

# Risk-Based Cost-Benefit Analysis of

CHALMERS

UNIVERSITY OF TECHNOLOGY

**Reliable Drinking Water Supply** 

A case study of Lake Kärnsjön, Munkedal

Master's Thesis in Infrastructure and Environmental Engineering

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Department of Architecture and Civil Engineering Division of Geology and Geotechnics CHALMERS UNIVERSITY OF TECHNOLOGY Gothenburg, Sweden 2018, ACEX30-17-2

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#### Abstract

Access to safe drinking water is essential for life and a basic human right. In Sweden, the good access to raw water sources has led to a society, where the access to safe drinking water have been taken for granted. However, e.g. climate change effects in combination with an increased population and an aging distribution system, has resulted in periods with restrictions regarding the use of drinking water in parts of Sweden. Maintaining and developing drinking water systems, to provide both the present and the future society with a high-quality drinking water supply is both a complex and expensive task. It is therefore of utter importance to allocate economic resources correctly, to enable an efficient use of available resources.

The main goal of this study is to evaluate if this can be done using risk assessment in combination with cost-benefit analysis, a systematic approach that compares benefits and costs expressed in monetary terms. To investigate how this can be applied, a case study has been performed to evaluate the use of Lake Kärnsjön as a raw water source for the municipality of Munkedal and its neighboring municipalities. The CBA aims to facilitate the decision-making for the local drinking water producer (Västvatten), to ensure continued safe and reliable drinking water supply for the municipalities. The CBA was developed by identifying and analyzing risks that could cause complete interruption in the drinking water supply for the municipalities, and the damage costs related to those risks. Uncertainties associated with input variables and output results were analyzed using Monte Carlo simulations. The decision model puts emphasis on societal benefits obtained from providing redundancy in the drinking water systems, and the monetization of these effects. The analysis resulted in a positive Net Present Value (NPV) and therefore showed that it could be profitable – from a societal point of view – to provide redundancy to the neighboring municipalities, in addition to securing the future demand of Munkedal. An uncertainty and sensitivity analysis were performed, to investigate the uncertainty of the results and the sensitivity of the model. In addition to this, were different scenarios analyzed, to see how certain assumptions affect the alternatives ranking. These additional analyses provide information to what parameters that can be investigated, to further reduce the uncertainties of the model.

Keywords: Cost-benefit analysis, risk assessment, drinking water system, decision analysis, Fault tree analysis

#### Preface

This report concludes our studies at Chalmers University of Technology. It is the final part of our master's program Infrastructure and Environmental Engineering. We hope that it shed some light about how Cost-Benefit Analysis can be used in combination with risk assessment of the reliability of water supply.

We would like to thank everyone that has assisted us with this thesis. Starting with one of our supervisors Andreas Lindhe, who has always been there to support us with valuable input and guidance. Also, we would like to thank our supervisor Viktor Bergion for the brain-storm sessions at the coffee machine, and we are also grateful for the help and support from Lars Rosén, our examiner. A special thanks to David Andersson and Karin Zetterström at Västvatten, who has laid the foundation for this thesis, assisting us with valuable input and their expertise. Finally, we would also like to thank our classmate Calle, for his companionship and help during this study.

Göteborg, January 2018

Petter Bolander, Erik Martinsson

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## List of Notations

The following notations are used in the thesis:

ALARP	As Low As Reasonably Possible				
BWR	Basic Water Requirement				
CBA	Cost-Benefit Analysis				
CCP	Critical Control Point				
CE	Choice Experiment				
CEA	Cost-Effectiveness Analysis				
CVM	Contingent Valuation Methodology				
DALY	Disability Adjusted Life Years				
DRICKS	The Drinking Water Research Program, coordinated by				
	Chalmers University of Technology				
DWS	Drinking Water System				
DWTP	Drinking Water Treatment Plant				
EPA	United States Environmental Protection Agency				
ETA	Event Tree Analysis				
FEMA	The Federal Emergency Management Agency (USA)				
FTA	Fault Tree Analysis				
GDP	Gross Domestic Product				
HACCP	Hazard Analysis and Critical Control Point				
IEC	International Electrotechnical Commission				
ISO	International Organization for Standardization				
IWA	International Water Association				
MCDA	Multi-Criteria Decision Analysis				
MSB	Swedish Civil Contingencies Agency				
NPV	Net Present Value				
QMRA	Quantitative Microbial Risk Assessment				
REL	Residential Economic Loss				
SGU	Swedish Institute of Geology				
SWWA	Swedish Water and Wastewater Association				
UN	United Nations				
VAB	Care of sick child				
WHO	World Health Organization				
WSP	Water Safety Plan				
WTP	Willingness To Pay				

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# 1

### Introduction

#### 1.1 Background

Access to safe drinking water is essential for life and a basic human right. According to the World Health Organization, improving access to safe drinking water could result in tangible benefits to health (WHO, 2011). Target 7.B of the Millennium Development Goals, to halve the proportion of the population without sustainable access to safe drinking water and basic sanitation, was achieved in 2015 (UN, 2015*a*). Despite this, the same year, only 71% of the world population used a safely working drinking water service (WHO, 2011). Furthermore, 17 sustainable development goals were set by members of the United Nations in 2015, with targets to achieve by 2030 (UN, 2015*b*). Goal number six of these sustainable development goals is Clean water and Sanitation, which aims to achieve safe water sources and sanitation for everyone.

The Geological Survey of Sweden states that Sweden has nearly an endless supply of good quality source water (SGU, 2017). Yet, due to climate change in the last decades, different parts of Sweden during recent years have experienced a far more strained water situation than normal. The islands of Gotland and Öland was subject to water shortage during the summer of 2016, and prior to the summer of 2017. The Swedish Water and Wastewater Association issued a warning regarding risk of water shortage in several regions in Sweden due to exceptionally low groundwater levels (SWWA, 2017*a*).

In order to ensure a safe drinking water supply, a reliable raw water source is of primary importance. The process of identifying, evaluating and comparing alternative raw water sources can be a difficult task. Furthermore, changing raw water source or connecting a new source to the existing system is typically associated with high costs. It is thus of great importance that decisions on how to improve the raw water supply are based on relevant and useful information. Risk assessment is performed to identify problems within a drinking water system (DWS). Based on the information obtained from the risk assessment, it is possible to estimate the benefit of different alternatives. However, the results must be combined with relevant decision analyses to provide useful decision support. Since economic resources are limited, methods such as cost-benefit analysis (CBA) and cost-effectiveness analysis (CEA) can be applied to perform an economic evaluation of alternative options. CBA is not typically applied within the Swedish drinking water sector but an ongoing research project (Risk-based Decision Support for Safe Drinking Water, funded by the Swedish Water and Wastewater Association, SWWA) is focusing on how CBA can be combined with other analyses to provide useful decision support. The project is performed within DRICKS (The Drinking Water Research Program), coordinated by Chalmers University of Technology. A CBA makes it possible to compare, in monetary units, e.g. costs related to implementing a specific alternative with the benefits in terms of risk reduction etc.

#### 1.2 Aim

The overall aim of this master's thesis project is to assess how CBA can be used in combination with risk assessment as decision support to evaluate reliable drinking water supply.

The specific objective of the report were to perform a case study, investigating different alternatives on how to use Lake Kärnsjön in Munkedal, Sweden, as a raw water source. The goal is to secure the future water demand of Munkedal and to evaluate the worth of providing redundancy for the neighboring municipalities of Uddevalla, Sotenäs, and Lysekil. A key result of the CBA is to show if the alternatives are profitable for society, with respect to the identified and analysed costs and benefits. With the CBA it is possible to compare and rank the alternatives. However, the list of identified costs and benefits within the CBA are of great value to enable wellinformed decisions. A structured decision analysis provides transparency by clearly showing what aspects are considered and how the alternatives meet the defined decision criteria. Furthermore, a probabilistic approach will be used in this study.

#### 1.3 Limitations

The analysed risk-reduction alternatives are identified in collaboration with Västvatten and representatives from the Chalmers University of Technology. There could be other possible alternatives, in addition to the identified ones.

Only critical hazardous events, identified by Västvatten, that could lead to a complete interruption in the drinking water supply for a long period of time are considered. Local and short-term interruptions (less than a day) are therefore not included in this study.

The benefit estimation for the CBA in this study is limited to reduced damage costs due to complete interruptions in the supply of drinking water. It does not consider chains-of-events in the calculations, such as interruption in the drinking water supply leading to drinking water quality issues (e.g. microbial contamination).

## 2

### Drinking water and risk

This chapter explains the different frameworks of risk assessment and management, and how it can be related to the drinking water system.

#### 2.1 Drinking water systems

Even though drinking water systems (DWS) may differ throughout the world, the general drinking water system consists of three main sub-systems; raw water source, treatment, and distribution (See Figure 2.1). Variations of different DWS can depend on natural conditions, economic resources or the local demand for water (Lindhe, 2010). A drinking water system could be considered as a supply chain, and the three sub-systems cover the entire chain from source to tap. The DWS aims to meet quality and quantity requirements towards the consumer.



Figure 2.1: Schematic illustration of drinking water systems (Lindhe, 2010).

#### Raw water source

In Sweden, the source of raw water is either groundwater, surface water (from e.g. a lake or river) or a combination of both. Groundwater is often considered to have a higher and more even quality compared to surface water, due to natural infiltration. Surface water, on the other hand, is often of lower and more uneven quality, due to its open surface being exposed to different kinds of runoff (e.g. agricultural). The benefit of using surface water is that it is easy to obtain large quantities of water (SWWA, 2008). In areas where groundwater resources are limited, artificial recharge can be used in order to increase quantity and obtain water with qualities similar to groundwater.

According to The Swedish Water and Wastewater Association (SWWA), around 90% of the Swedish population is connected to publicly owned waterworks. Roughly half of these consumers get their drinking water from a surface water source. The other half of these consumers are about equally distributed between waterworks using naturally and artificially recharged groundwater. The other 10% of the population is most likely connected to private wells (SWWA, 2016).

#### Treatment

According to Hammer and Hammer (2012), the objective of municipal water treatment is to provide potable water – one that is microbiologically and chemically safe for human consumption. For domestic use and thereby drinkable water, the treated water must also be aesthetically acceptable, i.e. free from apparent turbidity, odor, color and objectionable taste (Hammer and Hammer, 2012).

As previously mentioned, groundwater generally has a higher and more even quality compared to surface water and therefore requires fewer (or sometimes none) treatment steps in order to meet the demands of potable drinking water (NFA, 2001).

The commonly lower and more uneven quality of surface water requires more treatment steps in order to make the water potable (SWWA, 2016). Typical treatment steps in a common Swedish drinking water treatment plant (DWTP) with surface water as raw water source are screening, chemical treatment, sedimentation, filtration, UV-treatment and chlorination (SWWA, 2017b).

#### Distribution

Water distribution can be considered as a system consisting of an interconnected series of components, which includes pipes, storage facilities (water towers or reservoirs) and components that convey drinking water (e.g. pumping stations) (EPA, 2017). The piping system is required to reach all consumers, while the storage facilities function is to ensure that the distribution system handles demand variations from the consumers. Different types of leakages in the distribution networks represents on average 20% of the publicly produced drinking water in Sweden (SWWA, 2012).

#### 2.2 What is risk?

Risk can be defined in different ways, depending on context and source. It is therefore important to present what definition of risk that is being used for the situation. According to Kaplan and Garrick (1980), risk is a function of probability and consequence, but not necessarily in such a linear way as defining it is as probability times consequence. Kaplan and Garrick (1980) states that there are three fundamental questions concerning the definition of risk:

- What can happen? (Hazards/Hazardous events)
- How likely is it that this will happen? (Probability)
- If it does happen, what are the consequences? (Consequences)

There are also a few expressions that are good to be familiar with, when looking at risk.

- A hazard is a source of potential harm, and could be considered as a risk source.
- An event is an occurrence or change of a particular set of circumstances (ISO, 2009).
- A hazardous event could be, for example, a leakage from a wastewater treatment plant, deterring the water quality in a water source.
- Likelihood is the possibility for a hazardous event to occur that can be expressed in general terms or in mathematical metrics such as probability (Bergion, 2017). Probability expresses the likelihood of an event occurring on a scale 0–1, where 0 is impossible to occur and 1 is certain to occur.

An example on how risk assessment can be used for water supply reliability, is assessing the risk of pipe breakage. Pipe breakage could be caused by internal factors (e.g. pressure) or external factors (e.g. landslide), and the probability for this can be assessed. Pipe breakage could result in supply failure, meaning that societal functions (schools, industries etc) lose access to water services, causing extensive costs for the society (consequence).

Furthermore, one important aspect of risk is uncertainties. How uncertainties relate to risk, and how it is connected to the DWS, is further explained in Section 2.4.

Now, with the foundation on what risk is, how it can be defined, and an illustration of how risk assessment can be done; the question is: why is important to handle and manage risks in the DWS? This is addressed in the following section.

#### 2.3 Historical events of drinking water supply failure

Below, historical events of failure in the DWS are presented to provide a foundation to why risk assessment and management is necessary to ensure a safe and reliable drinking water supply.

#### Milwaukee, USA 1993

In 1993, a well-known outbreak of the protozoa Cryptosporidium occurred in the Milwaukee area in the USA. For more than two weeks Cryptosporidium was distributed in the DWS, before the source of the outbreak was detected (the treatment plant) and disconnected from the system. During these two weeks, more than 400 000 people were affected, out of them were 4 000 people hospitalized and over 100 people died (Riksrevisionen, 2008).

#### Örnsköldsvik, Sweden 1999

A distribution failure occurred in Örnsköldsvik in 1999, due to a burst of a main water pipe. This forced schools to close due to malfunctioning toilets, patients had to be transferred to other hospitals and certain industries and businesses dependent on water were affected, costing multiple millions of SEK.

#### Bergen, Norway 2004

An large outbreak of gastroenteritis hit the region of Bergen, Norway in 2004. This was due to an outbreak of the parasite Giardia in the drinking water system. 5000 people became ill due to the parasite, and the societal cost was estimated up to 40 MNOK (Törneke and Engman, 2009).

