensive decision support framework. Within WA4, six risk assessment case studies have been carried out at different drinking water systems during 2007-2008, where applicability of different risk assessment methods has been tested and evaluated. Among the case studies, risks for the drinking water systems in Bergen (Norway) and Březnice (Czech Republic) have been assessed qualitatively using risk matrices. In this report, results from the previous studies in Bergen and Březnice will be integrated into a decision analysis of different risk reduction alternatives in order to facilitate a selection of the best alternative.

1.2 Aim and objectives

The primary aim of the study is to develop a method for decision analysis by integrating results from qualitative risk assessments. A structure for analysing decision alternatives will be proposed and its applicability will be evaluated by performing a decision analysis where alternative risk reduction measures are evaluated and compared for the drinking water systems in Bergen and Březnice. A method will be developed for supporting decision-makers to make a well informed and good decision regarding the most suitable actions for increasing drinking water safety. As part of the method a set of suitable alternatives are identified, their pros and cons are described with respect to a set of evaluation criteria and finally the alternatives are compared in order to facilitate the selection of a "best" alternative. The method will be developed based on multi-criteria analysis (MCA). The cost effectiveness of the alternatives will also be included in the proposed method.

The study can be summarized into the following specific objectives:

- Summarizing results from previous studies.
- Identifying undesired events based on the previous analysis for which control measures are important to be identified and implemented.
- Identifying a set of relevant alternatives for each undesired event.
- Propose and describe key criteria and a structure for the MCA method for evaluating and comparing the alternatives.
- Apply the suggested method in order to provide examples and check its applicability.

1.3 Limitations

The study is primarily based on a literature review. Information presented and used for the example case studies are collected from previous case study reports and interviews conducted within TECHNEAU. Current practices of decision making have only been studied on a general level, except for the two systems in Bergen and Březnice.

2 Risk and Risk Management Issues in Drinking Water

In this chapter, a general description of background literature of the study is presented. At first, the concept of risk and a range of risk categories associated with water utilities are presented. The purpose of presenting risks in the drinking water sector is to give an overview of the current and potential risks. How water utilities traditionally managed risks is presented followed by a short description of the WSP concept (WHO, 2004) and the TECHNEAU risk management framework and its different components. Finally, a general description of the decision making process and the decision support framework suggested by TECHNEAU is presented.

2.1 What is risk?

Although the word "Risk" is used frequently in everyday life, its meaning varies depending on its context (Lindhe, 2008). In most cases, it is used when a rational decision is to be made. In spite of its frequent use, there is no universally agreed definition of risk (Vatn, 2004). Rosén et al. (2007) pointed out two situations where a definition of risk is essential, i.e. while communicating risk to other people and while assessing risks. A well known definition of risk is given by Kaplan & Gerrick (1981). According to them, an analysis of risk should answer the following questions:

- What can happen?
- How likely is that to happen?
- What are the consequences?

Based on the answers of these questions, risks are expressed as a set of triplet (S_i, L_i, X_i) where S_i denotes the scenario or the outcomes of that event, L_i is the probability that the scenario would occur and X_i is the loss or damage the scenario would cause if it occurs.

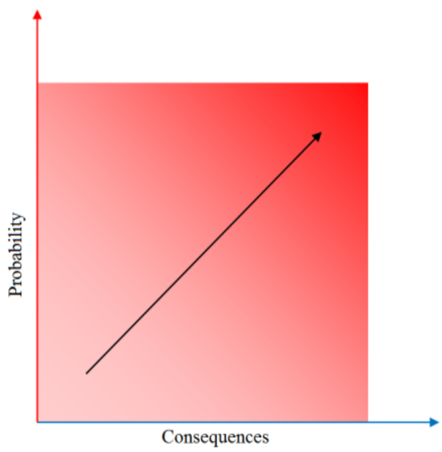

Figure 2.1 A simple expression of risk based on the combination of probability and consequence.

Rosén et al. (2007) and Lindhe (2008) reported that the most common definition of risk is the combination of probability and consequence, see *Figure 2.1*, where increase or decrease of risk is caused by increase or decrease of either probability or consequences or both. However, it also involves more subjective issues. Klinke and Renn (2002) defined risk in a way that takes into account things that humans value, rather than considering merely on probability and consequences. According to them, risk is the possibility that human actions or events lead to consequences that harm aspects of things that human beings value. Since the meaning of risk varies with a particular situation and people's perception on it, a clear definition should be given when using the word. In this report, the TECHNEAU definition of risk will be considered, i.e. a combination of the frequency, or probability, of occurrence and the negative consequences of a specified hazardous event.

2.2 Risks in drinking water systems

The primary goal of a drinking water system is to supply water that is safe, i.e. free form any pathogenic microorganism and chemical; that is acceptable, i.e. free from odours, tastes good and is trusted by the consumers; and that is reliable, i.e. provide uninterrupted supply. In order to realize these objectives, water suppliers need to manage risks associated with different aspects of water and components of the system. Based on the supply objectives, two broad categories of risks i.e. quality and quantity risks can be addressed (Lindhe, 2008). However, quality risks are of primary importance irrespective of size and complexity of a system and has been emphasised by the WHO.

It is evident from the existing literature that risks in drinking water systems are no longer limited to the aspects of quality and quantity. Emergence of risks is primarily driven by increasing customer expectations and stringent regulatory requirements (Hrudey et al., 2006). Other challenges due to increased sectoral changes, for example, privatization, sector globalization, increased competition, emerging technologies, trends towards financial self-sufficiency are also paving the way of encountering a variety of new risks (Hrudey et al., 2006). In addition to the existing risks, TECHNEAU recognized the importance of considering possible future risks that are likely to be encountered by the water companies. The following seven risk categories were identified and reported by Rosén and Lindhe (2007):

- Sabotage
- Terrorist attacks
- Conflicts
- New chemicals
- Emerging pathogens
- Public concern
- Climate change
- Aging distribution systems

Pollard et al. (2004) reported six risk categories at three different organisational levels i.e. operational, programme and strategic levels. Risks on the strategic level are mainly related to regulatory compliance, commercial targets and financial activities of a water utility. These strategic level risks are primarily associated with decisions about infrastructure investment, merger and acquisition activity, company reputation and long term viability of investment decisions. Risks associated with asset management and with the existing watershed are considered in the programme level. Lindhe (2008) reported a list of factors that pose risk to the water infrastructures: growing consumption by expanding populations, industrial and public pollutions, tragedies caused by both natural and human accidents, emergence of threats from domestic terrorists, disgruntled employees and computer hackers. Operational level risks are related to the failure of specific process component at the plant level. Four risk categories at the process level were reported by Pollard et al. (2004) that are health and safety, water quality, water quantity and environmental. In total, six major risk categories concerning water utility decision-making were identified by Pollard et al. (2004), see *Table 2.1.*

Table2.1 Risk categories and causes (Pollard et al., 2004).

1. Financial risk	Arises principally from financial operations and management of business, both from internal and external perspectives.
2. Commercial risk	Generates from competition among the companies due to privatization and financial instability.
3. Public health risk	Failure and inadequacy of the treatment and distribution process can threat human health from different contaminants.
4. Environmental risk	Caused by failure of equipment or human errors that lead to environmental impacts.
5. Reputation risk	From losing consumer confidence and trust.
6. Compliance/legal risk	Failure to comply with water quality standards, handling and storage of treatment chemicals, discharge of waste and maintaining health and safety of the operational staff and people living nearby.

Because of strong interconnectedness between the risk categories, consequences of one risk could affect others to different degrees (Pollard et al., 2004). Therefore, it is important to develop a framework that could take into account all categories of risks involved in a water utility.

2.3 Traditional risk management in the water sector

Traditionally, water utilities manage risks using a retrospective approach where past experiences of incidents or near mishaps provide major inputs for developing design standards and operational procedures. Based on the description by MacGillivray & Pollard (2008), the risk management performed in the water sector can be described as the cycle in *Figure 2.2*. Utilities use established design standards and operational procedures for exercising good practice. According to MacGillivray & Pollard (2008), the traditional risk management cycle starts when analysis is undertaken following an incident or a near mishap for identifying its root causes. The analysis concludes with appropriate solutions in technical, operational or administrative areas in order to prevent its recurrence. Identified solutions are later adapted to the organizations that may comprise any individual utility or groups of them. In turn, the solution might be accepted by the whole sector resulting in generalisation of learning reflected by the changes in the national codes, standards and/or regulations.

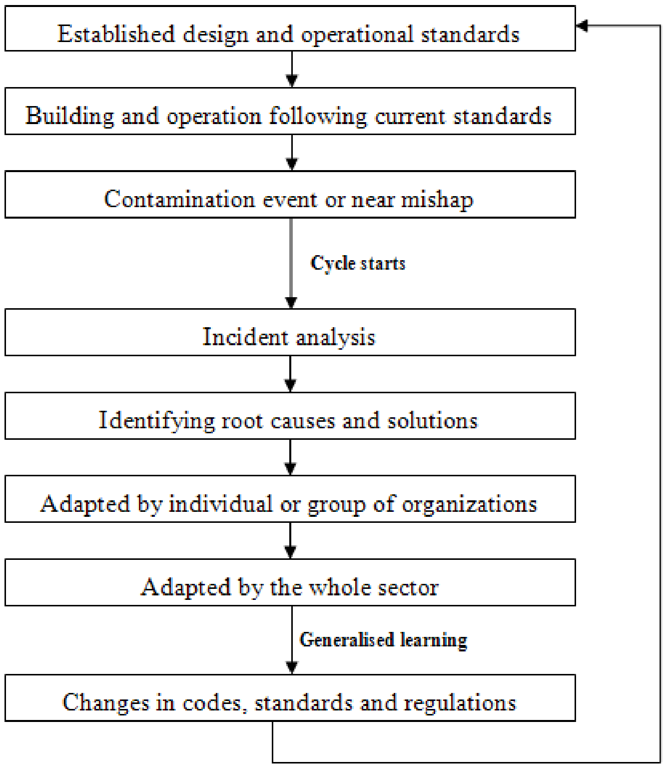

Figure 2.2 Traditional risk management processes in the water sector (Based on MacGillivray and Pollard, 2008).

2.4 Risk management frameworks

This section is divided into two sub sections where the first one consists of a brief description on the Water Safety Plan (WSP) concept including its key components and implementation steps. The purpose is to give a general overview of the framework presented by the WHO as this study is a part of implementation of WSP within Bergen and Březnice water supply systems. However, different steps performed in the case studies are largely based on the TECHNEAU risk management framework. Therefore, the second sub-section is rather an elaborated description on the TECHNEAU risk management framework. The purpose of this section is to introduce the framework as well as its key components. The framework was originally developed by the partners within Work Area 4 *Risk Assessment and Risk management* of the TECHNEAU project. Rosén et al. (2007) presented the framework along with descriptions of the supporting methods and tools constituted for its development. They also presented examples of its application carried out at different drinking water systems. The generic description presented in this report has been extracted from Rosén et al. (2007) unless otherwise specified.

2.4.1 Water safety plans

In 2004, the World Health Organisation (WHO) presented a framework for drinking water safety. The framework comprises five key elements, of which three make up the WSP, see *Figure 2.3*. A WSP is described as a means of ensuring safety of drinking water supply through the use of a comprehensive risk assessment and risk management approach from catchment to consumer (WHO, 2004). It is a preventative risk management approach that considers all components of a system as a whole and has been developed based on the principles of the multi-barrier approach, hazard analysis and critical control point (HACCP) and other systematic management approaches. The development of a WSP is to be guided by health based targets and overseen through independent surveillance (Rosén et al., 2007). Health based targets should be established by high level authority under realistic operating conditions with the specific objective to protect and improve public health. The following four types of targets are of importance:

- Health outcome targets of reducing risk of disease burdens.
- Water quality targets expressed as guideline values for drinking water constituents that pose health risk over long term exposure or varying concentrations.
- Performance targets addressing the constituents having health risk over short term exposure and health implications for fluctuation in numbers and concentration.
- Specified technology targets, e.g. for smaller municipal, community and household drinking water supplies.

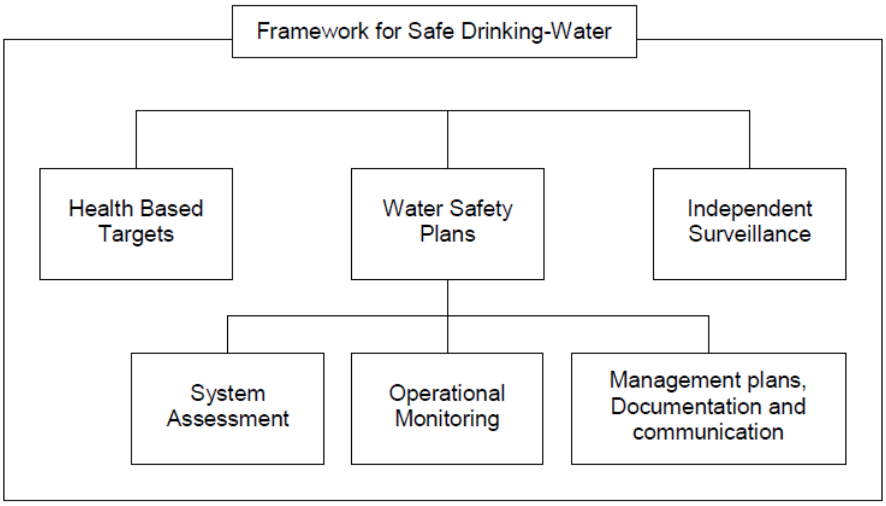

Figure 2.3 Framework for safe drinking water (WHO, 2004).

A WSP comprises three successive components: system assessment, operational monitoring and management plans. It starts with assessing the system of interest with the aim to determine whether the final quality of delivered water would routinely meet the health based targets. A capable system is a prerequisite for implementing a WSP. If the assessment identifies a system that is insufficient for maintaining water quality throughout, the system must be upgraded by identifying critical control points and suitable control measures. A control measure has been defined by the WHO as actions implemented in the drinking water systems that prevent, reduce and eliminate contamination. Different components of a system might have different control measures, e.g. catchment management actions, disinfections in the treatment etc. Their collective operation would ensure meeting health based targets. The second step of a WSP is the operational monitoring, which is a planned observation and measurement of the control measures for assessing whether they are working properly or not. Finally, the management plan documents and describes plans and activities for the system assessment and operational monitoring. It also outlines procedures and other supporting programs required for optimal operation of the system. *Figure 2.4* shows key steps of developing a WSP. All aspects of safety and compliance with the WSP are to be reviewed periodically by an independent surveillance agency through a systematic programme of surveys.

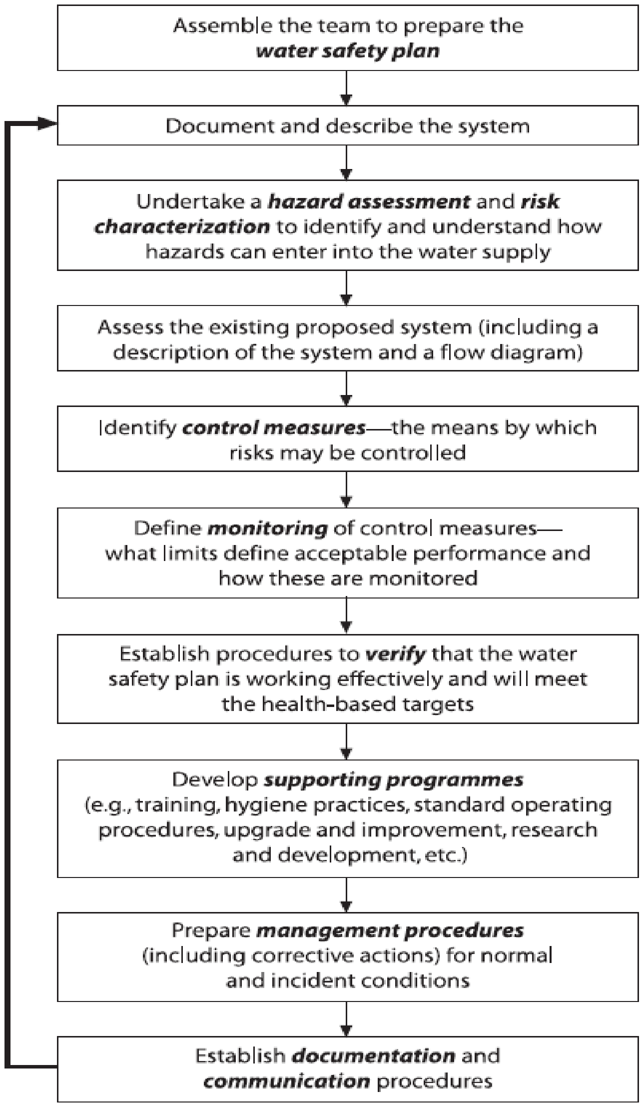

Figure 2.4 Overview of the key steps of developing a WSP (WHO, 2004).

System assessment might identify deficiencies that require improvement of the system. Since a system's improvement might result in budgetary implications, the guideline recognizes the need for detailed analysis and careful prioritization of the improvement plans in accordance with the risk assessment results. However, it does not provide any further guidance on how to analyze and prioritize the options.

2.4.2 The TECHNEAU risk management framework

TECHNEAU has developed a framework to assist water utilities by providing a structure and toolbox for risk management *(Figure 2.5)*. It defined risk management as a systematic application of management policies, procedures and practices to the tasks of analysing, evaluating and controlling risk. The framework is equally applicable for the systems based on either surface or ground water irrespective of its size and complexity. Further, risks associated with operational level as well as strategic level of an organisation can be considered during its implementation. Principal objectives of the framework are summarised as follows (Lindhe, 2008):

- Supports establishing good practice within an organisation and integrated risk management in WSPs.
- Facilitates transparency and rational decision making.
- Stresses on the importance of an iterative process of continuous updating as new information becomes available and as condition changes.
- Emphasises stakeholder involvement and communication with them.
- Includes methods and tools for risk assessment i.e. for risk analysis and risk evaluation.

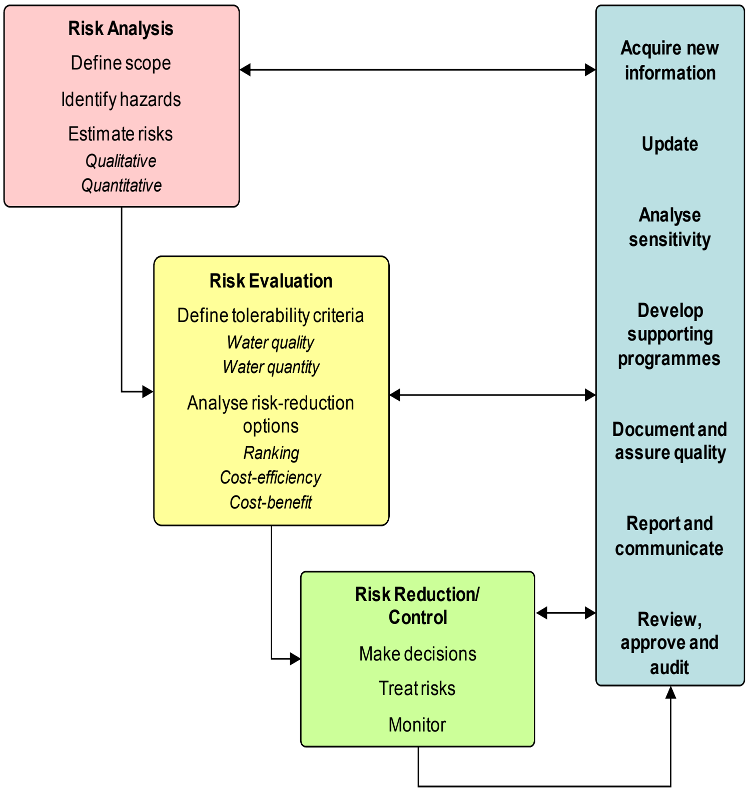

Figure 2.5 The TECHNEAU risk management framework (Rosén et al, 2007).

