THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Decision support for sustainable water security

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ABSTRACT

Society's large dependence on water, in combination with climate, socio-economic and demographic changes, places a massive pressure on our freshwater resources. As a result, water crisis, defined as a significant decline in the available quality and quantity of freshwater, is now considered to be among the most critical global risks to society. The overall aim of this thesis is to increase the understanding of how decision support methods based on risk, cost-benefit and multi-criteria decision analyses can be used to facilitate our collective action towards water security. In the thesis, a sustainability assessment model is presented which can rank alternative drinking water options from the most preferred to the least preferred within each of the social, environmental and economic sustainability domains and with regards to all domains. The thesis further presents a marginal abatement cost curve to provide a common starting point for cross-sectoral dialogue on water scarcity mitigation. It enables a comparison of the cost-effectiveness of alternative mitigation measures, providing guidance for businesses, households, farmers and water utilities. Furthermore, a scenario-based risk assessment approach is presented to enable a comprehensive view on risk when evaluating water supply systems and risk reduction options. The approach allows for thorough analyses of economic losses under a range of water supply disruption scenarios, facilitating prioritizations on measures that aim to reduce the overall risk rather than individual risks. The provided methods are all exemplified in Swedish case studies, demonstrating different ways of evaluating and comparing management responses to the water-related challenges we face. In conclusion, the methods can help us strengthen the ongoing discussions regarding challenges and opportunities while providing structure and transparency to decision-making, and by that contribute to an enhanced water security.

Keywords: water security, sustainability, drinking water supply, water scarcity, water availability, decision support, multi-criteria decision analysis, cost-benefit analysis, risk assessment, marginal abatement cost curves

Parts of the material in this thesis have previously been published in the licentiate thesis written by the author: Sjöstrand, K. (2018). *Decision Support Model for a Sustainable Regional Water Supply,* Licentiate Thesis, Chalmers University of Technology.

LIST OF PAPERS

This thesis is based on the work contained in the following papers, referred to in the text by Roman numerals:

I. **Sjöstrand, K**., Lindhe, A., Söderqvist, T., Rosén, L. (2019). Cost-benefit analysis for supporting inter-municipal decisions on drinking water supply. *Journal of Water Resources Planning and Management*, 145(12), 1-12.

II. **Sjöstrand, K**., Lindhe, A., Söderqvist, T., Rosén, L. (2018). Sustainability assessments of regional water supply interventions — Combining cost-benefit and multi-criteria decision analyses. *Journal of Environmental Management*, 225, 313-324.

III. **Sjöstrand, K**., Lindhe, A., Söderqvist, T., Dahlqvist, P., Rosén, L. (2019). Marginal Abatement Cost Curves for Water Scarcity Mitigation under Uncertainty. *Water Resources Management*, 33(12), 4335-4349.

IV. **Sjöstrand, K**., Lindhe, A., Söderqvist, T., Rosén, L. (2020). Water Supply Delivery Failures—A Scenario-Based Approach to Assess Economic Losses and Risk Reduction Options. *Water,* 12(6), 1746.

V. **Sjöstrand, K**., Klingberg, J., Sedehi Zadeh, N., Haraldsson, M., Rosén, L., Lindhe, A. (2020). The value of water – estimating water-disruption impacts on businesses. *Submitted manuscript*.

Division of work between the authors

In Paper I, all authors formulated the decision problem and defined the aim and objectives of the study. Sjöstrand structured the cost-benefit model, gathered and analyzed the input data, performed all simulations and was the main author of the paper.

In Paper II, Sjöstrand, Rosén and Lindhe defined the aim and objectives of the study, designed application scenarios and developed the model. Söderqvist contributed with expert knowledge regarding cost-benefit and multi-criteria decision analyses. Sjöstrand gathered all data, performed all calculations and was the main author of the paper.

In Paper III, Sjöstrand formulated the decision problem and defined the aim and objectives of the study. Söderqvist suggested the study design. Sjöstrand gathered all data, performed all calculations and was the main author of the paper.

In Paper IV, Lindhe, Rosén and Sjöstrand formulated the decision problem. Sjöstrand gathered all data, performed all calculations and was the main author of the paper.

In Paper V, Sjöstrand formulated the decision problem and defined the aim and objectives of the study. Sjöstrand, Klingberg and Sedehi Zadeh gathered and analyzed the data. Sjöstrand was the main author of the paper.

Publications not appended

In addition to the work presented in this thesis the author has published or contributed significantly to the following publications, which are not appended to the thesis:

- **Sjöstrand, K**., Lindhe, A., Söderqvist, T., Dahlqvist, P., Rosén, L. (2019). *Water demand management – challenges and possibilities*, RISE Report 2019:79, (In Swedish: *När vattentillgången brister*).
- Dahlqvist, P., **Sjöstrand, K**., Lindhe, A., Rosén, L., Nisell, J., Hellstrand, E., Holgersson, B. (2019). Potential Benefits of Managed Aquifer Recharge MAR on the Island of Gotland, Sweden. In *Proceedings of the 10th International Symposium on Managed Aquifer Recharge,* Madrid, May 20-24, pp. 580-582.
- Dahlqvist, P., **Sjöstrand, K**., Lindhe, A., Rosén, L., Nisell, J., Hellstrand, E., Holgersson, B. (2019). Potential Benefits of Managed Aquifer Recharge MAR on the Island of Gotland, Sweden. *Water, 11*(10), 2164. doi:10.3390/w11102164
- **Sjöstrand, K**. (2018). *Decision Support Model for a Sustainable Regional Water Supply,* Licentiate Thesis, Chalmers University of Technology.
- **Sjöstrand, K**., Lindhe, A., Söderqvist, T., Rosén, L. (2018). *Input data report for economic assessments of water supply interventions in the Göteborg region.* Chalmers University of Technology
- **Sjöstrand, K.** (2017). *Sustainability and Water Supply Governance — A Literature Review on Regional Water Governance, Multi-Criteria Decision Analysis, Cost-Benefit Analysis and Sustainability Assessments*. Chalmers University of Technology.
- **Sjöstrand, K**., Rosén, L., Kärrman, E., Blom, L., Ivarsson, M., Lång, L.-O-, Friberg, J., Lindhe, A. (2017). *Holistic decision support model to ensure a sustainable regional water supply.* Abstract presented at the Swedish Water and Wastewater Conference Research and Innovation for Safe Drinking Water (Forskning och Innovation för Säkert Dricksvatten), Stockholm, Nov 28-29.

- **Sjöstrand, K**., Rosén, L., Kärrman, E., Blom, L., Ivarsson, M., Lång, L-O., Lindhe, A. (2017). *Water supply decision-making for a sound prioritization of society's limited resources.* Abstract presented at the Fifth Annual International Conference on Sustainable Development (ICSD), New York City, Sept 19-20.
- **Sjöstrand, K**., Rosén, L., Kärrman, E., Blom, L., Ivarsson, M., Lång, L-O., Lindhe, A. (2017). *Sustainability Assessment of Water Supply Plans Using Cost Benefit Analysis and Multi Criteria Analysis.* Abstract presented at the 2017 Sustainable Water Management Conference, New Orleans, March 19-22.
- Söderqvist, T., Lindhe, A., Rosén L., **Sjöstrand, K.**, Bergion, V. Soutukorva, Å. (2016). *Dricksvattenutredningens preliminära förslag till åtgärder för trygg och säker dricksvattenförsörjning: Vilka är de samhällsekonomiska nyttorna och vad behövs för att dessa ska bli verklighet?* Chalmers University of Technology, Report 2016:13.
- **Sjöstrand, K**., Rosén, L., Kärrman, E., Blom, L., Lindkvist, J., Ivarsson, M., Lång, L-O., Lindhe, A. (2016). *Combining cost benefit analysis with multi criteria analysis for sustainability assessment of regional water supply policies.* Abstract presented at the Society for Risk Analysis Annual Meeting, San Diego, Dec 11-15.
- **Sjöstrand, K**., Rosén, L., Kärrman, E., Blom, L., Lindkvist, J., Ivarsson, M., Lång, L-O., Lindhe, A. (2016). *Decision support for assessing the socio-economic value of a regionalized water supply.* Abstract presented at the 2016 AWRA Annual Water Resources Conference, Orlando, Nov 13-17.
- **Sjöstrand, K**., Rosén, L., Kärrman, E., Blom, L., Widerberg, A., Lindkvist, J., Lång, L-O., Lindhe, A. (2016). *Decision-support for a sustainable regional water supply management.* Abstract presented at the 10th Nordic Drinking Water Conference, Reykjavik, Sept 28-30.

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Atlantic Highlands, September 2020
Karin Sjöstrand

TABLE OF CONTENTS

1 INTRODUCTION

The first chapter provides the background to the thesis. The aim and objectives are presented and the scope of the work is specified. Important limitations of the thesis are also presented.

1.1 Background

We must treat water as if it were the most precious thing in the world, the most valuable natural resource.

– Mikhail Gorbachev (2001)

Water is the indispensable natural resource on which nearly all social and economic activities depend (WWAP, 2015). The access to a safe and reliable drinking water sets the framework for economic development, human health and social well-being. Further, water is an essential input in the production of most goods and services, and about 78% of the global workforce is working in either heavily water-dependent or moderately water-dependent jobs (WWAP, 2016). However, society's large dependence on water places a massive pressure on our freshwater resources. Over the last 100 years, the global freshwater withdrawal has increased by a factor of seven (Aquastat, 2015), and the demand is expected to continue to increase with 20–30% to the year 2050 (Burek et al., 2016). According to the World Economic Forum's Global Risk Report (WEF, 2019), *water crisis*, defined as *a significant decline in the available quality and quantity of freshwater*, is now considered to be among the most critical global risks to society with short and long-term effects on citizens, ecosystem services, biodiversity and the economic sectors that depend on a reliable water access. In Europe, at least 11% of the EU population and 17% of its territory had experienced water scarcity by 2007, and the number of areas and people affected by droughts went up by almost 20% between 1975 and 2006 resulting in total costs of 100 billion euro (EC, 2012b). It is expected that both the probability of water scarcity and its societal consequences will increase as a result of increased water demand and hydro-climatic changes (Schlosser et al., 2014; Veldkamp et al., 2016). Unless there is a substantial progress in improving water resource efficiency, it is likely that the world will face a 40% water deficit by 2030 (EU, 2013).

However, despite the substantial challenge of balancing variable and uncertain water supplies with changing and uncertain demands, it is not the only concern for water managers. Today's water managers, in Sweden as well as in other countries, have to deal with an increasing number of complex challenges and future unknowns, and they are faced with difficult decisions on resource allocation and prioritizations of risk-reduction measures. Their responsibilities include managing challenges and uncertainties related to e.g. ageing infrastructure; urbanization; altered land and water use; chemical and microbiological health hazards; as well as other climate, socio-economic and demographic changes (Jiménez Cisneros et al., 2014; Palaniappan et al., 2007; Rygaard et al., 2014). In addition, several local water management institutions are suffering from limited financial and personnel resources, significantly reducing their ability to handle the challenges accordingly (SOU 2016:32). Furthermore, the development of mitigation actions are often constrained by data scarcity and inadequate decision support (WWAP, 2015).

UN-Water (2013) has defined water security as *the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability*. To achieve water security and deal with the uncertainties and the societal and environmental consequences that the above-mentioned threats entail, we must change the way we assess, manage and use our water resources (UNESCO, 2019; WWAP, 2015). Among other things, we need to integrate risk-based approaches into water management and combine estimated risks and uncertainties regarding water security with information on social, environmental and socio-economic consequences to better inform and support water management decisions (Döll et al., 2014; Lindhe et al., 2009; Veldkamp et al., 2016; WWAP, 2012). By improving the understanding and awareness of socio-economic costs and other negative consequences associated with the threats, the decision-makers can address the problems from a more informed position. Estimating the effects can in itself be a challenging task, but it is necessary to help determine the value of investing in water improvements. Significant social, economic and environmental gains can be obtained by investing in improved technologies and management systems for water provision, productivity and efficiency, and the costs of investment should be weighed against these gains (Livernois, 2001).

The responsibility of water management is shared between many different actors and institutions in the public and private sectors. This has resulted in diverse and fractioned sectoral water management practices when dealing with the various resource, use and service-related issues. To address the water challenges, water management must shift towards more collaborative and participatory decision-making processes and responses. Engaging the broad range of societal actors in cross sectoral decision-making can facilitate the development of more creative solutions, give new perspectives on decision-problems, and simplify the gathering of additional information. It can also facilitate compromises and trade-offs between competing water users and other stakeholder groups as well as increase the legitimacy and transparency of water governance (Mysiak et al., 2010; WWAP, 2015).