#### Galway, Ireland 2007

Due to heavy rains during 2007, the surface treatment plants in Galway, Ireland were incapable to treat the water to an acceptable drinking water level, and high levels of Cryptosporidium were distributed for a long time in the DWS. An area of 100 000 people had to boil water for over 5 months (Bergstedt et al., 2007).

#### Östersund, Sweden 2010

In the winter of 2010/2011, an outbreak of Cryptosporidium occurred in the city of Östersund. In the aftermath, approximately 27 000 people were affected and the societal costs due to outbreak were estimated up to 220 MSEK (Lindberg et al., 2011). The cause or source of the outbreak has not been established.

#### Lund, Sweden 2017

During a repair work drinking water pipes in the winter of 2016 in Lund, organic material got stuck on the inside of the pipes (Sydsvenskan, 2017). This lead to a bacterial growth that made the water non-potable in the spring, and in March a boiling recommendation was issued. The warning lasted for a month and affected a big portion of the city. The source of the contamination was located around the area of the city hospital, causing huge logistic problems for the hospital.

#### 2.4 Uncertainties

Bedford and Cooke (2001) states that the two basic categories of uncertainties are aleatory and epistemic uncertainties. Aleatory uncertainty is basically natural variation or patterns, which is possible to measure and quantify, e.g. precipitation. Epistemic uncertainty is due to incomplete knowledge, but can be quantified using statistical methods or expert judgment. The difference between epistemic and aleatory uncertainty is not always crystal clear, and it is not always that important to tell the difference between them. It is, however, possible to represent them both with probability density functions. Bedford and Cooke (2001) state that the aim of separating these two uncertainties exists to make it easier for decision makers to determine how and which uncertainties that are possible/reasonable to reduce. For example, an epistemic uncertainty can provide the decision maker with insight on how lack of knowledge can affect the results which in turns affects the decision making. Drinking water systems are often complex and consist of several subsystems (see Section 2.1), and therefore both aleatory and epistemic uncertainties exist within the system (Bergion, 2017).

There are different ways of presenting uncertainties. With the help of frequentist methods, estimated point data can be obtained from hard data, and the uncertainty can then be presented using confidence intervals. The Bayesian approach provides a probability distribution for both the input data and the uncertainties and it can be based on expertise, knowledge, measurements, and statistics. The Bayesian Approach makes it possible to combine hard data with expert knowledge (Bedford and Cooke, 2001).

An advantage of the Bayesian approach, in comparison with frequentist methods, is that if there is a lack of hard data, then the input of experts could assist the risk estimation and be integrated into the analysis in a mathematically formalized way (Lindhe, 2010). Another advantage is that it is possible to update probability distributions with new information (Bedford and Cooke, 2001). For this report, a Bayesian approach is used.

#### 2.5 Risk assessment and management

There are many purposes to why risk management is used. One important aspect, is to be able to support decision-makers with information that explains the existing risks and what can be done to reduce it (Lindhe, 2010). Today there are a lot of frameworks explaining the different steps of the risk assessment and management process. For example, Bergion (2017) who made an adaption (see Figure 2.2) from the framework presented in ISO (2009), from which it is easy to comprehend the different steps of the risk assessment and management procedure. Another illustration that includes a more detailed description of the process is presented in Figure 2.3.



Figure 2.2: Risk assessment and management framework (Bergion, 2017).



Figure 2.3: Risk assessment and management framework (IEC, 1995).

Figure 2.3 presents the risk assessment process as risk analysis followed by a risk evaluation and risk reduction/control. However, it is important to understand that the procedure is iterative, and the boundaries between the steps are not strict. Following, a more in-depth description of the risk assessment and management procedure is described.

#### 2.5.1 Risk analysis

The goal of risk analysis is to understand and estimate the risks involved. Risk estimation is often followed by risk evaluation to decide whether or not a risk is tolerable (Rosén et al., 2007).

The risk analysis usually starts with scope definition. The following step is to identify hazards or hazardous events within the system. This can be done in different ways (Rosén et al., 2007). Beuken et al. (2008), for example, provides two different approaches that can be used as guidelines for hazard identification. They have also identified current and future hazards in the water supply system and provides checklists, which could be used as support when performing hazard identification.

In the process of identifying different hazardous events, one way to sort the different event is to divide the risks in to two sub-groups. One, is that there is not enough water produced and distributed to the customers, i.e. a quantity problem. The other one, is that the delivered water is of poor quality, i.e. a quality problem (Söderqvist et al., 2016). Table 2.1 present examples of different events, in the sub-systems of the drinking water system, that could compromise the quality and quantity of the drinking water supply.

	Water source	DWTP	Distribution network
Compromise	Microbial	Failure of	Intrusion of
of quality	contamination	treatment	contamination
Compromise of quantity	Drought	Overflow	Pipe burst

Table 2.1: Examples of quality and quantity compromising events in the DWS.

However, quantity and quality failure should not be considered solely separate. There are events that can cause both. If there is a pressure drop in the distribution network, due to e.g. pipe breakage, then pipe intrusion could occur and contaminate the drinking water. This means that if pressure is lost in the system (causing quantity failure), flushing pipes might be required in order to avoid quality failure. This should be considered when looking at the societal cost of water quantity failure.

Another important aspect of hazard identification in the DWS is to consider future hazards and events, e.g. population increase that is followed by an increase in water demand, climate change, or aging of piping network deteriorating the water quality (Söderqvist et al., 2016). Guidelines for identification of future hazards in the DWS is also presented in the study by Beuken et al. (2008).

#### 2.5.2 Risk estimation and evaluation

Hazard identification can be followed by risk estimation if necessary. Depending on the scope of the risk analysis, this procedure can be performed quantitatively, semi-quantitatively or qualitatively (Rosén et al., 2007). The qualitative way is to describe the risks with words while the quantitative method uses numerical values (Lindhe, 2010). Semi-quantitative is a mix of qualitative and quantitative analysis, e.g. using scoring (Rosén et al., 2007).

#### Semi-quantitative analysis

An example of a semi-quantitative analysis is the use of risk matrices, which also provides the basis for the risk ranking approach that can be used in a Water Safety Plan (WSP) (Lindhe, 2008). For more information regarding WSPs, see Section 2.7.1.

In a risk matrix, the risk is illustrated using a probability and consequence form and presented in a table format (see Figure 2.4). To be able to evaluate the risk matrix results, risk tolerability levels (thresholds) must be set. A common approach is to use the As Low As Reasonably Practicable (ALARP) principle, which is also presented in Figure 2.4. Based on this principle, there are three different areas of risk tolerability. The acceptable risk (green zone), where no measures need to be taken, and unacceptable risk (red zone), where the risk cannot be accepted under any circumstances and measures must be taken to reduce it. Between these two levels is the ALARP region (yellow zone). Within this area, the risk should be reduced if it is economically and/or technically reasonable to do so.

The advantage of the risk matrix is that it is easy to present and understand. The disadvantages of this method, is that it cannot consider chains of events, their interactions and it does not enable an uncertainty analysis. Another difficulty is to decide the thresholds for acceptable risk, tolerable risk (ALARP region) and unacceptable risk (Rosén et al., 2010).



Figure 2.4: Risk matrix and illustration of ALARP (Rosén et al., 2007).

#### Quantitative analysis

If instead a quantitative approach would be used, like for example fault tree analysis (FTA) or quantitative microbial risk assessment (QMRA), then it is possible to model chains-of-events, interactions and so forth (Lindhe, 2010). It is also possible to see where in the system that a risk-reducing measure would be most effective, avoiding sub-optimization. This is possible because the risks are quantified and estimated in the same way, making it easy to compare risks at different sub-systems to an acceptable risk level.

Even though there are different approaches to risk analysis and evaluation, the purpose is the same. To estimate risks of the identified hazards and/or events, and to evaluate if it is acceptable or not. If the risk level is acceptable, just controlling it may be sufficient. If the risk level is considered unacceptable, then different risk-reducing measures needs to be analyzed in order to identify the best risk-reducing option. To be able to decide if a risk is acceptable or not, thresholds (risk tolerability lines) must first be set (Rosén et al., 2010).

#### Risk tolerability

When talking about ALARP, risk matrices and so forth, common terms that are used are risk tolerability and risk acceptance. Tolerability can be considered as thresholds which divides the entire risk spectrum into different zones of risk acceptance. For example, the ALARP principle divides risk tolerability into three zones; acceptable risk, non-acceptable risk, and ALARP. An example of tolerability and acceptance for DWS is the use of the health metric Disability Adjusted Life Years (DALY). DALY is a way of quantifying a disease's impact on health and can be used to quantify water quality tolerability levels (Rosén et al., 2010).

Deciding upon thresholds for drinking water supply that are deemed to be reasonable is a difficult matter. What risk managers can do, is to provide a transparent method so it is possible for the public eye to see if the risk managers have their health as their number one priority (Rosén et al., 2010).

#### 2.5.3 Risk-reduction control

After evaluating the risk, the next step is risk reduction/control. If the risk is not deemed to be at an acceptable level, then measures should be investigated to reduce it. There are different ways to approach this. If the risk is defined as a combination of probability and consequence, then the risk can be reduced by either lowering the consequence, reducing the probability or simultaneously reducing both of them (see Figure 2.5). For example, a car crashes near a raw water catchment area, causing oil to leak to the catchment site, resulting in a contaminated water source. The risk in this example could be reduced either by increasing the traffic safety (using e.g. lower speed, widening the roads etc. in order to decrease the probability of an accident to occur), or prevent an oil leakage to spread in the event of an accident by e.g constructing collecting dikes (and thereby reducing the consequences).



Figure 2.5: Ways of reducing risk.

#### 2.6 Decision analysis

According to Rosén et al. (2007) the purpose of decision analysis is to provide decision support for decision makers. Bergion (2017) and Lindhe (2010) mentions a few of different analyzing tools that can be used to provide decision support. For example, there is cost-effectiveness analysis (CEA) where an objective is defined (e.g. a certain risk level) and the aim is to find out what measure that fulfills this objective at the lowest cost. Another tool that can be used is a multi-criteria decision analysis (MCDA) which is a method that is used to compare and evaluate different types of measures and is based on pre-defined criteria and the ranking of those. A third analyzing tool is a cost-benefit analysis (CBA), which will be used in this report.

In the following section, the decision-making process is described, followed by an indepth description of CBA; what it consists of and how it can be applied as support for decision analysis.

#### 2.6.1 Decision-making process

The difficulty in making a good decision is, according to Aven (2012), the understanding of uncertainties. To make a good decision, two different ways of thinking can be used. Either a model approach or a more formal risk analysis and decision analysis approach (Aven, 2012). The model approach makes it possible to see which option that maximizes a certain criterion, for example, CBA. However, this should not be solely trusted upon as it does not take all information into account. It should instead be used as a tool in the decision-making process, as it provides valuable input. The other approach, which Aven (2012) finds more suitable, is to see the decision-making process as a formal risk and decision analysis. The decisionmakers are provided with information (e.g. output data from a CBA) and then they do managerial review and judgment, and come up with a decision. This process has been illustrated by Aven (2012) with a schematic illustration, see Figure 2.6.



Figure 2.6: Decision-making process (Aven, 2012).

#### 2.6.2 Cost-Benefit Analysis

An economic valuation of a project, from a societal point of view, can be approached in different ways. A CBA does this through quantifying a project's cost and benefits in monetary terms (Atkinson and Mourato, 2008), and thereafter weighing them towards each other (Naturvårdsverket, 2003). The goal is to analyze whether a project/measure is profitable from a societal point of view. The advantage of a CBA is that it can present information in a structured, transparent and systematic way (Naturvårdsverket, 2003). The CBA can be performed in different ways, depending on its goal and purpose. One way could be to perform the CBA ex-ante, analyzing whether a measure should be implemented or not. Another way could be to analyze an events impact after it has occurred (ex-post), like Lindberg et al. (2011) who analyzed the impact that a Cryptosporidium outbreak had on the society of Östersund 2010/2011.

A CBA should not be limited to financial costs and benefits, e.g. investment cost or reduced investment cost (Naturvårdsverket, 2003). Intangible costs, like direct or indirect environmental impacts or services, should be included. The monetary value of this service/impact can be difficult to estimate, as there are no market price valuations (Atkinson and Mourato, 2008) These, so-called non-market goods and services, can be estimated using shadow prices (Naturvårdsverket, 2003). The shadow price should represent the service/products value, which can be quantified using methods such as stated preferences or revealed preferences, see Section 3.1 for more information.

Furthermore, it could be beneficial to separate the benefits and costs into categories. One approach, for the DWS, is to divide them into two categories; water quality (health risk) and water quantity (supply interruption).

The benefit that arises due to measures improving the water quality (reducing the health risk) is usually said to be the avoided cost of quality failure (Söderqvist et al., 2016). This cost is dependent on when the failure is detected. The societal cost if e.g. microbial contamination (quality failure) is discovered after it has reached the taps of the consumers is higher than if the failure is detected before the water has been supplied to the consumers, due to e.g. medical costs. Another aspect to consider regarding water quality failure is time, since a quality failure can lead to either long-term diseases or more temporary conditions, resulting in different societal costs.

For water quantity failure (supply interruption) the societal cost is similar to that of water quality failure, except that the illness-related costs (medical costs, absence from work etc.) are not included (Söderqvist et al., 2016). This is because that many businesses and public services becomes unable to continue their operations during a water shortage after a while. The cost varies depending on how long the interruption is and how many that are affected. Water quality and water quantity should, however, not be solely looked at as two separate systems. There are examples where water quantity failure leads to water quality failure, e.g. pipe breakage resulting in intrusion of contaminants, previously mentioned in Section 2.5.1. Furthermore, water-dependent industries, where the water quality does not matter, is another cost that needs to be considered due to quantity failure (Söderqvist et al., 2016). For information regarding how CBA is applied for this report, see Section 5.2.

#### 2.7 Risk management in drinking water systems

According to the International Water Association (IWA), a reliable supply of good and safe drinking water is fundamental to a healthy community and its economic

development (IWA, 2004). Furthermore, the IWA states that the delivery of water of such high quality requires a comprehensive understanding of contamination risks and the control of those. There are several different approaches drinking water producers in Sweden can use in order to manage different risks related to drinking water. One approach is the Water Safety Plan (WSP).