The framework has been developed based on the risk management process by International Electrotechnical Commission (IEC, 1995) and the WSP approach; see *Figure 2.5*. The main structure of the framework is divided into three major steps that are basically adopted from the risk management process. However, other aspects of WSP have been included to link it specifically to the drinking water sector. Three major steps that constitute the framework are risk analysis, risk evaluation and risk reduction or control. Detailed description on each step is presented in the following subsections.

2.4.2.1 Risk analysis

Risk analysis is the first step of risk management which gathers information and creates knowledge about risks. TECHNEAU defined risk analysis as a systematic use of available information to identify hazards and to estimate the risk to individuals or populations, property or the environment. The primary goal of risk analysis is to produce most relevant and useful information for sound risk management decision making (Pollard et.al. 2004). The risk analysis process consists of three main steps i.e. scope definition, hazard identification and risk estimation. The entire risk analysis process, according to IEC (1995), is presented in *Figure 2.6*. It should be noted that the process may vary at different systems depending on the purpose of analysis and level in an organisation.

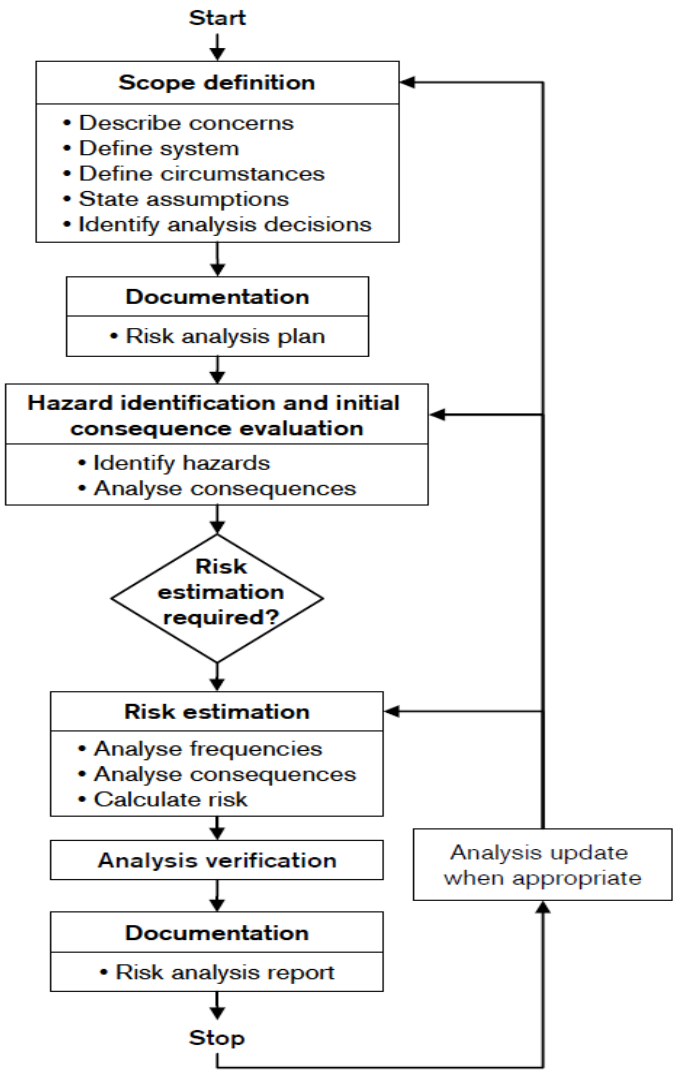

Figure 2.6 Risk analysis process by IEC, 1995.

Scope definition

Scope definition describes purpose of the analysis and the problem of concern including a description of the system being analyzed. The system description should include the technical system, system boundaries, operational conditions and the environment of its locality. Description of the system in the context of risk analysis is essential to generate valid and acceptable outcomes to the stakeholders (MacGillivray and Pollard, 2008). Assumptions and constraints that could influence the analysis should also be described in this step. Rosén et al. (2007) suggested that the first step of a WSP, which is to assemble a team, is a part of the preparatory work which is to be done actually before starting the risk management work and could be included in the scope definition. They argued that the reason why scope definition is not included in a WSP as a separate part is because it is understood that a WSP is focused on health risks related to drinking water. They commented that if scope definition were included in the WSP, it would have broadened the field of its application.

Hazard identification

Hazard identification is the identification of situations, events or substances that have potentials of causing adverse consequences (MacGillivray and Pollard, 2008). TECHNEAU defined this step as a process of recognising that a hazard exists and the hazard is a source of potential harm, i.e. a hazardous agent, or a situation with a potential to cause harm, i.e. a hazardous event. This definition of hazard included a wide range of risks that could be generated in a drinking water system apart from that given by the WHO. According to the WHO, hazard is a biological, chemical, physical or radiological agent that has the potential to cause harm. To compare with WSP, Rosén et al. (2007) stated that the 2nd step of WSP, describing the water supply, is a part of scope definition and hazard identification. They argued that to be able perform a hazard identification, knowledge of the system is required and system description is also a part of the documentation work.

Rosén et al. (2007) presented a number of techniques for identifying hazards in a system. The process of hazard identification is largely based on questioning. Therefore, while formulating questions, consideration should be given to the whole system or process and efforts must be made to identify all root causes of a risk. It should be noted that if any hazard is excluded, the risk would remain in the system until next update. Rosén et al. (2007) recommended that a combination of checklist and what-if analysis could be used in order to obtain more systematic hazard identification. TECHNEAU developed a hazard database (Beuken et al., 2007) that contains a comprehensive list of hazards and hazardous events and can serve as a checklist for water utilities. Definitions of the hazard identification techniques are presented in *Table 2.2*. Besides, they also described hazard and operability analysis (HAZOP), which is a systematic technique for identifying hazards, particularly unforeseen hazards, and operability problems throughout a plant. HAZOP analysis is most suitable for identifying hazards in the treatment system and the distribution network in a drinking water system. Main objectives and steps of a HAZOP analysis along with an example of use on drinking water treatment process are presented by Rosén et al. (2007).

Table 2.2 Definitions of the hazard identification techniques (Rosén et al, 2007).

Brainstorming	A process that generate ideas about possible hazards and hazardous events that may occur within a system being analysed through spontaneous contribution from members
Experience from the past	Analyses of accidents and incidents happened in the past and available reliability data to identify problem areas and also to provide input into frequency analysis
What-if analysis	A creative brainstorming examination of a system, process or an operation by a group of experienced personnel who ask questions beginning with “what if” e.g. what if the pump inlet pipe is blocked?
Checklists	A list of specific items to identify known type of hazards and potential accidents

Risk estimations

Usually, risks are estimated using one of two approaches, the qualitative or the quantitative approach. The primary difference between the approaches is that risks estimated using a qualitative approach is expressed in words (Lindhe, 2008) whereas in a quantitative approach risks are calculated and are often expressed as the product of the numerical values of probability and consequences. In order to calculate risks quantitatively, a quantitative evaluation of the probability and the consequences have to be carried out. Although defining and estimating risk quantitatively is sometimes subject to criticism (Lindhe, 2008), its importance has also been recognized when a rational decision is to be made. To be able to weigh risks compared to other cost and benefits requires a clear quantitative approach (Kaplan and Garrick, 1981). Lindhe (2008) argued that even if risk is expressed quantitatively, human perception of risk should be considered in the decision making process. In addition to the approaches described above, sometimes a semi-quantitative approach is also used for risk estimation. It is actually a combination of the two principal approaches in which numbers are assigned on discrete probability and consequence scales (Lindhe, 2008).

The purpose of this section is to describe the methods used in the risk assessment case studies in Bergen and Březnice. In both case studies, a qualitative approach has been used to estimate risks; therefore, in this section a qualitative approach is described broadly. A quantitative approach of estimating risk is applied e.g. in the Goteborg case study, see Lindhe et al. (2010).

A qualitative risk estimation method aims at ranking risks using risk matrices. In order to express risk in the matrix, the probability of the hazard and its consequences need to be assessed according to some type of scale. Since it is likely that all the systems are somewhat different, no single scale can be used (Lindhe, 2008). Establishment of probability and consequence scales are therefore subject to each system being studied. An example of the risk scoring matrix along with a probability and a consequence scales is presented in *Figure 2.7*. To qualitatively assess the probability of an undesired event, possible probability categories have to be identified first. In the example, five categories of probability have been selected, i.e. almost certain, likely, moderate, unlikely and rare. These categories need to be defined for a specified timeframe so that expected or likely frequency of an undesired event could be represented.

Example of a simple risk scoring matrix for ranking risks with risk categories

Likelihood	Severity of consequences: Insignificant	Minor	Moderate	Major	Catastrophic
Almost certain	H	H	E	E	E
Likely	M	H	H	E	E
Moderate	L	M	H	E	E
Unlikely	L	L	M	H	E
Rare	L	L	M	H	H

Note: The number of categories should reflect the needs of the study.
E – Extreme risk, immediate action required; H – High risk, management attention needed;
M – Moderate risk, management responsibility must be specified; L – Low risk, management by routine procedures.

Examples of definitions of likelihood and severity categories that can be used in risk scoring

Item	Definition
Likelihood categories	
Almost certain	Once a day
Likely	Once a week
Moderate	Once a month
Unlikely	Once a year
Rare	Once every 5 years
Severity categories	
Catastrophic	Mortality expected from consuming water
Major	Morbidity expected from consuming water
Moderate	Major aesthetic impact possibly resulting in use of alternative but unsafe water sources
Minor	Minor aesthetic impact causing dissatisfaction but not likely to lead to use of alternative, less safe sources
Insignificant	No detectable impact

Figure 2.7 Risk ranking matrix with probability and consequence scales (WHO, 2004).

The same procedure is applicable to establish a consequence scale. However, in the example in *Figure 2.7*, consequence categories are presented for quality failures. When developing the consequence scales, consideration must be given to the site-specific sensitivities. For example, if a system considers maintaining customer trust and confidence is essential in their business context, it can select a representative category for those undesired events that causes loss of customers trust and confidence. When both scales are created, each undesired event is set to the matrix against their corresponding probability and consequence categories. To decide whether a risk is unacceptable or acceptable, risk tolerability criteria must be defined. This is further described in risk evaluation below. Sometimes each category of probability and consequence scales are assigned numeric values, facilitating the calculation of semi-quantitative risk index (Lindhe, 2008).

2.4.2.2 Risk evaluation

Risk evaluation measures the significance of a risk and answers the question if identified risks are tolerable compared to predefined risk acceptance criteria (RAC). TECHNEAU defined risk evaluation as a process in which judgements are made on tolerability of risk on the basis of risk analysis and taking into account socio-economic and environmental aspects. Establishing RAC forms the basis for evaluating the acceptability of risk i.e. whether to mitigate or accept risk (MacGillivray and Pollard, 2008). There are a number of factors that need to be considered upon deciding on RAC. One such important factor is to consider on which level of a utility RAC will be applied. According to Rosén et al. (2007), RAC can be applied on both lower and top levels, where RAC on a lower level are defined for e.g. a specific equipment or process.

Another important factor whereas RAC on a top level is defined for e.g. total risk within a system. To consider various normative issues related to a water utility, it also includes people's perception of risk and risk aversion. According to Hokstad et al. (2004), the following are main normative issues that need attention during selection of RAC:

- Dimensions (aspects) of risks need attention e.g. water quality, quantity, environmental issues etc.
- Preferences and tradeoffs among the dimensions
- Arriving at actual acceptance limits for various risks

Rosén et al. (2007) emphasised that a discussion is needed for selecting dimensions for evaluation. Establishing RAC is one of the important steps of risk evaluation where stakeholder participation or incorporating stakeholder's values plays an important role. Grimvall (1998) pointed at three kinds of stakeholders who are directly affected by a decision that involves risks. They are those who are exposed to the risk, those who are generating the risk, and the decision makers. Rosén et al. (2007) emphasised that selection of risk tolerability criteria or principles should be agreed upon among the affected stakeholders. Finally, they suggested that RAC should have an ethical foundation without compromising the safety. In addition, measuring the significance of a risk requires considering the overall threat it poses to the community (threats in terms of safety), other consequence costs if it happens and costs for mitigation.

TECHNEAU suggested application of the ALARP (As Low As Reasonably Practicable) principle for evaluation of risks. It uses upper and lower acceptance limits to separate unacceptable and acceptable risks. Unacceptable risks must be reduced to an acceptable level whereas a risk in the ALARP zone requires further investigations that include identification, cost assessment and efficiency of possible reduction options. Equally, acceptable risks are recognised and can be left for control at the time of its occurrence. The ALARP principle and its use in a risk matrix are presented in *Figure2.8.*

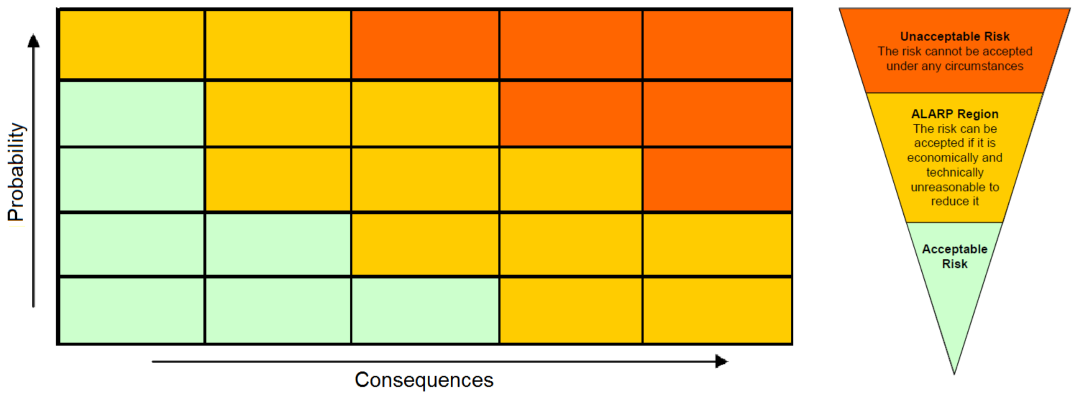

Figure 2.8 ALARP principle (right) and its use in a risk matrix.

2.4.2.3 Risk reduction/ control

Results from risk evaluation provide guidance on further actions/decisions needed to manage risks. If a risk is identified as unacceptable, measures should be taken in order to reduce it. Sometimes risk reduction is also termed "risk treatment". Rosén et al. (2007) suggested the following three approaches for reducing risks (based on the definition that risk is a combination of probability and consequence), and is also illustrated in *Figure 2.9:*

- Reducing probability
- Reducing consequences
- Reducing both parameters (probability and consequence)

Risk analysis, particularly frequency and consequence analyses, may provide guideline on selecting an appropriate approach for risk treatment. If probability provides the major contribution to the risk, reducing probability might be reasonable for substantial risk reduction. Similarly, if the outcome of the consequence analysis provides major contribution to the risk, reducing consequence might be a better solution. However, the risk could also be contributed more or less equally by both of the factors. In that case, reducing both of them could bring a good outcome. On the other hand, adoption of an approach might depend on the available risk reduction alternatives. For example, some alternatives might offer positive consequences in addition to reducing negative outcomes. This has been denoted as risk optimization. Rosén et al. (2007) mentioned another measure, "risk avoidance", that is a process or an activity to make sure a source of risk is not started or is discontinued.

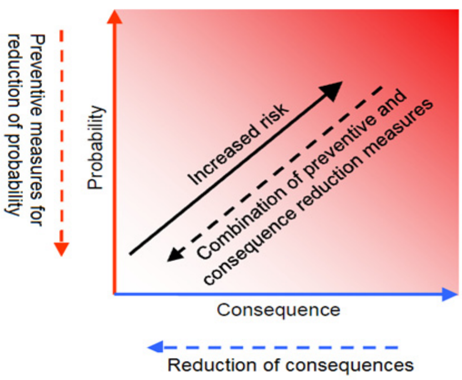

Figure 2.9 Illustrations of the risk reduction approaches/principles.

Proper evaluation of the effectiveness of the decisions that have been implemented is ensured by deploying a monitoring system. Monitoring allows decision makers and other stakeholders to compare actual benefits and costs with those that have been estimated during the decision analysis process. At this stage, reassessment of the decision making process is appropriate.

2.5 The decision making process

In this section, an overview of the risk-based decision making process is presented. Risk analysis is always part of the decision context (Aven and Korte, 2003). While risk analysis identifies different levels of risk, decision making is the identification of the optimal solution for managing those risks. It follows a rigorous process of identifying a number of relevant alternatives, analysing the alternatives and applying expert review and judgement for selecting the optimal alternative. Different steps of a risk-based decision making process are illustrated in *Figure 2.10*. The steps are not as straightforward as depicted; nevertheless, each step requires different considerations depending on the objectives of the study, decision situations and the system being studied. Aven and Korte (2003) prescribed a structure for a decision making process, although not in details, the process includes important considerations for its different steps. In the later part of this section, the process has been described.

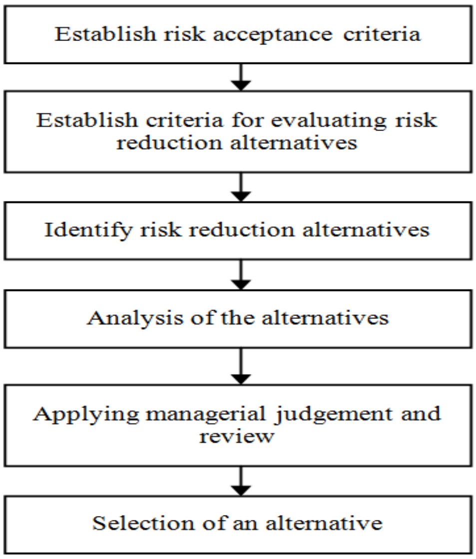

Figure 2.10 Different steps of a decision making process (Aven et al., 2007).

To be able to arrive at a good decision, Aven and Korte (2003) suggested that decision making should be considered as a process with the following three steps:

- Formal risk analysis
- Formal decision analysis
- Informal managerial judgement and review process

The rationale is that results of formal risk and decision analyses would support decision makers to apply their judgement and also to review the process in order to select the best available solution. *Figure 2.11* illustrates the structure of the process that has been drawn from the above mentioned hypothesis.

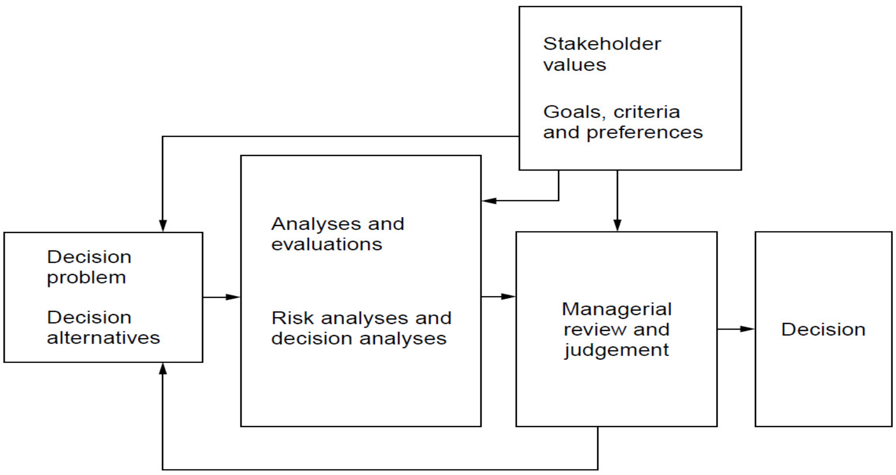

Figure 2.11 Basic structure of the decision making process (Aven and Korte, 2003).