1.2 Aim and objectives

The overall aim of this thesis is

> *to increase the understanding of how decision support methods and tools based on risk, cost-benefit and multi-criteria decision analyses can be used to enhance water security through sustainable water management.*

The aim is hence to facilitate our collective action towards water security (i.e. to safeguard sustainable access to adequate quantities of acceptable quality water) by helping decision-makers, across societal sectors, identify efficient and sustainable water management choices when facing complex and uncertain decision situations. This is done by strengthening the link between risk analysis and decision analysis and by increasing the visibility of economic, social and environmental aspects, along with their associated uncertainties, to provide experts, stakeholders and decision-makers with a composite perspective on decision alternatives. Thus, the approach is to use decision analysis for structuring the evaluation and comparison of different decision alternatives so that effects from these alternatives can be openly shown and addressed, thereby increasing the potential for well-founded and viable decisions. To meet the overall aim, the thesis has the following specific objectives:

- Develop a generic sustainability assessment model for water supply decision-making that incorporates uncertainties and that enables to combine monetized costs and benefits with effects in the social and environmental sustainability domains.
- Develop a cross-sectoral decision support tool for water scarcity mitigation that can compare the cost-effectiveness and water availability potential of both water demand and supply measures, while taking the underlying uncertainties into account.
- Provide a structured and transparent approach of identifying, quantifying and evaluating risks of water supply disruption, that enables estimation of welfare losses under various levels of disruption events as well as comparisons of potential risk-reduction measures.
- Provide exemplifications and background data to facilitate estimations of the economic value of water for various sectors in society.

- Develop the methods and tools using a probabilistic approach to enable uncertainty and sensitivity analyses of input data and results.
- The methods and tools developed should include approaches to formally involve relevant stakeholder groups in decision-making on water management, and these approaches should be exemplified in the case studies.

1.3 Scope of the work

The scope of the thesis is to describe decision support methods and tools that can assist public and private decision-makers in their effort to deal with water challenges in an efficient and sustainable way. The theoretical background of the methods is described and case studies are used to exemplify their practical applications. The work is presented in the following five papers appended to the thesis:

Paper I: Cost-benefit analysis for supporting inter-municipal decisions on drinking water supply

Paper II: Sustainability assessments of regional water supply interventions – combining cost-benefit and multi-criteria decision analyses

Paper III: Marginal abatement cost curves for water scarcity mitigation under uncertainty

Paper IV: Water supply delivery failures – a scenario-based approach to assess economic losses and risk reduction options

Paper V: The value of water – estimating water-disruption impacts on businesses

Figure 1.1 shows a schematic illustration of the research focus in the different papers, as well as the methods used and the main target groups. All papers provide decision support or background data for water utilities, while Papers III and IV also focus on industry and agriculture.

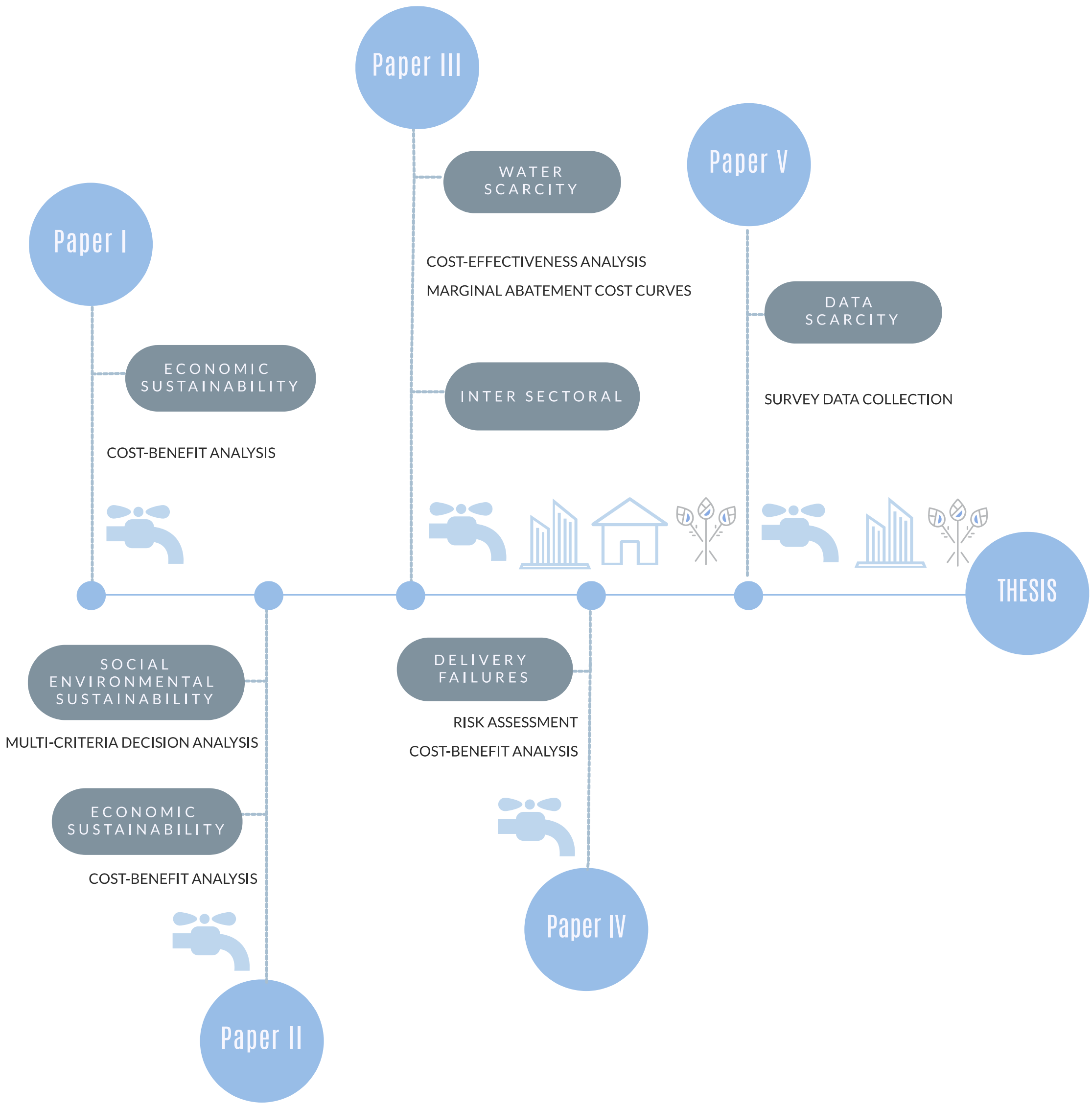

Figure 1.1 *Schematic illustration of the research focus in the different papers (dark grey boxes) along with methods used (plain text) and main target groups (icons illustrating water utility, industry, household and agriculture).*

1.4 Limitations

The decision-making process consists of many different steps. This thesis focuses on methods, tools and estimates of background data, to facilitate the prioritization between alternative options. The thesis does not, however, focus on the creation of alternatives or on their implementation.

Developed methods and tools are exemplified by application solely in Swedish case studies, even though the decision support methods are general and thus applicable also in other countries with different prerequisites. Further, the focus in the thesis is on the practical application of the methods rather than their theoretical foundations.

2 THEORETICAL BACKGROUND

In this chapter the theoretical background to the contents of the thesis is presented. The chapter includes descriptions of the Swedish water sector, integrated water resources management and decision analysis.

2.1 The Swedish water sector

Water provision and water use

In Sweden, the responsibility for providing water supply to residents and society lies on the 290 municipalities. The municipalities are characterized by a wide variety in land area, number of inhabitants, water use and water availability, see e.g. how the water use vary across the country in Figure 2.1. On a national level, Sweden is considered to have good access to natural water resources. Only 1% of the renewable water is extracted for use in households, agriculture and industry (Eurostat, 2017). Thirty-five percent of total freshwater withdrawals, and 88% of household water, is provided via the public water supply system for which the municipalities are responsible (Statistics Sweden, 2017).

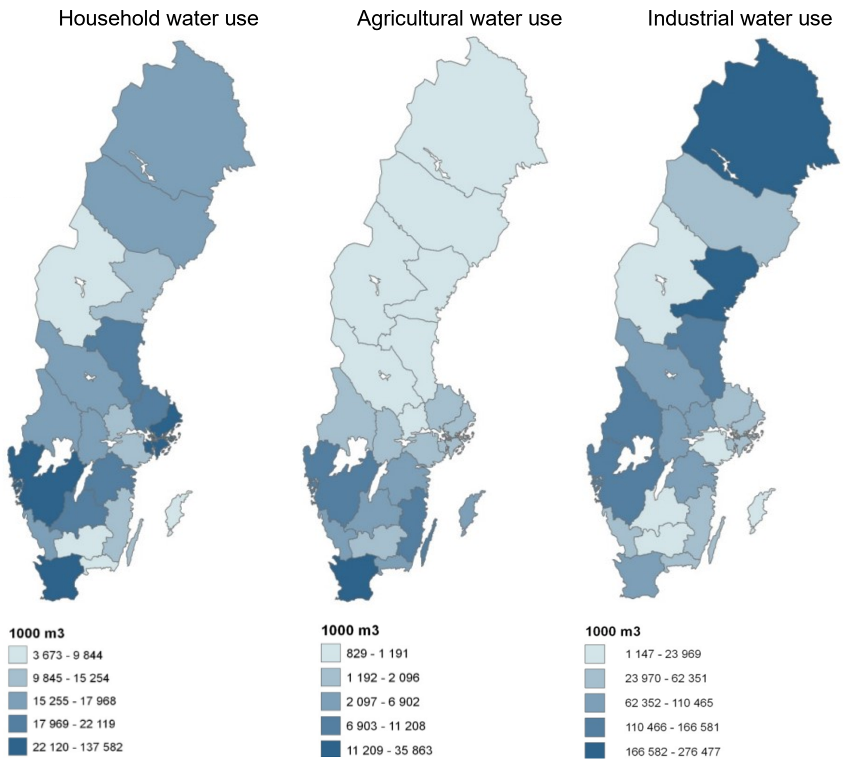

Figure 2.1 Water use by households, agriculture and industry in 2010 (Statistics Sweden, 2012).

In 2015, a total of 2,431 million cubic meters of freshwater and 639 million cubic meters of seawater were used in Sweden. The main source of freshwater, about 80%, was surface water from lakes and streams. Groundwater accounted for about 13%. The remaining 7% were of unclear origin. About 61% of the freshwater was used by industry, 23% by households and 3% by agriculture. The remaining 13% was used within other user categories, such as construction, retailing, hotel and restaurant, transport, and public administration. The water flows in the Swedish society is presented schematically in Figure 2.2 (Statistics Sweden, 2017).

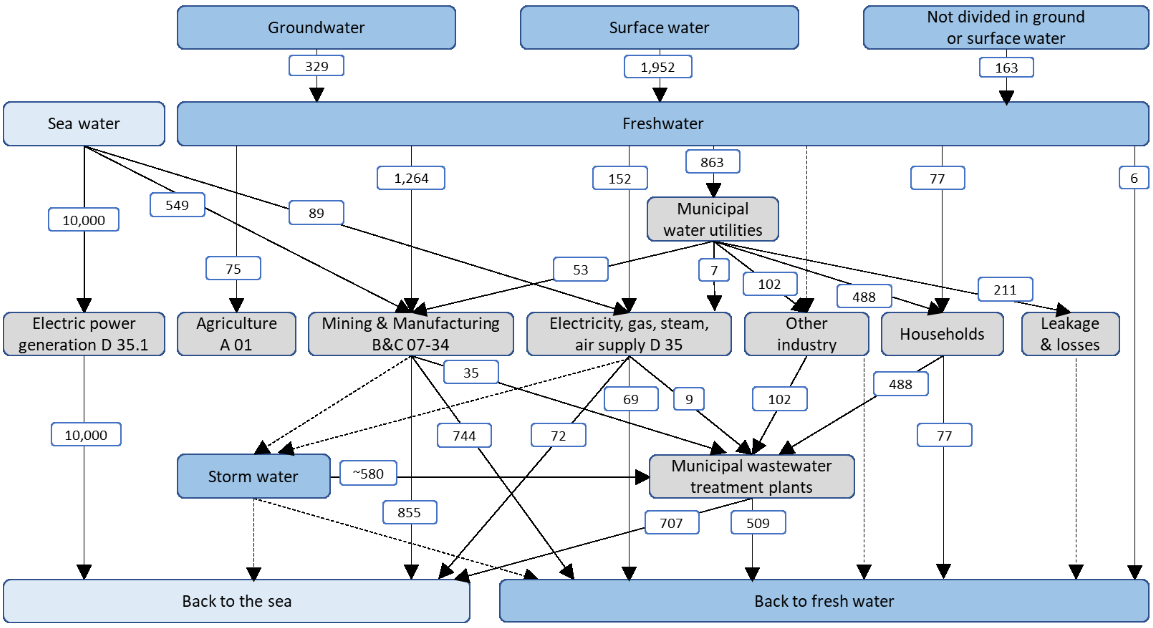

Figure 2.2 Water flows in the Swedish society in 2015, in million cubic meters. Adapted from Statistics Sweden (2017). Dashed arrow = unknown flow.