#### 2.7.1 Water safety plan

Safe drinking water, as defined by the WHO (2011), does not represent any significant risk to health over a lifetime of consumption, including different sensitivities that may occur between life stages. WHO has presented a framework for safe drinking water, that consists of health-based targets, Water Safety Plans (WSP) and independent surveillance (see Figure 2.7). The health-based targets should be based on evaluations of health concerns by a high-level authority, and reflect a risk acceptance level (Lindhe, 2008). The health-based targets should be used as guidance for the development of the WSP, while the surveillance of an independent third party should ensure that the WSPs works as intended.



Figure 2.7: Framework for safe drinking water (Davison et al., 2005).

A WSP consists of three key components: system assessment, effective operational monitoring, and management. The purpose of a system assessment is to determine if the drinking water can be of a quality that meets the health-based target, throughout the entire supply-chain (from source to tap). The operational monitoring aims to ensure that the quality maintains through the DWS and that any deviation from the required performance is detected. Management plans describe action plans for the DWS, both during normal operation but also during deviations from normal operation or critical situations in the supply-chain. The main objective of a WSP is to ensure a good practice for drinking-water supply (WHO, 2011).

Even though WSPs is a fairly common tool used by drinking water producers in Sweden, it should be mentioned that there is no legislation in Sweden that forces drinking water producers to use WSPs (SWWA, 2017b). The use of WSP in public drinking water can, therefore, be considered as an available tool that public drinking water works in Sweden can use in their risk management. However, it should be mentioned that many of the methods used today in Sweden (e.g. the HACCP concept, see Section 2.7.2) is a part of the general WSP idea, but the entire WSP concept is not fully implemented in Sweden currently.

#### 2.7.2 Hazard Analysis and Critical Control Point

According to Mortimore and Wallace (2000), the Hazard Analysis and Critical Control Point (HACCP) concept is a systematic approach to food (and water) safety management. It is based on recognized principles which aim at identifying hazards that may occur in any step of the food (or water) supply chain, and implementing control that prevents that from happening (Mortimore and Wallace, 2000). The approach is based on the seven principles of HACCP (FSAI, 2016):

- 1. Identify the hazards
- 2. Determine the critical control points (CCP)
- 3. Establish critical limits
- 4. Establish a system to monitor control of the CCP
- 5. Establish the corrective action to be taken when monitoring indicates that a particular CCP is not under control
- 6. Establish procedures for verification to confirm the HACCP system is working effectively
- 7. Establish documentation concerning all procedures and records appropriate to these principles and their application

Drinking water producers in Sweden are obliged to follow regulations The National Food Agency has presented. The regulations are based on the HACCP principles (SWWA, 2017b).

#### 2.7.3 Integrated approach

For the drinking water system there are multiple ways of performing risk assessment, where the previously mentioned WSP and HACCP are two examples of this. Another way is to use an integrated approach, which is which takes the entire drinking water system, from source to tap into consideration similar to the WSP (Lindhe, 2010). This enables an effective way of using resources, as the entire system that is usually divided into three sub-systems (water source, treatment plant, and distribution network) actually consists of multiple smaller parts that interact with each other. Using the integrated approach to risk assessment makes it possible to identify where it is most optimal to implement risk-reducing measures. For example, improving the protection of the water source or adding treatment steps to the treatment plant. Another reason to why an integrated approach is useful for the drinking water system is that it can take compensating factors into consideration. This is useful for the drinking water system, a failure in one sub-system does not always result in the entire system failing. An example for this is the use of water reservoirs during treatment plant downtime. However, Lindhe (2010) stresses that an integrated analysis is not sufficient to use alone in the risk assessment procedure. It should rather be seen as a complement to other analysis. An integrated approach using FTA is used in this report.

#### 2. Drinking water and risk

## 3

## Economic valuation of water supply

The following chapter starts with describing general valuation methodologies, that could be applied to quantify benefits of improvements in the water supply. It is followed by previous drinking water related studies of this subject.

#### 3.1 Valuation methods

The process of identifying and quantifying non-financial benefits is according to Atkinson and Mourato (2008) and Baffoe-Bonnie et al. (2007) an important part of a CBA. This section presents different economic valuation methods that can be used to quantify benefits.

#### 3.1.1 Stated Preference methods

Stated preference methods are based on hypothetical markets, where an individual is asked to estimate his/her valuation of a certain service/product through surveys or interviews. This enables price estimations of product/services that do not have market values (Johansson and Forslund, 2009). Two commonly used stated preference methods are Contingent Valuation Methodology and Choice Experiment and can be applied to a wide range of areas (Johansson and Forslund, 2009), e.g. to estimate the cost of discomfort due to sickness (Söderqvist et al., 2016).

#### Contingent Valuation Methodology

When applying a Contingent Valuation Methodology (CVM) an individual is provided with a scenario, and asked to estimate how much he/she is willing to pay for certain qualities/quantities of this service/product, i.e. their willingness to pay (WTP) (Baffoe-Bonnie et al., 2008). The person could also be asked how much he/she wants to receive as compensation if the product/service is not provided (Johansson and Forslund, 2009). The question can be asked as an open or closed question, where a closed question means that there are fixed alternatives to choose between.

#### **Choice Experiment**

In a Choice Experiment (CE) a respondent can choose between different options of service and its correspondent price (Baffoe-Bonnie et al., 2008). The individuals

ranking is then used to estimate their WTP (Johansson and Forslund, 2009). The methodology of CE makes it harder for an individual to make strategic decisions regarding their WTP.

#### 3.1.2 Revealed preference methods

Revealed preference methods are based on how individuals react to already existing markets (Johansson and Forslund, 2009). Three common revealed preference methods are the travel cost method, hedonic price evaluation and the production function method.

#### Travel cost method

The travel cost method is used to estimate a value of recreational activities (Hanley and Barbier, 2009). Typically, travel costs are made up of monetary expenses such as fuel costs, along with the time costs of traveling to a certain site for recreational activities. For example, ASEK 6.0 by Trafikverket (2016) contains information regarding time valuations for reduced travel time.

#### Hedonic price evaluation

The aim of hedonic price evaluation is to find a relationship between environmental qualities (such as noise levels, air pollution levels etc.) and market goods (e.g. houses) in order to monetize intangible parameters (Hanley and Barbier, 2009). For example, estimating how much property values change due to its access to quality drinking water (Söderqvist et al., 2016).

#### Production function method

The so-called production function method can be used to estimate how businesses/industries use water in their services and/or production. It is then applied to estimate the extra cost and/or lost profit that this businesses/industry would face, if there would be changes in water services like supply interruption (Söderqvist et al., 2014).

#### 3.1.3 Replacement cost method

The replacement cost method consists of estimating the cost of a measure necessary due to change in water services, e.g. the cost of buying bottled water if the water quality is worsened (Söderqvist et al., 2014).

#### 3.1.4 Market-price evaluation

Market-price evaluation of groundwater services could be estimated by looking at the market-price of groundwater and then multiplying it with the change in water outtake, the decrease or increase (Söderqvist et al., 2014).
# 3.1.5 Statistical values of life

A statistical value of a life can be approximated with the help of WTP studies MSB (2012). For Sweden, a statistical value of life s approximately 24 MSEK (SEK2014), according to the Swedish Transport Administration's risk evaluation for deaths caused by traffic accidents (Trafikverket, 2016).

# 3.2 Generalization of damage costs

In this section, previous studies that describe and/or estimate damage costs due to interruptions in the water supply are presented and described. For clarification, damage costs for this report are defined as the effect that water supply interruption has on societal functions, businesses, and regular consumers. In order to compare different events of water supply interruption (with varying duration and number of affected people), the costs are presented in cost per person per day for the affected area. The table below is a summary of the damage costs from previous studies.

**Table 3.1:** Summary of estimated damage costs per person per day (SEK2017) from previous studies, which investigated the impact of interruptions in the drinking water supply.

Analysis/Condition	Presented in	Cost			
		[SEK/person/day]			
Total interruption in drinking water	Section 2.3	20			
supply, year 1999 in Örnsköldsvik (per-					
formed ex post) <sup>1</sup>					
Two American studies (performed ex	Section 3.2.1	409-1988			
ante) analyzed damage costs of water					
interruption based on businesses GDP,					
resilience to interruption and a math-					
ematical expression for regular con-					
sumers $WTP^2$					
Interview-based scenario analysis (per-	Section 3.2.2	182-693			
formed ex ante) of two made-up munic-					
ipalities in Sweden, analyzing damage					
costs of water interruption. <sup><math>3</math></sup>					
Note: 1) Inflation SEK (2001-2017): 17.6%					
2) Inflation USD (2010-2017): 13.1%, 1 USD=8.448 SEK (December, 2017)					
3) Inflation SEK (2010-2017): 4%					

# 3.2.1 Economic impact from loss of water services

Brozović et al. (2007) developed a methodology which estimates, in monetary value, how water supply interruption can affect residential customers and businesses. For

businesses, the economic impact is calculated based on resilience to water shortage and business activity (total sales, shipments etc). For residential consumers Brozović et al. (2007) constructed an equation (see Equation 3.1) that aims to capture consumers WTP to avoid a total supply interruption for a certain time. It is derived from integrating a constant elasticity demand curve, between unrestricted consumption and a restricted quantity (see Figure 3.1). An important variable in this equation is the residential price elasticity of demand (Dalhuisen et al., 2002). The price elasticity of demand is a representation of how the change in water demand is affected by the change in water price. For example, a price elasticity of -0.5, means that a 10% price increase, results in a 5% decrease in water demand. Another important aspect of this calculation is that it assumes that the basic water requirement (BWR) is supplied by the government or the water producers, meaning that the WTP calculated for residential consumers only takes water demand above the BWR into consideration. Furthermore, the calculation does not account for the logistical and distributional costs of supplying the BWR and should, therefore, be a lower limit according to Brozović et al. (2007).

$$REL = \frac{\eta}{\eta + 1} \times P \times Q \times \left[1 - \left(\frac{BWR}{Q}\right)^{\frac{1+\eta}{\eta}}\right]$$
(3.1)

where:

REL is equal to residential economic loss  $\eta$  is equal to residential price elasticity of demand P is equal to water price, under normal conditions Q is equal to the average consumption per person per day BWR is equal to the basic water requirements



Figure 3.1: Residential economic loss due to water supply interruption (Aubuchon and Morley, 2012).

The American Federal Emergency Management Agency (FEMA) has based on the methodology of Brozović et al. (2007) created a general guideline on how to esti-

mate the loss of water services in case of a total water supply interruption (FEMA, 2011). The estimated cost (loss) is divided into economic activity (businesses and industries) and residential customers. The impact that loss of water services has on the Economic Activity is estimated based on the different sectors Gross Domestic Product (GDP) and resilience to water shortage. FEMA (2011) presents the economic impact for each sector as a flat rate per capita per day of lost service, see Table 3.2 below. The total economic impact was estimated to be around 42.83 USD (\$2010).

Francis sector	Loss of production*		
Economic sector	$[\mathrm{USD}/\mathrm{capita}/\mathrm{day}]$		
Construction	2.24		
Manufacturing - Non-durable Goods	4.03		
Manufacturing - Durable goods	5.97		
Transportation, Warehousing	0.72		
Utilities	0.98		
Wholesale Trade	1.43		
Retail Trade	1.53		
Real Estate, Rental, Leasing	3.30		
Finance, Insurance	2.19		
Information	1.19		
Professional & Business Services	3.14		
Education, Healthcare, Social	4.52		
Arts, Entertainment, Recreation	3.77		
Accommodation & Food service	2.84		
Other Services, Except Government	0.61		
Government	4.36		
TOTAL	42.83		
Note: *) \$2010 values			

Table 3.2: Economic impact due to loss of water service (FEMA, 2011).

For residential customers, FEMA (2011) use Brozović et al. (2007) equation (Equation 3.1) to calculate the residential loss due to water supply interruption, calling it *welfare loss*. In addition to the welfare loss, FEMA (2011) include the cost of supplying enough water to meet the BWR (25 liters based on Gleick (1996)). The cost per liter water is based on the average bottled water price. The total economic impact on regular consumers, with regards to both welfare loss and cost of BWR, was then estimated to be around 60 USD (\$2010). Table 3.3 below presents the estimated economic impact on both residential customers and economic activity (FEMA, 2011):

Category	Economic impact
Impact on Economic activity	\$42.83
Impact on Residential Customers	\$60.00
Total Economic Impact	\$100.83

Table 3.3: Economic impact (\$2010) due to loss of water services (FEMA, 2011).

A study performed by Aubuchon and Morley (2012) aimed to provide confidence in the results from the report by FEMA, through investigating uncertainties and taking more local data into regard (downscaling the analysis). Instead of providing a single nominal value, like FEMA (2011), a range is provided. The total economic impact due to loss of water services was estimated to be between 67 and 457 USD per capita per day (\$2010). Aubuchon and Morley (2012) recommends a use of  $208 \text{ USD per capita per day ($2010), which is larger than the estimation by FEMA$ (Table 3.3)). The largest uncertainties for the calculation by Aubuchon and Morley (2012) were businesses resilience to supply interruption and price elasticity on demand of water. Aubuchon and Morley (2012) states that FEMA (2011) probably underestimate the cost that residential customers are facing, as it would be more suitable to use a lower elasticity value (interruptions in the water supply is mostly short-term events). In FEMA (2011) the residential price elasticity of the demand for water was assumed to be equal to -0.41, and in Aubuchon and Morley (2012) elasticities of -0.26, -0.35 and -0.41 are used. These values are based on previous price elasticity studies, which corresponds to Reynaud (2015) that states that the price elasticity usually is somewhere between -0.5 and -0.1. However, according to Dalhuisen et al. (2002) the price elasticity in Europe and in other locations is distinctly different from those in the United States, and according to Reynaud (2015) the price elasticity is generally smaller in Europe compared to the US. In Sweden, for example, Reynaud (2015) estimates that the price elasticity can be -0.28 and/or -0.58.

Another approach, looking at the use of price elasticity, could be that a more inelastic price estimate can represent consumers WTP to avoid "loss of free time" (Aubuchon and Morley, 2012).