2.5.1 Decision problem

The process, as described by the authors (Aven and Korte, 2003), starts with decision problem that arises when a number of alternatives are identified. There are different situations in different phases/life cycles when a decision problem can arise, for example, during the design stage, during operation if specific problem encountered. Initially experts and managers identify and present a set of alternatives for discussion. Development of these alternatives is driven by the boundary conditions that include stakeholder values, e.g. formulated as organisational goals, criteria, standard and preferences. Different views expressed by politicians, environmentalists and others as well as experts' experience, knowledge and preferences can also significantly influence the selection of the alternatives. The authors suggested that appreciation of the subjective elements in this creative part is necessary. The process should involve a sufficient broad group of personnel and generated alternatives should provide the necessary basis for identifying a good alternative.

2.5.2 Decision analysis

When alternatives are at hand, decision makers need support as a basis for decisions. Risk analysis and analyses of the alternatives provide such support for both the decision makers and stakeholders. Risk analysis supports basically by generating information on the exposure pathways, consequences of the risk if realized and associated probabilities of occurrence. However, risk analysis is an important source of supporting information; decision analysis is particularly assessing and comparing the performance of the alternatives on different attributes, for example, effects on the risk levels, various costs related to each alternative such as implementation, operational and maintenance costs. A number of tools can be used for decision analysis depending on whether effects on any specific or multiple attributes is to be evaluated. Typical tools for such analysis are cost-benefit analysis and methods based on multi-attribute utility theory. The authors also mentioned possible application of cost-effectiveness analysis where resources are limited. Altogether, decision analysis should provide coherent and meaningful information for the decision makers.

2.5.3 Applying managerial judgement and review

For making the final decision, decision makers need to review and evaluate all the supporting information produced during risk and decision analyses. However, this task has been described as informal and no strict rule is prescribed. Decision makers can consider important aspects, if necessary, even outside their boundaries, i.e. incorporating factors of relevance that go beyond the formal analysis. For example, if they need to put more importance on some specific attribute e.g. safety; they can incorporate it before making the final decision. Typically, at this stage, decision makers relate supporting information with the values formulated as goals, criteria and preferences.

2.5.4 Other aspects of decision making in drinking water

The purpose of describing important aspects of decision making for the drinking water utilities is to identify and describe their fundamental goals as well as listing a number of generic criteria that can be used for evaluating risk reduction measures and other actions. Generally, the overall goal of drinking water utilities is to supply water that does not pose any unacceptable risk. Meeting the goal requires that the supplied water is safe in terms of quality and is sufficient in quantity. As described in the Bonn

Charter (IWA, 2004), there are a number of fundamental objectives for which water suppliers should strive:

- Access to good, safe and reliable water supply depending on the situation of the locality. Where already high quality of water is available, the objective is to continue improvement. In contrast, where waterborne disease or other quality deficiencies are prevalent, the basic provision of safe and good supplies is vital.
- Water that is not just safe to drink but considered of good aesthetic quality by the consumers.
- Water supplies in which consumers have confidence.

In addition, water utilities might consider other long term goals in their business context, for example, building reputation to be competitive over other organizations, financially and technically stabilize the company for operational optimisation etc. Furthermore, utilities might adopt sustainability principles that include multiple objectives in natural resource planning (Hajkowicz & Collins, 2007). In a risk management decision context, decision objectives that are the desired outputs of a decision situation should be explicitly defined and formulated in line with utility's long term goals in order to keep the analysis in the right direction and for allowing gathering and analysing specific information.

An array of criteria is required in a multi objective decision situation where criteria would measure each alternative's performance on achieving the goals and objectives. However, criteria originate primarily from the objectives; the procedure for deriving criteria is, among other considerations, basically recapitulating the goals and the decision context that includes mainly the problem concerned, purpose and aims of the decision analysis, information on who are the decision makers and other stakeholders (Community and Local Government, 2009). The procedure should also accompany, by brainstorming, responses to the question "What would distinguish between a good choice and a bad one in this decision problem?" Below, a simple example on how criteria can be derived is presented. This is not essentially the case for every situation. Stakeholders play the central role on deriving criteria either through the organization´s goals, values and preferences or any other form of stakeholder gathering for this specific purpose.

One of the primary objectives of drinking water utilities is to comply with the state´s legislation concerning the drinking water supply. Utilities are usually obliged to maintain water quality standard as well as supplying sufficient quantity of water to the public. In order to express this objective as a measure for the alternatives on how well they perform on complying regulations, a higher level criterion, for example, *regulatory compliance* can be used. To represent components, it can be further split into two sub criteria as water quality and water quantity. In order to evaluate alternative´s overall regulatory compliance, an assessment should measure how much an alternative contribute for improving water quality and for ensuring supply reliability.

A number of groups (i.e. main and sub criteria) of relevant criteria that cover a wide range of issues on water utility decision context are identified in the literature review and presented in *Table 2.3*. These sets do not represent all issues involved but hopefully would help deriving criteria in these case studies. Before choosing a set of criteria, its comprehensiveness, applicability, transparency, tractability and practicability should be checked for a particular project (Foxon et. al., 2002). It should be noted that overall sustainability can be measured using a combination of a number of criteria e.g. economic, social, environmental and technical (Butler et al., 2003).

Table 2.3 Sets of main and sub criteria relevant for using in risk management decisions for water utilities.

Economic	Life cycle cost (covering costs for all stages from cradle to grave including capital, operation and maintenance costs), Willingness to pay (for attributes covering product, environmental, safety and health factors), Affordability (ability of all classes of customers to pay for the service delivered), Financial risk exposure (risk of loss for the company associated with particular kind of investment), Cost-effectiveness (cost for an option achieving a specified target level of performance).
Social	Human health risk, Acceptability to stakeholders, Public awareness, Fairness and equity (equally addressing all classes of people), Political impact, Public health
Compliance	Regulatory compliance (includes water quality standards and supply requirements related to water quantity according to the state´s legislation), Other quality standards, Contractual compliance
Reputation	Consumer trust and confidence, Customer services, Community relationships, Environmental partnerships
Environmental	Resource utilisation (includes use of water resources, land, energy, materials and chemicals), Environmental impact (covering a wide range of impacts on water, land, air or biodiversity and wildlife).
Technical	System´s performance, System´s flexibility and adaptability (ability to make future changes in the system), Reliability (effectiveness to control water demands even after any incident and during maintenance), Durability (expected lifetime of the system).

2.5.5 The TECHNEAU decision support framework

A decision support framework for evaluating risk reduction alternatives for managing risks in the drinking water sector is presented in this section. The framework has been developed by TECHNEAU based on the general risk management process by IEC (1995) and the basic structure of a decision making process (Aven and Korte, 2003) presented in the previous section of this report. The purpose of the framework is to guide development of risk-based decision support methods for prioritisation of risk reduction alternatives. Being risk-based, the decision problems are results of a risk analysis carried out in the specific system at hand. It also aims to describe the connections between risk assessment and decision making process as well as the steps included in the work (Lindhe et al., 2010). The framework is presented in *Figure 2.12* to show the basis on which the decision support method has been developed. It should be noted that it is equally applicable for decisions related to both operational and strategic levels of an organization.

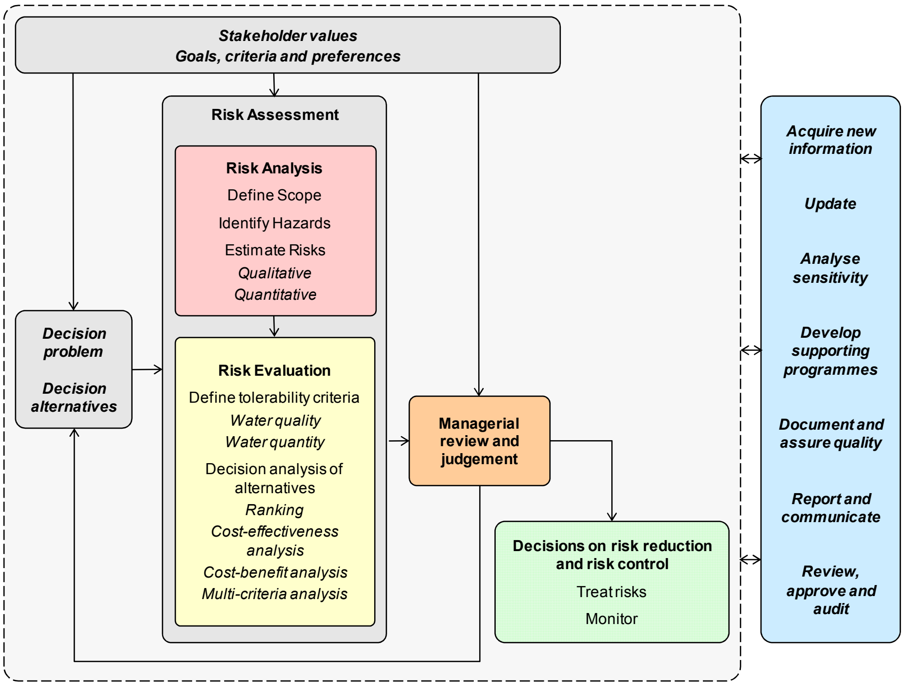

Figure 2.12 Suggested decision support framework for risk management (Rosén et al., 2010.)

3 Method

3.1 Overview of method

In this section, the outline of the method proposed for evaluating and comparing the risk reduction alternatives is presented. The proposed method consists of eight consecutive steps that result in a Multi-Criteria Analysis (MCA) for ranking the alternatives, see Figure 3.1. A short description of the MCA technique is given in Section 3.2. The method presented here starts with identifying the most severe risks that need to be reduced. This first step connects risk analysis with the subsequent decision analysis. Following steps altogether form the decision analysis in which step two and three guide the analysis in the desired direction. These steps include formulation of the decision maker's objectives in line with the long term goals and derivation of evaluation criteria from the objectives. Identification of relevant alternatives, assessment of their performances on each of the criteria and making their comparison are the other key steps of the procedure. In the last step, sensitivity analysis has been included in order to check the influences of the weights assigned to each criterion to the priorities obtained after the analysis. The order of the steps must be followed except the third and fourth ones which can be interchanged. All the steps are described in detail in section 3.3.

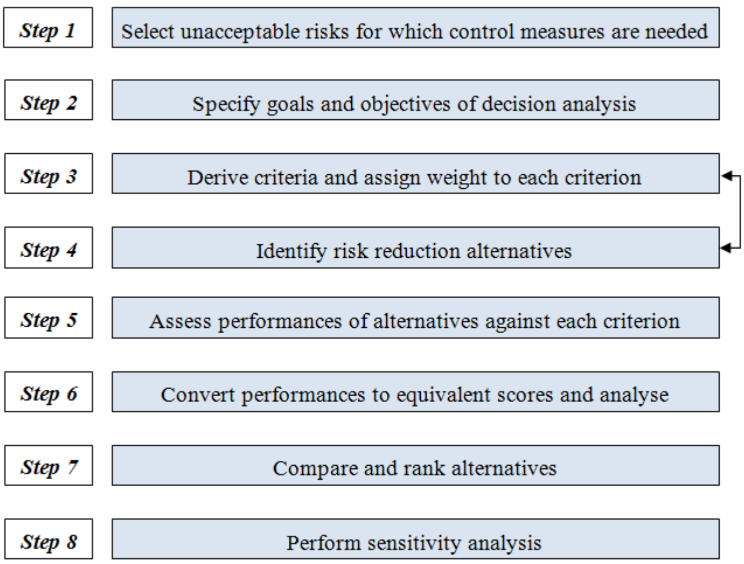

Figure 3.1 Proposed step-by-step procedure for decision analysis

3.2 Multi-Criteria Analysis

Multi-Criteria Analysis (MCA) is a decision support tool that can be used to identify a single most preferred option, to rank among a number of options, to short list a limited number of options for subsequent detailed appraisal or simply to distinguish acceptable from unacceptable possibilities. A comprehensive description of MCA has been given by the Department of Communities and Local Government in the UK (Communities and local government, 2009). The main advantage of the technique is that the decision makers can consistently handle a large amount of complex information with it. An important feature of MCA is its emphasis on the judgement of the decision makers at its different steps which is also a concern since different steps of the technique relies largely on the decision maker's own preferences. A number of

MCA methods exist and they use different approaches. The selection of a suitable approach depends on a number of factors, of which the technique's logical soundness, transparency, eases of handling, relevant software availability, and compliance of its data requirements with the problem being considered, are important. It provides transparency and all information can be updated when necessary

The technique measures potential options to what extent they meet the objectives that are to be achieved. This is done by setting the decision objectives at initiation and deriving an array of measurable criteria that measure performances of the options on achieving the objectives. In order to express varying significance of the criteria, they are assigned weights. Each of the options is then scored in a defined scale against each criterion. Performance of an option on a specific criterion is calculated by multiplying the option's score on that criterion and its corresponding weight. Finally, sum of performances on all criteria express an option's overall performance. A sensitivity analysis is often an integral part of the technique. A short description of sensitivity analysis is given in section 3.3.2.

3.3 Steps in proposed method

The proposed method is developed to be combined with the result from risk ranking using risk matrices. It should, however, be noted that, the risk ranking procedure is not part of the method presented here, but risk ranking provides an input to it. The eight steps of the proposed method are chronologically described below.

1) Select unacceptable risks that are considered most important and for which control measures are needed. This is based on the results from a risk ranking and evaluation of risk tolerability.

2) Describe goals of the decision maker and formulate objectives for the decision analysis in line with the goals and risk management decision context.

3) Derive evaluation criteria from the goals of the decision maker and objectives of the decision analysis. Each criterion should be assigned a weight (numeric value) that represents its relative importance over other criteria. Assigned weights are to be normalised that is sum of the weights must be set to one. Rationales for using a specific set of criteria and their corresponding weights as well as the indicators that would be used for assessing performances of the alternatives should also be described in this step.

4) Identify a number of relevant risk reduction alternatives for each of the selected risks. Alternatives can be identified by means of, for example, brainstorming sessions.

5) Assess performances of the alternatives on each criterion and summarize in a table.

6) Assign scores for the performances on a scale from 0 to 100. Assigned scores should represent estimates of the decision maker's preferences where a score 100 is to be given to an alternative that performs best against a specific criterion and 0 to the one that performs worst against that criterion. Other performances in between should be scored according to their proportions.

However, estimating preferences is an iterative process and care must be taken so that best possible estimates are to be obtained.

7) Compare the alternatives based on the assigned weights of the criteria and scores of the alternatives against those criteria. The basis of the comparison is the overall performance score calculated by multiplying an alternative's score on a criterion by the weight of that criterion, then summing up the products to get the overall performance score for that alternative. Same process is to be applied for the remaining alternatives. Alternatives can be compared using the Web-HIPRE software (Web-HIPRE, 2010). A short description on the software is presented in *section 3.2.3*.

8) Finally, perform sensitivity analysis in order to explore how changes in weights and scores causes recommended decisions to alter. The purpose and importance of the sensitivity analysis is shortly described in *section 3.2.2.*

3.3.1 Calculation of risk reduction

Here, it is described how the risk reduction by an alternative is calculated based on risk ranking results, see *section 2.4.2.1.* In order to estimate risk reductions, initially risk priority number is to be calculated for each cell in the risk matrix. A risk priority number expresses the risk numerically and the difference between the risk levels represents the relative difference in severity. The difference between each category of probability and consequence is to be expressed by assigning discrete values to each category. Then risk numbers are to be calculated for each cell in the matrix by multiplying corresponding probability and consequence values assigned for those categories. As illustrated in *Figure 3.2*, discrete values are assigned for each category of probability and consequence and calculated risk values are presented in each cell of the matrix. For example, consequence categories small, medium, high and very high (C_1, C_2, C_3 and C_4) are assigned values 1, 2, 4 and 8 respectively. It should be noted that the highest risks presented in the example risk matrix in Figure 2.7 are in the upper right corner of the matrix whereas the matrix presented for calculation of risk reduction in Figure 3.2, the highest risks are in the lower right corner. This matrix has been presented because the matrix used for risk assessment in Bergen, Norway is similar to this one. However, the method of calculating risk reduction is applicable either of the matrices.

		C_1	C_2	C_3	C_4
		1	2	4	8
P_1	1	1	2	4	8
P_2	2	2	4	8	16
P_3	4	4	8	16	32
P_4	8	8	16	32	64

Figure 3.2 Risk matrix including an index for each risk level (green, yellow and red colours represent acceptable, ALARP and unacceptable risks respectively).

A risk reduction alternative may reduce the probability and/or the consequence of an event. The change in risk level an alternative (*j*) may provide is used to calculate effect (E_j) of that alternative. Thus, E_j is calculated using Equation 1 where R_0 is the current risk level of a specific undesired event and R_j is the expected new risk level after alternative *j* has been implemented.

$$E_j = [(R_0 - R_j)/ R_0] * 100 \qquad (1)$$

The effect (E_j) thus expresses, in percent, how much the original risk level is expected to be reduced.

3.3.2 Sensitivity analysis

The reason a sensitivity analysis should be performed is to see how changes in the input parameters to a model influence the results of the decision analysis. If a small change in any of the attributes used for defining the model alters the recommended decision, the model is sensitive to that attribute. Sensitivity analysis identifies the attributes to which the model is sensitive to and allows decision makers to concentrate on, or possibly, reconsider the issues. Thus, sensitivity analysis is a central step of an iterative decision-making process. In this study, one way sensitivity analysis is used, i.e. the weights used in the model is changed (one at a time) and the changes in the results are analysed.

3.3.3 Web-HIPRE

Different software for conducting MCA calculations exist. The applications presented in this thesis are performed using Web-HIPRE (HIerarchichal PREference analysis in the World Wide Web). Web-HIPRE is a Java-applet for multiple criteria decision making which can be used to build models, perform calculations, present results and perform sensitivity analysis (Web-HIPRE, 2010).

4 Case Study Sites

This chapter covers background information for the decision analyses performed for the drinking water systems in Bergen (Norway) and Březnice (the Chez Republic). The drinking water systems are shortly described and previously performed risk assessments are summarised for both systems. Descriptions of the systems have been excerpted from the previous study reports; see Røstum and Eikebrokk (2009) and Kožíšek et al. (2008). Summary of risk assessment includes the method used for risk analysis and the results obtained from that study.

4.1 Bergen

Bergen is the second largest city in Norway with a population of approximately 25,000. The municipality of Bergen owns the water supply infrastructures and it is operated through a public water company, Bergen Water KF, which is also owned by the municipality. In 1972, the old Bergen municipality and four other surrounding municipalities merged into one new municipality that resulted in a water company with 18 larger and smaller water works. Later in 1989, it was decided to increase the water supply safety by reducing the number of water works and building five larger water treatment plants and establishing a common water distribution network. At present, the system has five water treatment plants included in a common distribution system. Although each treatment plant has a primary supply zone, all zones can be interconnected. In *Figure 4.1* an overview of the Bergen water supply system is presented.

4.1.1 System description

All raw water sources and their catchment areas in Bergen are regulated. Certain anthropogenic activities that may cause contamination to the sources are prohibited e.g. bathing, fishing, camping, use of boat and horse riding etc. One advantage with four of the water sources is their location in mountainous areas with no settlement leaving possible contamination sources limited to wild animals and birds, grazing sheep and recreation activities.