Challenges for the public water sector

Between 2013 and 2016, the Swedish government investigated the public drinking water sector with the aim of identifying current and potential challenges to a safe drinking water supply, and, if necessary, propose appropriate measures. The inquiry (SOU 2016:32) identified a number of challenges for Swedish water providers, including an aging infrastructure; a continuous population growth in the larger cities; a depopulation of the countryside; and climate changes with higher average temperatures, increased and more extreme precipitation, changed patterns for drainage and evaporation, rising sea levels, altered land and water use, and a predicted increase in chemical and microbiological health hazards. The inquiry also emphasized the considerable variation in local conditions between the municipalities, and acknowledged that several municipalities are facing limited personnel and financial resources. The Swedish municipalities' abilities to handle the above challenges vary significantly, and especially the smaller and middle-sized municipalities are likely to face problems meeting the challenges. To cope with present and future challenges and uphold a safe and reliable water supply, the inquiry recommends a regionalization of the Swedish water sector, including extended regional planning and coordination as well as an increase in inter-municipal cooperation. Regionalization is seen as a prerequisite for providing stability and sustainability to the economic, technical and professional capacity challenges. It may also facilitate a necessary change towards a more regional approach to the protection and utilization of water resources (SOU 2016:32).

2.2 Inter-municipal cooperation

Similar to the Swedish conclusions in SOU 2016:32 , regional cooperation is recommended in several other countries as a means to tackle present and future challenges and achieve sustainable water services. In the United States, the American Water Works Association (AWWA, 2015) emphasizes that regional cooperation is a valuable tool for the utilities to provide safe and reliable water services to their customers in a sustainable way. They highlight benefits such as knowledge sharing, increased efficiency, minimized capital expenditure and enhanced source water protection; and they conclude that a successful cooperation should be structured to enhance service, achieve balance between responsibility and authority, and equitably account for all parties involved. In Germany, the German Bundestag (2006) states that regional cooperation is a key element when modernizing infrastructure, and argues that cooperation is a basis to ensure long-term safety, reliability and sustainability in the water sector.

About 35 percent of the Swedish municipalities already operate the water supply in some form of inter-municipal cooperation. The most common form of cooperation is inter-municipal agreements, which can be reached on almost all kinds of water cooperation, e.g. shared source waters and joint drinking water production. Joint committee is another form of cooperation, in which a committee is comprised in one of the cooperative municipalities' organizations. The committee is not a legal entity, and each municipality is still responsible of the issues administrated thereof. Yet another form of cooperation is municipal alliances, which is a public entity responsible for the issues handed over from the member municipalities. And finally, municipalities may also form joint companies in which a board is responsible for, and governs, the operations. The undertakings of the company is governed by ownership directives (SOU 2016:32).

The main drivers for regionalized water systems are typically the potentials of increased efficiency through economies of scale, improved access to water resources, enhanced professional capacity, integrated water resource management, access to finance and private sector participation, and cost sharing between higher and lower cost service areas (Frone, 2008). However, the above mentioned benefits are strongly dependent on the context and can hence not be taken for granted (Kurki et al., 2016). There are also recognized challenges associated with regionalization, which policy- and decision-makers need to take into account for proper evaluations of reform proposals. Some general, potential benefits and constraints of local versus regional water services are summarized in Table 2.1. A few of the main benefits are described from an international perspective in the sections below.

Table 2.1 Benefits (+) and constraints (-) of local versus regional water services in Sweden (SOU 2016:32).

ASPECTS	LOCAL +	LOCAL -	REGIONAL +	REGIONAL -
Operational planning	Ties to other municipal plans	Missing regional perspective	Ties to regional developmental responsibility	Comprehensive task
Financing	Closeness and participatory	Vulnerable in small municipalities, higher taxes	Economies of scale, larger and more robust base of tax-payers	Difficult for consumers to participate and have influence
Competence provision	-	Difficult in small municipalities	Economies of scale, facilitates strategic work	New experiences may need to be established
Operation	Local knowledge	Vulnerable in small municipalities	Economies of scale, cope with future challenges	New experiences may need to be established
Backup systems and redundancy	-	Inter-municipal cooperation is often a pre-requisite	Economies of scale, flexibility	-
Emergency preparedness	Local knowledge, principle of subsidiarity, participation	Consumers in small municipalities are exposed	Economies of scale, ties to other regional responsibilities (e.g. health)	-

Economies of scale

The water sector is characterized by high capital intensity, with significant investment costs required to build, maintain and develop the water infrastructure systems. Scale economy, i.e. the cost advantage that may arise of an increased production, is therefore often one of the major drivers of regionalization. A significant number of studies have been investigating scale (dis)economies in the water sector. The most frequently used method to evaluate efficiency has been the econometric approach to estimate cost functions (Abbott and Cohen, 2009). Even though the studies use a variety of evaluation methods and output measures, there is generally a consensus that the water sector has important economies of scale up to a certain output level after which diseconomies of scale appear (Carvalho and Marques, 2016; González-Gómez and García-Rubio, 2008; Saal et al., 2013). Countries with excessive fragmentation, such as Germany and Portugal, may benefit economically from merging utilities whereas countries with a high degree of consolidation, such as the UK and the Netherlands, may cause increased costs if merging further (Saal et al., 2013). The optimal scale is found to vary between countries and over time (Nauges and van den Berg, 2008). For overview of scale economy studies, see for example Abbott and Cohen (2009), Martins and Fortunato (2016) and Sjöstrand (2017). In accordance with the above text, the Swedish national inquiry (SOU 2016:32) also highlights investment planning and financing as benefits of a regionalized water sector.

Professional capacity

Ensuring competence provision, with access to sufficient and right skilled personnel, is another major driver for regionalization. Even though small municipalities usually have enough personnel for routine activities, they are often short of staff to perform highly skilled operating and management activities (Frone, 2008; Schmidt, 2014). Many challenges in smaller municipalities are associated with the lack of personnel, which also makes them vulnerable to new and unexpected situations (Thomasson, 2015). Larger organizations are often seen as more attractive employers due to their career opportunities (Thomasson, 2013). Hence, transforming to larger, regional organizations may increase the chances to hire and retain highly skilled personnel (Frone, 2008; Kurki et al., 2016; Lieberherr, 2011). A larger organization also tends to facilitate exchange of experience within the organization as well as pooling of personnel between the municipalities (Lieberherr, 2011). There is, however, a risk of losing local knowledge when transforming from a local to a regional organization (Kurki et al., 2016).

Shared water resources and facilities

Ensuring access to sufficient amount and quality of source waters is another driver for regionalization. The potential of sharing unevenly spaced water resources can be particularly obvious in water scarce areas or areas with insufficient water quality, where management of the water systems may need to be carried out at a regional scale in order to ensure water safety and reliability. A predicted shortage was for example one of the drivers leading to the establishment of 10 Regional Water Authorities in England and Wales in 1974 (Okun, 1975). Water scarcity in the coastal zones was also a main driver when regional wholesale water companies were formed in Finland (Kurki et al., 2016). By connecting several municipal systems into a regional water supply system, each municipality may benefit from having access to multiple source waters and treatment plants in the event of failure of any particular one (Palaniappan et al., 2007).

2.3 Water scarcity

Raindrops in a reservoir [...] That is what we've got

– A Camp (2009)

Definition and metrics

Water scarcity and drought are two related concepts which can have similar effects, and the terms are often used in an indistinct manner. In order to facilitate appropriate policy design to adequately address these concepts, the European Commission proposed a set of definitions to distinguish between the water scarcity and drought phenomena (EC, 2012a):

- *Water scarcity* is a man-made phenomenon. It is a recurrent imbalance that arises from an overuse of water resources, caused by consumption being significantly higher than the natural renewable availability. Water scarcity can be aggravated by water pollution (reducing the suitability for different water uses), and during drought episodes.
- *Drought* is a natural phenomenon. It is a temporary, negative and severe deviation along a significant time period and over a large region from average precipitation values (a rainfall deficit), which might lead to meteorological, agricultural, hydrological and socioeconomic drought, depending on its severity and duration.

Table 2.2 further summarizes the distinction between water scarcity, drought and other related concepts as agreed upon by the EU Member States (Strosser et al., 2012).

Table 2.2 Timescale and causes of water scarcity, drought and related concepts (Strosser et al., 2012).

		TIMESCALE		
		SHORT-TERM (DAYS, WEEKS)	MID-TERM (MONTHS, YEARS)	LONG-TERM (DECADES)
CAUSES	NATURAL	Dry Spell	Drought	Aridity
	MAN-MADE	Water shortage	Water scarcity	Desertification

In order to measure and evaluate progress towards reducing water scarcity, quantitative metrics are usually beneficial. There are a number of ways of measuring water scarcity, from simple threshold indicators to comprehensive measures of human environments and freshwater sustainability (Damkjaer and Taylor, 2017). Two widely used metrics are the Water Stress Index (WSI) (Falkenmark et al., 1989) and the Water Exploitation Index (EEA, 2005).

The Water Exploitation Index (WEI), or withdrawal ratio, is defined as the ratio of the annual total freshwater withdrawals to the long-term annual average of available water from renewable freshwater water resources in an area. A higher index thus means that more water users are competing for limited water supplies. The freshwater resources are estimated based on the mean annual precipitation minus the mean annual evapotranspiration plus the mean annual inflows in the area (Lallana and Marcuello, 2004). A WEI above 20% indicate that the water resources in the given area are under water stress, and values above 40% indicate that water stress is severe. Sweden has one of the lowest water exploitation indices in Europe (Figure 2.3), with just over 1% of the water being withdrawn for use by households, industry and agriculture (Eurostat, 2018). The WEI+ is an advanced version of the Water Exploitation Index, which addresses regional and seasonal aspects of water scarcity. It also considers the amount of water returned after abstraction (EEA, 2019).

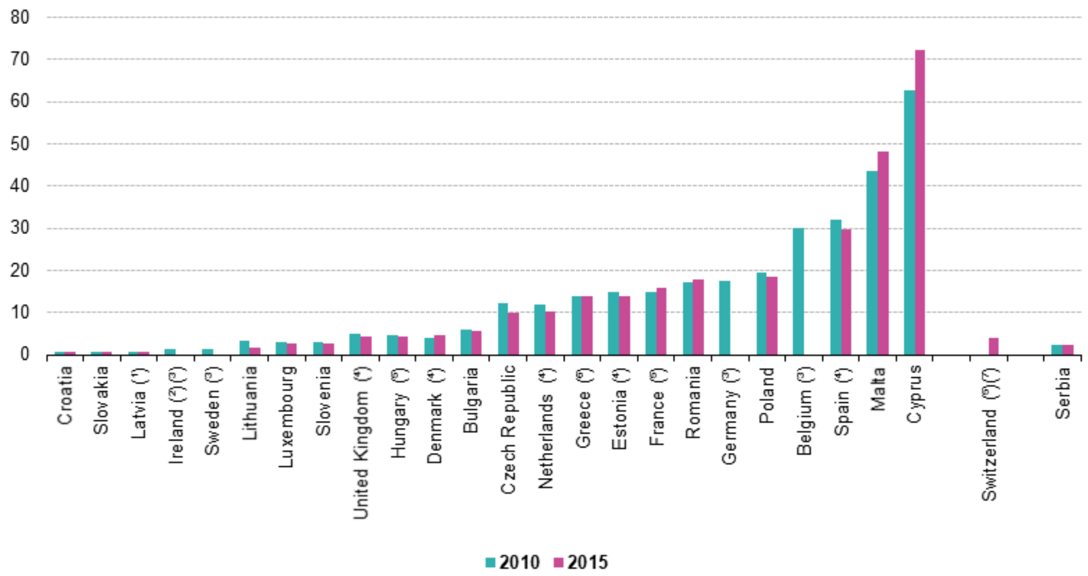

Figure 2.3 Water exploitation index in European countries for 2010 and 2015 (Eurostat, 2018).

The WSI (or the Falkenmark indicator) relates the total available freshwater resources in a given area with its population, representing the pressure that population puts on the water resources including the needs for natural ecosystems (Lallana and Marcuello, 2004). The index thresholds 1,700 m^3, 1,000 m^3 and 500 m^3 per capita per year (Table 2.3) are used to distinguish between water stressed, scarce and absolute scarce areas (WWAP, 2012). In Sweden, there is just under 20,000 m^3 water available per capita (Eurostat, 2017), see the overview for all European countries in Figure 2.4.