# 3.2.2 Case study by Törneke and Engman

Törneke and Engman (2009) performed a scenario analysis in 2009 at the request of the Council of Water and Wastewater Cooperation in Stockholm (VAS-rådet). The study aimed to identify and estimate societal costs due to large-scale drinking waters disturbances. In the study, Törneke and Engman (2009) analyzed two hypothetical municipalities –Municipality A and B–. The largest difference between the municipalities is that Municipality B, compared to Municipality A, included a larger population (60 000 vs 20 000 people), an emergency hospital, and two process industries. Three water interruption scenarios were analyzed; a total interruption in water supply, non-potable water, and waterborne contamination. The authors conducted interviews with representatives from different business areas and societal functions, to estimate how they were affected by the scenarios. Table 3.4 displays how many representatives from each business area that were interviewed.

Sector	Number of representatives		
	interviewed per business		
Industry/manufacturing	7		
District heating	3		
Public service	5		
Shop and trade	4		
VA-huvudman	2		

Table 3.4: Interviewed representative from different sectors.

Based on the information obtained from the interviews and from historical studies, Törneke and Engman (2009) estimated damage costs for each scenario and municipality. The damage costs accounted for is presented in Table 3.5.

**Table 3.5:** Estimated flat rate costs<sup>\*</sup> due to water interruption (Scenario: Water supply interruption) (Törneke and Engman, 2009).

Health care / Hospital	Cost [SEK /unit /day]		
Emergency hospital	9 000 000		
Health care center	90 000		
Dental care center, small size**	52 300		
Dental care center, large size***	135 500		
Private dental care center	20 000		
Firefighting	10 000		
Business / Industry	Loss of production [SEK/business/day]		
Large industry	600 000		
Small industry	15 000		
Distant heating	10 000 000		
Super markets	500 000		
Grocery stores	50000		
Restaurants (Lunch restaurants)	20 000		
Closing of schools	$\operatorname{Cost}$		
	[SEK/person/VAB-day]		
School and preschool	1500		
Water producer cost	[Cost]		
	[SEK/person/day]		
Tank trucks with water	11		
Repair cost in case of water leak	50 000		
Note: *) All costs are SEK-values for 2010 **) Small size dental care center for around			
20 000 people ***) Large size dental care center for around 60 000 people			

The main results of the scenario analysis were:

- Scenario: Total interruption in water supply. The total interruption lasted for 2 days, causing problems for the emergency hospital and district heating in Municipality B. One death was accounted for, and this was due to patients being moved from the emergency hospital. A total cost of 7 MSEK and 80 MSEK were estimated for municipality A and B, respectively.
- Scenario: Non-potable water. This scenario required water to be boiled before being used for drinking, but it could be used for hygiene purposes. The grocery stores in both municipalities and the emergency hospital in municipality B were heavily affected in this scenario. The total costs were 37 MSEK and 160 MSEK for municipality A and B, respectively.
- Scenario: Waterborne contamination. The difference between non-potable water and waterborne contamination is that with the waterborne contamination around 40% of the municipalities is infected, resulting in sick leave and cost of one death. Sickness leave and death were large cost posts for this scenario, and except for those were the costs for the grocery stores in both municipalities and emergency hospital in municipality B large. For the waterborne contamination were the total costs 136 MSEK and 415 MSEK for municipality A and B, respectively.

# 3.2.3 Benefits of a safe and reliable drinking water supply

In year 2013, the Swedish government assigned an investigator to evaluate the DWS in Sweden, from source to tap, in order to identify current and potential challenges for a safe drinking water supply in the country, which resulted in the report SOU 2015:51 (SOU, 2015). Based on that report, Söderqvist et al. (2016) identified societal benefits that could occur due to the implementation of the suggested actions in SOU 2015:51 and also identify prerequisites and conditions that are essential to reach mentioned benefits.

Even though the Söderqvist et al. (2016) treats both quantity and quality related disturbances in the drinking water supply, it is mostly focused on quality failures in the DWS, such as microbial contamination. Söderqvist et al. (2016) claims that there is not a lot of previous studies, estimating costs for interruptions in the DWS that is not quality related. Furthermore, Söderqvist et al. (2016) states that the cost due to quantity related interruptions can vary a lot depending on the size and length of the disturbance.

In the report by Söderqvist et al. (2016), societal costs that are expected to be large in case of water supply interruption are presented. In combination with the large societal costs are also methodologies (approaches/suggestions) presented, which can be used to quantify these costs, see Table 3.6.

Type of damage cost	Common ways of quantifying the		
	damage cost		
Production loss	Flat rate cost based on salary from ab-		
	sent personnel, and/or lost service/pro-		
	duction time and/or quality		
Extra costs beyond production loss (es-	Data regarding the cost from public		
pecially for food-related industries and	sector and companies		
other water-dependent industries)			
Health care cost, including extra cost	Costs for health care from e.g. the		
for the service of health care	health care sector		
Extra costs due to extra sampling and	Cost data from drinking water produc-		
analyzing of the water	ers		
Loss of spare time for households (ev-	Fair estimation and valuation of time		
erything involved with buying, collect-	lost for households.		
ing and/or boiling water)			
Costs of death	Use of statistical valuation of life, e.g.		
	from public administrations.		

**Table 3.6:** Table over different types of damaged costs that can be expected due to water supply disturbances, adaption from Söderqvist et al. (2016).

# 3.2.4 Climate and vulnerability investigation

In the report Sweden facing climate change – threats and opportunities SOU (2007), an estimation of damage costs for a total water supply interruption were estimated. The report estimates the cost, if a main drinking water supply were damaged, to be around 10-50 MSEK (SEK2007) per event, assuming that the event lasts for several days and that there is no reserve water supply available. However, the input data and method behind this damage cost estimation are not presented in the study, which limits the possibility to use this data in other studies.

# 3.2.5 Willingness To Pay for a reliable water supply

FEMA (2011) and Aubuchon and Morley (2012) estimated consumers WTP to avoid loss of water services through a mathematical approach, using the equation from the study of Brozović et al. (2007). Another approach that is common is to use CVM (as previously described in Section 3.1.1) to measure consumers WTP for water supply reliability (Howe and Griffin Smith, 1994). For example, the CVM study performed by Koss and Khawaja (2001) describes consumers WTP for reliable water supply in California. In that study, consumers were asked what their WTP were to avoid a certain frequency of interruptions (occurrences/years) and a shortage of interruptions (reduction in service). This study showed that residential customers in California have a higher WTP to avoid large interruptions that occur less frequently, in comparison to short frequent interruptions. Furthermore, the highest mean monthly WTP for this study (\$16.92 USD2001) was to avoid shortages with 50% reduction in service that occurs once every 20 years. Although, it is not suitable to use this data for studies in Sweden, since that certain conditions varies between Sweden and California such as i.e. water supply, which will have a large impact on the WTP.

# Case study

The municipality of Munkedal will need an upgraded raw water source and a new treatment plant in the near future. The case study of this report will, therefore, investigate whether it could be beneficial to invest in a solution that could (apart from securing Munkedal future drinking water demand) also provide redundancy for the neighboring municipalities.

The current situation is first presented, providing a background regarding the investigated site and municipalities. It is followed by a presentation of the different risk-reducing alternatives that are investigated in this case study.

# 4.1 Background

### 4.1.1 Västvatten

Västvatten is the official drinking water provider of the municipalities of Munkedal, Sotenäs, Uddevalla and Färgelanda, and is thereby responsible for the entire supply chain, from source to tap. Västvatten is owned by the four mentioned municipalities. According to Västvatten <sup>1</sup>, is it possible that Lysekil also joins Västvatten in the future, but it has not yet been decided.

Since that all included municipalities in Västvatten have their own drinking water supply chain (raw water – treatment – distribution), Västvatten needs to be able to work differently for every municipality in order to secure a safe reliable drinking water for everyone who is connected to the public DWS.

One of Västvatten's current concerns is the future raw water supply and treatment for Munkedal, which is presented in Section 4.1.2.

# 4.1.2 The municipalities in the region

Following is a description of Munkedal and the surrounding municipalities Sotenäs, Lysekil, and Uddevalla. For a regional map, see Figure 4.1.

<sup>&</sup>lt;sup>1</sup>Andersson, David (Production Manager, Västvatten) [Interview, 2017-04-06]



**Figure 4.1:** Map over parts of Bohuslän, including the municipalities of Munkedal, Sotenäs, Lysekil and Uddevalla (Lantmäteriet, 2017)

#### Munkedal

The municipality of Munkedal belongs to the province of Bohuslän, which is located on the west coast of Sweden, see Figure 4.1. In year 2016, there were 10 361 people living in Munkedal (Munkedal kommun, 2016). The municipality has a goal of reaching 11 000 inhabitants by the year 2025 (Munkedal kommun, 2010).

In 1978, three groundwater wells were drilled in the eastern bank of Lake Kärnsjön. These wells are still in operation and constitute one out of five raw water sources that provide Munkedal with drinking water. In order to manage and reduce the high levels of iron and manganese, the water in the wells is oxygenated in order to precipitate the iron and manganese. The method is called Vyredox. The water is then transported to a water tower, along with water from the water sources of Obbön, Håby, Dingle, and Hällevadsholm. The water is thereafter treated with UV-light before ending up in the distribution network. If for some reason, the water supplied from Lake Kärnsjön would be interrupted, the amount of water delivered from the other water sources (Öbbön, Håby, Dingle, and Hällevadsholm), would not be sufficient to meet the demand (Sweco, 2014). Looking at the daily abstraction from groundwater wells adjacent to Lake Kärnsjön, the average is around  $1\ 022\ {\rm m}^3/{\rm day}$  according to Västvatten (2017). This can be compared to the allowed average abstraction of 1 400  $\text{m}^3/\text{day}$  and the maximum of 2 300  $\text{m}^3/\text{day}$  (Sweco, 2014). However, the wells are (more or less) unable to deliver any more water than the current levels, due to the Vyredox installation, which has reached its maximum capacity according to Västvatten<sup>2</sup>. This can be problematic, as the water demand will increase along with the increasing population.

#### Lysekil

Lysekil is located southwest of Munkedal. In 2016, the population was 14 464 people (Lysekil kommun, 2016). The daily treated water usage is around 4 700 m<sup>3</sup>/day (LEVA, 2017). Similar to Munkedal, Lysekil uses Lake Kärnsjön as its raw source. However, instead of treating the water near Lake Kärnsjön, Lysekil transport the raw water to Lysekil where a treatment plant is located (LEVA, 2017). Lysekil is not a part of Västvatten, they have their own municipality owned water utility organisation, LEVA (Lysekil Elnät Vatten Avlopp). Lysekil is, however, included in this study, as they can obtain benefits from the alternatives that are analyzed.

#### Sotenäs

Sotenäs is located west of Munkedal and has currently a population of just over 9 000 people (Sotenäs kommun, 2017). Popular summer destinations such as Kungshamn, Smögen, Hunnebostrand etc are located within the municipality, resulting in an increase in population during summers up to tens of thousands. According to Västvatten (2017), in summertime the drinking water production is around 8 000 m<sup>3</sup>/day while during the winter it is closer to 4 500 m<sup>3</sup>/day. Sotenäs gets its water from Lake Dale, where the surface water is treated. Sotenäs is a part of Västvatten since 2017.

### Uddevalla

Uddevalla is located east of Munkedal and is the largest city in the region, with a population of 55 165 people in 2016 and it is expected to increase up to 61 900 people in the year 2026 (Uddevalla kommun, 2017). The raw water for the people who are connected to the public drinking water supply is obtained from Lake Öresjö. The water is transferred from Lake Öresjö to Lake Köperödssjön, where it is stored before supplied to the treatment plant Marieberg. The city of Uddevalla is part of Västvatten, and Västvatten<sup>2</sup> have expressed their concern regarding the future water supply in Uddevalla considering the expected population increase. According to Västvatten<sup>2</sup>, in the event of a severe pollution of the raw water, the reserved water for the city would only last for a few weeks.

# 4.1.3 Lake Kärnsjön

Lake Kärnsjön, located in the municipality of Munkedal, is a long and narrow lake, approximately 9 km long and 1 km wide. The lake is created from a fracture zone in the metamorphic crystalline bedrock, and the soils in the area are dominated by glacial till with a glaciofluvial deposit (sand-gravel) on the east-side of the lake). The lake contains relatively high levels of manganese and iron. On the eastern side of the lake, is a glaciofluvial deposit (Sweco, 2014). Lake Kärnsjön is currently used as a raw water source for the municipalities of Munkedal and Lysekil. It also serves as a raw water source for oil refineries outside of Lysekil. The oil refineries use their own separate raw water distribution pipe to obtain water from Lake Kärnsjön, and are not connected to the public treatment or distribution network. Therefore, the

<sup>&</sup>lt;sup>2</sup>Andersson, David (Production Manager, Västvatten) [Interview, 2017-09-04]

water outtake for the refineries is not accounted for in this report. For more information regarding the water usage in Munkedal and Lysekil, see Section 4.1.2.

# 4.2 Risk-reducing alternatives

Different alternatives on how to use Lake Kärnsjön are presented in this section. The alternatives have been selected in collaboration between water utility personnel at Västvatten and representatives from Chalmers University of Technology. Due to the requirement of meeting the future water demand of Munkedal (the current situation will not suffice), there will be no status quo- alternative in the CBA (where no alternation of the current situation is implemented). Instead, a reference alternative will be used. The other alternatives (1 and 2) will be used as basis in order to evaluate how much the benefits of increase redundancy could be worth.

### 4.2.1 Reference alternative

The Reference alternative aims at securing the future water supply of Munkedal. A new drinking water treatment plant (DWTP) is to be constructed near Lake Kärnsjön, and will use the lake as its raw water source. The new DWTP is then connected to the existing public distribution network in Munkedal. The new DWTP replace all current water sources in Munkedal. For a simple graphical layout of the Reference alternative, see Figure 4.2.



Figure 4.2: Simplified illustration of the Reference alternative.

#### 4.2.2 Alternative 1

Alternative 1 aims at securing the future water supply of Munkedal along with providing redundancy for both Sotenäs and Lysekil. Besides constructing a new DWTP for Munkedal, redundancy pipes will be connected to both Sotenäs' and Lysekil's distribution networks. To be able to provide redundancy for Sotenäs, and Lysekil (one at the time), the new DWTP needs to have the capacity to supply Munkedal with drinking water on a daily basis, as well as to provide Lysekil and Sotenäs in case of an emergency (see Figure 4.3 for an illustration of Alternative 1).