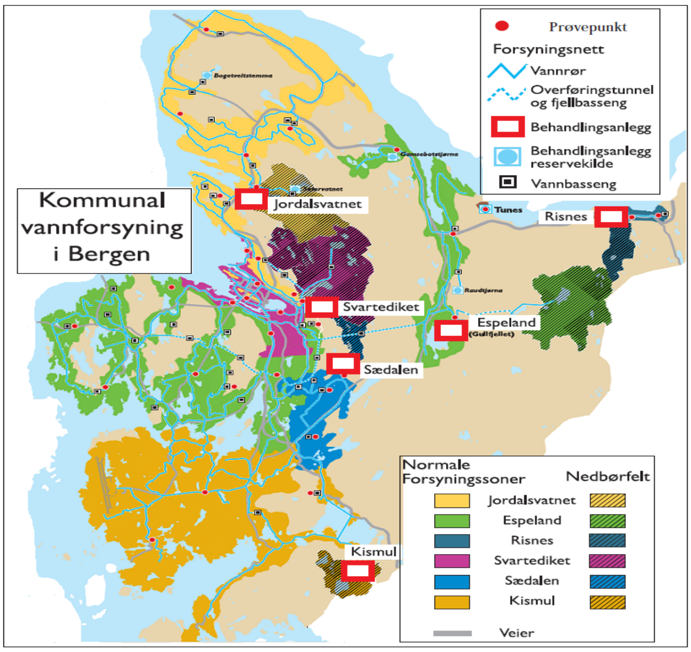

Figure 4.1 Overview of Bergen water supply system (modified after www.bergenvann.no)

Among its five treatment plants, four follow the same treatment steps consisting of coagulation, filtration, corrosion control and disinfection by UV and/or chlorination. One of the treatment plants is left out of coagulation due to its acceptable microbial quality and very low NOM (Natural Organic Matter) and turbidity levels. Since the whole system is interconnected, it allows any of the treatment plants to be down for maintenance without affecting the system's capacity to deliver water to the city. A typical flowchart of the water treatment steps and also the overall path of water from catchment to consumer are illustrated in *Figure 4.2*.

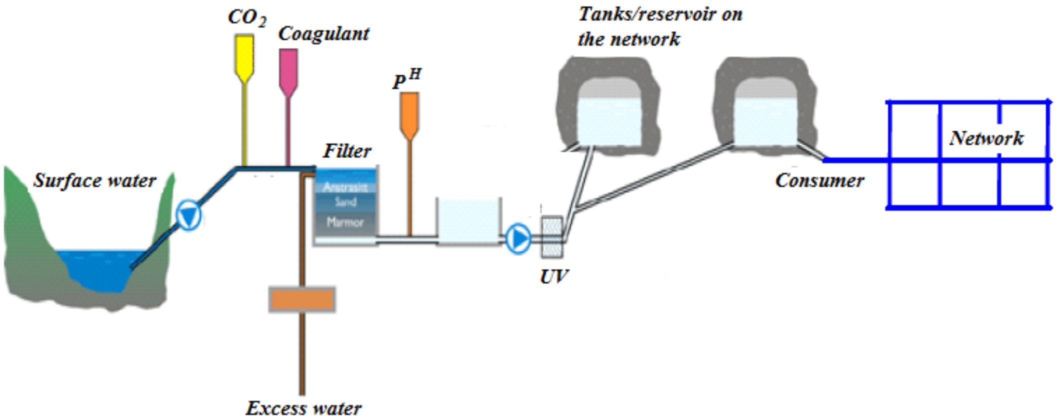

Figure 42 Generic description of the drinking water system in Bergen (www.bergenvann.no)

Bergen water distribution network consists of:

- 900 km public and approximately 900 km private pipelines.
- 65 water reservoirs and 37 water tanks / basins with a capacity of 282,000 cubic meter equivalent to approximately 2 days of consumption
- 78 pumping stations
- 10,000 manholes and 25,000 valves of different types

4.1.2 Risk assessment

4.1.2.1 Method

The risks to the Bergen drinking water supply have been assessed using a risk ranking method called Risk and Vulnerability Analysis (RVA) (Røstum and Eikebrokk, 2009). The method is a traditional type of risk ranking method and is termed Course Risk Analysis (CRA) in the TECHNEAU project (Røstum and Eikebrokk, 2009). However, the RVA in Bergen also used some elements from the WSP and HACCP principles. The concept of RVA is based on the identification of threats, their chain of causes that lead to an undesired event and consequences as illustrated in *Figure 4.3*. Hazards were identified using a combination of the TECHNEAU hazard database (Beuken et al., 2007), i.e. a checklist and from detailed flow diagrams of the system combined with a plenary discussion and onsite inspection.

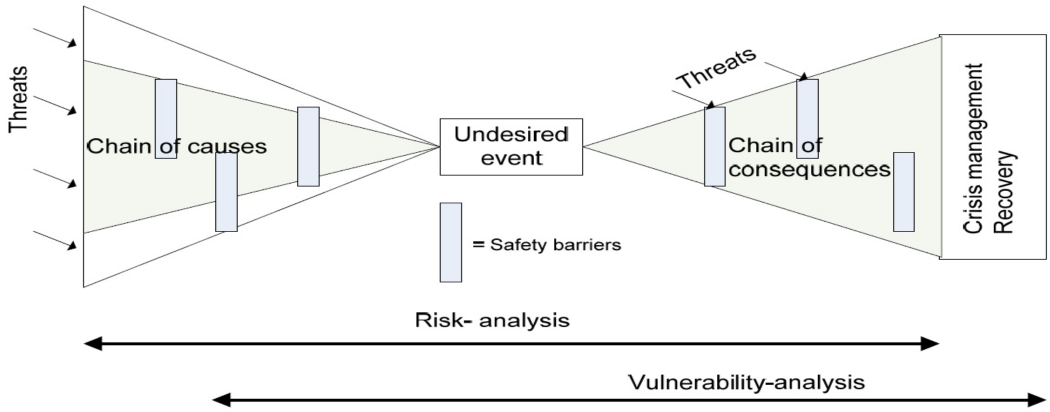

Figure 4.3 Illustration of the RVA method, also called bow-tie diagram (Røstum and Eikebrokk, 2009)

For each hazard, probabilities and consequences are assessed in the scales categorised as small, medium, high and very high. Assessing probabilities and consequences used a set of indicators. Probability and consequence categories as well as corresponding indicators are presented in *Tables 1 and 2* in the Appendix A. Finally, risks are expressed in standard risk matrices.

4.1.2.2 Summary of risk assessment results

The risk assessment performed in Bergen identified 85 undesired events. These events are registered in a database, which can be updated when necessary. Before entered into the database, all hazards were categorised based on their effects either on water quality, on water quantity and on reputation/economy. Risks are estimated and ranked using separate matrix for each of the category. A summary of the major hazards is presented in the Appendix A.

4.2 Březnice

Březnice is a small town in central Bohemia of Czech Republic with nearly a population of 3,500. Its drinking water system is primarily based on groundwater sources. Different authorities govern different components of the system e.g. the Ministry of Environment is responsible for the protection of water sources (through the Water Act) while the Ministry of Agriculture regulates (through the Act on Water Supply and Sewage Systems for Public Needs) the use of water sources, drinking water production and supply to the consumers. On the other hand, regular monitoring (through the Public Health Act) of drinking water quality is performed by the Ministry of Health. Water quality is also monitored at the tap by the utility within the scope and frequency given by the Drinking Water Directive. Treated water leaving the plant and water in the sources are also monitored. At present, the municipality of Březnice owns water infrastructures and has leased it to a professional water company Vodovody a kanalizace Beroun (VAK Beroun) -www.vakberoun.cz for its operation. The system produces 380-520 m^3/day potable water for its consumers.

4.2.1 System description

The drinking water system uses three groundwater sources located in Nouzov, Obora and Martinice. Nouzov is situated around 5 km west from the city. It consists of upper and lower spring areas and in each area water is collected from a Y shaped subsurface gallery to a collection chamber. The upper spring area is in the forest and the area over the gallery is started to overgrown by trees. The lower area is located in the midst of fields that are used for grain yield and cattle grazing. Neither spring areas are

fenced. Water from the upper area is chlorinated in the collection chamber by dripping method and transported through a cast iron pipe (60 mm diameter) to the lower spring area, from where through another larger diameter (100 mm) cast iron pipe transported to an old reservoir, Březnice-Stráž I, which is located close to the city. A zigzag pipeline along the boundaries of the fields indicates a potential for pressure loss. Average discharge from the source is 1 l/s (maximum discharge 1.5 l/s). Raw water quality from this source poses acceptable quality and requires only chlorination.
Water is extracted from the source Obora through wells. There are 12 boreholes of which 7 are functional. This source is located at the city border between a small river and the Castle Park. This source is also the nearest to the treatment plant. About half of the well field area is covered with grass but poorly fenced. The other half is an intensively cultivated land and contains two boreholes that are fenced properly. Raw water from the boreholes is directly pumped to the treatment plant through three plastic mains. Total discharge from the source is 6.5 l/s.

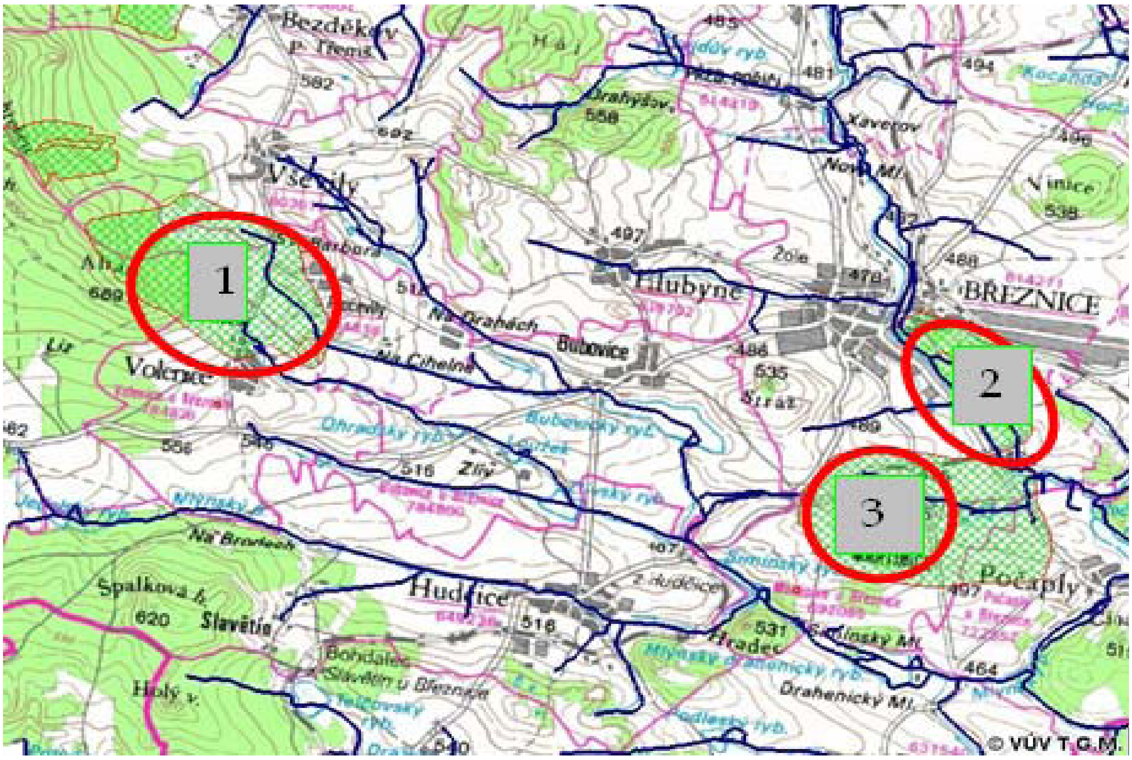

Figure 4.4 Three drinking water sources and their catchments of the Březnice water supply: 1. Nouzov; 2. Obora; 3. Martinice (Kožíšek et al., 2008).

Source Martinice is situated about 2 km south from the city, located close to a pond, covered with grass and protected with fencing. There are 5 functional boreholes with depth ranging from 30-50 m. Raw water from this source is pumped through a 100 mm diameter cast iron pipe to the treatment plant. Total discharge from the source is 10 l/s. Source Obora and Martinice produce water with high Fe and Mn concentration, therefore need to be treated.

The primary treatment requirements of the raw water are removal Fe and Mn. The plant has a capacity of 25 l/s and uses a number of treatment steps e.g. oxidation (potassium permanganate; 1.5 kg per 1600 litre), flocculation, filtration, disinfection (gas chlorine: residual about 0.6 mg/l) and reserve to service tankers. Three water quality parameters P^H, manganese and residual chlorine are monitored manually in the plant. Two reservoirs, each having a volume of 210 m^3, are used to store treated water which is then pumped to a new service reservoir, Březnice-Stráž II, located next to the old reservoir.

A summary of the main features of the distribution system is presented below:

- Total pipe length 33 km (consists of 20.5 km in Březnice, 0.6 km in Bubovice and feed pipelines from source to treatment plant).
- 70%, 25% and 5% of the pipeline is made of cast iron pipe, asbestos cement pipe and plastic pipe respectively; however, some service connections are still in lead.
- The network is not a closed circuit i.e. any failure in the line would cause troublesome consequences.
- The network has a serious problem with leakage which is about 20% of annual supply.
- The old reservoir, Březnice-Stráž I, has two chambers each having a capacity of 110 m^3. Due to high pressure losses, this reservoir now serves as a pumping station to pump water to the other reservoir, Březnice-Stráž II. One of the chambers is currently in use where disinfection by sodium hypochlorite also takes place.

Březnice-Stráž II has two equal chambers with a total capacity of 1300 m^3 and is used to mix and store water from all three sources. Water is then distributed from this reservoir to consumers by gravity. Estimated retention time is about 3 days.

4.2.2 Risk assessment

4.2.2.1 Method

Risk assessment in Březnice has been carried out using the method Coarse Risk Analysis (CRA) where a description of the system and a list of potential undesired events provided the basis for CRA. For identifying hazards and hazardous events following techniques have been used.

- Checklist (TECHNEAU hazard database and main hazards for small water supplies from the Swiss Gas and Water Association)
- Past experiences (of personnel from the utility and local public health authority)
- Brainstorming sessions

Each identified undesired event has been assessed for probability of its occurrence and subsequent consequences. Definitions of probability/likelihood and consequence categories used in this case study are presented in *Tables 1 and 2* in the Appendix B. Later, risks are estimated as a combination of probability and consequence by using risk matrix, for example see *Figure 2.7*. Finally, all results are documented in a modified CRA table that consists of six columns (Hazard – Hazardous event – Consequence category – Probability – Consequence – Risk level); see Kožíšek et al. (2008). In order to express risk levels, following four risk categories have been used:

- Extreme – risks those require immediate action
- High – risks those need management attention
- Moderate – risks for which management responsibility must be specified
- Low – risks that would be managed by routine procedures

In addition, supply reliability of the reservoir has been assessed using the methods Preliminary Hazard Analysis (PHA) followed by Failure Mode and Effects Analysis (FMEA). Initially hazards are identified from the hazard catalogue developed by a Czech national research project (WaterRisk) and divided into natural, social and technological categories. Based on the identified hazards, possible undesired events have been generated and Probability and consequences of each of them have been assessed in order to estimate the risk. The scales used for assessing the probability and consequence are somewhat different, however, apply same principle as used in CRA. For a details description of the used methods, see Kožíšek et al. (2008).

4.2.2.2 Summary of risk assessment results

During the risk analysis, a total of 44 risks have been ranked at four risk categories. Identified risks are associated with all the three components (i.e. source, treatment and distribution network) of the system. Below, in *Table 4.1*, a summary of the number of risks in each category for each component is presented. From the reliability analysis of the reservoir, three undesired events, all ranked as medium risk (according to FMEA method), were identified. As falling in the ALARP region, all three would be subjected to further discussion and not included in the following table.

Since there is no risk tolerability criteria developed by the utility, it has been assumed that any risk that could result non compliance to water quality standard, generate consumer's complaints or lead to any health problem would be regarded as unacceptable. The WSP team also agreed that both extreme and high risks must be reduced while moderate risks would be considered in the ALARP risks in order to identify whether those are economically or technically reasonable to reduce.

Table 4.1 Summary of the identified risks at Březnice (modified after Kožíšek et al., 2008)

Component of the system	Risk Categories			
	Extreme	High	Moderate	Low
Source	1	9	7	7
Treatment	0	2	4	4
Distribution	0	4	5	1
Total	1	15	16	12

5 Multi-Criteria Analyses

5.1 Bergen

5.1.1 Step 1 - Selected hazards for treatment

Four undesired events have been selected for which control measures are needed. For these events at least one risk categories (i.e. water quality risks, water quantity risks or reputation risks) were found unacceptable. Therefore, the risks need to be reduced to an acceptable level. All the undesired events are described chronologically in the following part of this section. Other details of the events are presented in *Table 5.1*. Risk value for each undesired event is calculated using the method presented in section 3.3.1 where each risk value (presented in the parenthesis) in *Table 5.1* is the product of corresponding probability and consequence values assigned to each category. In this case, corresponding values for P_1& C_1, P_2& C_2, P_3& C_3 and P_4& C_4 are 1, 2, 4 and 8 respectively.

Table 5.1Risk levels of each undesired event including probability and consequence categories.

Undesired Event	Component of the system	Current Probability	Current consequence category and corresponding risk values in parenthesis		
			Water Quality	Water Quantity	Reputation/ Economy
Event 1	Source	P_2	C_1 (2)	C_4 (16)	C_2 (4)
Event 2	Treatment	P_4	C_2 (16)	C_1 (8)	C_2 (16)
Event 3	Distribution	P_3	C_3 (16)	C_1 (4)	C_2 (8)
Event 4	Distribution	P_2	C_1 (2)	C_4 (16)	C_3 (8)

(green)	Acceptable risks	Value range 1-3
(yellow)	ALARP risks	Value range 4-6
(red)	Unacceptable risks	Value range 8-16

1. Water Scarcity

Primary cause for this undesired event is the long lasting drought due to dry and cold winter. At present, Bergen has about 4-6 months reserve of raw water. To be specific, total volume of raw water, if all reservoirs are full, would serve 180 days without any rain. Concern over water scarcity has intensified after a dry and cold winter the region has faced in the last Winter (from December, 09 to March, 10) when Bergen had a severe water scarcity with few days of remaining reserve before the rain had has started again. However, vulnerability is reduced to some extent due to the redundancy supplies it has from other water treatment plants as well as due to reduced leakages in the network and reinstalled old alternative raw water sources; however, have found insufficient for future increases in demand.

2. UV disinfection failure (<40 mJ/cm^2)

UV disinfection failure could be caused by either short or long term power failures. There is a regulatory obligation on disinfection dose which has been set minimum 40 mJ/ cm^2. Every year around 20 short term voltage fluctuations occurs in the treatment plant that could result regulatory non compliance on meeting the minimum dose. In such cases of failures, either supply is maintained from other treatment plants or additional chlorine disinfection is applied in order to prevent severe consequences. However, the system doesn't have any barrier for reducing probability of such occurrences.

3. Water contamination

Occurrence of this undesired event can be caused by ingress of contaminants through the open pipelines, corrosion holes, valves or joints during low pressure situations and also while repair and rehabilitation works are carried out in the network. There are some existing barriers in order to reduce either probability or consequences of the event. Probabilities are reduced through some good practices such as repairing pipes when the pipes are still pressurised, preventing backflows through the fire valves and reducing leakages while disinfection after repair, routine maintenance and announcement for boiling water after repairs are the measures usually applied for reducing consequences.

4. Pipe breaks on large water mains causing water quantity problems in specific areas and also risk for water quality problems

Reasons identified for pipe breaks are either mechanical failures or some other external causes such as digging, heavy vehicle loads etc. Risks of such breaks are varies on locations and some areas are more vulnerable than others. However, since the system is partially looped, still some parts could be delivered after such breaks. A rough estimation of the network condition is also routinely performed for early detection of vulnerable pipes.