Table 2.3 Summary of Water Stress Index thresholds.

CATEGORY	INVERTED WSI (people/flow units)*	CONTEMPORARY WSI THRESHOLD (m^3 $capita^{-1}$ $year^{-1}$)
No Stress	<600 people/flow unit	>1,700
Water stress	600–1,000 people/flow unit	1,700–1,000
Water scarcity	1,000–2,000 people/flow unit	1,000–500
Absolute water scarcity	>2,000 people/flow unit	<500

* A flow unit in the column for Inverted WSI is equal to 10^6 m^3.

Several other indices to quantitatively measure and evaluate water scarcity and water stress are discussed by e.g. Brown and Matlock (2011). However, all metrics reported at a national level have limitations as they do not reflect the local and regional variations in e.g. water availability and degree of utilization.

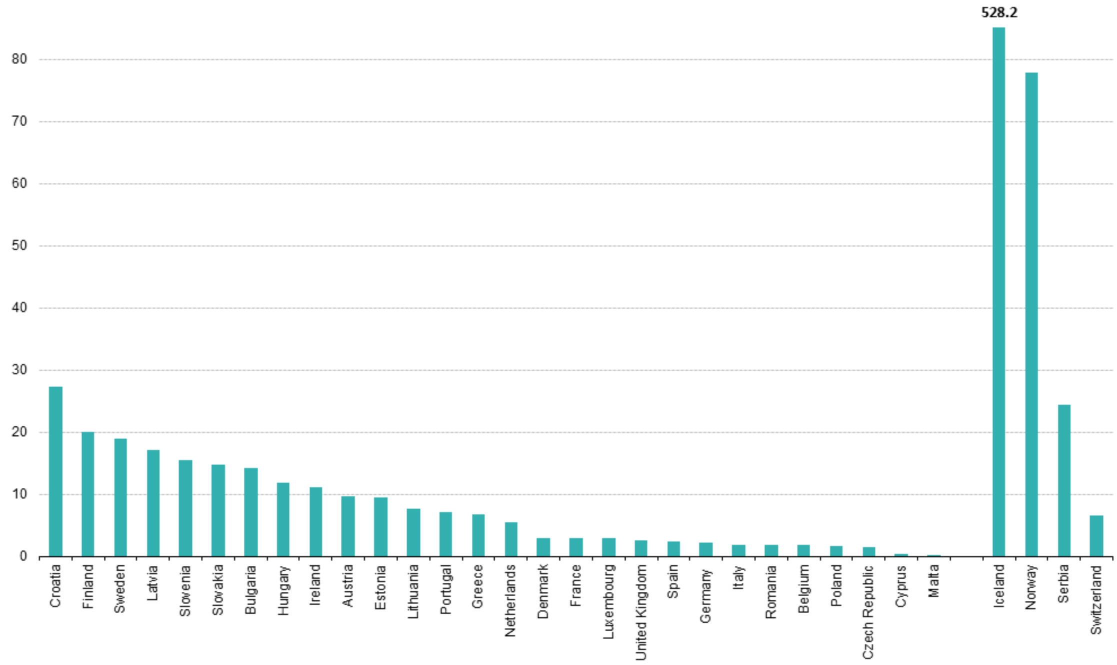

Figure 2.4 Freshwater resources per inhabitant – long term annual average (1,000 m^3/inhabitant) (Eurostat, 2017).

Global water stress and scarcity

Water stress affects every continent on the globe. The highest water stress levels occur in Northern Africa and in Western, Central and Southern Asia (UN, 2018). In 2010, around 1.9 million people (27% of world population) lived in potential severe water scarce areas. This number is expected to increase to between 2.3 and 3.2 billion people by 2050. When monthly variation is considered, there is already 3.6 billion people (51% of world population) living in areas that are potentially water-scarce at least one month per year. This population is also projected to increase to some 4.8–5.7 billion by 2050 (Burek et al., 2016). Some of the main causes for the predicted increase in water scarcity are the increasing world population, the rising demand for food production and economic development, as well as the changing spatial and temporal pattern of water supply.

Currently, agriculture accounts for about 70% of the global freshwater withdrawals, the industry for 20% and the municipalities for 10%. Over the last 100 years, the total global water withdrawal increased by a factor 7.3 while the world population increased by a factor 4.4 (Aquastat, 2015). Hence, the global water withdrawal increased 1.7 times faster than world population (Figure 2.5). The increase in water withdrawal has however slowed down in comparison to population growth over the last decades. It is estimated that the global water demand in 2010 was about 4,600 km^3/year, and it is projected that it will increase with 20–30% to between 5,500 and 6,000 km^3/year by 2050 (Burek et al., 2016; WWAP, 2019). On a global level, the water demand from the industrial and domestic sectors are expected to increase faster than the agricultural demand, but the agriculture sector will remain the largest water user (WWAP, 2018).

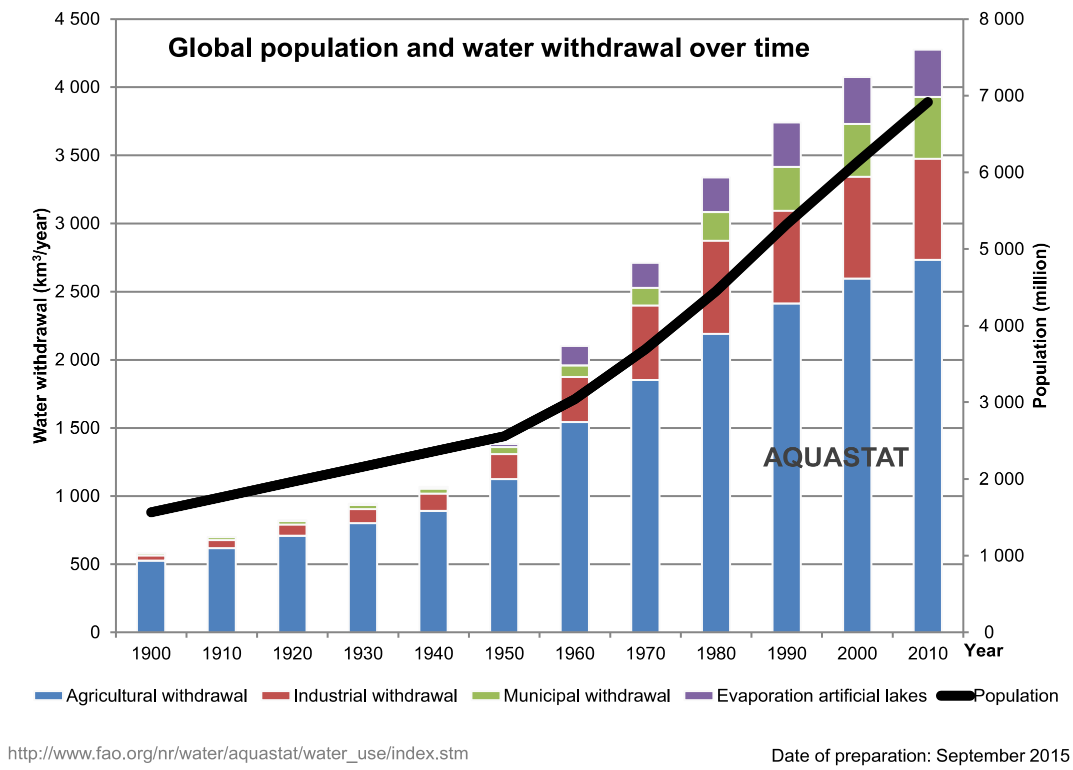

Figure 2.5 *Global population and water withdrawal over time (Aquastat, 2015).*

Drought and water scarcity in Europe and Sweden

Since the beginning of the 21st century, Europe has experienced a number of extreme hot and dry summers with record-breaking heatwaves in combination with a lack of precipitation during the summer months (Hanel et al., 2018). Between 1976 and 2006 the number of people and areas affected by droughts went up by almost 20% and the total costs amounted to 100 billion €. By 2007, more than 11% of the EU population and 17% of its territory had experienced water scarcity (EC, 2012b).

Even though Sweden on a national scale is considered to have good access to natural water resources, local water imbalances are not uncommon. Particularly the southern, central and coastal areas along the Baltic Sea can experience water scarcity during summers (Statistics Sweden, 2017). But it was not until 2016 - 2018, when Sweden experienced low precipitation and high summer temperatures for three consecutive years, that water scarcity was brought up on the national agenda. In the summer of 2018, around 30% of the Swedish municipalities prohibited urban irrigation and called for careful use of drinking water. Farmers experienced their worst harvest since the 1950s, and the lack of grazing and feed led to emergency slaughter of livestock and six-month long waiting times to the slaughterhouses (Sjökvist et al., 2019). Since then, discussions have focused on how we can be better prepared for the next dry periods; how we should use and manage our water resources; which measures that can reduce the effects or lower the probability of water scarcity and drought; who should be involved in the decision-making processes and responses; and what needs to be taken into account when prioritizing between alternative water management measures and policies (Grahn et al., 2020; Sjöstrand et al., 2019; SMHI, 2019; SwAM, 2018; Swedish Food Agency, 2019; Sydvatten, 2019).

2.4 Integrated Water Resources Management

To achieve water security, we must protect vulnerable water systems, mitigate the impacts of water-related hazards such as floods and droughts, safeguard access to water functions and services, and manage water resources in an integrated and equitable manner.

– Maria C. Donoso (2019), Director of UNESCO IHP

Integrated water resources management (IWRM) has been widely accepted by water managers, decision-makers and politicians around the world as a sustainable and problem-solving approach to improve water security and address challenges such as water scarcity, water pollution, climate change, and fractioned sectoral water management practices. The IWRM concept had been around for decades, but it was not until the International Conference on Water and the Environment in Dublin and the World Summit on Sustainable Development in Rio, both in 1992, that the water community agreed upon principles, the so called Dublin Principles, for more efficient and sustainable water resources management (ICWE, 1992):

- "Freshwater is a finite and vulnerable resource, essential to sustain life, development and the environment;
- Water development and management should be based on a participatory approach involving users, planners and policy makers at all levels;
- Women play a central part in the provision, management and safeguarding of water; and
- Water has an economic value in all its competing uses and should be recognized as an economic good".

The Global Water Partnership later defined IWRM *as a process that promotes the coordinated development and management of water, land and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems* (GWP-TAC, 2000). IWRM is guided by the Dublin Principles together with the goals of economic efficiency, social equity and the sustainability of ecosystems (Lenton and Muller, 2009):

- "Social equity: ensuring equal access for all users to an adequate quantity and quality of water necessary to sustain human well-being.
- Economic efficiency: bringing the greatest benefit to the greatest number of users possible with the available financial and water resources.
- Ecological sustainability: requiring that aquatic ecosystems are acknowledged as users and that adequate allocation is made to sustain their natural functioning".

IWRM is often seen as the water element of the broader sustainable development approach, offering a way to balance efficiency, equity and environment. To achieve this balance, water resources management requires both a holistic perspective and an increased involvement of users at different levels. Stakeholder participation is thus one of the of the most important issues in IWRM (Rahaman et al., 2004). The water sector must work together with other sectors of the economy, and different levels of decision-making, from local and national to transnational, must seek to reinforce and complement each other (WWAP, 2009).

As each country and region, and even each municipality, has its own set of economic, environmental and social challenges (and priorities), the most appropriate water resource management approach will differ. But even though there is no IWRM blueprint that fits all, Lenton and Muller (2009) listed a number of strategies that usually are involved in good water resources management:

- "sound investments in infrastructure – to store, abstract, convey, control, conserve and protect surface and ground water;
- a strong enabling environment – setting goals for water use, protection and conservation; improving the legislative framework; enhancing financing and incentive structures; and allocating financial resources to meet water needs;
- clear, robust and comprehensive institutional roles – laying out institutional forms and functions, building institutional capacity, developing human resources, establishing transparent processes for decision-making and for informed stakeholder participation; and
- effective use of available management and technical instruments – for such purposes as water resources assessment, water resource management planning, demand management and social change, conflict resolution, allocation and water use limits, using value and prices for efficiency and equity, information management and exchange".

2.5 Sustainability assessment

Water flows through the three pillars of sustainable development – economic, social and environmental.