Figure 4.3: Simplified illustration of Alternative 1.

#### 4.2.3 Alternative 2

Alternative 2 aims to secure the future water demand of Munkedal, and also provide redundancy for Sotenäs, Lysekil and Uddevalla. To be able to provide Uddevalla, Sotenäs and Lysekil with redundancy (one at the time), the new DWTP need to have the capacity to supply Munkedal with drinking water on a daily basis, as well as to provide Lysekil, Sotenäs, and Uddevalla in case of an emergency. For an illustration, see Figure 4.4.



Figure 4.4: Simplified illustration of Alternative 2.

5

# Method

In order to estimate the risk of supply interruptions, the effect of the risk-reducing alternatives and its social profitability, the following three steps are performed:

- The probability of supply interruption is calculated, based on a hazard identification performed together with Västvatten.
- The economic risk is estimated through integrating the probability assessment with economic consequences of not meeting the supply-demand, using a CBA.
- A Bayesian approach is used to estimate probability distributions for the input data, enabling uncertainty and sensitivity analysis using Monte Carlo simulations.

# 5.1 Probability of supply interruptions

Analyses of cause and consequences of events can be performed by the use of logic tree models, such as fault trees and event trees (Lindhe, 2010). A fault tree analysis (FTA) is a structured and transparent way of analyzing system failures, and can easily be updated, with regards to both structure (changing events and logic gates) and input data to model the effect of risk-reducing measures. A FTA is performed in this report.

In a FTA, the aim is to develop a deterministic description of the occurrence of an event, such as system failure (Bedford and Cooke, 2001). The system failure is represented as a 'top event' in the fault tree model, and under-laying events that lead up to this top event are called 'intermediate events' where the events in the lowest level of the model are called 'basic events' (Lindhe, 2010). The basic events are the events that initiate a system failure. For an illustration of the structure of a fault tree model, see Figure 5.1.



Figure 5.1: A simplified example over a fault tree, including different events along with OR- and AND-gates

In Figure 5.1, there are two different types of logic gates illustrated; OR- and ANDgates. The logic gates represent interactions between events, based on Boolean logic. In an AND-gate, every input event needs to occur simultaneously in order for the output event to occur. For an OR-gate, only one input event is enough to make the output event occur (Lindhe, 2010). A fault tree in itself does not give enough information to allow an estimate to be made of system reliability (Bedford and Cooke, 2001). However, together with reliability data for the basic events, the FTA provides estimates of system reliability. The probability of the top event  $(P_F)$ is calculated based on the probability of the basic events  $(P_i)$  using Equation 5.1 for OR-gates and Equation 5.2 for AND-gates.

$$P_F = 1 - \prod_i (1 - P_i) \tag{5.1}$$

$$P_F = \prod_i P_i \tag{5.2}$$

For this study, a FTA is conducted in order to estimate the probabilities of hazardous events that could lead to total water supply interruptions in the affected municipalities. These so-called critical events are identified in collaboration with Västvatten.

To enable uncertainty estimations of the input data, a probabilistic approach is used for the FTA (Lindhe, 2010). To assess which variables in the FTA that contributes most to the uncertainty of the results, rank correlation coefficients are calculated. The input data for the probabilistic approach are obtained by collaboration between experts (water utility personnel from Västvatten) and the authors. The experts are asked to identify critical hazardous events in the DWS (raw water source, treatment and distribution network) of the previously stated municipalities. Furthermore, they are asked to estimate values of the frequency of the event (used to estimate the annual probability of occurring) and its duration. Based on this information, the 5th and 95th percentiles are estimated for the events and its variables, providing probability distributions. The uncertainties are represented by beta and log-normal distributions.

The construction of the FTA, with its calculations, is done using Microsoft Excel and the Monte Carlo simulations are performed using Palisade @Risk, an add-in software to Excel.

# 5.2 Cost-Benefit Analysis

In order to compare costs and benefits, a CBA is performed. The CBA is performed ex-ante, meaning that the benefit of the different alternatives is equal to the avoided (reduced) risk cost. To be able to compare the alternatives' societal profitability, the Net Present Value (NPV) is chosen as a criterion for comparison.

According to Baffoe-Bonnie et al. (2007), NPV is a robust indicator of the financial and economic performance of a project. The NPV measures the net benefit of the project, and it estimates the summation of the annual net benefit of the project over the period of analysis (its time-horizon) (Baffoe-Bonnie et al., 2007). Assuming that the benefits are higher than the costs, then an overall benefit is achieved through implementation of the project (comparing with the current situation). As monetary values are not constant over time, the so-called discount rate is used in social economic analyses (Söderqvist et al., 2014). With the discount rate, it is possible to calculate the costs and benefits that occur over time and translate them in to a NPV. A discount rate of zero results in the future costs and benefits being equal to today's costs and benefits. The higher discount rate, and the further into the future a consequence occurs, the lower resulting NPV. For Sweden, a commonly used discount rate for CBAs related to infrastructure investments is 3.5% (Trafikverket, 2016).

The NPV is calculated as:

$$NPV = \sum_{t=0}^{T} \frac{B_t}{(1+r)^t} - \sum_{t=0}^{T} \frac{C_t}{(1+r)^t}$$
(5.3)

where:

T is the time horizon B is the benefit of respective year C is the cost of respective year r is the used discount rate t is each respective year during time-horizon T.

As previously mentioned, the benefit is here the avoided risk cost. To be able to estimate a risk cost, the consequences of an event needs to be estimated, along with its probability. Figure 5.2 below, is an illustration on how the process of risk assessment and CBA are performed in this study, starting from identifying critical events in collaboration with Västvatten, finishing with estimating the benefit for risk-reducing alternatives. For a more detailed description of the methodology behind the estimation of benefits and costs, see Section 5.2.1 and Section 5.2.2, respectively.



Figure 5.2: Illustration on how risk assessment and CBA works together.

#### 5.2.1 Benefits

The benefit of the risk-reducing alternatives is - as previously mentioned - the avoided cost, which is the risk-cost that is eliminated due to the implementation of a risk-reducing alternative. The avoided risk cost (benefit) is calculated with Equation 5.4.

Benefit = 
$$R_0 - R_1 = \sum_{i=1}^{n} P_{F,i} \times C_i - R_1$$
 (5.4)

where:

i = 1,..,n critical events

 $R_0$  = The original risk

 $R_1$  = The remaining risk after risk-reducing alternative has been implemented (in this case study,  $R_1$  is assumed to be 0)

 $P_{F,i}$  = Probability of critical event causing total water supply failure.

 $C_i$  = Consequences of failure event is calculated as duration of event multiplied with damage cost. The damage costs depends on what societal functions and groups that are effected by the event, and it is calculated as cost per person per day According to Söderqvist et al. (2016) avoided damage costs are a central part of the calculated benefits for measures that ensure and improve the safety and reliability of drinking water supply. The following list is common types of damage costs that could occur due to an interruption in the water supply, based on Söderqvist et al. (2016) and Törneke and Engman (2009):

- 1. Regular consumers
- 2. Loss of production
- 3. Schools/education
- 4. Health care
- 5. Water producers

Based on this list, a damage cost estimation for water supply interruption is performed for the municipalities. However, not all damage costs are monetized due to an inherent difficulty to quantify, large uncertainties etc. Also, as previously mentioned, for this study only benefits gained from additional redundancy implemented in Alternatives 1 and 2 are accounted for.

Following, the methodology to estimate the above-stated damage costs is presented, including mentions of damage costs that are not monetized in this study.

#### **Regular consumers**

Regular consumers are affected by a total supply interruption, and the damage cost can be estimated with different approaches.

First, looking at the studies of FEMA (2011) and Aubuchon and Morley (2012), (as described in Section 3.2.1). The flat rate cost from their report would not be appropriate to use for events in Sweden, as the results are based on input data from the US. Also, the flat rate cost calculated for residential customers in FEMA (2011) includes the cost of supplying water to meet the BWR, based on the average cost of bottled water. Using this flat rate estimate would mean a risk of double counting, if separate calculations are made for the costs of emergency water supply. However, the equation used in FEMA (2011), which actually is derived from a study of Brozović et al. (2007), could be applied to estimate the economic impact of residential customers in Sweden. The input data can be retrieved from previous studies and governmental websites as well. More specifically, average water consumption and water price under normal conditions could be retrieved from governmental websites. Price elasticity of demand for water in Sweden can be retrieved from previous studies such as Reynaud (2015), and the amount of water necessary for BWR could be based on the study of Gleick (1996).

Another approach could be to estimate the spare time lost due to everything involved with obtaining water from a government relief agency and/or buying water from a grocery store. Söderqvist et al. (2016) states that loss of spare time could be a large damage cost in case of a water supply disturbance. The study states that it can be estimated using a fair estimation of how much spare time that is lost, and how much it is worth. The cost estimation can be performed using the travel cost method (time cost valuation), as previously mentioned in Section 3.1. By combining the travel cost method with a fair estimation of the spare time lost, the cost for regular consumers could be estimated. Furthermore, an assumption could be that regular consumers are not immediately supplied with enough water to meet the BWR in case of a total supply interruption, or that consumers would like to buy water for drinking purposes. In that case, a cost estimation of buying bottled water for drinking purposes could be applied, in addition to the cost of lost spare time, using the replacement cost method (also described in Section 3.1). For this study, the travel cost method has been used to estimate the cost due to loss of spare time, and the replacement cost method to estimate the cost of buying bottled water for drinking purposes.

#### Loss of production

In case of a total supply interruption businesses/industries can face costs due to loss of service/production time, lowered quality of services/products and so forth. Water-dependent industries, e.g. food-related industries, are especially effected by water shortage (Söderqvist et al., 2016). The cost is commonly referred to as loss of production. Following, methodologies, and studies estimating the costs of loss of production are presented.

The application FEMA (2011) used to estimate the economic impact due to water supply interruption for the so-called economic sector is based on US data and is generally for the entire US. Aubuchon and Morley (2012) who further analyzed results from FEMA (as described in Section 3.2.1), made it more applicable for state-level calculations in the US. It still cannot be directly applied to estimate a cost of water supply interruptions for the economic sector in Sweden as it is based on US data. However, the same methodology to estimate the impact on the economic sector like FEMA (2011) and Aubuchon and Morley (2012) could be applied for Sweden. If the input data like GDP for different economic sectors and their resilience to water supply interruption is retrieved for national and/or local levels. Although, that has not been performed for this study.

Another study that could be useful in order to estimate the loss of production for industries/businesses is Törneke and Engman (2009), previously described in Section 3.2.2. The estimated damage costs in the report by Törneke and Engman is based on water interruption for businesses/industries in Sweden and is especially useful when investigating municipalities with similar sizes used in that study. The hypothetical municipalities for their report are similar in sizes to the ones investigated in this reports case study. However, due to uncertainties in some of the results (unclear definitions, assumptions and so on), only the flat rate cost for grocery stores by Törneke and Engman (2009) will be applied for this report when estimating the loss of production.

Restaurants are another business which faces production loss in case of loss of water services. For this, it is assumed that restaurants need to close immediately as water is necessary for hygienic reasons. The damage cost is estimated based on the restaurants turnover, a similar approach to Törneke and Engman (2009).

Previous studies have shown that water-dependent industries are a large cost post, when it comes to water supply failure. In this study, only large water-dependent industries have been taken into consideration. This is due to uncertainties regarding how many small industries within the municipalities that are water-dependent, and how they are affected by the water shortage. There are other studies, such as FEMA (2011) that has a flat rate cost for manufacturing, wholesale trade etc., but it is derived from US data, and therefore it is not applied to this report. Also, in Törneke and Engman (2009) case study, small water-dependent industries were only a fraction of the total cost, indicating that it probably will not have a large effect on the total damage costs.

The damage cost, large water-dependent industries face in case of a total supply interruption is quantified using the production function method, as described in 3.1.2. This is similar to what Törneke and Engman (2009) and FEMA (2011) did. Large water-dependent industries are identified within the municipalities and contacted to see how they're affected by water shortage. The cost is then estimated based on their annual turnover and how their production is affected by an interruption in the water supply.

#### Schools/Education

Both Söderqvist et al. (2016) and Törneke and Engman (2009) state that a likely outcome of a large drinking water supply failure is that schools are forced to shut down during the first couple of days of the interruption. In order to estimate the damage costs due to closing of preschools and elementary schools in the event of water supply interruption, a similar method as Törneke and Engman (2009) is used. The cost is seen as production loss, resulting from parents going home from work to take care of their children (so-called VAB), as the schools close. The calculation of production loss is based on the number of children in preschool and elementary school, the number of children per parent and median salary. It is assumed that schools are only closed for the two first days of an interruption and that the schools are able to open for service on the third day using e.g. mobile water closets and so forth.

#### Health care

Health care in this study consists of hospitals, health care centers and dental care centers. The estimation of damage costs for dental care centers and health care centers is estimated using the flat rate costs from Törneke and Engman (2009). Health care centers are assumed to be closed for only a couple of days (before portable toilets and other temporary solutions are installed), while dental care centers are closed (or limited) during the entire interruption.

The only hospital in the region is Uddevalla Hospital. The cost for a hospital, resulting from a total water interruption is hard to quantify (cost of canceling planned surgeries, relocating patients etc.). For this report, the cost for hospitals is based on daily turnover, same as Törneke and Engman (2009) did in their study.

#### Water producers

Söderqvist et al. (2016) states that major costs for water producers, in case of supply interruption, could be testing/analyzing, and also distribution/handling of alternative water sources. Söderqvist et al. (2016) further states that a common way to estimate this cost is to obtain that cost information from water producers, which is performed in this study.

#### Non-monetized damage costs

In order to provide transparency, non-monetized damage costs that have not been used in the calculations in this report are presented in Section 7.

### 5.2.2 Costs

The costs related to the risk-reducing alternatives in this report are limited to the investment and operational costs of constructing a new drinking water treatment plant (DWTP) and the addition of new water distribution pipes. Costs due to environmental impacts, land redemption etc are not included as costs in this study. The investment costs are considered to be a one-time cost, while the operational costs are annual. The investment cost of the DWTP is based on its required future capacity. The future capacity for the alternatives is calculated based on a predicted increase in demand, which depends on population increase along with estimated water usage. Converting required capacity of DWTP into investment cost is performed based on an assumed ratio between investment cost and DWTP capacity, see Appendix A.1 for cost estimations.