5.1.2 Step 2 - Goals and objectives of the decision analysis

According to the website (www.bergen.kommune.no), Bergen municipality is entitled to ensure an adequate and sustainable supply of good quality drinking water to the people of Bergen. The municipality's overall vision has been stated as "Pure, clean water for all purposes" that encompasses provision of both drinking water and wastewater services. Further, it explicitly stated its long term vision on health, environment, customer satisfaction, and distribution network renewal plan as follows:

- Health: Supply of drinking water and management of water resources must be done in such a way as to promote the health and welfare of all residents
- Environment: Avoid polluting the environment
- Customer satisfaction: Water supply must be carry out in such a way that the recipients of the services are satisfied and trust the municipality
- Rehabilitation: 1% of the water pipes (9 km) are to be renewed every year

Specifically, the municipality's goal on drinking water supply is to maintain the water quality in accordance with the standard stipulated by regulations and to provide a continuous supply i.e. 24 hours of the day and 365 days of the year. In addition, all operational activities are orientated on enhancing and protecting consumer trust and confidence. In line with its long term goals, a number of objectives of the decision problem are set and presented below. These objectives are formulated generic for both the case studies.

- Reduce unacceptable risks to an acceptable level
- Enhance network reliability in order to avoid risks of failures and supply interruptions
- Protection and conservation of the environment
- Protection and enhancement of reputation by improving service level
- Selection of a cost effective solution

5.1.3 Step 3 - Evaluation criteria and assigned weights

In order to measure performance of an alternative on achieving the objectives, a total of five criteria are selected. Each criterion is then given a weight according to their relative importance on decision making. All criteria with corresponding weights in the parenthesis are presented in *Figure 5.1*. Later in this section, rationale for assigned weights is described.

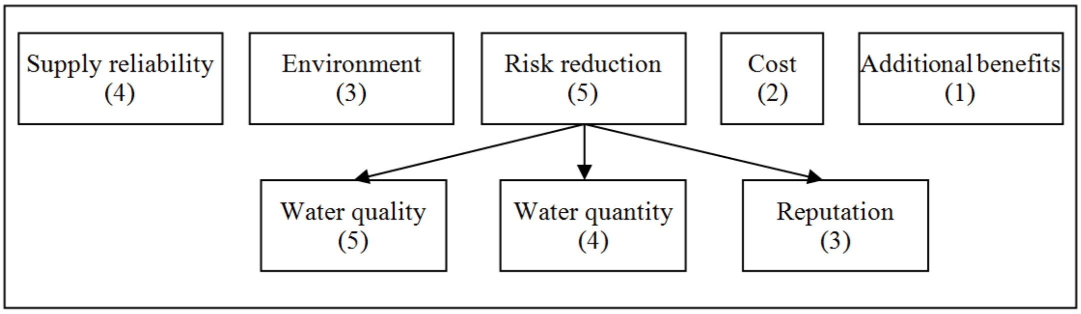

Figure 5.1 the set of evaluation criteria for measuring performances on achieving the objectives and corresponding weights in the parenthesis.

1. Risk reduction

Among the criteria, risk reduction has been given the highest importance with a numeric value 5. Firstly, it is motivated by the fact that, in a risk management decision context, reducing risks are of primary importance. In the risk assessment, since risks are categorised into risks on water quality, water quantity and reputation/economy, the criterion is divided into three sub criteria in order to measure corresponding risk reductions. Water quality and quantity aspects of drinking water are generally regulated by act and obligatory to comply with. For this reason, risks that might result regulatory non-compliance on these aspects should be treated with paramount importance. However, instead of assigning equal weights, water quality is ranked a bit higher (also the highest importance overall) than water quantity, since public health is at stake. Moreover, managing water quality risks are also emphasised by the World Health Organization. Besides, reputation largely depends on both the quality and quantity aspects that how well those are maintained. As they are already given the highest priorities, reputation is weighted a bit less with a value 3. Its importance also reflected on the municipality’s goals as it considered customer satisfaction as a long term goal.

2. System’s reliability

System’s reliability has been considered 2nd important criterion because the company emphasized on building a robust and flexible system in order to prevent inconveniences during emergencies and maintenances. A reliable system is also essential for maintaining quality, quantity and reputational aspects. An alternative's performance on this criterion is assessed based on the following indicators:

- Ability to reduce supply interruptions and water quality failures
- Ability to improve system's inadequacies and flexibility
- Ability to meet future demands beyond current capacity

3. Environment

Environment is also considered as a separate criterion as conservation of the environment is incorporated into municipality's goals. It has been assigned a relative weight 3. Following three indicators have been used in order to assess environmental performance of an alternative:

- Intensity of energy consumption during construction and operation
- Impacts on ecology
- Conservation of water resources

4. Cost

Although in most decision situations cost is the most important determining factor, this is not the case for Bergen. It has been given the 4^{th} importance and assigned a value 2. An interview with one of the senior adviser of the company revealed that cost used to receive higher rank before the Giardia outbreak in 2004. The situation has been changed due to the recognition of water supply system as a critical infrastructure. Costs are assessed primarily based on construction, operation and maintenance costs.

5. Additional benefits

It is found that most of the alternatives provide some additional benefits apart from their desired outputs within the range of objectives. Therefore, it has been included as a criterion and given a weight 1.

It should be noted that, assigning weights should largely be based on the importance given by the stakeholders and decision makers on each criterion, therefore, could differ and could subject to change in other cases.

5.1.4 Step 4 - Risk reduction alternatives

A number of risk reduction alternatives are identified for each undesired event. For simplicity and ease of handling during the analysis, each alternative is expressed as Alt i.j where i denote number of the undesired event given in the previous section and j denotes number of the alternative of that event. In this section, short descriptions on the alternatives identified for undesired event 1 are presented. Due to lack of information, descriptions on the alternatives of other events are left out; however, they are presented in the appendix. Descriptions largely contain general information as well as pros and cons of an alternative for system's reliability and environmental performances. It should be noted that system's reliability and environmental performances are assessed by the author while performances on the other three criteria are assessed by the municipality.

Alternatives for undesired event 1

Alt 1.1: Construction of a new dam at Gulfjellet

If the dam is built, existing volume of the reservoir would substantially increase and would result a more reliable supply of raw water, thus would reduce probability of supply interruptions. Eventually, concerns over the risk would mitigate largely. However, there is no expected contribution on reducing water quality failures. Major contribution of the alternative is expected on meeting increased water demands in future due to increased population or city expansion. Therefore, performance of the alternative on achieving system's reliability is considered medium. Although the project had been planned several years before, it has been postponed due to the opposing stance of different NGO's for its negative environmental impacts especially for limiting outdoor life activities. In addition, it is perceived that the overall impacts on the environment and ecosystem would be low compared to the other alternatives, however, not assessed in detail. Finally, the project has become relevant after the long lasting winter in 2009-2010.

Alt 1.2: Leakage reduction by repairing pipe leaks and rehabilitation of the network

Raw water reserve won't be supplemented by implementation of the alternative rather it would reduce losses, thus has potentials to increase delivering efficiency. It is expected that the alternative would reduce probability of supply interruptions and possible water quality threats i.e. ingress of contaminants through pipe defects. Moreover, the alternative would greatly reduce deficiencies in the distribution network. Regarding contribution to the future demands, a substantial decrease in water consumption has already been observed after regular leakage repairs in the network since last 15 years. During that time, even if, population have increased fifty thousand, consumption has decreased from 53 to 41 million m^3/year. The alternative, if implemented, would help maintaining sufficient pressure in the network which in turn would result efficient fire protection as well as better service quality. Considering all these benefits, it has been assumed that the alternative would provide medium network reliability. Reducing losses and more water demands would also render some environmental benefits, for example, efficient use of water resources and lesser energy consumption by the system. In addition, the alternative won't have any negative effect on the ecology.

Alt 1.3: Installation of water meters to control demand

Similar to the previous one, this alternative would primarily benefit by reducing water demands and losses during consumption. As a result, increases in water pressure and delivery efficiency are expected. However, the level of performance on reliability might not reach the level of the previous alternative. Therefore, it is assumed that performance on system's reliability would be achieved low. Besides, environmental benefits are expected to be achieved similar to the previous alternative however lesser magnitude.

Alt 1.4: Establishing new water treatment plant/ intake to the new areas

Establishing a new treatment plant with new intake in the newly developed areas would further improve robustness of the already flexible system. It is expected that reliability of the system would be high if the alternative is implemented. The alternative would reduce probability of supply and quality failures. It is also expected that the alternative would perform best meeting future changes in demands. In contrast, on environmental point of view, it would result more natural resource consumption including energy particularly over its life time. However, perhaps direct damages on ecology might not reach the level assumed for Alternative 1.1. On this ground, environmental performance is ranked low.

5.1.5 Step 5 - Performance assessment of the alternatives

5.1.5.1 Calculation of risk reduction

Evaluating risk reduction performances requires that all expected as well as current risk levels are estimated. Expected probability and consequence categories, after implementation of an alternative, are assessed by the municipality and used for calculating the effect of an alternative according to the method described in *section 3.3.1*. All risk reductions by the alternatives are calculated and presented in *Table 5.2*. It shows, for each risk category, the existing risk level as well as the risk level expected to be achieved after implementation of an alternative. Besides, red, yellow and green colours are used in order to show the actual risk levels.

Table 5 2 Calculation of risk reduction performances for the Bergen system.

Undesired Events	Alternatives	Probability		Performances of alternatives on risk reduction																
				Water Quality					Water Quantity					Reputation				
				Consequence level		Risk value		Risk Reduction %	Consequence level		Risk value		Risk Reduction %	Consequence level		Risk value		Risk Reduction %
		Existing	After	Existing	After	Existing	After		Existing	After	Existing	After		Existing	After	Existing	After	
1	1.1	2	1	1	1	2	1	50	8	2	16	2	87.5	2	2	4	2	50
	1.2	2	2	1	1	2	2	0	8	8	16	16	0	2	2	4	4	0
	1.3	2	2	1	1	2	2	0	8	8	16	16	0	2	2	4	4	0
	1.4	2	1	1	1	2	1	50	8	1	16	1	93.75	2	2	4	2	50
2	2.1	8	4	2	2	16	8	50	1	1	8	4	50	2	2	16	8	50
	2.2	8	2	2	1	16	2	87.5	1	1	8	2	75	2	2	16	4	75
	2.3	8	8	2	2	16	16	0	1	1	8	8	0	2	2	16	16	0
	2.4	8	2	2	1	16	2	87.5	1	1	8	2	75	2	2	16	4	75
	2.5	8	4	2	1	16	4	75	1	1	8	4	50	2	2	16	8	50
3	3.1	4	2	4	4	16	8	50	1	1	4	2	50	2	2	8	4	50
	3.2	4	2	4	2	16	4	75	1	1	4	2	50	2	1	8	2	75
	3.3	4	2	4	4	16	8	50	1	1	4	2	50	2	2	8	4	50
	3.4	4	2	4	4	16	8	50	1	1	4	2	50	2	2	8	4	50
	3.5	4	2	4	1	16	2	75	1	1	4	2	50	2	8	8	16	-50
4	4.1	2	1	1	1	2	1	50	8	1	16	1	93.75	4	4	8	4	50
	4.2	2	1	1	1	2	1	50	8	8	16	8	50	4	4	8	4	50
	4.3	2	2	1	1	2	2	0	8	8	16	16	0	4	4	8	8	0

5.1.5.2 Performances on other criteria

Performances on *Risk reduction* and *Additional benefits* criteria are evaluated as percentage of risk reduction (effect) and number of other hazards affected by an alternative respectively. On the other hand, performances on other three criteria (Cost, Environment and Supply reliability) are assessed qualitatively in a scale of high, medium and small. Detail cost assessments are performed by the municipality, however, due to restrictions; it is not available for presenting in this report, and rather it has been expressed qualitatively in the above mentioned scale. Performances on environment and system's reliability are roughly assessed by the author based on three selected indicators for each as mentioned in *section 5.1.3*. The assessment is crude and reliability of it can be questioned, however, it could be used for qualitative performance assessment for an alternative, provided that details and accurate information are collected and used. It can be argued that since primary objective of the study is to develop the method, a deviation from accurately assessed values won't affect the analysis. A summary of the performances is presented in *Table 5.2*.

Table 5.2 Performances of the alternatives on all the criteria except risk reduction.

Undesired event	Alternative	System's reliability	Environment	Cost	Additional benefits (no. of hazards affected)
Event 1	1.1	M	L	M/H	2
	1.2	M	M	M/H	4
	1.3	L	M	M	1
	1.4	H	L	H	3
Event 2	2.1	L	0	L	0
	2.2	L	0	M	0
	2.3	M	0	H	5
	2.4	M	0	M	1
	2.5	M	0	M	1
Event 3	3.1	L	0	L	0
	3.2	M	M	M/H	3
	3.3	L	H	M	2
	3.4	L	0	L	0
	3.5	0	0	M	5
Event 4	4.1	H	M	M	5
	4.2	M	0	M	3
	4.3	M	0	L	1

Note: H, M and L denote high, medium and low performances respectively where 0 is used for negligible impacts on environment.

5.1.6 Step 6 - Performance scores

In order to facilitate comparison, equivalent scores have been assigned to the performances within the range of zero to one hundred where zero is given to the alternative that performs worst and one hundred for the one that performs best on each criterion. As described in the previous section, risk reductions are expressed as percentages and these values are directly used as scores in the further analysis. An assessment by the municipality found that alternatives affect positively up to five other hazards in addition to their intended outcomes. Alternative that affects five other hazards are given a score 100 whereas 0 is scored to the alternative that doesn't affect any additional hazard. Alternatives that affect number of additional hazards in between 0 and 5 are scored proportionally. For example, if an alternative affects 2 other hazards, its performance is scored 40. Since performances on environment, cost and system's reliability are assessed qualitatively, it is difficult to score alternatives within the same performance category. To avoid difficulty, the overall range (0-100) of score is divided into three equal segments 0-33, 34-66 and 67-100 that represent equivalent scores for small, medium and high performances, therefore, alternatives in the same category would be assigned different values within the range. Performances of all the undesired events are scored in *Table 5.3*. It should be noted that alternatives with negative risk reduction, i.e. an increased risk, are scored zero. One column on each risk category has been added and symbolized with the stars in order to identify easily the risk level of an undesired event that remains after the implementation of an alternative. This could be helpful for the decision makers on short listing alternatives if risk reduction is the primary outcome. This is presented only to provide additional information for the decision makers, however, doesn't have any use in the analysis.

Table 5.3 Equivalent scores of the performances

Alternatives	Evaluation Criteria									
	System's reliability (4)	Environment (3)	Risk reduction (5)						Cost (2)	Additional benefits (1)
			Water quality (5)		Water quantity (4)		Reputation (3)			
1.1	60	70	50	*	87.5	***	50	*	80	40
1.2	40	35	0		0		0		65	80
1.3	30	40	0		0		0		50	20
1.4	100	85	50	*	93.7	***	50	*	100	60
2.1	30	05	50	**	50	***	50	**	10	0
2.2	20	05	87.5	***	75	***	50	***	50	0
2.3	45	05	0		0		0		100	100
2.4	50	05	87.5	***	75	***	50	***	60	20
2.5	55	05	75	***	50	***	50	**	55	20
3.1	15	05	50	**	50	*	50	***	10	0
3.2	65	35	75	***	50	*	75	***	70	60
3.3	30	10	50	**	50	*	50	***	50	40
3.4	10	05	50	**	50	*	50	***	15	0
3.5	0	25	87.5	***	50	*	-50		55	100
4.1	75	40	50	*	93.7	***	50	***	65	100
4.2	55	05	50	*	50	**	50	***	50	60
4.3	45	05	0		0		0		25	20

*** Unacceptable and ALARP risks that are reduced to an acceptable level
** Unacceptable risks that are reduced to ALARP level
* Further reduction of acceptable risks

5.1.7 Step 7 - Comparison of the alternatives and their ranks

Finally, alternatives are analysed using the software Web-HIPRE. A value tree is constructed that connected the objective, main criteria and sub criteria with the alternatives, see *Figure 5.1*.

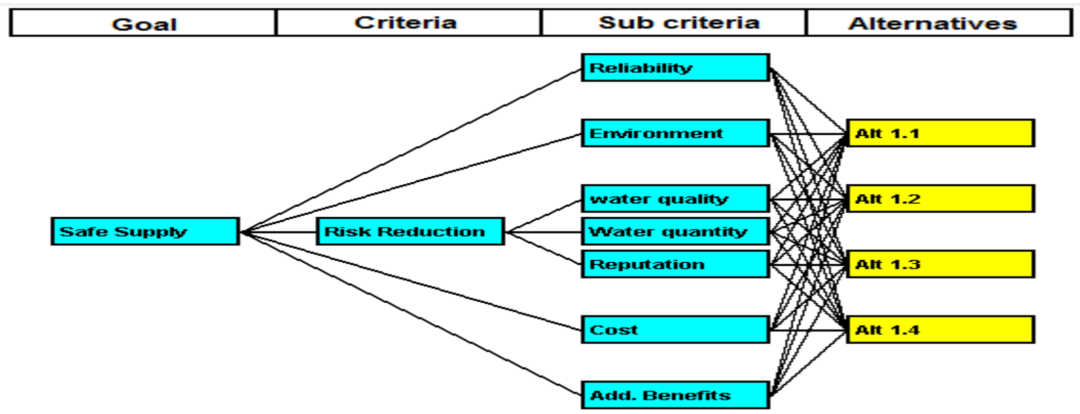

Figure 5.2 Web-HIPRE model for undesired event 1

In order to present clearly the connections between different elements in the model and also for a better visual, all criteria except risk reduction are presented under sub criteria. However, result of the analysis won't be affected by such replacement. Although separate models are created and analysed for each event, only the one constructed for undesired event 1 and bar diagram result (see *Figure 5.2*) of it is presented in this section while other diagrams are presented in the Appendix A, see *Figures 1, 3 and 5*. However, results for all undesired events are presented in *Table 5.4* that summarizes values constitute the bar diagram and ranks alternatives based on the sum of all contributing elements. The basis of the ranking is the overall performance of an alternative that is calculated as described in section 3.3 (step 7).

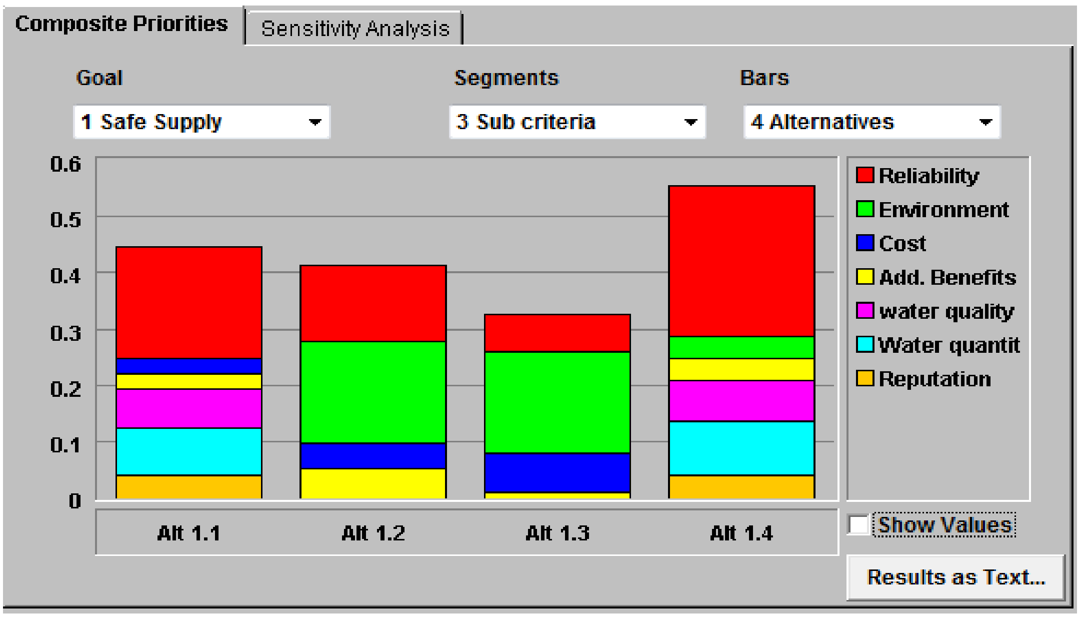

Figure 5.3 Ranking of the alternatives for undesired event 1(Web-HIPRE result)

Table 5.4 Summary of results for all undesired events.