– Ban Ki-moon (2015)

The integrated approach to water management, described above, partly emerged to meet challenges that traditional water management could not address. However, as this meant that water should be managed to benefit several different sectors, it became crucial to discuss which criteria that should guide such management efforts. The goals and criteria for individual sectors are often relatively clear. Within the drinking water sector, for example, the goal has been expressed as *to provide good safe drinking water that has the trust of consumers* (IWA, 2004). But how should we define and prioritize criteria when considering many sectors, as well as social, economic and environmental development, at the same time? The solution has been to acknowledge that multiple criteria must be used to guide a sustainable water resources management (Lenton and Muller, 2009). However, the use of multiple sustainability criteria, and thus the estimation of the most sustainable way forward, may differ depending on which definition of sustainability we adopt and which ethical theories we embrace. This section aims to provide an overview of which conditions and interpretations of the sustainability concept that is used in this thesis, and particularly in Paper I and Paper II.

Strong and weak sustainability

Although there are many definitions of sustainability, nearly all contain some perception of that human society and economy are intimately connected to the natural environment (Caradonna, 2014). These three dimensions (or domains) of sustainability, i.e. economic development, social development and environmental protection, are often seen as interdependent and equally supporting pillars of the concept (UN, 2005). The current 17 Sustainability Development Goals (SDGs), agreed upon by all 193 Member States of the UN General Assembly (2015), were designed to balance and integrate these three pillars of sustainable development – economic, social and environmental (UN, 2018). The three domains also form the basis of the decision support model developed in Paper II. Figure 2.6 shows two common sustainability models based on the three components.

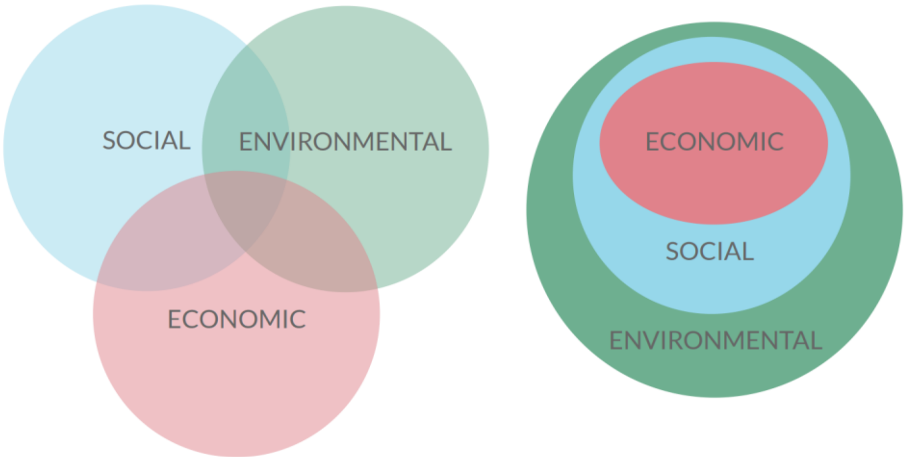

Figure 2.6 Sustainability models consisting of the three pillars economy, society and environment.

To the left in the figure, the three domains are shown as separate yet connected systems. Sustainability is defined as the common ground where the three circles converge. This model is sometimes referred to as the weak sustainability model as it tends to encourage trade-offs, i.e. assumes that a degradation in either the economic, social or environmental domain can be compensated for by improvements in one of the others (Williams, 2008). According to the view of weak sustainability, sustainability is attained as long as the sum of natural and human capital does not decline (Pearce and Atkinson, 1993). There is no difference in the value provided by natural capital, such as water resources, and human-made capital, such as production plants and infrastructure, and hence they can be substituted for one another (Ang and Van Passel, 2012).

The model to the right (sometimes called the strong sustainability model), emphasizes the environment, without which neither society nor economy can exist. In this interpretation of sustainability, economy only exists in the context of a society and is therefore seen as a subset thereof. Both society and economy are however totally constrained by the natural systems of our environment. According to the view of strong sustainability, certain environmental functions cannot be substituted by human made capital. Human and natural capitals are regarded as complements rather than substitutes (Ang and Van Passel, 2012). To achieve sustainable development, neither natural nor human-made capital may hence decline. Uncertainties about the future and risks of irreversible natural loss are arguments that support strong sustainability (Munda, 1995).

However, both the weak and strong sustainability concepts have shortcomings which make them hard to implement in in their purest forms. Depending on our preferences on how valuable e.g. certain natural capitals are for our well-being we will end up somewhere on the scale between the two extremes (Hedenus et al., 2015). The decision support model proposed in Paper II allows for trade-offs between sustainability domains and can hence only be used to enforce weak sustainability. However, the model can identify whether certain alternatives lead towards strong or weak sustainability, i.e. whether there is an actual compensation between sustainability domains or sustainability criteria. Moreover, if the requirement is strong sustainability, the model can be used to identify in which respects a measure must be improved in order to achieve strong sustainability. It can thus also be used to identify which measures are disqualified if the requirement is strong sustainability.

Ethical theories

In the process of developing a decision support model based on the concept of sustainability, it was important to also distinguish between different views on sustainability based on which moral ethics we embrace. This subsection gives a short overview of the two ethical theories *consequentialism* and *deontology* and describes how sustainability can be interpreted based on these theories.

In consequentialism (Anscombe, 1958), the rightness of an action is judged on the basis of its consequences. Thus, for a consequentialist, an action is morally right if its consequences are good, generally summarized by the saying *the end justifies the means* (Mizzoni, 2010). In utilitarianism (Bentham, 1789; Mill, 1863), which is a form of consequentialism, an action or decision is judged on the basis of its contribution to overall utility, i.e. human well-being (Sidgwick, 1874). The definition of sustainable development as put forward in the Brundtland Report (WCED, 1987), has an anthropocentric, i.e. human-centered, utilitarian perspective which focus on achieving and maintaining human well-being now and in the future (Farley and Smith, 2014; Imran et al., 2014).

In deontological ethics (Kant, 1785), actions are not judged on the basis of their consequences but on a set of principles or moral duties. It is our duties to intrinsic moral value principals like justice and equity rather than fulfilment of well-being that guide our actions (Howarth, 1995). In the case of sustainable development, our duty to leave an unharmed world to future generations is for example grounded in both moral intuition and formal ethical principles (Laslett and Fishkin, 1993).

Depending on which concept of sustainability and moral reasoning we adopt, the right action moving forward might differ. Paper II proposes a decision support model based on a combination of the two ethical theories. Economic consequences of alternative interventions are assessed by means of cost-benefit analysis based on impacts on human well-being (Paper I), whereas social and environmental consequences are assessed based on impacts on moral principles of deontological ethics such as final[1] values of the environment (Peterson and Sandin, 2013). The decision support model then allows for weighing the economic, social and environmental domains differently, depending on the decision-makers preferences regarding sustainability.

2.6 Decision analysis

Decision analysis is a formalization of common sense for decision problems which are too complex for informal use of common sense.

– Ralph L. Keeney (1982)

The purpose of decision-making is to make *good* decisions. A good decision is one that is logically consistent with our preferences regarding the potential outcomes, the alternatives and the uncertainty assessment. Decision analysis is a formalized way of helping decision-makers make good decisions in complex decision situations, with e.g. multiple and possibly conflicting objectives, multiple stakeholders, important uncertainties, and/or significant consequences. Decision analysis can create value in two important ways: by helping decision-makers choose between different options, and by improving selected options by increasing their value and/or reducing their risk (Parnell et al., 2013).

But how do we know if a decision is good, and how can we improve the conditions for a good decision? According to Matheson and Matheson (1998), a good decision requires high quality in each of the six elements shown in Figure 2.7: 1) an appropriate frame; 2) creative and doable alternatives; 3) meaningful and reliable information; 4) clear values and trade-offs; 5) logically correct reasoning; and 6) commitment to action. This means that a good decision needs a frame with clear goals, objectives and value measures, which preferably are identified together with a broad group of stakeholders and experts.

[1] A final value is a value that something has *for its own sake* rather than as a means to something else.

It further needs to involve the right people and address the right problem. A good decision also requires alternatives that can create value for decision makers and stakeholders, and it needs meaningful and reliable information regarding those alternatives. This includes addressing uncertain key parameters and model assumptions in a proper way, e.g. by the use of probability distributions and alternative model scenarios. The decision-makers' and stakeholders' values and preferences should be clearly stated and provide a basis for the comparison of alternatives. The decision should further be based on logically correct reasoning, which in short implies that there is a logical desire to make decisions that maximize expected utility. Hence, the alternative with the highest probability of the best outcome should be chosen. And finally, the decision-makers should be prepared to implement the decision. As Parnell et al. (2013) points out, all of the six elements are important and the decision is only as good as its weakest link.

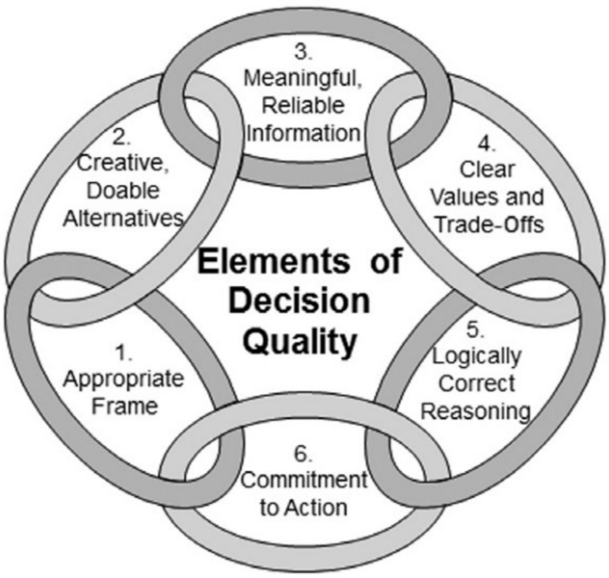

Figure 2.7 Six elements of decision quality (Matheson and Matheson, 1998).

According to Aven (2012), a good decision can be reached by either: 1) establishing an optimization model and choose the alternative that maximizes or minimizes a specific criterion or 2) using a formal process of risk and decision analysis to provide decision support, followed by an informal process of managerial judgement and review that result in a decision. The second approach, which is the preferred approach in most decision situations according to Aven, is schematically described in Figure 2.8 from a risk-based perspective. This decision-making process usually begins with a decision problem to choose between different decision alternatives. The alternatives are typically developed by experts and managers within the boundary conditions of the decision problem, and the boundary conditions are based on stakeholder values and preferences.

The number of alternatives to be analyzed must be manageable. Hence, several alternatives could be excluded before initiating detailed evaluations. Several different decision support methods can then be used to provide the decision-makers with information about consequences of choosing one alternative over another. Risk analysis, cost-benefit analysis and multi-criteria decision analysis are examples of such methods. Before making a decision, the decision-makers review all decision-support information and evaluate it in relation to formulated objectives, values and preferences. The managerial review can then give rise to more detailed analyses, or identification of new alternatives, before a final decision is made.

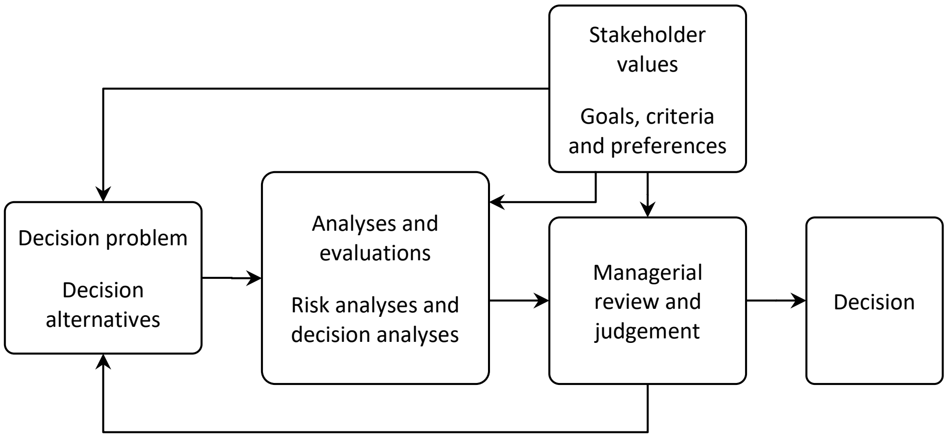

Figure 2.8 Basic structure of the decision-making process (Aven and Kørte, 2003).

This thesis focuses on providing decision support methods and tools that can give input to decision-makers in complex and uncertain decision situations. The methods aim to shed light on the consequences of choosing one alternative over another. By using a well-established approach to risk management (ISO, 2018), described in more detail in Chapter 3, a systematic handling of uncertainties is made possible and predictions of the performance of the alternatives can be provided along with associated risks and uncertainties. The probabilistic approach used throughout the thesis enhances the transparency of the uncertainties and assumptions involved in a way that they can be addressed and considered. It also facilitates calculations of probabilities that alternative options exceed certain cost limitations or environmental threshold values, providing a structured approach for rational decision-making on uncertain outcomes (Dekay et al., 2002).