The cost (investment and operational) for DWTP is calculated for the reference alternative, and then reduced from the calculated investment and operational costs for Alternative 1 and 2. This is because the CBA will evaluate the worth of providing redundancy, therefore only the additional investment and operational costs (in addition to the Reference alternative) are weighed against the benefits of redundancy.

The investment cost for distribution pipes (for redundancy) are based on approximations provided by the water utility personnel at Västvatten. The annual operational costs for both the DWTP and the redundancy pipes is derived from the report by SWWA (2017c), and calculated over the selected time-horizon and discount rate.

# 5.3 Uncertainty analysis

In order to analyze the uncertainties in the input data and the results, a Monte Carlo simulation approach is used. Monte Carlo is a random numerical sampling method (Bedford and Cooke, 2001). An iterative calculation is made, based on probabilistic distributed input data (probability and consequence), providing results (risk) as a distribution. The amount of iterations performed is based on the users choice. For

example, 500 iterations mean that a random value from each distribution is selected 500 times to calculate the results. For this study have 5000 iterations been used. To perform Monte Carlo simulations, the add-on to Microsoft Excel called @Risk is used.

In order to perform a sensitivity analysis, correlation coefficients are calculated. Equation 5.5 reflects on how input variables contribute to the uncertainty in the output and is defined as Spearman's correlation coefficient.

$$\rho = 1 - \frac{(6 * \sum d_i^2)}{n(n^2 - 1)} \tag{5.5}$$

where  $\rho$  is the correlation coefficient, d is the rank difference between the output and the input and n is the number of correlation sets. The correlation coefficient  $\rho$ can vary between -1 and +1. A  $\rho$  close to +1 or -1 shows a high importance to the results, where -1 has the reserve/negative impact compared to +1. A  $\rho$  close to 0 shows low importance.

# 5. Method

# 6

# Results

In this chapter, the results from the study are presented; probability of supply interruptions, damage cost estimation, CBA and uncertainty analysis.

# 6.1 Probability of supply interruptions

In collaboration with Västvatten<sup>1</sup>, a hazard identification was performed (see Appendix A.3). Four critical hazardous events that could cause a total interruption in the water supply were identified for Uddevalla. Due to the sensitivity of this information, no descriptions of these events are presented here. Instead, they are labeled events 1-4. The identified critical events used in this study are based on the current risk situation for Uddevalla and are adapted to the preconditions in the municipalities of Sotenäs and Lysekil (in consent with Västvatten).

Figure 6.1 shows the fault tree that has been constructed, based on the identified events and the relation between them. The fault tree is divided into three intermediate events, representing failure in the sub-systems raw water source, treatment and distribution network. For the treatment sub-system, two critical events were identified while for raw-water and distribution only one critical event per sub-system was identified. Information regarding the critical events probabilities of occurrence and the resulting interruption's duration, based on the input from Västvatten, is presented in Table 6.1. This is further used as input data for the CBA, presented in Section 6.3.





<sup>&</sup>lt;sup>1</sup>Andersson, David (Production Manager, Västvatten) [Interview/Workshop, 2017-10-23]

Critical event	Annual probability of		Duration of			
Critical event	occurrence, P		interruption [		[days]	
	P05	P50	P95	P05	$\mathbf{P50}$	$\mathbf{P95}$
1	0.020	0.029	0.040	14	45.8	150
2	0.010	0.015	0.020	30	73.5	180
3	0.002	0.004	0.005	3.2	5	6.8
4	0.020	0.029	0.040	2.2	3.5	4.85

**Table 6.1:** Table displaying probability and duration for identified critical events, presented in 5th, 50th and 95th percentiles.

The probability for complete interruption in the drinking water system, the top event in the fault tree, is around 7.5% (P50).

# 6.2 Damage cost estimation

The estimated damage costs for societal functions/groups in relation to the municipality is presented in Table 6.2. The largest damage cost for Lysekil and Sotenäs is the loss of production for large water-dependent industries, while for Uddevalla it is the cost due to schools closing (VAB). However, this applies only to interruptions that are shorter or equal to two days, due to the assumption that schools and health care centers will re-open after two days (as previously mentioned in Section 5.2). For events that are longer than two days, the hospital represents the largest damage cost for Uddevalla (as damage costs for schools and health care centers are then no longer accounted for), while it stays the same for Lysekil and Sotenäs. In Table 6.3, two different damage costs are presented for the municipalities, in relation to duration of the interruptions. Input data used to estimate the damage cost is presented in Appendix A.2. The damage cost estimations are further used in the benefit estimations for the CBA as avoided damage costs, presented in Section 6.3.

Damage cost [SEK/person/day]				
	Lysekil	Sotenäs	Uddevalla	
Health care center*	23.7	18,9	15.6	
Dental care center	12.2	15.2	11.4	
Large industries	134.7	359.3	20.6	
Restaurants	20.5	47.2	23.2	
Grocery stores	19.8	36.7	25.9	
Water utility personnel	2.4	2.4	2.4	
Hospital	0	0	52.8	
Schools (VAB)*	63.5	52.8	73.4	
Regular consumers	72.5	72.5	72.5	
*) Damage cost not valid for interruptions $> 2$ days.				

**Table 6.2:** Estimated damage cost (50th percentile) distribution for the societal functions/groups in relation to the affected municipality.

Estimated damage cost				
[SEK/person/day]				
	Lysekil	Sotenäs	Uddevalla	
$\hline {\rm Interruption} <= 2 {\rm ~days}$	349.2	605.1	297.8	
$\fbox{Interruption > 2 days}$	262.0	533.4	208.8	

 

 Table 6.3: Estimated damage cost (50th percentile), depending on length of interruption.

Figure 6.2 show how the total damage cost vary over the length of an interruption, as an illustration to the magnitude of consequences that is followed by a complete interruption in the water supply. For example, Uddevalla it is already 50 MSEK after 2 days, and 150 MSEK after 7 days.



**Figure 6.2:** Total estimated damage cost (50th-percentile) for the municipalities in relation to duration of interruption.

# 6.3 Cost-Benefit Analysis

The CBA has been performed for a time horizon of 50 years, using a discount rate of 3.5%. The resulting NPV, benefits, and costs for the alternatives are presented in Figure 6.3 to Figure 6.5.

The 5th percentile for both Alternative 1 and 2 presents a negative NPV after 50 years, while the 50th percentile and 95th percentile present positive NPVs. For the NPV there is a large difference between the 5th percentile and 95th percentile. This is due to uncertainties in the benefit estimation, which can be seen in Figure 6.5. To address uncertainties, and examine sensitivity of input variables, an uncertainty and sensitivity analysis have been performed, presented in Section 6.4.





Figure 6.3: NPV for the two alternatives, using a 3.5% discount rate and 50-year time horizon.



**Figure 6.4:** Cost for the two alternatives, using a 3.5% discount rate and 50-year time horizon.



Figure 6.5: Benefit for the two alternatives, using a 3.5% discount rate and 50-year time horizon.

#### 6.4 Uncertainty and sensitivity analysis

To see what input variables that contribute most to the uncertainties in the results, Spearman rank correlation coefficients were calculated. Figure 6.6 presents the six largest correlation coefficients. From this figure, it is possible to see that the probability and duration of Critical events 1 and 2 have the largest effect on the uncertainties of the resulting NPV presented in Section 6.3. These events should be prioritized, to create a CBA with a higher degree of reliability.



■ Alternative 1 ■ Alternative 2

Figure 6.6: Spearman's rank correlation coefficients relation between the input data and the NPV.

#### Scenario analysis

In order to further evaluate the uncertainties in the study different scenarios have

been analyzed. The scenarios have been identified based on the Spearman rank correlation coefficients. Scenario 1 and 2, altering Critical events 1 and 2, and the ordinary scenario (the first CBA) were analyzed using different discount rates (1%, 3.5%, and 5%)). For scenario 3, six sub-scenarios (a-f) were investigated, where damage costs are only accounted for a certain amount of days using the discount rate of 3.5%.

- Original scenario: The original CBA, presented in Section 6.3.
- Scenario 1: Critical event 1 does not occur during the time period.
- Scenario 2: Critical event 2 does not occur during the time period.
- Scenario 3a-3f: Regardless of the duration of an events interruption, damage costs are only accounted for a maximum of certain days. Starting with one week for sub-scenario a, increasing with one week for each sub-scenario (Scenario f, maximum of six weeks).

For the ordinary scenario there was no alteration to the parameters, except for the change in discount rate. This had, however, no effect on the ranking of the alternatives, Alternative 2 were still more profitable than Alternative 1. The additional scenarios (1-3) had a large effect on the NPV and benefit, but not on the cost of the alternatives. The costs are only affected if there is a change in discount rate, as the input data used to derive the costs has not been altered in the scenarios. Therefore, the change in cost is not presented. The NPV and benefit for the scenarios, with a discount rate of 3.5% is presented in Figure 6.7 and Figure 6.8, respectively.

Almost all scenarios present negative values for the NPVs 50th percentile, and for most of the analysed scenarios, Alternative 2 is more profitable than Alternative 1. Furthermore, it is possible to see in Figure 6.8 that scenario 3, which limits the length of which the damage costs are accounted for, has a large effect on the benefit of the alternatives. This is directly correlated to the reduced NPV. Also, the difference between the percentiles is much smaller for this scenario, compared to the ordinary analysis, indicating a more stable and less uncertain NPV. The complete results from the scenario analysis can be seen in Appendix B.



Figure 6.7: NPV for all scenarios. Time horizon 50 years, with 3.5% discount rate



(b) Alternative 2, benefit

**Figure 6.8:** Benefit for all scenarios. Time horizon 50 years, with 3.5% discount rate.

In addition to the scenarios, benefits and NPVs, presented in the figures above, the probability of positive NPV has also been estimated, see Figure 6.9. There is a large difference in the probability of positive outcome when comparing the ordinary analysis with the scenarios. Also, alternative 2 presents a higher probability of a positive outcome than alternative 1 for all scenarios.



Figure 6.9: Probability of positive outcome for the scenarios NPV. Time horizon 50 years, with 3.5% discount rate.

The figure above displays, as previously described, the probability of positive outcome. However, it does not present any value for scenario 3a and 3b, as they have zero probability of presenting a positive outcome. Therefore, it is of interest to see how the NPV for Alternatives 1 and 2 varies with respect to the duration, Scenario 3a-f (Figure 6.10). From the figure it is possible to derive that scenario 3a-3c presents a larger NPV (50th percentile) for Alternative 1 in comparison to Alternative 2. This means that if damage costs for events are limited to a maximum of 21 days, Alternative 1 presents a higher NPV (50th percentile) than Alternative 2. From the figure, it is also possible to see that if damage costs are accounted for a maximum of around 4 weeks, Alternative 2 presents a positive NPV, while it is between 5-6 weeks to achieve a positive NPV for Alternative 1.



Figure 6.10: Alternative 1 and 2's NPV (50th percentile) for scenarios 3a-3f. Time horizon 50 years, with 3.5% discount rate.

Another interesting comparison between the alternatives is the probability of each alternative being the one with the largest NPV for each scenario respectively (Figure 6.11). It is more probable that Alternative 2 results in a higher NPV, in comparison with Alternative 1, for the ordinary analysis and 5 out of the 8 analysed scenarios. This is a strong indication that Alternative 2 is a better option than Alternative 1, from a societal point of view.



Figure 6.11: Probability of alternatives having highest NPV for each scenario respectively. Time horizon 50 years, with 3.5% discount rate.

# 7

# Discussion

To evaluate the results of this study, it is important to emphasize what has already been stated in the report (see Section 2.6); A CBA can be considered as a decision analyzing tool which can be used as decision support. It describes the advantages and disadvantages of the alternatives, b and the contribution of a CBA should be seen as one important part, but not the only, of the decision basis

# 7.1 The case study

The generated NPV (50th percentile) for Alternative 1 and 2 in the baseline scenario were both positive, indicating that adding redundancy to the neighboring municipalities could be societal beneficial. However, the sensitivity analysis and the scenario analysis indicate that further studies are required to reduce the uncertainties in the results. Also, since two events had a large impact on the results (Critical events 1 and 2), it could also be worth considering other risk-reducing alternatives that would mitigate the probabilities and consequences for these events.

#### Damage costs

The damage costs estimations presented a wide range between the municipalities, from 297 to 605 SEK/person/day for short interruptions and 208 to 533 SEK/person/day for long interruptions. It can be discussed whether it is reasonable for one municipality to have more than twice the damage cost per person, compared to another one. However, it is important to point out that Sotenäs (which had the highest damage cost per person) have more water-dependent industries (seafood industries) that faced a large loss of production, than for example Uddevalla. Even though the damage costs per person are different between the municipalities, they are all within same the range as reported from previous studies (see Section 3.2), indicating credibility of this study's result. However, the focus of the previous studies has been on interruptions that only last for a few days. Therefore, due to the lack of basis from large-scale and long-lasting interruptions in Sweden (or other similar countries), it is hard to estimate whether the total damage costs in this study are large or small. It is also difficult to reason on how damage costs for different societal functions vary over time. For example, restaurants and water-dependent industries are affected during the entire interruption, but the question is to what degree.

For the damage cost estimations for large industries/businesses (loss in production), information regarding their resilience to interruptions in the water supply are required. This information could be retrieved from the industries/businesses, as it can be hard to estimate. However, it is not certain that industries/businesses have any awareness regarding this issue, resulting in uncertain assumptions. Also, the variation of damage costs over time is an unknown variable, as e.g. businesses operation capacity, or human behavior, after one or two weeks of water supply shortage will look different. As mentioned in Section 5.2.1, interviews were conducted with representatives from several of the largest industries in the municipalities. This was to estimate the businesses resilience to interruptions in the water supply, and the costs in case of such an event.