Alternatives	Contribution of the alternatives to each criterion							Total	Rank
	System's reliability	Environment	Risk reduction			Cost	Additional benefits		
			Water quality	Water quantity	Reputation				
1.1	0.200	0.000	0.069	0.083	0.042	0.027	0.027	0.448	2*
1.2	0.133	0.180	0.000	0.000	0.000	0.047	0.053	0.413	3
1.3	0.067	0.180	0.000	0.000	0.000	0.067	0.013	0.327	4
1.4	0.267	0.040	0.069	0.098	0.042	0.000	0.040	0.556	1*
2.1	0.080	0.010	0.069	0.056	0.042	0.120	0.000	0.377	3
2.2	0.053	0.010	0.122	0.083	0.042	0.067	0.000	0.377	3*
2.3	0.120	0.010	0.000	0.000	0.000	0.000	0.067	0.197	4
2.4	0.133	0.010	0.122	0.083	0.042	0.053	0.013	0.456	1*
2.5	0.147	0.010	0.104	0.056	0.042	0.060	0.013	0.432	2
3.1	0.040	0.190	0.069	0.056	0.042	0.120	0.000	0.517	3
3.2	0.173	0.130	0.104	0.056	0.063	0.040	0.040	0.606	1*
3.3	0.080	0.180	0.069	0.056	0.042	0.067	0.027	0.521	2
3.4	0.027	0.190	0.069	0.056	0.042	0.113	0.000	0.497	4
3.5	0.000	0.150	0.122	0.056	0.000	0.060	0.067	0.455	5
4.1	0.200	0.120	0.069	0.104	0.042	0.047	0.067	0.649	1*
4.2	0.147	0.190	0.069	0.056	0.042	0.067	0.040	0.611	2
4.3	0.120	0.190	0.000	0.000	0.000	0.100	0.013	0.423	3

* Alternatives that left none of the risks unacceptable

Following four alternatives are recommended for corresponding undesired events:

Alt 1.4: Establishing new water treatment plant/ intake to the new areas

Alt 2.4: Installation of an UPS

Alt 3.2: Network rehabilitation

Alt 4.1: Construction of new pipeline at Åsane

5.1.8 Step 8 - Sensitivity analysis

Sensitivity analyses are performed for all undesired events in order to check sensitivity of the recommended alternatives to the assigned weights i.e. if changes of weights can alter the recommendations. Sensitivities of all four recommended alternatives are described chronologically below.

1) Apparently Alt 1.4 is not sensitive to any small changes of weight in any of the criterion, see *Figure 5.4*. However, alternatives that are ranked lower would be affected by such changes; for example, if risk reduction is given a weight four, 2nd and 3rd choice would be altered. If any of the two criteria, either environment or cost are given the highest importance recommendation would be altered. It is evident that recommendation is not at all sensitive to the system's reliability.

2) Alt 2.4 is somewhat sensitive to the weights of risk reduction and cost criteria if weights are decreased to half and increased to twice respectively; see *Figure 2* in the Appendix A. Any change of weight to the environmental criteria couldn't affect the recommendation.

3) Alt 3.2 is mainly sensitive to the changes of weight to the cost criterion. An increase of weight twice would alter the recommendation. It also sensitive to the environment and system's reliability criteria but a large change is required. However, recommendation is not sensitive to the risk reduction criterion; see *Figure 4* in the Appendix A.

4) Alt 4.1 is very sensitive to the environmental criterion. Even if environment is weighted a step up recommendation would be altered, see *Figure 6* in the Appendix A. Changes of weight to the cost criterion would also alter the recommendation if given the most importance. Although a large decrease in weights to the other two criteria will change the recommendation, a decrease in such magnitude is not relevant to this decision context.

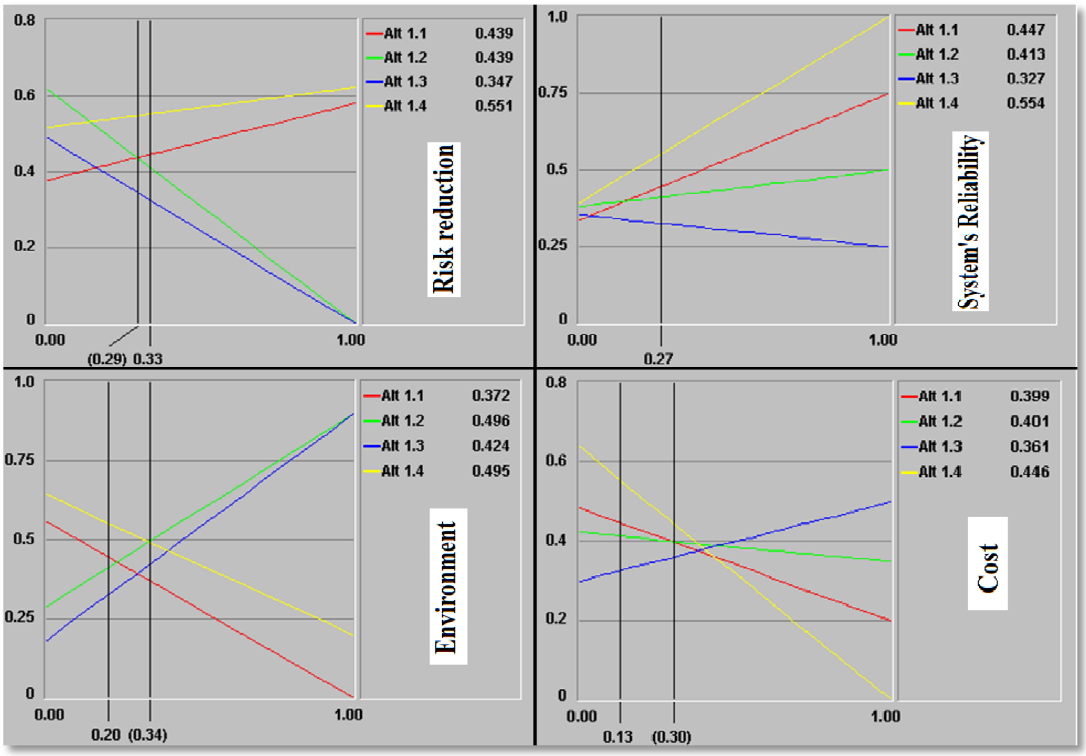

Figure 5.4 Sensitivity analysis results for undesired event 1

5.2 Březnice

5.2.1 Step 1 - Selected hazards for treatment

Finally, three undesired events have been selected by the operator for which risk reduction alternatives will be identified and analyzed. All the events are presented and described shortly in this section. Risks posed by the undesired events are categorized as *high* with the same severity of consequence as *morbidity expected from consuming water*. Other key feathers of the hazards are presented in *Table 5.5*.

Table 5.5 Level of risk and other related information of the selected undesired events

Undesired Event	Component of the system	Effects on	Current Probability	Severity of consequence	Risk level
Event 1	Source	Water quality	*D*	*4*	*High*
Event 2	Treatment	Water quality Water quantity Reputation	*E*	*4*	*High*
Event 3	Distribution	Water quality Water quantity Reputation	*D*	*4*	*High*

Undesired event 1: Low quality of untreated source of drinking water after snow melting or heavy rains

After heavy rainfall or snowmelt water quality of the upper spring area deteriorates with the potentials of microbial contamination as well as higher turbidity levels. Primary causes of such deterioration are excretion of wild animals and other organic materials (e.g. roots from the trees) generate in the surrounding area. Any measure for protecting the source from such contaminants has been restricted due to environmental reasons. Although a hygienic barrier (disinfection by chlorination) exists, it is not efficient. On the other hand, concern over contamination in the lower spring area is even higher from grazing farm animals and pesticides from agricultural activity, however, it is not exactly known if deterioration of water quality is caused by either both of the spring areas or just one of them. Current remedial measure at such occurrence is that the utility shut down the source after being informed by an employee family living in Bubovice when visible turbidity level appears in the delivered water. Consumers in the Bubovice village are not protected since water from this source is delivered directly without any further treatment. Moreover, the existing measures don´t guarantee safety as the water delivered might have already been microbiologically contaminated and consumed before being informed.

Undesired event 2: Unstable plant building that may collapse with the consequence that no water supplied to the consumers

The principal reason identified for this event is the unsuitable design of the building. The filter beds are located in the upper floor and the beds are leaking making the ground floor vulnerable for dampness and growing algae which in turns might deteriorate water quality. It also makes the pipes and valves susceptible for corrosion. The building is designed oversize compared to the functions and needs which causes more maintenance cost and inefficient heating in winter. Furthermore, the static of the building is compromised so that there is a risk of emergency shutdown of the building and the treatment process. The response in an emergency would also be delayed since valves are located in a remote part of the building.

Undesired event 3: Unsuitable pipe materials in the distribution network

Apart from other design limitations, the major hazard identified in the distribution network is that part of the network consists of unsuitable pipe materials such as asbestocement, old cast iron etc. Moreover, there are pipe joints without any inner lining (particularly cast iron), steel pipes with bitumen lining and service connections with lead pipes. This part of the network is vulnerable both form mechanical reliability and water quality point of views. The pipes may deform or even break during building activities or by heavy transport. In such cases, supply would be disrupted to various degrees depending on the situation with the probability of being contaminated. Since the network is not enclosed (not designed circled), any interruption of supply at a point would affect the whole network after that point. From water quality point of view, these pipe materials could be a source of chemical contamination from its surfaces. Such pipes would also lower the efficiency of chlorine residual.

5.2.2 Step 2 - Goals and objectives of the decision analysis

The set of objectives used for the Bergen case is considered generic for both cases, see *section 5.1.2*. However, the goals described in that section are for the Bergen system only.

5.2.3 Step 3 - Evaluation criteria and assigned weights

In this case study same set of criteria that has been used for the Bergen case is used, see *sub section 5.1.2*. However, there are some changes particularly in the risk reduction criterion and relative importance of each criterion. Although, risks have been categorised considering that quality, quantity, or reputational aspects of water are likely to be affected by the hazards, those are not estimated separately. Rather risks are estimated as total risk of all categories. Therefore, the risk reduction criterion is not divided into sub criteria and is used to measure overall risk reductions. Regarding changes of weights, cost has been given the 2nd importance with a numeric value four while supply reliability and environment are stepped down to 3rd and 4th importance respectively. Since additional benefits of an alternative are not assessed, this criterion is left out from the set.

5.2.4 Step 4 - Risk reduction alternatives

Several risk reduction alternatives have been identified for selected undesired events following a brainstorming session between TECHNEAU partners involved in the study and personnel from the operator of the system. Similar to the previous case study, all alternatives are represented by Alt i.j where i denote the event number as mentioned in the *section 5.2.1* and j denote the alternative number for that specific event.

Alternatives for undesired event 1

Alt 1.1: Installation of a mechanical filter and a disinfection step (either UV lamp or chlorination). It also includes construction of a pump station between the lower collection gallery and Bubovice village. The pump station is required because the water could no longer be delivered by gravity only. Constructing a pump station would also require buying a piece of land; however, it is not assessed in details whether it would be easy or difficult.

Alt 1.2: Stopping direct supply to Bubovice by transporting water from Nouzov to a reservoir where proper disinfection and perhaps sand or other filtration would be applied. Treated water would then be supplied to the village through another newly built pipeline.

Alt 1.3: Monitoring precipitation and establishing empirically its critical level beyond which water quality may be influenced so as to close the intake before quality get worse.

Alt 1.4: Online measurement of raw water quality by installing automatic turbidity meter with remote data transfer. This would also allow closing the source when turbidity reaches critical level.

Alt 1.5: Abandoning the source. It would not benefit the system any other way except removing the risk.

Alternatives for undesired event 2

Alt 2.1: Wait until the treatment plant building collapses. This option would not improve current status of the system.

Alt 2.2: Renovation of the existing plant building. Major disadvantage of the option is that it won't reduce maintenance cost since the way it is being used won't be changed.

Alt 2.3: Construction of a new building at the same site of the existing plant building keeping reservoirs in place. Although the option is selected, it is unfavourable since keeping reservoirs in operation would require repairing the whole water treatment plant building. Otherwise renting or purchasing rooms would be necessary in order to keep the plant operational.

Alt 2.4: Construction of a new plant building near the reservoir. This option has two advantages: one is that water would be pumped directly to the reservoir instead of pumping twice (first in the treatment plant and later in the reservoir). The second one is that reservoir in Straz will have to be repaired so that significant savings in investment as well as in operation could be achieved.

Alternatives for undesired event 3

Alt 3.1: Do nothing - just repair as needed.

Alt 3.2: Make up a strategy to replace the bad/worst pipes "slowly".

Alt 3.3: Make up a strategy to replace the bad/worst pipes more "rapidly".

5.2.5 Step 5 - Performance assessment of the alternatives

5.2.5.1 Calculation of risk reductions

Similar to the Bergen case, probability categories are assigned numbers ranges from one to five where one is given to the category that is likely to occur once in five years (rare) and five is given to the one that is likely to occur every day (almost certain). It should be noted that, in this case study five probability categories are defined whereas in the Bergen case four categories were used. Since in the risk assessment levels of severity of consequences were expressed using numeric values, no separate values are assigned. Existing risk level of the undesired events as well as the risk level expected to be achieved after implementation of the alternatives are calculated by multiplying the corresponding values for probability and consequences and presented in *Table 5.6*. Besides, red, yellow and green colours are used to show changes of risk levels. The effect of the alternatives is finally calculated according to equation 1 as percentage of risk reduction which represents both performance as well as corresponding score of an alternative against risk reduction criterion. However, alternatives that make the risks even higher (as marked negative) are scored zero.

Table 5.6 Calculation of risk reduction performances by the alternatives.

Undesired Event	**Alternatives**	**Probability (Assigned values in parenthesis)**		**Risk reduction**				
				Severity of Consequence		**Risk value**		**Risk Reduction %, *(Ej)***
		Existing	**After**	**Existing**	**After**	**Existing**	**After**	
Event 1	1.1	2	1	4	2	8	2	75
	1.2	2	1	4	3	8	3	62.5
	1.3	2	1	4	4	8	4	50
	1.4	2	1	4	4	8	4	50
	1.5	2	0	4	0	8	0	100
Event 2	2.1	1	5	4	4	4	20	-400
	2.2	1	1	4	2	4	2	50
	2.3	1	0	4	0	4	0	100
	2.4	1	0	4	0	4	0	100
Event 3	3.1	2	4	4	4	8	16	-100
	3.2	2	3	4	4	8	12	-50
	3.3	2	1	4	3	8	3	62.5

5.2.5.2 Performances on other criteria

Performances on other three criteria are summarized in *Table 5.7*. Two of them, system's reliability and environment are assessed on a scale of high, medium and low while costs for all the alternatives are estimated in Euros. The set of indicators used in the Bergen case, see *section 5.1.2*, have also been used for Březnice in order to assess performances on system's reliability and environment. It should be keep in mind that costs are assessed by the municipality while performances on other two criteria are assessed by the author, therefore reliability could be questioned. It is highly suggested that before making the final decision, validity of these performances should be checked and if necessary, should be adjusted to the local conditions.

Table 5.7 Performances of the alternatives on other three criteria

Undesired event	Alternative	System's reliability	Environment	Cost*1000 Euro
Event 1	Alt 1.1	M	L	34
	Alt 1.2	H	M	261
	Alt 1.3	L	M	8
	Alt 1.4	L	M	7.2
	Alt 1.5	L	H	105
Event 2	Alt 2.1	L	L	3.8
	Alt 2.2	L	M	492
	Alt 2.3	M	L	576
	Alt 2.4	H	M	404
Event 3	Alt 3.1	L	L	414
	Alt 3.2	M	M	1665
	Alt 3.3	H	H	1590

Note: H, M and L denote high, medium and low performances respectively.

5.2.6 Step 6 - Performance scores

As described in the *section 5.1.6* (scoring of performances for Bergen case), in order to facilitate comparison of the alternatives, performances on system's reliability and environment are scored with equivalent numeric values within the range of 0-100 which is then divided into three equal segments 0-33, 34-66 and 67-100 that represent equivalent scores for small, medium and high performances. Equivalent scores for costs are converted assuming 100 for the highest cost and calculating other scores proportionally. *Table 5.8* shows the scores given for the alternatives. An additional column is created adjacent to the risk reduction scores in order to notify which alternative reduces unacceptable risks to an acceptable level; however, it has no use in the analysis. Although alternatives for each event can be recognised from the numbers, each set of alternatives have been further differentiated with different colours.

Table 5.8 Equivalent scores on each alternative's performances

Alternatives	Evaluation Criteria				
	System's reliability (3)	Environment (2)	Risk reduction (5)		Cost (4)
1.1	55	25	75	***	13.03
1.2	75	50	62.5	**	100
1.3	20	50	50	*	3.07
1.4	30	40	50	*	2.76
1.5	5	75	100	***	40.23
2.1	5	30	0	*	0.66
2.2	30	40	50	***	85.42
2.3	55	33	100	***	100
2.4	75	40	100	***	70.14
3.1	25	25	0	*	24.9
3.2	50	50	0	*	100
3.3	75	75	62.5	**	95.5

*** Unacceptable risks that are reduced to an acceptable level
** Unacceptable risks that are reduced to ALARP level
* Unacceptable risks that are still in the unacceptable level or further increase in risk level

5.2.7 Step 7 - Comparison of the alternatives and their ranks

Separate value trees are created for each set of alternatives and analysed using Web-HIPRE, for example see *Figure 5.2*. Results of the analyses are presented in bar diagrams, see *Figure 5.5*. In addition, values that constitute the overall diagram have also been summarised and presented in *Table 5.9*. Finally, alternatives are ranked based on the sum of their contributions to each criterion and calculated as described in section 3.3 (step 7).