The way decision support is viewed in this thesis is in line with Aven (2012), i.e. its principal aim is not to recommend hard decisions but to construct a liable help for decision-makers that reflects his or her preferences and considerations as well as those of affected societal groups. Decision support is thus meant to guide, inform and support rather than replace managerial judgement. Ethical and political discussions and negotiations are still needed to guarantee a just evaluation of values and preferences. Hence, human judgement is vital in making a final decision (Ashley et al., 2004; Aven, 2012; French and Insua, 2000).

3 METHODS

This chapter includes a description of the underlying methods and techniques used in the papers presented in this thesis.

3.1 Cost-benefit analysis

The future is already here – it's just not very evenly distributed.

– William Gibson

Cost-benefit analysis (CBA) is a systematic analytical technique to compare the positive and negative effects caused by a measure (or a policy), in order to analyze whether it is economically beneficial or not (Johansson and Kriström, 2016). The different steps of the analysis are summarized in Figure 3.1. CBA has been used as a decision-support tool to compare and rank alternative options in a wide variety of water policy contexts, e.g. water source improvements (Cha et al., 2018); Water, Sanitation and Hygiene (WASH) projects (Azqueta and Montoya, 2017); desalination (Sarica, 2018); water loss reduction (Malm et al., 2015); hydropower (Johansson and Kriström, 2013); irrigation reservoirs (Varouchakis et al., 2016); microbial risk mitigation (Bergion et al., 2018); and flooding (Rai et al., 2020).

The decision-metric of the CBA is the net present value (*NPV*), calculated as

$$NPV_a = \sum_{t=0}^{T} \frac{1}{(1+r_t)^t} [B_{a,t}] - \sum_{t=0}^{T} \frac{1}{(1+r_t)^t} [C_{a,t}] \qquad (3\text{-}1)$$

where a is the alternative measure, t is the time when benefit or cost occur, T is the time horizon, r_t is the discount rate at time t, C are the costs and B are the benefits in relation to the reference alternative. The benefits (desired effects) and costs (undesired effects) are as far as possible measured in monetary terms (see further in section 3.2). A measure is considered economically profitable when its total benefits to society are larger than its total costs to society, i.e. when its *NPV* is positive. The society in this meaning is the sum of individuals' well-being (preferences) for which the CBA is performed, i.e. the aggregated willingness to pay (WTP) for benefits and willingness to accept (WTA) compensation for losses (OECD, 2018). CBA was used in Papers I and II to evaluate the economic domain of the developed sustainability assessment model, and in Papers III and IV as a basis for marginal cost and economic viability estimates.

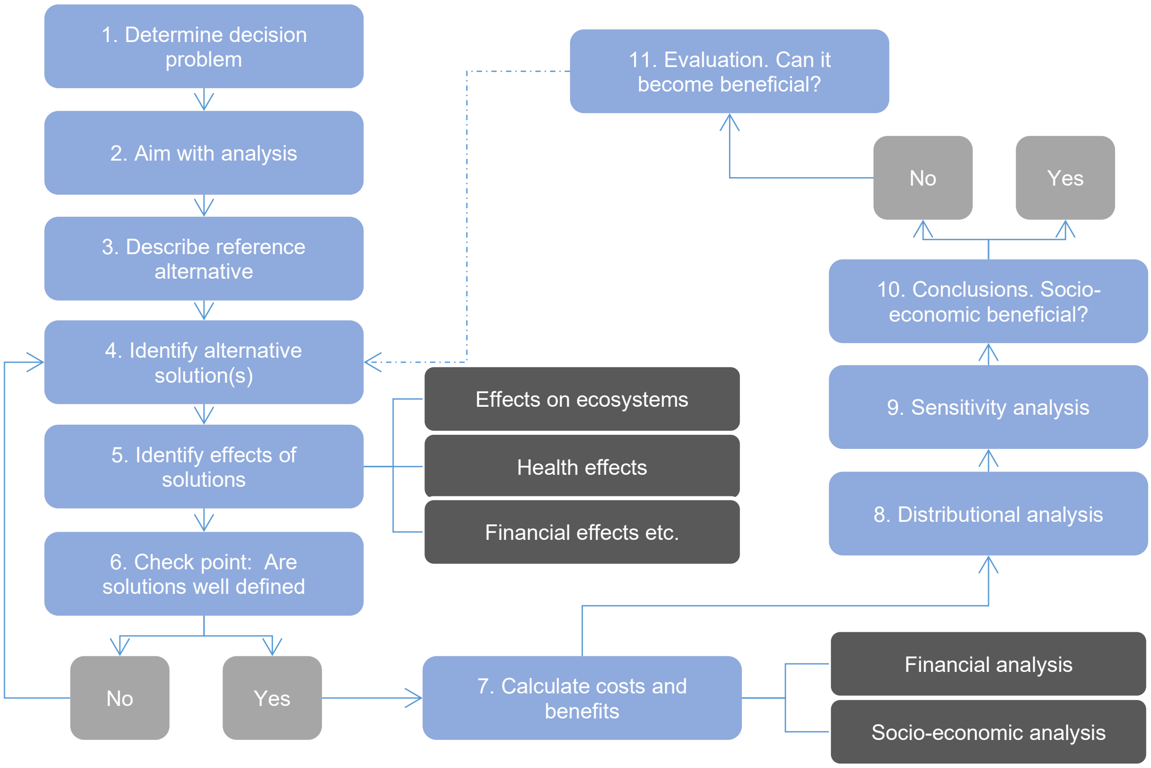

Figure 3.1 *CBA step by step. Adapted from Kriström and Bonta Bergman (2014).*

When a multi-year analysis is performed, costs and benefits must be measured in real values (constant prices) instead of nominal values (current prices). Thus, the costs and benefits are discounted using specified discount rates. There is an extensive literature on the subject of discounting and the selection of discount rates. There is, however, no objective and collectively acknowledged rate to be used in a CBA. The choice of discount rate is instead one of the most disputed subjects of economic theory (Munda, 1995). The discount rate illustrates how we value e.g. equity between generations, and environmental resources versus capital resources. Using a low discount rate suggests that we are more interested in, and willing to pay for, the welfare of future generations compared to when using a higher rate. To increase the weight devoted to the welfare of future generations, some countries (e.g. Norway and UK) use declining discount rates (Johansson and Kriström, 2018). In Papers I, II, III, and IV, the discount rates of 1.4%, 3.5% and 5% were used for sensitivity analysis. The rates reflect the average discount rate used in the Stern Review on Climate Change (Stern, 2006) and the suggested social and private rates of the Swedish Transport Administration (2018) guidelines for cost-benefit analysis, respectively.

3.2 Economic valuation of cost and benefit items

When the well is dry, we know the worth of water.

– Benjamin Franklin (1746)

There are several economic valuation methods, based on welfare theory, for quantifying the benefits and costs of nonmarket goods and services in monetary units. The goal is to quantify the trade-offs that individuals are willing to make between income and a positive or negative change in the provision of nonmarket goods or services. That is, to quantify their willingness to pay/accept compensation (WTP/WTA) for a specific change (Freeman et al., 2014). The methods are often grouped in the following categories (Figure 3.2): direct market valuation methods, revealed preference methods and stated preference methods (Bouma and van Beukering, 2015; TEEB, 2010). The categories are briefly described below, together with some water-related valuation examples, although far from all valuation methods described are used in this thesis.

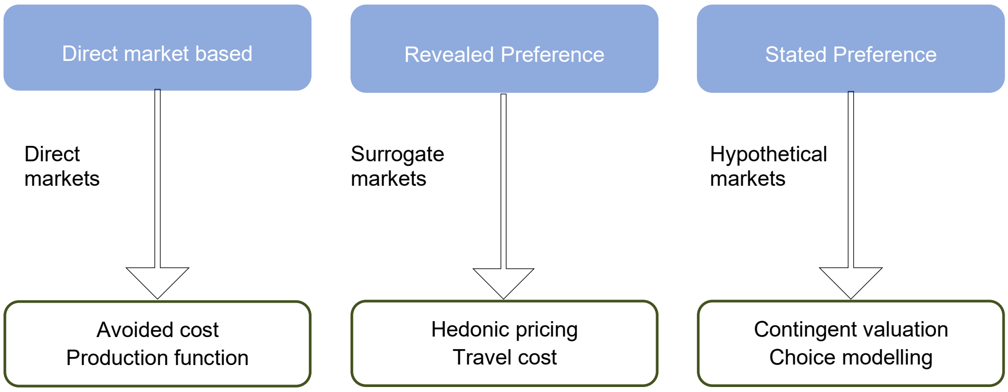

Figure 3.2 Examples of economic valuation approaches.

In market based methods, prices from well-functioning markets provide information on the economic values. The avoided cost method is an example of direct market based approaches. In the avoided cost method, WTP is estimated by measuring the resource costs incurred by the negative change, including both direct and indirect costs. Direct costs are for example costs of medical visits due to polluted drinking water, whereas indirect costs reflect opportunity costs of e.g. reduced production (Young and Loomis, 2014).

Revealed preference methods rely on individuals' expenditure choices on market goods and services to assess their WTP to related non-market goods and services (Johansson and Kriström, 2018). Two commonly used revealed preference methods are the travel cost method and the hedonic pricing method. The travel cost method is typically used to value sites that are used for recreation. Individuals' cost incurred in reaching the site is used as a value for the site, or for the water quality of the site assuming the water quality is a decisive factor for the travel behavior. The hedonic pricing value method uses differences in property pricing to estimate individuals' values on e.g. nearby water resources (Young and Loomis, 2014).

Stated preference methods use structured questionnaires to estimate individuals' values of goods and services not commonly traded on existing markets. The contingent valuation method and the choice experiment method are two frequently used stated preference methods. In the contingent valuation method, individuals are asked directly what they would be willing to pay to obtain a specified good (or willing to accept to give up the good). In choice modelling, individuals are presented with consequences and costs of alternative interventions and are asked to rank the interventions or choose the most preferred one. The rankings or choices are then analyzed to determine their WTP for different interventions (Freeman et al., 2014; Young and Loomis, 2014).

When primary economic valuation studies are considered too expensive or infeasible to conduct, estimates of benefits and costs can be provided using benefit transfer. The benefit transfer approach makes use of previously performed valuation studies from another area and extrapolates the economic values to the area for which a valuation is required. However, transfers can be difficult to perform because measurement values that are correct in one context do not necessarily have to be accurate in other contexts. And if estimates are transferred from more than one primary study, it can end up in estimates that do not reflect budget constraints (Johansson and Kriström, 2018). Benefit transfer is thus usually considered a second-best solution, but may be the only means to provide empirical economic information when time, funding or other constraints prevent the use of the above mentioned methods (Johnston et al., 2015).

Paper I provides examples of how some key costs and benefits, such as health effects and effects of water supply disruptions, can be valued economically. Health effects of insufficient water quality was valued by the avoided cost method as the sum of health care costs, costs of lost production, and costs of discomfort (Johansson and Forslund, 2009). Effects of water supply disruptions was valued based on a combination of effects on residential consumers and economic sectors (ATC, 1991; Brozović et al., 2007; FEMA, 2011). Previously estimated water importance factors for American economic sectors were used to estimate the percental reduction of value added for Swedish economic sectors in Papers I and IV. To increase the understanding of how water supply disruptions affect Swedish economic sectors, Paper V generated time-dependent water resiliency factors through a survey of the Swedish sectors.

3.3 Marginal abatement cost curves

Every drop in the ocean counts.

– Yoko Ono

Marginal abatement cost curves (MACC) are frequently used in climate policy-making to provide guidance on greenhouse gas mitigation measures in a variety of sectors, e.g. in the cement, iron and steel sectors (Hasanbeigi et al., 2013; Worrell et al., 2000), the transport sector (Peng et al., 2018), and in forestry and agriculture (Eory et al., 2018a; Moran et al., 2009). MACCs have also been used in other policy areas, e.g. to assess air pollutants (Rentz et al., 1994) and waste reduction (Beaumont and Tinch, 2004), but only a few studies have applied them to water challenges (Addams et al., 2009; Chukalla et al., 2017). The cost curves have become a popular decision support tool as they manage to illustrate and compare a range of complex measures from various sectors in an easily understandable format.

In Paper III, a MACC was developed to provide decision support for water scarcity mitigation by comparing the cost-effectiveness of measures aiming to increase the water availability, see schematic description of this kind of MACC in Figure 3.3. A cost-effectiveness analysis (CEA) is based on a single indicator of effectiveness, in this case water volume, which is to be compared to the cost (OECD, 2018). The alternative measures are ranked and displayed as bars on the curve in order of their cost of adding or conserving water, i.e. increasing water availability by one unit, from the cheapest to the most expensive. The height of each bar represents the cost per unit of water added or conserved by the measure, and the width of each bar displays the annual amount of water made available by each measure in cubic meters.