The literature review in this thesis and conducted telephone interviews for the case study revealed a low preparedness in the society regarding water supply interruptions, e.g. no backup plans for businesses or industries. However, the interviews were somewhat brief and the representatives were not prepared for the questions, which means that the costs used in this report need to be considered as rough estimates. However, more or less all representatives (regardless type of business) said that there was no real backup plan in case of sudden (and long-term) water supply interruption. Supporting the fact that people are not prepared and cannot fully comprehend how the loss of water services could affect them, which could be one reason that causes the large damage costs. For example, looking only at the consequences (duration and damage cost) for an interruption, the cost for Uddevalla is around 50 MSEK after 2 days, and 150 MSEK after 7 days.

Even though the quantified damage costs were large, there are other identified damage costs that have not been quantified in this study. Examples of non-monetized damage costs of relevance for this study are:

- Water quality issues resulting from interruptions in the water supply. E.g. microbial contamination from intrusion in pipes, enabled by a pressure loss that occurs due to pipe breakage. This can result in damage costs such as discomfort, health care costs and loss of production due to waterborne contamination causing sickness.
- Indirect costs, such as loss of future income for hotels and restaurants caused by customer dissatisfaction and so on.
- Discomfort due to being without water. For example, malfunctioning toilets.
- Possible increase in property values due to improved access to drinking water.
- Firefighting services. Firefighting service is affected by a total supply interruption, due to fire hydrants and certain sprinkler systems losing its access to water. If there is a large fire at the same time as an interruption in the water supply, then large consequences could be followed.
- Elderly care. The working load will increase for those that work at the elderly homes, and the care quality could be lowered.
- Small businesses and services (small industries, retail trade etc.) are affected by water supply interruption to some extent.
Adding these non-monetized damage costs to the calculations would increase the NPV. However, for this study no valuation methods to estimate the above-identified damage costs have been performed. The non-monetized costs still fill a function in the decision support as they highlight parts that are affected by an interruption.

#### Probability of supply interruption

In collaboration with Västvatten, four critical events were identified for Uddevalla's DWS that could cause total interruption for the entire municipality. The assessed risks for Uddevalla was assumed to be the same for Lysekil and Sotenäs, based on the recommendation from Västvatten. It was discovered in the sensitivity analysis, that two out of these four events have the largest effect on the uncertainties of the result. However, as a probabilistic approach has been used, it is possible to update the current distributions or add new ones, when new data becomes available. So, the variables that have the largest effect on the uncertainties in the result could be further investigated and updated.

Furthermore, a fault tree was used in this study with the aim of achieving an integrated approach. However, as the risk was calculated separately for each event, were not the aggregated probability for total supply interruption of interest for this case study. This means that the FTA had no impact on the resulting risk. However, it still describes the relations between the identified events, and what sub-system they are related to in the DWS. The fault tree is possible to update if further studies are performed to obtain an improved risk model. This can be done through e.g. performing a similar hazard identification (which was done for Uddevalla) for Sotenäs and Lysekil respectively since it is possible that the risk situations look different between the municipalities.

#### Results from the analysis

For the baseline scenario, the damage cost estimation was assumed to be constant for almost every societal function and group, with a few exceptions. The results presented a high probability for the NPV is positive for both alternatives, with Alternative 2 most likely presenting a higher NPV than Alternative 1 (see Figure 6.3 and Figure 6.11). There was, however, a large difference between the 5th and 95th percentile for the NPV for both alternatives, due to the uncertainties in the benefit estimation (see Figure 6.5).

Through a sensitivity analysis, calculating Spearman rank correlation coefficient's, duration and probability of Critical events 1 and 2 were identified as variables contributing the most to the uncertainties of the result, as previously mentioned. A scenario analysis was performed based on the uncertainty and sensitivity analysis, to obtain an estimation of how Critical events 1 and 2 and a varying damage cost could affect the resulting NPV. By using the model with different scenarios, not only could it be determined that the result of the sensitivity analysis were correct (i.e. that the Critical events 1 and 2 had a large impact on the result), but it also made it possible to see that the variation of the damage costs (scenario 3a-3f) highly affected the NPV. Also, comparing the alternatives, it was presented in Figure 6.11

that Alternative 2 most likely provides a higher NPV than Alternative 1 for most of the scenarios. In Figure 6.9 could it be seen that Alternative 2 also have a higher probability of presenting a positive outcome for all the scenarios, meaning that the ranking of the alternatives does not change with the scenarios. Additionally, investigating a longer time horizon did not affect the outcome. Thus, the sensitivity and uncertainty analysis along with the scenario analysis, provides valuable information as decision support.

Due to the large costs of the alternatives and the uncertainties behind the benefit estimation, affecting the NPV, could it be argued that the resulting NPV is not the main outcome of the case study. Instead, the results from the case study highlight the value of redundancy, due to a large number of damage costs that are accumulated only after a few days of a large-scale interruption. Also, the methodology behind the case study highlights other important aspects that could be considered when evaluating reliable water supply, which is further discussed below.

# 7.2 Risk assessment and CBA as decision tools

To circle back to the overall aim –to assess how a CBA can be combined with risk assessment to evaluate different alternatives for future drinking water systems– it could be concluded that CBA as a method, in combination with risk assessment, could be a useful tool for decision support. The advantages of performing a CBA is that it can be transparent and holistic, which is especially useful for the public sector.

A CBA provides another side to decision support, investigating and highlighting the costs and benefits of reliable drinking water supply from a societal point of view. The analysis includes businesses, societal functions, as well as regular consumers. This could ease the decision making, as people obtain a better understanding of what benefit they receive with different alternatives/measures in the DWS. Furthermore, it also provides a better understanding of how resources can be allocated correctly in the already complex DWS to obtain as much value as possible, facilitating decision making for water producers.

The transparency of a CBA can be seen in this study, as the results are clearly presented in combination with the methodology, its estimations, and assumptions. Also, non-monetized damage costs are also presented, highlighting societal functions that are affected even though they are not included in the cost and benefit estimations. It is therefore easy to see what costs and benefits that are included, its effect on the results and what aspects that can be further evaluated with future studies (e.g. chains-of-events like firefighting costs).

The methodology used to monetize damage costs, as presented in Section 5.2, is based on previous studies and recommendations. It is, however, hard to provide a general estimation of how different societal functions, businesses, and regular consumers are affected by a total supply interruption. For example, as previously mentioned, how damage cost for interruptions varies over time. CBA has previously been performed within the drinking water sector, however mostly related to quality issues (such as contamination) and not about large-scale drinking water interruptions as this study has focused on.

In combination with the damage cost estimation, probabilities and durations were assessed for different events to evaluate the avoided risk of adding redundancy. For this study, a fault tree was established, and as previously mentioned the fault tree is useful due to its flexible nature and transparency. Also, as mentioned earlier this study's fault tree could be considered small but the level of detail is based on the study's aim, and it is possible to further adjust and adapt it.

Another aspect which is important in risk assessment, to assess and estimate future risks and events. For this study, only the current situation and circumstances have been evaluated, meaning that future risks have not been taken into consideration. For the drinking water system, it could be expected that the risk for water supply interruption increases over time, due to climate change (causing landslides, droughts etc.), changed human behavior (such as urbanization), the increased threat of sabotage/terrorism, aging of piping networks etc. Incorporating these risks could improve the model. However, since a FTA is used in this study, it is possible to extend and incorporate additional risks if requested.

Furthermore, the risk assessment procedure in this study was conducted with a probabilistic approach to enable uncertainty analysis. An uncertainty and sensitivity analysis provides valuable information as decision support. By studying uncertainties, more information regarding the effect of the alternatives is obtained. For example, how can the end result vary (e.g. NPV), what uncertainties affect the result the most and so on. By looking at the conducted case study, the sensitivity analysis showed that it could be economically beneficial to evaluate other types of risk-reducing alternatives which would aim at mitigating the effects from Critical events 1 and 2 (which were identified in the uncertainty analysis as the input variables with the largest impact on the uncertainties of the resulting NPV). So, instead of highlighting what alternative that is most profitable from a societal point of view, as presented in the case study, this study provides information on how a new approach can be used to evaluate different water supply alternatives. It is therefore important to look at the entire study, and not only at the numbers presented in the results. CBA is important as a process, as things that otherwise might have been overlooked, must be valued transparently. The results from the process, is at least as important as the end-results.

## 7. Discussion

8

# Conclusions & further research

For the case study, the aim was to use a CBA in order to evaluate the worth of providing redundancy for the neighboring municipalities of Munkedal. The main findings of the case study are:

- The generated NPVs for the alternatives had a high probability of being positive in the baseline scenario, while the scenario analysis generally provided a negative outcome due to uncertainties in the estimated benefits. The analysis proves that Alternative 2 is the best alternative, and multiple scenarios displayed a profitable end-result. Furthermore, when non-monetized benefits were accounted for, the conclusion that Alternative 2 is profitable were strengthened.
- The uncertainty and sensitivity analysis, showed that two events had the largest effect on the uncertainties of the outcome (NPV). This was mainly due to their long duration, which would lead to great societal damage costs (i.e. benefits, in the CBA). The scenario analysis concluded that either removing one of these events or reducing on the duration of damage costs, have a large negative impact on the resulting NPV for both alternatives.
- The results highlight the value of redundancy due to large damage costs that are followed by a complete interruption in the water supply.
- As two events were identified as the most sensitive variables, it could be of interest to consider other types of risk-reducing alternatives that would mitigate the probabilities and consequences for these two events.
- It is important to involve stakeholders and experts in an early stage of the process, through e.g. workshops.
- The literature reviews and conducted interviews revealed a low preparedness in the society (businesses, regular consumers etc.) regarding water supply interruptions. This could be one reason behind the large consequences (i.e. damage costs) that is followed by an interruption. For example, the total damage costs for Uddevalla is around 50 MSEK after only 2 days.

The overall aim of this thesis was to assess how CBA can be used with risk assessment as a decision support to evaluate reliable water supply alternatives. The main findings of this thesis are:

- The cost-benefit analysis provides a systematic and transparent process, which is important for decision-making for public services. It enables comparison between different alternatives and highlights benefits and costs from a societal point of view, facilitating decision-making for water producers.
- A great benefit with CBA is its process and the transparency it results in. Things that might have been overlooked with other analysis, must be valued openly with a CBA, and the results from the process is at least as important as the end-results.
- The performed uncertainty and sensitivity analysis is essential for transparency of the CBA. It highlights the uncertainties in the input data and results, and presents the input variables which have the largest effect on the uncertainties of the results. These variables could be further investigated, to reduce the uncertainties related to them.
- A fault tree analysis is a good tool for probability estimation, as basis for calculating risk cost for a CBA.

Here follow some recommendations for further studies:

- To improve the results of the case study and reduce its uncertainties, it could be of interest to further develop the risk analysis and the fault tree. This can be done by performing a separate risk assessment with Lysekil and Sotenäs, respectively. The uncertainties of the risk analysis could also be reduced through involving additional experts and other stakeholders.
- Since large-scale and long-term supply interruptions are relatively uncommon, the long-term effects of one are unknown. Therefore, a deeper study on how damage costs due to interruptions in the water supply vary over time, could reduce the uncertainties of this study and improve future studies.
- An even more holistic approach could be obtained, through investigating how the non-monetized costs identified in the case study (see Section 7.1) could be quantified and included in a damage-cost estimation.
- The CBA results in an estimation of the NPV, i.e. an aggregation of all benefits and costs. It would be interesting to see how the benefits and costs are divided among the stakeholders, i.e. a distributional analysis. For example, who faces the largest cost, and who receives the most benefit, to further improve the decision support.

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# Cost and benefits

А

Following, input data on costs and benefits used in the CBA is presented.

# A.1 Costs

The investment and operational costs are dependent on current population/water demand, future population/water demand and predicted pipe length. Therefore, this data is presented first and thereafter information on investment and operational costs.

#### Data for investment and operational costs

Table A.1: Water usage

Current water usage		
Water usage for average person $[m^3/person/day]^*$	0.277	
Degree of connected users	90%	
Note: *) Average water usage per person, including regular consumers consumption, industrial		
usage, and water loss in distribution and treatment. (SWWA, $2017c$ )		

	Population [people]			
Year \Municipality	Munkedal	Sotenäs	Lysekil	Uddevalla
$2017^{*}$	10361	9085	14464	55164
2067**	13296	11658	18561	70788
Note: *) scb.se kommunitatistik (statistics for the municipalities)				
**) SCB projects approximatively $0.6\%$ yearly population increase. A $0.5\%$ yearly				
increase is used for thes	e municipalities			

Table A.2: Predicted population/water demand increa	ıse
---	-----

	Water demand $[m^3/day]$					
Year \Municipality	Munkedal*	Sotenäs**	Lysekil***	Uddevalla*		
2017	1600	4500-8000	4700	12000		
2067****	2332 6016 5721 15895					
Note: *) Personal communication, David Andersson, Västvatten (2017)						
**) Personal communication, Anders Klasson, Västvatten (2017).						
$4500 \text{ m}^3/\text{day}$ winter consumption, $8000 \text{ m}^3/\text{day}$ summer consumption.						
***) According to levaily sekil.se						
****) Calculated based on population increase and Table A.1						

**Table A.3:** Estimated pipe length from potential DWTP at lake Kärnsjön to the municipalities of Sotenäs, Lysekil and Uddevalla

	Pipe length [km]*	Pipe length 120% [km]**	
Connecting to municipality/			
Connection point			
Sotenäs/Ödby	23.5	28.2	
Lysekil/Brasta	17.5	21	
Uddevalla/Torp	19.2	23.04	
Note *) Estimated with google earth, shortest distance approximation			
**) Add 20% of shortest pipe length due to uncertainties, according.			

#### Investment cost

The investment costs cover the cost of a newly constructed water treatment plant along with the costs of new piping. The costs depend on the capacity of the plant, and whether it is a surface water treatment plant or an artificial infiltration plant. Following, in Table A.4 are the investment costs presented.

#### Table A.4: Investment cost

Post	Cost per unit	Unit	
DWTP	1.0-1.5*	[MSEK/(l/s)]	
Pipes	3000-5000**	[SEK/m]	
*) Karin Sjöstrand, Västvatten (2017). Uniform distribution U(min,max)			
**) David Andersson, Västvatten (2017), uniform distribution U(min,max)			

#### **Operational** cost

The operational costs are based on the type of treatment plant, capacity of the plant and lengths of the eventual pipes related to the alternative, see Table A.5.