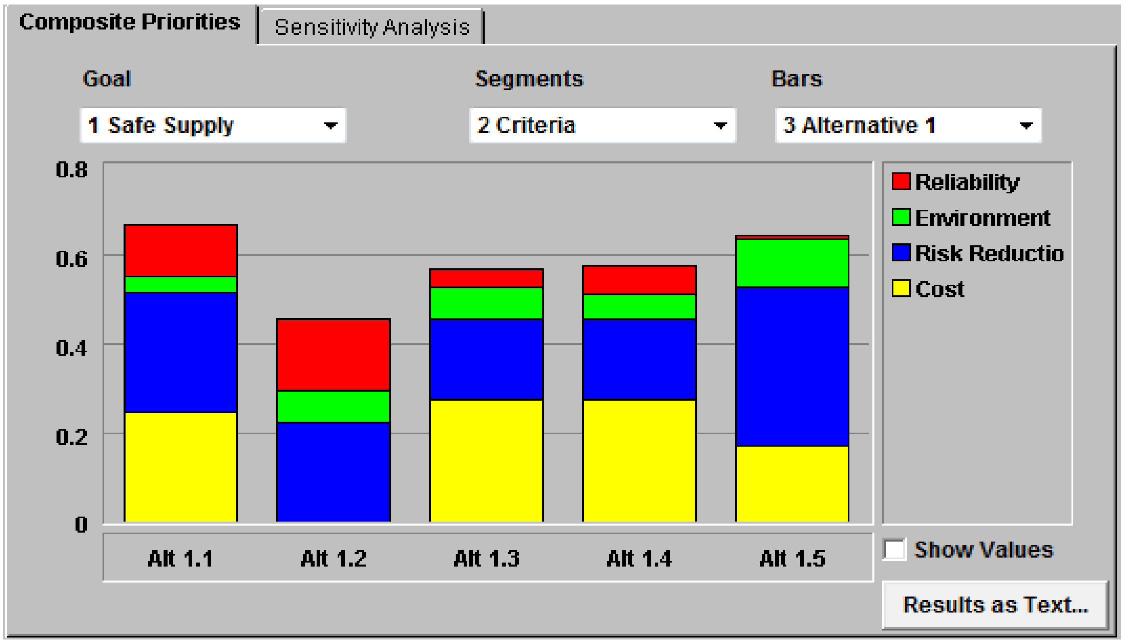

Figure 5.5 Ranking of the alternatives for undesired event 1 (Web-HIPRE result)

Table 5.9 Summary of results for all undesired events

Undesired events	Alternatives	Contribution of the alternatives to each criterion				Total	Rank
		System's reliability	Environment	Risk reduction	Cost		
Event 1	Alt 1.1	0.118	0.036	0.268	0.248	0.670	1*
	Alt 1.2	0.161	0.071	0.223	0.000	0.455	5
	Alt 1.3	0.043	0.071	0.179	0.277	0.570	4
	Alt 1.4	0.064	0.057	0.179	0.278	0.578	3
	Alt 1.5	0.011	0.107	0.357	0.171	0.646	2*
Event 2	Alt 2.1	0.011	0.043	0.000	0.284	0.338	4
	Alt 2.2	0.064	0.057	0.179	0.042	0.342	3*
	Alt 2.3	0.118	0.047	0.357	0.000	0.522	2*
	Alt 2.4	0.161	0.057	0.357	0.085	0.660	1*
Event 3	Alt 3.1	0.054	0.036	0.000	0.215	0.305	2
	Alt 3.2	0.107	0.071	0.000	0.000	0.178	3
	Alt 3.3	0.161	0.107	0.223	0.013	0.504	1

**Risk is reduced to the acceptable level*

Following three are the recommended alternatives for the corresponding undesired events:

Alt 1.1: Installation of a mechanical filter and a disinfection step (either UV lamp or chlorination).

Alt 2.4: Construction of a new plant building near the reservoir.

Alt 3.3: Make up a strategy to replace bad/worst pipes more “rapidly”.

5.2.8 Step 8 - Sensitivity analysis

Sensitivity of all the recommended alternatives are analysed for the assigned weights in order to check if changes of weights to the criteria alter the recommendations. Sensitivities of all three recommended alternatives are described chronologically below.

1) Alt 1.1 is very sensitive to all of the four criteria; see *Figure 5.6*. Even a small change of weight would alter the decision alternative. In all cases, its rival is the Alt 1.5.
2) Alt 2.4 is not sensitive to any other criterion except cost; see *Figure 2* in the Appendix B. Only a large increase in weight of the cost criterion would alter the recommendation, however, it is not relevant since alternative that would replace Alt 2.4 has the lowest rank in the priority order.
3) Similar to the previous one, Alt 3.3 isn’t sensitive to any of the criteria except cost, see *Figure 4* in the Appendix B. Although it is sensitive, a large increase in weight is required to alter the decision recommendation.

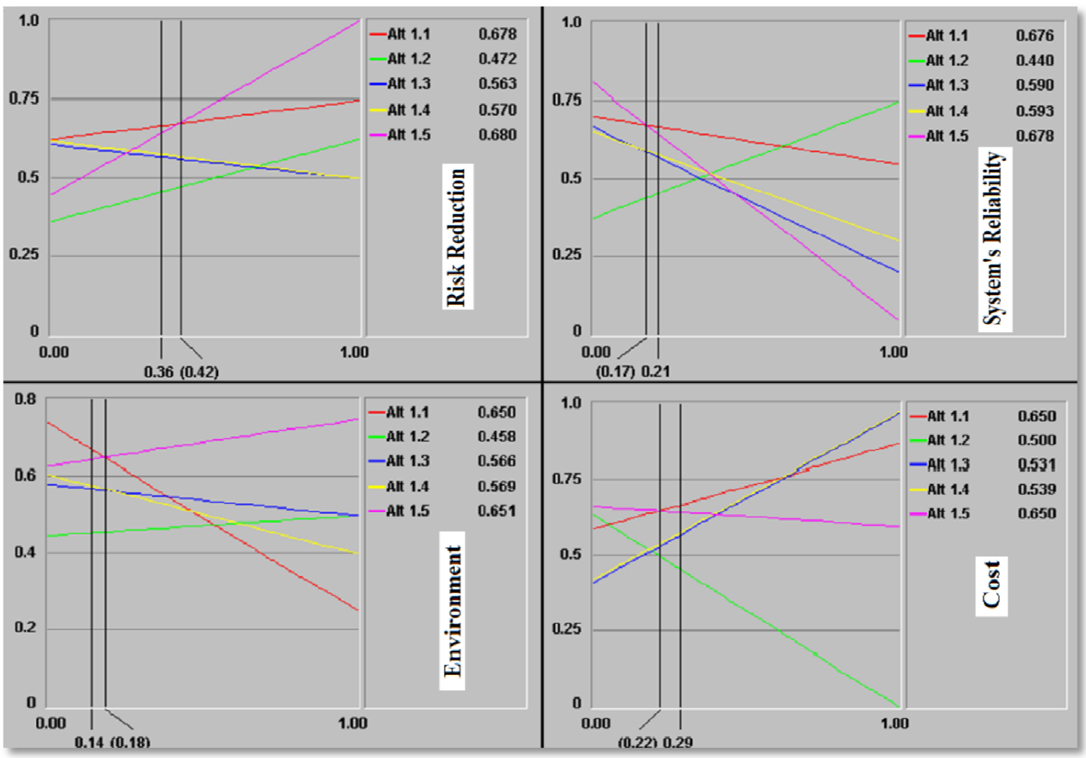

Figure 5.6 Sensitivity analysis results for undesired event 1

6 Discussion

There are important observations at different steps of the MCA-method that are relevant for both case studies since the steps performed do not differ between the two applications. The key observations on which the subsequent discussion is based on are:

- The ranking of alternatives is rather sensitive to the weights given to the criteria.
- Alternatives that contribute on most of the criteria have been top ranked.
- More expensive alternatives have taken higher ranks.
- All the top ranked alternatives reduced risks to an acceptable level.
- It is perceived that a set of relevant indicators as well as their assessment criteria need to be established before such an assessment, in order to obtain reliable results.

Results from both studies show that an alternative's performance on the criteria that are weighted higher have the major contribution on its rank. For the Bergen case, it has been observed that all the top ranked alternatives have performed best on either the system's reliability, on the risk reduction criterion, or on both. Similarly, for the Březnice case, the weight of the system's reliability was lower than the assigned weight of cost, and all the top ranked alternatives therefore performed best either on risk reduction, on cost or on both. However, it is not conclusive that alternatives that perform best on the highest weighted criteria would take the top rank. Instead, alternatives that contribute on most of the criteria have been top ranked.

For both of the cases, results show that more expensive alternatives have been ranked higher. However, very few from each set of alternatives have reduced risks to an acceptable level. Therefore, in a risk management decision context, especially for the Březnice case where cost is also an important decision criterion, a cost-effectiveness analysis is highly relevant in order to make a transparent decision which would also be accepted by the stakeholders. However, this might not be relevant for the Bergen case where there are other important criteria to consider before cost.

It is evident, and not surprising, that assigned weights and corresponding scores of the performances are the two major inputs of the analysis on which an alternative's rank directly depends. Therefore, it can be argued that care should be taken when weights are assigned and performances are assessed. Difficulties have been observed when the system's reliability and environmental performances are assessed qualitatively. It is suggested that a set of relevant indicators as well as their assessment criteria need to be established before such assessment in order to obtain reliable results.

The indicators selected for qualitative performance assessment are seemingly irrelevant for many of the alternatives, i.e. some of the alternatives do not have any direct impacts on either intensity of energy use, effects on ecology, or conservation of water resource, or sometimes to the overall environmental criteria. It has been observed that it creates difficulties when the same set of criteria and indicators are used for a range of undesired events as considered in these case studies. Each event should be analysed separately based on a set of criteria and indicators that are mostly relevant for that event. However, it might not be essential for all cases, rather attention should be given. It is highly suggested that, for the Bergen case, since the municipality has assessed costs of the alternatives, they should perform the analysis again replacing the values used here. In order to assess performances and assign relevant scores to these performances, a well-defined scale with explicit indicators is necessary.

7 Conclusion and Recommendations

The eight-step method proposed and applied in this study could be used for analysing risk-reduction alternatives in drinking water systems in order to support decision makers in to make well-informed decisions. It ranks the alternatives as well as provides information on all the contributing elements so that strengths and weaknesses of an alternative on achieving specific objectives, e.g. acceptable risk levels, will be noticeable.

The decision maker does not have to pick the top alternative. Instead, he/she can make a fair choice considering all the limitations of the system concerned, and even go back to any of the steps before. Therefore, the selection process may undergo iteration until a balanced decision is made. However, there are some limitations observed that should be addressed in order to obtain more reliable and transparent decisions. The following measures are recommended:

- Develop a structured framework for systematic involvement of stakeholders.
- Check relevance of each alternative before selection.
- Motivate clearly the weights assigned to the criteria and sub criteria.
- Define explicitly the relevant indicators and performance scales before assessing performances and assigning scores.

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Appendix A

Major hazards that are identified in the risk assessment

Below is the summary of major hazards identified after the risk assessment case study carried out in Bergen (TECHNEAU, 2009).

1. Failure in hygienic barriers (water quality)/induction of contaminated water into network:

- Contamination in water tanks (water surface)
- Induction due to low pressure/non-pressurized network
  - Operational and maintenance situations (e.g. valve operations)
  - Power failure
  - Work on non-pressurized network (e.g. repair, rehabilitation, construction)
  - Fire (huge water demands might lead to low pressure)
  - Water mains failure (might lead to non-pressurized system)
  - Incorrect operation of valves
  - Failure pumping stations in zones without water tanks
  - Water hammer
  - Pipe fracture valve closes without intention
  - Water tanks emptied due to communication error
  - Extraordinary water demand/tapping
  - In-pipe processes
- Cross-connection/backflow
  - Unintended backflow from building
  - Sabotage (intended backflow from building)

2. Failure water deliverance/quantity:

  - Operational and maintenance situations (e.g. valve operations)
  - Pipe failures
  - Rockslides/rock fall in tunnel
  - Water tanks emptied due to communication error
  - Failure pumping stations

- Failure equipment (e.g. valves)

Probability and consequence scales with corresponding indicators

Table 1 Probability categories and criteria for assessment

P1	Small	• The event not known within the water industry • The event cannot be totally excluded • Security evaluation indicates low probability
P2	Medium	• The event has occurred within the water industry the last 5 years • Professional and precautionary evaluations indicate that the incident might happen within the next 10-50 years. • Security evaluation indicates medium probability
P3	High	• The event occurs every year within the water industry • The water company has observed some events or the events has nearly happened • Professional and precautionary evaluations indicate that the incident might can happen within the next 1-10 years • Security evaluation indicates high probability
P4	Very high	• The event is regularly observed within the water company • Security evaluation indicates very high probability

Table 2 Consequence categories and criteria for assessment

C1	Small	• Quality: Quality hardly affected, compliance with drinking water regulations • Quantity: insignificant influenced • Reputation & economy: Reputation not threatened or economic loss less than 5 % of annual cost.
C2	Medium	• Quality: For a short period a minor non-compliance with drinking water regulations • Quantity: For a short period (hours) interrupted water supply to an area. • Reputation & economy: Reputation threatened or economic loss less than 5-10 % of annual cost.
C3	High	• Quality: non-compliance with drinking water regulations, consequences for health • Quantity: For a long period (days) interrupted water supply to an area. • Reputation & economy: Reputation lost for a short period or economic loss less than 10-20 % of annual cost
C4	Very High	• Quality: Serious violation of drinking water regulations, risk for life and health, Norwegian Drinking water regulations § 18 • comes into force • Quantity: For a long period (days) interrupted water supply to for most of the customers • Reputation & economy: Reputation lost for a long period or economic more than 20 % of annual cost

Risk reduction alternatives and results of analyses

Alternatives for undesired event 2

Alt 2.1: Measuring power supply quality

Alt 2.2: Increasing UV capacity

Alt 2.3: Installation of a new barrier in the treatment process

Alt 2.4: Installation of an UPS

Alt 2.5: Installation of emergency power supply

Web-HIPRE result (bar diagram)

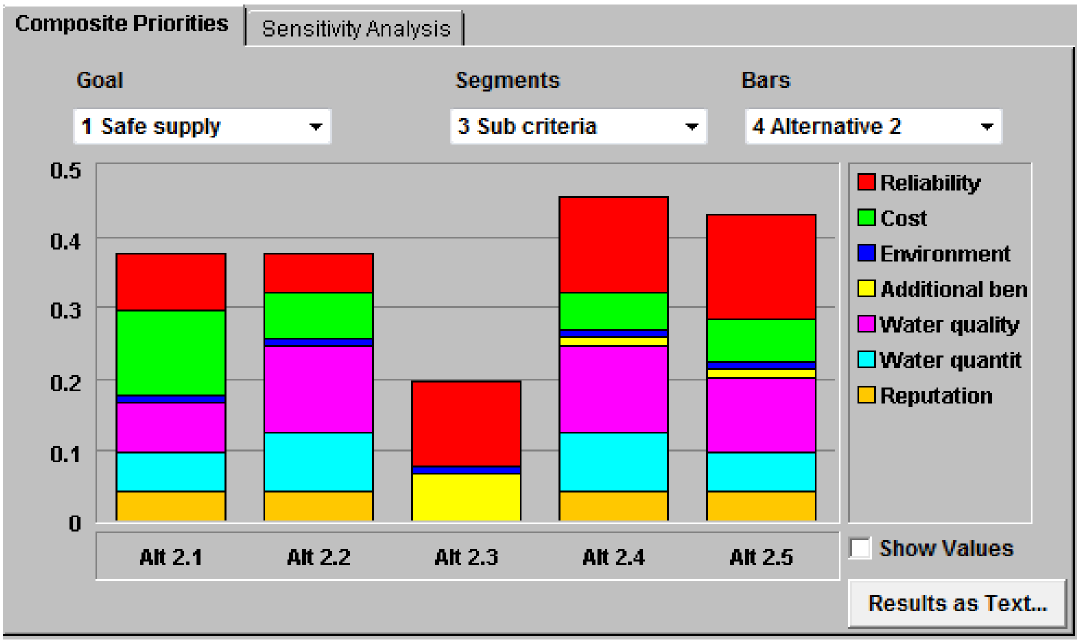

Figure 1 Ranking of the alternatives for undesired event 2

Results of sensitivity analysis

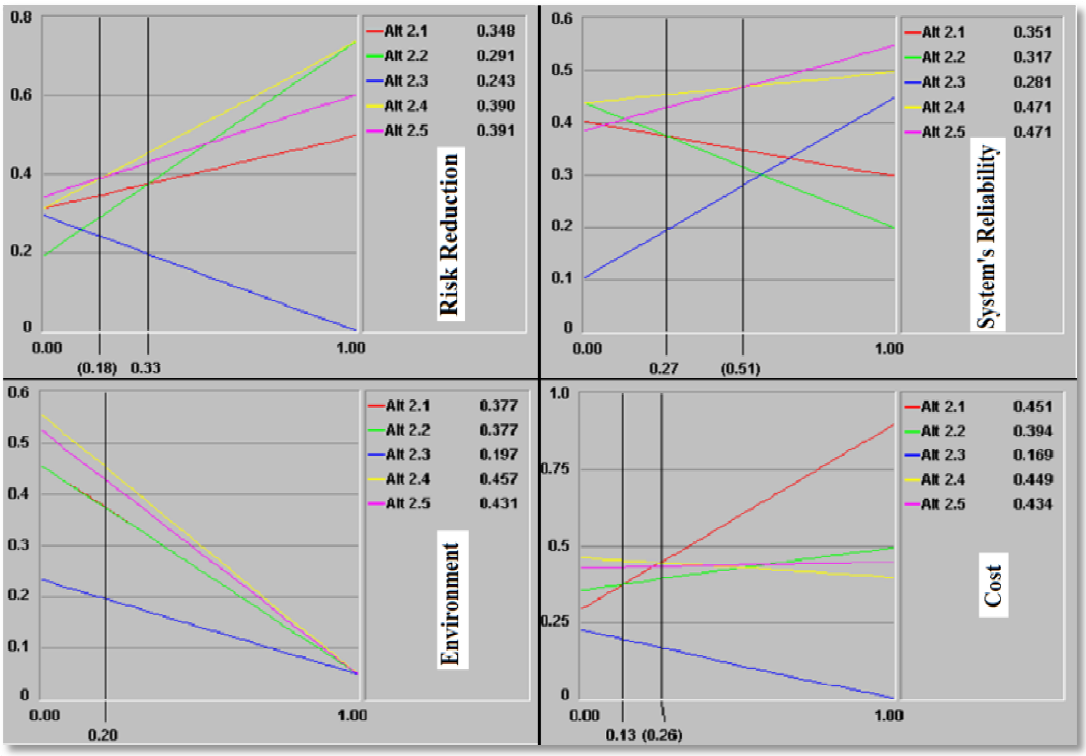

Figure 2 Sensitivity analyses results for undesired event 2

Alternatives for undesired event 3

Alt 3.1: Limiting number of low pressure situations

Alt 3.2: Network rehabilitation

Alt 3.3: Replacing valves with new types

Alt 3.4: Introducing flow cytometry as a new barrier after repairs

Alt 3.5: Consider boiling water more often

Web-HIPRE result (bar diagram)