There are two different method categories to construct a MACC; i.e. expert-based approaches and model-based approaches (Chukalla et al., 2017; Kesicki, 2012). Expert-based approaches focus on assessing the cost-effectiveness of *individual* measures based on expert input, enabling inclusion of high technological detail in the assessments. Model-based approaches derive the costs and potentials from different model runs, i.e. energy models in the case of CO_2-abatement. Strengths and weaknesses with the two approaches are discussed in Kesicki (2010) and Kesicki (2012). Paper III applied the expert-based approach.

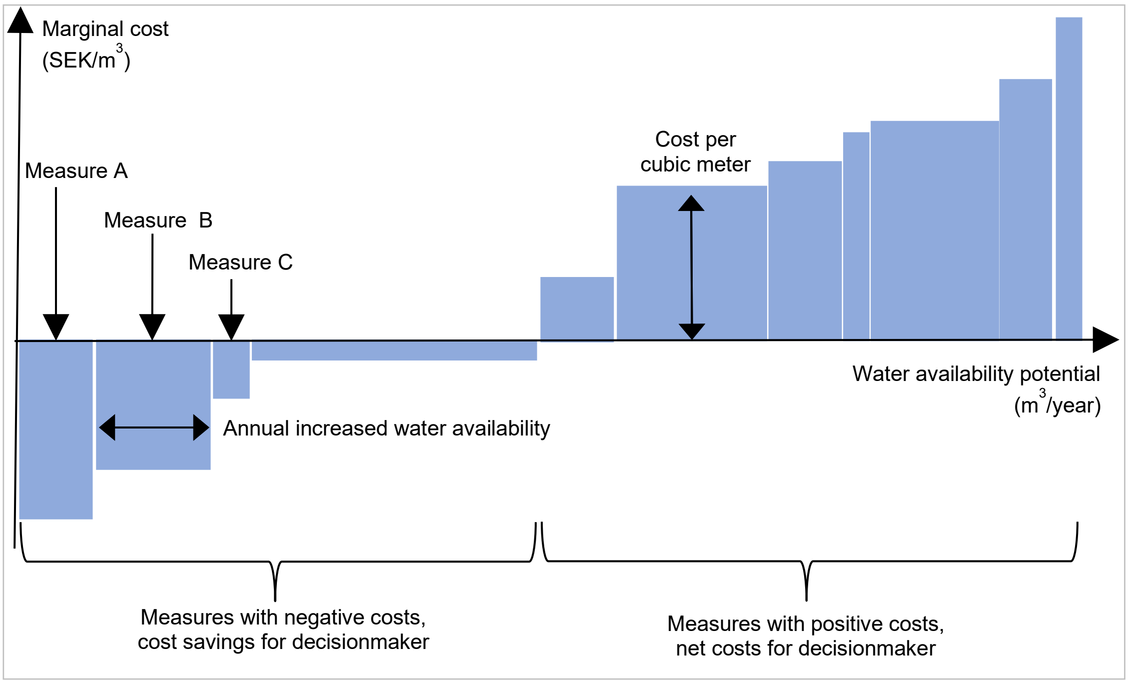

Figure 3.3 *Schematic description of a marginal abatement cost curve for water scarcity mitigation. Adapted from Addams et al. (2009).*

A combination of national and local literature data and expert opinions was used to identify and estimate the parameters needed to calculate the water availability potentials and costs of the selected measures. The costs associated with the measures (i) were presented in the form of present values (PVs), calculated as:

$$PV_i = \sum_{t=0}^{T} \frac{C_{i,t}}{(1+r)^t} \qquad (3\text{-}2)$$

where C is cost, t is the time when the cost occurs, T is the time horizon, and r is the discount rate. The PVs were then expressed as annuities distributed evenly over the time horizon, i.e. as equivalent annual costs ($EACs$) in SEK per year (Brealey et al., 2010):

$$EAC_i = \frac{r(PV_i)}{1 - \frac{1}{(1+r)^T}} \qquad (3\text{-}3)$$

The effectiveness of the measures in increasing water availability was calculated as the ratio of the EAC and the annual water availability potential of each measure in SEK per cubic meter.

3.4 Multi-criteria decision analysis

Water development and management should be based on a participatory approach, involving users, planners and policy makers at all levels.

– The Dublin Prinicples (1992)

Multi-criteria decision analysis (MCDA) is a general decision support framework commonly used in complex decision problems to synthesize a variety of information and compare alternatives with significantly different impacts (Figueira et al., 2005; Greco et al., 2016). MCDA can be used to integrate quantitative, semi-quantitative and qualitative information concerning alternative interventions (Rosén et al., 2015). It provides a structured approach in decision situations where stakeholder participation is central and where it is necessary to make use of the decision-maker's preferences to distinguish between the alternatives. Large emphasis is placed on the judgement of the decision-making team and involved stakeholders to establish objectives and criteria, to assess the relative importance between the criteria, and to decide whether trade-offs between criteria are allowed or not. Similar to CBA, MCDA has also been applied to compare options in a large number of water policy contexts, e.g. alternative source waters/technologies (Godskesen et al., 2018); desalination plants (Dawoud et al., 2020); river rehabilitation (Langhans and Lienert, 2016); drinking water safety (Lindhe et al., 2013); groundwater quality classification (Zahedi et al., 2017); and water allocation (Golfam et al., 2019).

The first steps of an MCDA focus on determining the decision context, objectives, and stakeholders, as well as defining alternative solutions that might meet the goals and objectives. Once that is settled, the evaluation criteria need to be determined. The criteria serve as performance measures in the MCDA, and hence, they need to be operational so that an expert judgement or a data measure can state how well an alternative perform in relation to a specific criterion. The criteria must also be set up to avoid double counting and they must be independent of each other.

Scoring

Each alternative is then evaluated by scoring it on each criterion, either qualitatively or quantitatively. The scores are measures of the performance of the alternatives with respect to each criterion. The scoring can be made in either absolute or relative terms. The sustainability assessment model in Paper II uses relative scoring in relation to a reference alternative. To score the alternatives' performance, the criteria need some sort of performance scales. The criteria measures might originate from a natural scale, i.e. based on their original units such as kg/m^3, or from a qualitative scale, e.g. ranging from very low to very high performance. If the criteria are measured on different scales, a unified scale is needed in order to compare and combine the scores. A common way to establish a unified scale is to remap the measures onto an interval scale, e.g. from 0 to 100. This interval scale needs to be defined by two reference points for each criterion, usually the min and max values. There are two different ways to determine these reference points, i.e. either by local scaling or global scaling. A local scale uses the alternative interventions at hand to determine the min and max values of its scale, i.e. the *best (worst) performing alternative* is remapped to e.g. 100 (0) in the local scale. In a global scale, on the other hand, the *best (worst) possible performance,* according to decision-makers' and experts' experience, define its max (min) values, e.g. so that 0 represents the worst possible performance and 100 represents the best possible performance. The decision-makers and involved experts are hence responsible for determining the endpoints in the global scale (Monat, 2009).

The scores can be assigned to the alternatives in three different ways: by using a value function to transform a measurement of the specific criterion to a score; by direct rating using expert opinions and judgements to assess the alternatives performance; or by pairwise assessments by experts on how each alternative perform relative to the other alternatives (DCLG, 2009). In Paper II, the performance was scored by direct rating using expert and stakeholder value judgements. The experts estimated minimum, most likely (mode), and maximum values for each criterion on a scale from -10 to 10.

Weighing

Each criterion is then assigned a weight, reflecting that criterion's relative importance for the decision problem to the other criteria. The weighting procedure, hence favor some criteria more heavily than others. One weighing procedure is the swing weighting method, which is based on comparisons between criteria. The weight of a criterion reflects the decision-makers' perception of how important that criterion's swing in values (i.e. the range difference between the worst and best alternatives) is compared to the swing in values of the other criteria. Another weighting method is called importance weighting, which is the method used in Paper II. Importance weighting is based on the decision-makers' perception of how significant a particular criterion is compared to the other criteria (Monat, 2009).

Weighted average

The weights and scores are then combined to give an overall assessment of each alternative. The calculation can be performed as a product, an average or a function (DCLG, 2009). The most commonly used method, and the one used in Paper II, is to calculate the weighted average of the scores. In Paper II, the overall assessment was in the form of a sustainability index (S) for each alternative (a) which was calculated as the weighted sum of the scores on all criteria (k) of a specific sustainability domain (d) by

$$S_{d,a} = \sum_{k=1}^{K} w_k \, z_{a,k} \qquad (3\text{-}4)$$

where z is the performance score, w is the weight for each criterion and

$$\sum_{k=1}^{K} w_k = 1, \qquad (3\text{-}5)$$

i.e. the sum of all weights must add up to 1.

3.5 Quantitative risk assessment

Opportunity and risk come in pairs.

– Bangambiki Habyarimana

According to ISO (2018), the risk management process for managing any type of risk can generically be described as in Figure 3.4 and includes the following steps:

- *Communication & consultation*: Assisting relevant stakeholders in understanding risk, and providing information to facilitate decision-making.
- *Scope, context & criteria*: Customizing the risk management process by defining its scope and context along with the decision criteria, based on which the significance of risk will be evaluated.
- *Risk assessment*
    - *Risk identification*: Finding, recognizing and describing risks, by considering factors such as causes and events; consequences and impacts on objectives; and vulnerabilities and capabilities.
    - *Risk analysis*: A detailed consideration of uncertainties, risk sources, consequences, likelihood, events, scenarios, controls and their effectiveness.
    - *Risk evaluation*: Comparing the results of the risk analysis to support decisions on whether action needs to be taken or not.
- *Risk treatment*: Selecting and implementing options for addressing risk.
- *Monitoring & review*: Improving the quality and effectiveness of implementation and outcomes by e.g. providing feedback.
- *Recording & reporting*: Documenting the process to assist communication with stakeholders and to improve activities.

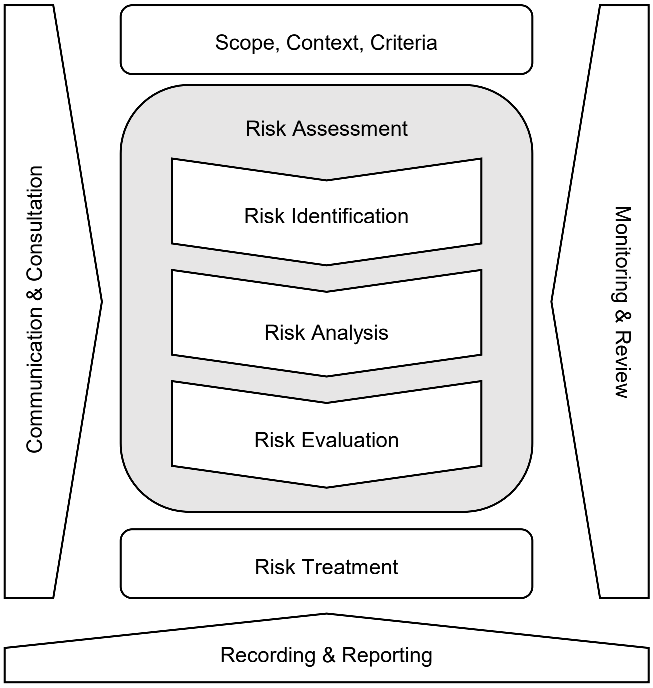

Figure 3.4 Schematic description of the risk management process. Adapted from ISO (2018).

In Paper IV, a quantitative risk assessment (QRA) approach is used to identify, describe and analyze risks for a water supply system to provide a basis for decision-making under uncertainty. The QRA follows a well-established approach which aims at answering the following three questions by defining a set of scenarios (Kaplan and Garrick, 1981):

- What can go wrong?
- How likely is it to happen?
- If it does happen, what are the consequences?

According to Kaplan et al. (2001), the set of scenarios in a QRA should preferably be complete, finite and disjoint. This means that a nonoverlapping subset of *N* scenarios together should represent all possible risk scenarios for the entire problem. By use of scenarios, the risk *R* can be defined based on the following triplets (Kaplan and Garrick, 1981):

$$R = \{(s_i, f_i, x_i)\} \quad (3\text{-}6)$$

where s_i is scenario i, $i = 1,2,\ldots,N$; f_i is the frequency with which the scenario occurs; and x_i is the consequence given that scenario *i* occurs. However, risk assessments are often complex in nature and many aspects of the risk may be subject to large uncertainties (Hall and Borgomeo, 2013). When we do not know the frequencies or the consequences by certainty, we can express them by probability distributions so that

$$R = \{(s_i, p_i(f_i), \zeta_i(x_i))\} \quad (3\text{-}7)$$

where p_i and ζ_i are the probability density functions for the frequency and consequence, respectively.