Table A.5:	Operational cost
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Post	Cost per unit	Unit	
DWTP	207-238*	[SEK/person/year]	
Pipes	14-28.7**	[SEK/meter/year]	
Note: *) SWWA (2017 $c$ ) provides an average operational cost of 207 SEK/person/year			
for DWTP in Sweden. This has been used in combination with an added extra $15\%$ for			
uncertainties, and calculated as a uniform distribution U(min, max)			
**) Based on VASSdata (SWWA database), uniform distribution used U(min,max)			

### Other costs

Other costs, such as handling of chemicals in the WTP, cost of environmental impacts etc are not included in the CBA.

# A.2 Benefits

Following, are the avoided damage costs (benefits) presented.

# **Regular consumers**

Table A.6:	Estimating	damage	cost for	regular	consumers
	0	0		0	

Cost of free time lost				
Value of free time $(2014)^*$	63	SEK/person/hour		
Value of free time	63.8	SEK /person /hour		
$(2017 \text{ prices})^{**}$	05.0	SER/person/nour		
Free time lost per household***	1-2	SEK/household/hour		
Total cost estimate of free time lost (P50)	150 5	SEK /household /day		
per household per day	109.0	SER/ nousenoid/ day		
Number of people per household**	2.2	persons/household		
Total cost estimate of free time lost (P50) 72.5 SEK/person/day				
Note: *) From ASEK 6.0 (Trafikverket, 2016) valuation of saved traveling time, traveling				
shorter than 100 km using a car for other purposes than work				
**) scb.se ***) Uniform distribution (min,max), estimation by authors				

Cost of buying bottled water for drinking purposes		
Average water price (bottled water) $*$	10	SEK/liter
Water bought for drinking purposes <sup>**</sup>	1.5-3	liters/person/day
Cost of buying bottled water (P50)	35	SEK/person/day
	c 1.	•1 •• ( • )

Note: \*) svenskvatten.se \*\*) Represented with Uniform distribution (min,max), assuming consumers buying 1-2 bottles of water (1.5 liters each) based on Gleick (1996) recommending 2-5 liters of water for drinking purposes.

Total cost for regular	consumers (P50)
108	SEK/person/day

# Loss of production

### Grocery stores

 Table A.7: Damage cost for grocery stores

Cost for grocery					
stores					
	Lysekil	Sotenäs	Uddevalla		
Number of grocery stores	6 7 30				
Cost per grocery store [SEK/day]* 100% of Tyréns estimation	52980				
Cost per grocery store [SEK/day]* 80% of Tyréns estimation	42384				
Cost per grocery store $[SEK/day]^{**}$		42384-529	80		
Cost for grocery stores (P50) [SEK/person/day]	20 37 26				
Note: *) Information regarding cost from Törneke and Engman (2009).					
Used scb.se function Prisomräknaren to convert to 2017 prices					
**) Uniform distribution (min, max)					

#### Restaurants

Restaurants and their daily turnover have been retrieved from various sites, allabolag.se, eniro.se, hitta.se.

 Table A.8: Damage costs for restaurants based on turnover

Restaurant cost					
	Lysekil*	Sotenäs*	Uddevalla <sup>**</sup>		
Number of restaurants	20	29	50		
Daily turnover					
[SEK/day]	9992-19592	9992-19592	8220, 24658, 43836		
Estimated $cost(P50)$	20	47	99		
[SEK/person/day]	20	41	20		
*) Uniform distribution (mi	n, max) $^{**}$ ) Tria	angular distribu	tion (min, most likely, max).		

## Large water-dependent industries

Large industries within the municipalities				
Municipality	Company	Yearly turnover [MSEK]		
Lysekil	Mechanical component factory	200		
Sotenäs	Seafood factory	770		
Sotenäs	Seafood factory	200		
Lysekil	Seafood factory	590		
Sotenäs	Seafood factory	354		
Uddevalla	Concrete factory	575		

Table A.9: Identified large water-dependent industries within the municipalities

Table A.10: Damage cost for large water-dependent industries based on turnover

Cost for large water-dependent industries [SEK/person/day]						
	Lysekil	Sotenäs	Uddevalla			
Cost if 100% turnover lost	149.6	399.3	22.8			
Cost if 80% turnover lost	119.7	319.4	18.3			
Estimated cost*	119.7-149.6	319.4-399.3	18.3-22.8			
Estimated cost (P50)         135         359         21						
*) Uniform distribution (min, max) based on 80% and 100% turnover lost						

### Schools (VAB)

 Table A.11: Amount of children in kindergarten and elementary school

Amount of children in:*	Lysekil	Sotenäs	Uddevalla		
Kindergarten	573	284	2740		
Elementary school (F-6) 1 000 537 4200					
Note: *) Municipality websites and scb.se					

 Table A.12: Input data for damage cost estimation for schools

Average number of children per family*	1, 1.85, 3***	children/family			
Median salary <sup>*</sup>	296 000	SEK/person/year			
Number of working days <sup>**</sup>	260	days			
Median salary	1138	SEK/person/day			
Note: *) scb.se **) forsakringskassan.se					
***) Triangular distribution (min, most likely max)					

	Lysekil	Sotenäs	Uddevalla	
Number of children in	1573	821	6940	
elementary school/kindergarten	1010	021	0340	
Number of parents staying home	807	491	3550	
due to VAB $(P50)^*$	001	421	0009	
Damage cost due to VAB [SEK/day]	918359	479321	4051755	
Damage cost due to VAB				
[SEK/person/day]	63	53	73	
Note: *) Based on the average number of children per family, scb.se				

# Table A.13: Damage costs for schools (VAB)

## Health care

 Table A.14: Number of health and dental care center

Number of centers in the municipalities <sup>*</sup>					
	Health care		Dental care		
		Public	Private		
Lysekil	2	1	2		
Sotenäs	1	1	1		
Uddevalla	5	2 3			
Note: *) Information retrieved from the municipalities website,					
Närhälsan (H	lealth care) and	private de	ntal care centers website		

Table A.15: Cost information for health and dental care

Cost information* [SEK/day]						
Public dental care center	$\operatorname{Cost}^*$	$\operatorname{Cost}$ (80%)				
Small municipality	110834	88667				
Large municipality	287152	229721				
Private dental care center	42384	33907				
Health care center	190728	152582				
Note: *) Information regarding cost for centers from Törneke and Engman (2009).						
Used scb.se function Prisomräknaren	n to conver	t to 2017 prices.				

Damage cost for health and dental care centers						
	Lysekil Sotenäs Uddevalla					
Damage cost dental care center	10	15	11			
(P50) [SEK/person/day]	12	10	11			
Damage cost health care center	r 24 10 16					
(P50) [SEK/person/day]	24	19	10			
Note: *) Obtained with uniform distribution (min, max).						
Min is 80% of Törneke and Engman (2	$2009), \max is$	s 100%.				

Table A.IU. Damage cost for meaning and deman care center	Table A.16:	Damage	cost for	health	and	dental	care	centers
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The damage costs for hospitals (Table A.17) are divided in to two estimations, damage cost estimation (1) and damage cost estimation (2). Both use different input data to estimate the daily turnover for Uddevalla hospital, as no exact number for this have been found. Both estimations are then used together as a minimum and maximum value for the daily turnover of Uddevalla hospital.

Table A.17:	Damage	cost for	hospital
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Damage cost estimation (1) for hospitals												
Yearly turnover for NU-hospital care*	4700	MSEK/year										
Daily turnover for NU-hospital care	13	MSEK/day										
Turnover large emergency hospital <sup>**</sup>	9	MSEK/day										
Turnover health care centers <sup>**</sup>	90 000	SEK/day										
Estimated daily turnover for Uddevalla***	2.08	MSEK/day										
Note: *) From nusjukvarden.se (2017). NU-hospital care consists of;												
emergency hospital (NÄL), 20 health care centers and Uddevalla hospital.												
**) Törneke and Engman (2009) cost estimation.	**) Törneke and Engman (2009) cost estimation.											
***) Daily turnover Uddevalla hospital estimated as NU hospital care turnover,												
subtracted by Törneke and Engman $(2009)$ estimation for a emergency hospital												
and health care centers $(x20)$ .												
Damage cost estimation (2) for hospitals												
Yearly turnover for NU-hospital care *	4700	MSEK/year										
Daily turnover for NU-hospital care	13	MSEK/day										
Number of employees NU-hospital care *	5500	people										
Number of employees Uddevalla hospital **	1600	people										
Estimated daily turnover, Uddevalla hospital ***	3.75	MSEK/day										
Note: *) nusjukvarden.se **) Uddevalla kommun (2015)												
***) The ratio of the employees from Uddevalla hospital ar	nd the whole I	NU-hospital										
care is used to estimate the turnover for Uddevalla												
Damage cost estimation for Uddevalla hospital												
Daily turnover for Uddevalla hospital <sup>*</sup>	2.08-3.75	MSEK/day										
Damage cost for Uddevalla hospital (P50)	53	SEK/person/day										
Note:*) Uniform distribution (min, max) based on damage cost estimation (1) & (2)												

# Water producers

Water utility company cost										
Daily cost Uddevalla*         50 000, 150 000, 200 000**         SEK/day										
Population Uddevalla 55 164 people										
Damage cost Uddevalla (P50)*** 2 SEK/person/d										
Note: *) Rough estimation of min and m	Note: *) Rough estimation of min and max cost by water producers.									
**) Triangular distribution (min, most likely, max).										
***) Assuming same cost per person per day for Sotenäs and Lysekil.										

 Table A.18: Damage cost for water producers

# A.3 Input to fault tree analysis

**Table A.19:** Hazardous events and probabilities for Uddevalla (estimations of events and probabilities provided by Västvatten).

Event*	Part of DWS	How many af-	Duration	Recurrence						
	affected	fected?	of inter-	$\operatorname{time}/\operatorname{Prob}$ -						
			ruption							
Event 1	Raw water	Entire Uddevalla	1-5 months	25-50 years						
Event 2	DWTP	Entire Uddevalla	1-6 months	50-100 years						
Event 3	Distribution	Entire Uddevalla	3-7 days	0.04						
Event 4	Distribution	Entire Uddevalla	3-7 days	25-50 years						
Note: *) Due to the sensitive nature of this information, the description of these events										
are not presented in this report										

# В

# Scenario analysis

For the scenario analysis that was performed in this study, different scenarios where produced in order to evaluate the model and different parameters based on the sensitivity and uncertainty analysis. The complete results from the scenario analysis are presented in Table B.1 and in Table B.2 as NPV and benefit respectively.

-																			
	P95	678, 63	1734,89	138, 23	458,86	438, 43	1179,58	I	ı	ı	ı	ı	ı	ı	I	ı	ı	ı	I
5%	P50	111,18	407,03	-131,03	-162,52	-91,13	-65,42	ı	1	ı	ı	ı	ı	ı	I	ı	ı	ı	I
	P05	-130,7	-133,66	-264.5	-441,65	-261,56	-437,26	ı	1	ı	1	ı	ı	ı	ı	1	ı	1	I
	P95	925, 29	2350,97	255,77	739,2	628, 61	1 587,48	-170,3	-286,81	-103,58	-122,95	-32,23	47,28	37,8	217,5	102, 12	374,77	178	537,98
3.5%	P50	224,38	678, 89	-88,07	-60,53	-33,73	71,64	-239,84	-405,68	-179,14	-262,85	-120,52	-129,44	-66,3	-2,4	-18,7	111,62	27,05	219,53
	P05	-76,29	-4,29	-244,73	-390,68	-244,18	-400,67	-312,47	-528,36	-259,47	-403,92	-210,05	-298,32	-171,4	-222,4	-145,85	-164,67	-129,73	-138,4
	P95	1706, 72	4131,37	613, 11	1  577, 32	$1 \ 183,03$	$2 \ 914,79$	I	ı	ı	ı	I	ı	ı	I	ı	ı	ı	I
1%	P50	570,2	1490, 49	47,6	261,55	135,44	475,24	I	ı	ı	ı	I	ı	I	I	ı	ı	ı	I
	P05	72,35	352,17	-197,97	-288,13	-195,35	-289,37	I	ı	ı	ı	I	ı	ı	I	ı	ı	ı	I
ate	le	Alt 1	Alt 2	Alt 1	Alt 2	Alt 1	Alt 2	Alt 1	Alt 2	Alt 1	Alt 2	Alt 1	Alt 2	Alt 1	Alt 2	Alt 1	Alt 2	Alt 1	Alt 2
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	P95	1000,97	2345,95	450,62	1061,4	765,43	1791, 31	ı		ı	1	ı	1	ı	ı	1	1	1	ı	
5%	P50	432,6	1020, 49	189,61	446,67	231,63	546,97	I	ı	I	ı	I	ı	I	I	I	I	ı	I	
	P05	207,4	490,87	84,74	202, 12	83,55	197,45	ı	1	ı	1	ı	ı	ı	ı	1	ı	1		
	P95	1275,93	2966,88	583, 19	1360,53	958,68	$2\ 226,04$	116,808	283,53	194, 21	464, 61	271,41	645,98	345,84	819,95	421,11	996,94	491, 39	1154.84	
3.5%	P50	557,02	1310,6	243,92	574,01	296,4	697, 13	93,217	226,38	154.5	369, 24	213,18	505,17	268,08	634,55	317,71	747,3	362,93	855.08	
	P05	270,26	637,74	109,11	259,95	105,6	255,13	73,359	178,36	119,98	286,64	158,06	375,52	185,01	439,3	207,5	487,33	217,38	513.13	
	P95	2071,44	4854, 48	975,43	2295,3	1546, 34	3633,4	1	1	ı	1	ı	ı	ı	ı	1	1	1	ı	
1%	P50	934,47	2197,18	409,15	965,16	495,18	1170,47	1	1	ı	ı	ı	ı	ı	ı	1	ı	1	ı	
	P05	450,81	1073, 43	183,53	432,89	179,3	430, 37	ı	1	ı	ı	ı	ı	ı	ı	1	ı	ı	ı	
rate	е	Alt 1	Alt 2	Alt 1	Alt 2	Alt 1	Alt 2	Alt 1	Alt 2	Alt 1	Alt 2	Alt 1	Alt 2	Alt 1	Alt 2	Alt 1	Alt 2	Alt 1	Alt 2	
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