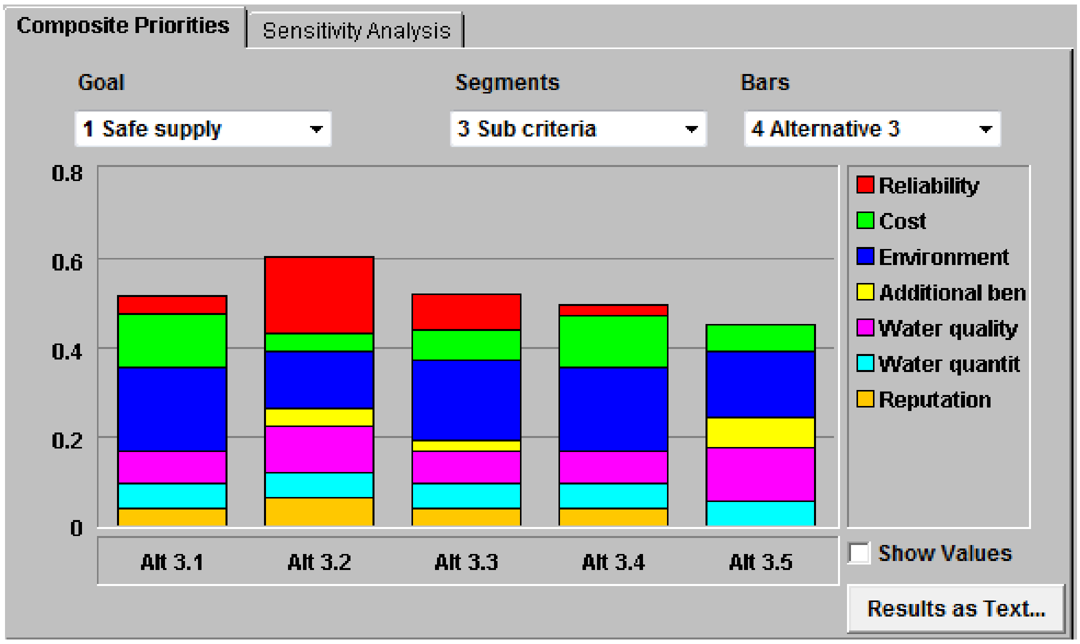

Figure 3 Ranking of the alternatives for undesired event 3

Results of sensitivity analysis

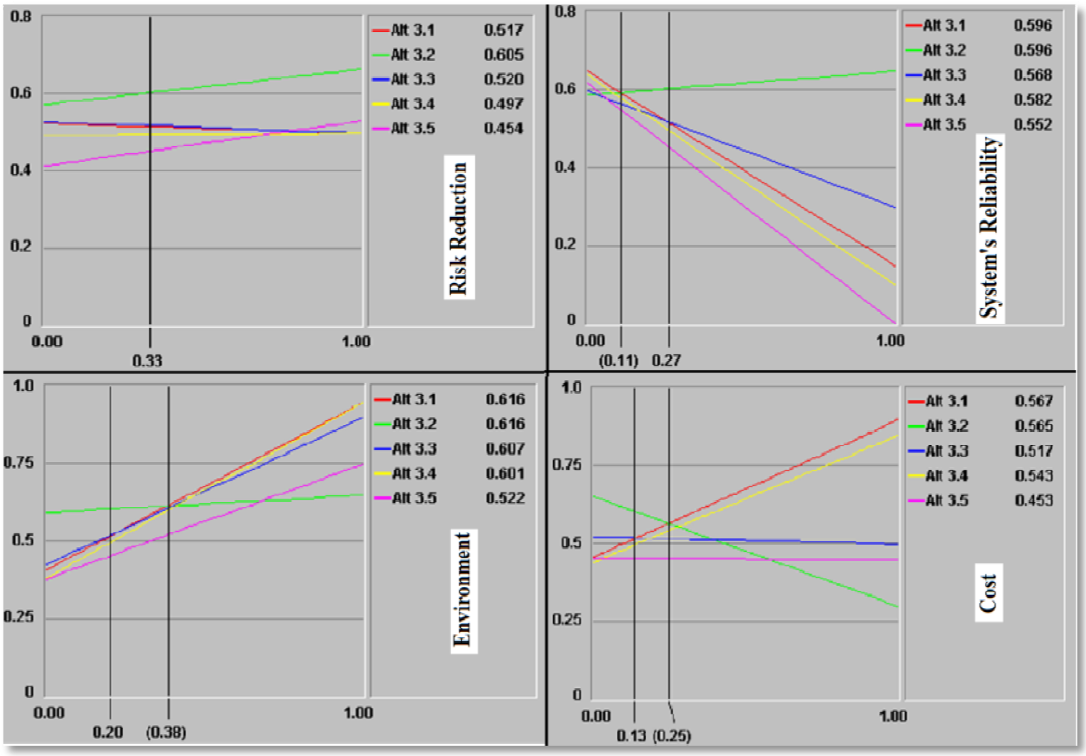

Figure 4 Results of sensitivity analyses for undesired event 3

Alternatives for undesired event 4

Alt 4.1: Construction of new pipeline at Åsane

Alt 4.2: Improving assessment of structural condition

Alt 4.3: Introducing network reliability analysis for indentifying pipelines at risk

Web-HIPRE result (bar diagram)

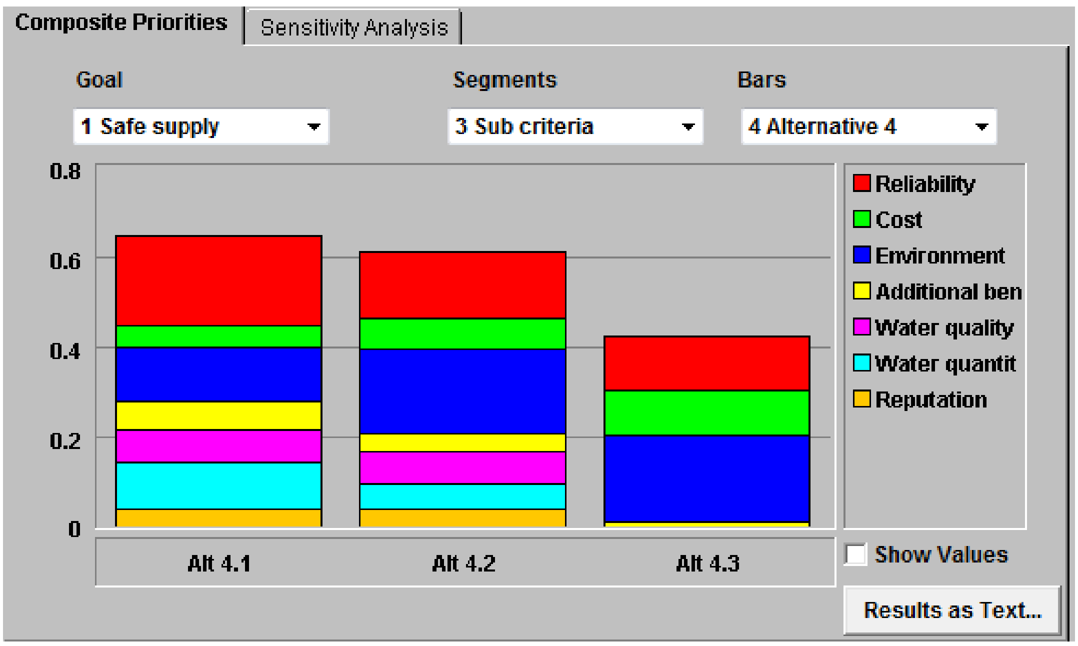

Figure 5 Ranking of the alternatives for undesired event 4

Results of sensitivity analysis

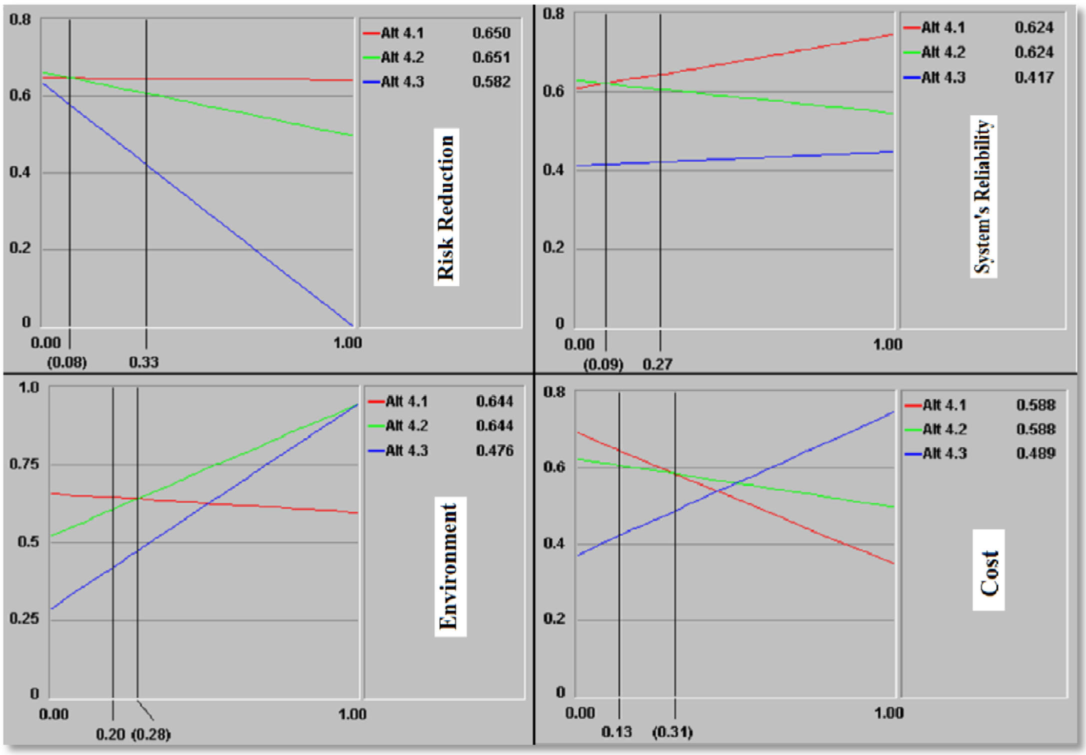

Figure 6 Sensitivity analyses results for undesired event 4

Appendix B

Probability and consequence categories and corresponding definitions

Table 1 Probability categories and assigned values

Probability level	Assigned value	Description	Expected frequency limits
A	5	Almost certain	Once a day
B	4	Likely	Once per week
C	3	Moderate	Once per month
D	2	Unlikely	Once per year
E	1	Rare	Once every five years

Table 2 Severity of consequence categories and definitions

Severity Level	Description	Indicators of consequences
1	Insignificant	No detectable impact
2	Minor	Minor aesthetic impact causing dissatisfaction but not likely to lead to use of alternative less safe sources
3	Moderate	Major aesthetic impact possibly resulting in use of alternative but unsafe water sources
4	Major	Morbidity expected from consuming water
5	Catastrophic	Mortality expected from consuming water

Web-HIPRE results (Bar diagram) for undesired event 2

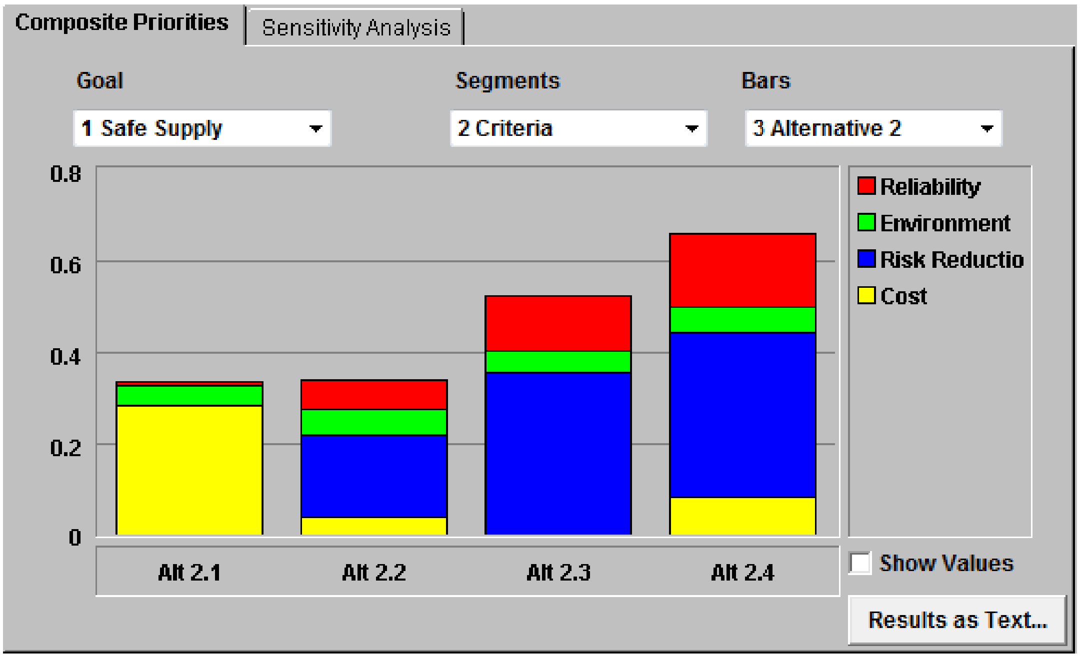

Figure 1 Ranking of the alternatives for undesired event 2.

Results of sensitivity analysis

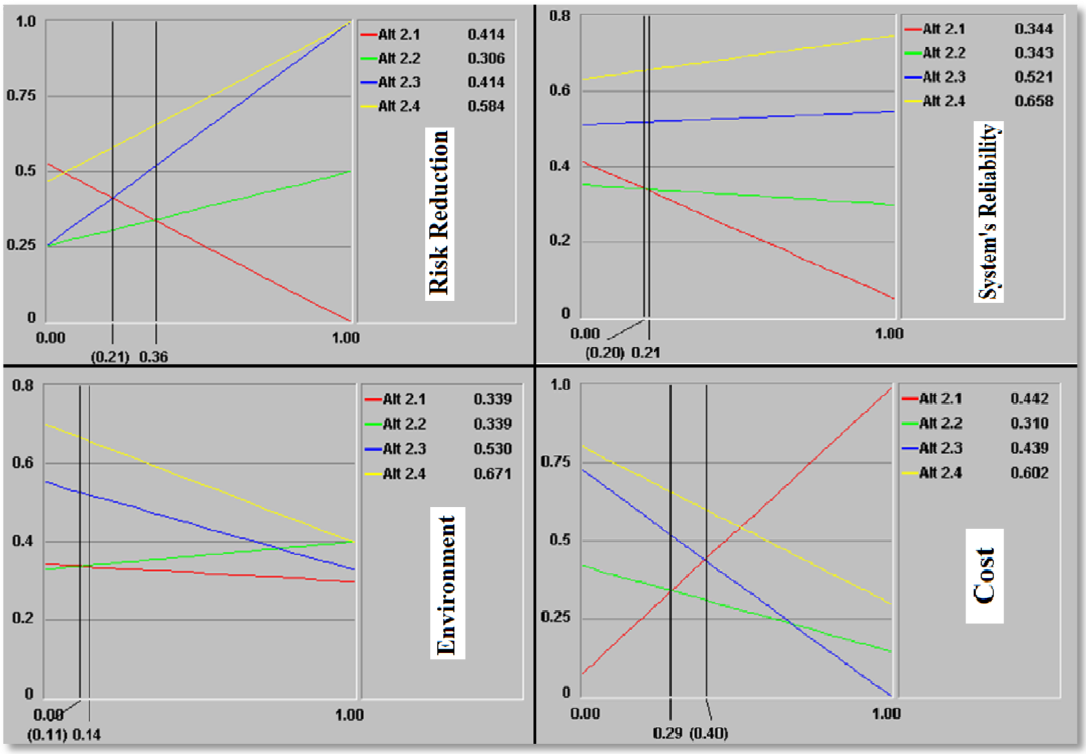

Figure 2 Sensitivity analysis results for undesired event 2.

Web-HIPRE results (Bar diagram) for undesired event 3

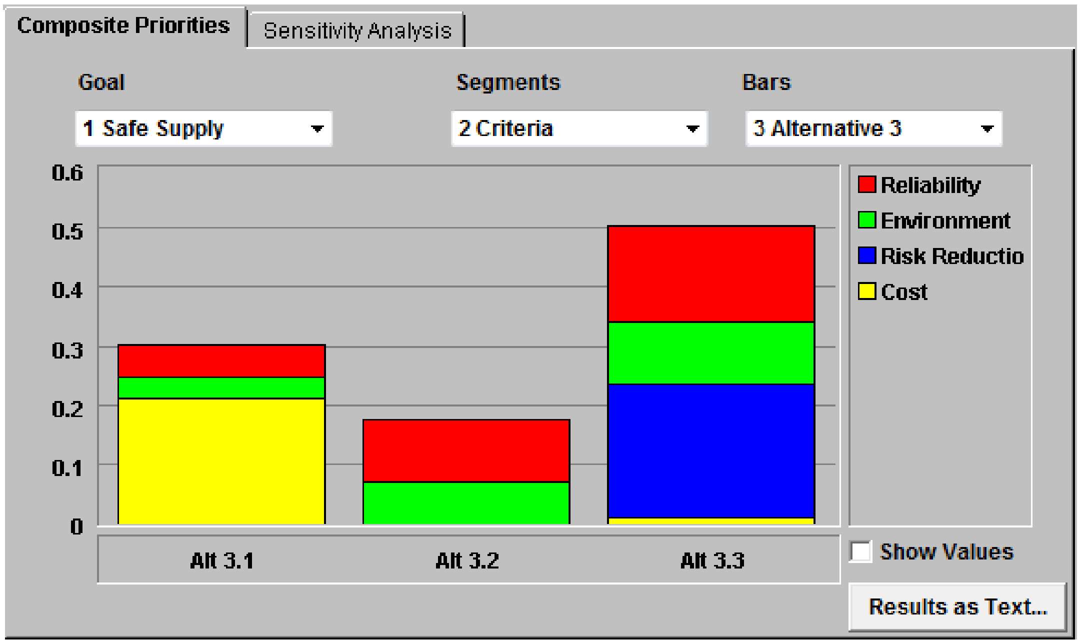

Figure 3 Ranking of the alternatives for undesired events 3.

Results of sensitivity analysis

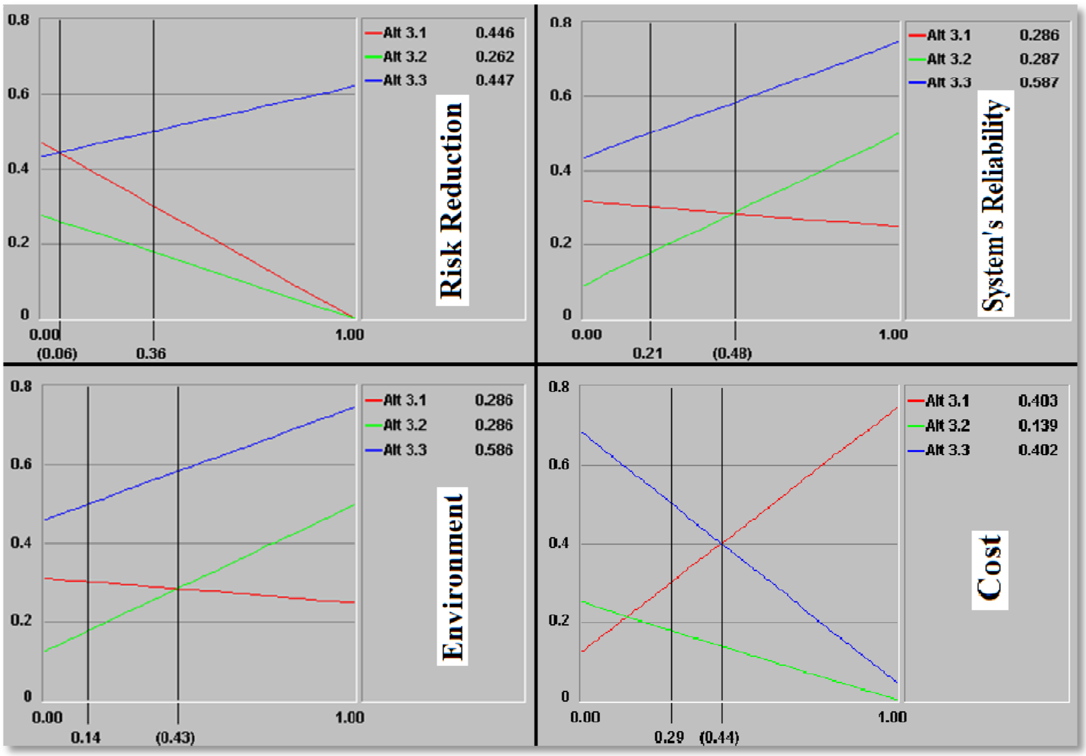

Figure 4 Sensitivity analysis results for undesired event 3.