In Paper IV, the result from the risk assessment was presented graphically by risk curves, see schematic description of staircase and continuous risk curves in Figure 3.5. In order to plot a risk curve, the frequencies must be expressed in terms of cumulative frequencies. For this, the scenarios must first be arranged in order of increasing consequences, i.e. $x_1 \leq x_2 \leq \cdots x_i \leq \cdots \leq x_N$, along with corresponding frequencies. Starting with the scenario with the most severe consequences, a cumulative frequency F_i, i.e. the frequency of having consequence equal to or greater than x_i, is calculated as $F_i = F_{i+1} + f_i$. By plotting (x_i, F_i) a staircase function of the analyzed risk scenarios is derived, representing a discrete approximation of the continuous reality. A smoothed risk curve R_x, drawn through the staircase, can then be regarded to represent the actual risk (Kaplan and Garrick, 1981). Each point of the curve does not belong to a specific event but instead represents the estimated return period of losses. The integral of the curve, i.e. the area underneath the curve, represents the total expected losses in any given year so that

$$R_{tot} = \int_0^{X_N} F(x)dx \quad (3\text{-}8)$$

in which R_{tot} is the total annual risk, N is the total number of analyzed scenarios, x is the consequences and F is the cumulative frequency as a function of consequence x. For risk estimation, the continuous function can for practical purposes be simplified by the staircase function to provide an approximative calculation of the total risk.

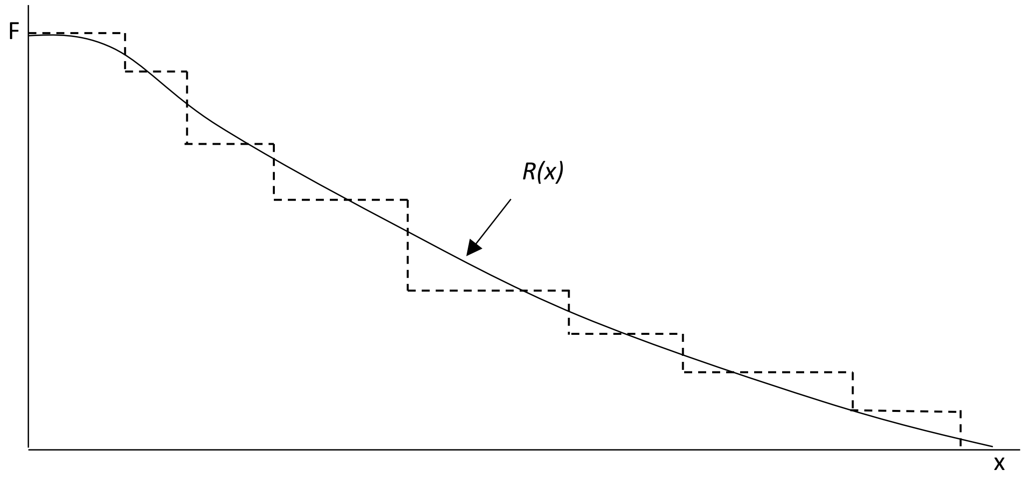

Figure 3.5 Schematic description of staircase and continuous risk functions. Adapted from Kaplan and Garrick (1981).

In Paper IV, the annual risk reduction (a benefit) of each alternative option is estimated by calculating the difference between the risk curve of the reference system and the risk curve of the risk reduction option.

3.6 Uncertainty analysis

Uncertainty is that which disappears when we become certain.

– Bedford and Cooke (2001)

Evaluations of alternative measures and their effects will almost always comprise uncertainties. Uncertainties are often categorized as either stochastic (aleatory) or knowledge-based (epistemic) uncertainties (Kiureghian and Ditlevsen, 2009). An epistemic uncertainty is one that is caused by lack of knowledge or data, and can hence be reduced by e.g. gathering more data. An aleatory uncertainty is one that is caused by the natural randomness of a phenomenon or experiment and is not possible to reduce. For decisions involving significant uncertainties, the decision should preferably be based on estimates of key performance criteria (e.g. cost) combined with uncertainty assessments to provide an improved perspective of the values and risks of each alternative (Aven, 2012; Parnell et al., 2013). Uncertainty analysis can hence help decision-makers manage the risks associated with decision alternatives by providing realistic estimates of uncertainty.

Uncertainties are commonly expressed by means of probabilities. There are two main statistical schools concerning the interpretation of probabilities, i.e. frequentist and Bayesian (Berger and Bayarri, 2004). For frequentists, probabilities are equal to the long-term frequency of occurrence of repeatable events. For a Bayesian, probabilities are related to our knowledge about the parameter in question. In the Bayesian view, a probability is the quantitative expression of someone's uncertainty about the parameter based on his/her state of information. In the Bayesian approach, hard data, from e.g. statistics on events, can be combined with expert judgements. As hard data on risks is often lacking, the Bayesian approach is often applied in risk assessments (Bedford and Cooke, 2001).

There are several approaches that can be used to quantify uncertainties and hence estimate probability distributions. If historical data is available, aleatory uncertainties can be quantified by use of classical statistical methods by fitting a distribution function to the data. This approach is appropriate if the observational data is judged relevant and sufficiently large for the uncertainty assessment (Aven, 2012). Aleatory (and epistemic) uncertainties can also be quantified by expert opinions, however epistemic uncertainties cannot be measured (Bedford and Cooke, 2001).

Formal expert elicitation methods can be used to capture probability distributions of uncertain parameters from experts in a structured and methodologically robust way (Cooke, 1991; O'Hagan et al., 2006; Werner et al., 2017). In Paper IV, the uncertain parameters were estimated by the Sheffield Elicitation Framework SHELF (Oakley and O'Hagan, 2016). The SHELF framework elicits a single judicious consensus distribution from an expert group for each uncertain quantity. The SHELF process begins by eliciting individual judgements from each expert independently, followed by a group discussion and a group judgement. The parameters estimated in Paper IV were the lower and upper plausible limits for the uncertain quantities, as well as the median and lower and upper quartiles. The MATCH Uncertainty Elicitation Tool (Morris et al., 2014) was then used to find the best fitted statistical distribution model for the group judgment.

Monte Carlo simulations can then be used to perform the calculations needed in an assessment, e.g. calculations of net present values. A Monte Carlo simulation samples values randomly from the input probability distributions and then calculates results over and over, involving thousands or tens of thousands of recalculations (iterations), each time with a different set of random values. The simulations produce histograms (see examples in Figure 3.6) that can be fitted to probability distributions of the possible outcomes. This is beneficial since it not only provides information regarding the magnitude of the outcome, e.g. the *NPV*, but also regarding how likely each outcome is. The information from the Monte Carlo simulation can hence help decision-makers make a more informed decision on which alternative to choose. Another advantage of Monte Carlo simulations is that the data generated can easily be presented graphically, facilitating communications with decision-makers and stakeholders.

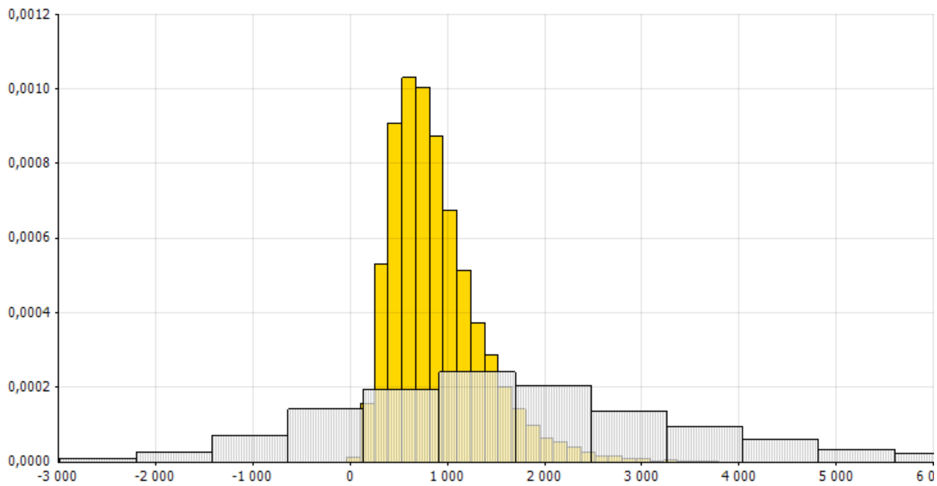

Figure 3.6 Example histograms produced by Monte Carlo simulations.

3.7 Sensitivity analysis

If a man will begin with certainties, he shall end in doubts: but if he will be content to begin with doubts, he shall end in certainties.

– Francis Bacon (1605)

It is common to combine the uncertainty analysis described above with a sensitivity analysis. A sensitivity analysis is a study of how variations in input parameters (e.g. the estimated uncertain quantities) create variations in the outputs (e.g. in the final result), with the aim to quantitatively estimate the relationship between input uncertainty and the subsequent effect on the outcome uncertainty and variability (Arriola and Hyman, 2009). This information can for example be used to support decisions on which input parameters to prioritize for further research and/or data collection in order to reduce uncertainties. These decisions should generally take the most influential input values into consideration and the cost of gaining new information. The sensitivity analyses can also provide information for a variety of other uses: e.g. to identify critical values or thresholds; to test the robustness of alternatives; to allow decision makers to select assumptions; to improve understanding of the decision model; and to assess the risks associated with specific alternatives (Pannell, 1997).

Sensitivity analyses are often confused with uncertainty analyses. But a sensitivity analysis does not express the uncertainty associated with the parameter values. However, it can be used to provide information for the uncertainty analysis by presenting the result as a function of a parameter value (Aven, 2012).

There are many different approaches to perform sensitivity analysis. In Papers I-IV, Monte Carlo simulations were used to calculate the final results using Palisade's risk analysis software @RISK. The Monte Carlo simulation facilitates sensitivity analyses by, for example, measuring the contribution of variance from each input variable to the total variance of the outcome. The results from a sensitivity analysis can be displayed in a number of different ways.

Figure 3.7 gives an example of sensitivity analysis, showing Spearman's rank correlation coefficients for input values of different sustainability criteria. The correlation coefficient is based on the monotonic relationship between the ranked values of the analyzed parameters and is express as a value from -1 to 1. A value of 0 means that there is no correlation between the input value and the result, whereas a value of 1 (-1) means a perfect positive (negative) correlation. The sensitivity analysis hence shows the importance of the different input values.

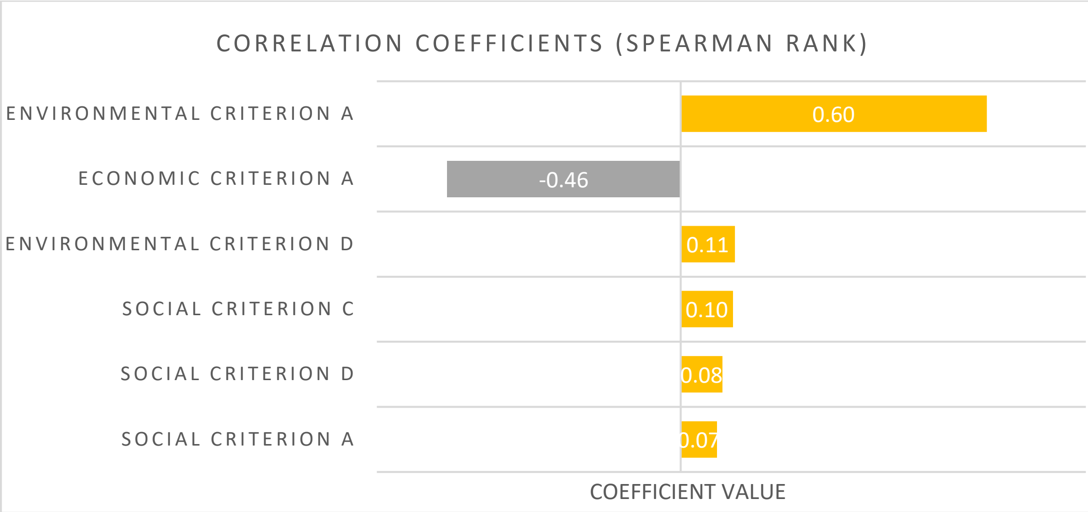

Figure 3.7 *Example of correlation coefficients of input values*.

In Papers I-IV, the impact of discount rates and time horizons were studied by scenario analysis. This means that the calculations of e.g. *NPV* were performed using different values of those parameters (e.g. 1.4%, 3.5% and 5% discount rate), representing different possible future scenarios. Scenario analysis is often used when dealing with discrete outcomes and can be used to study alternative realities over which there is no probability distribution.

4 THE PAPERS

This chapter is made up of summaries of the five papers that are part of this thesis.

4.1 Overview of the papers

An overview of the five papers included in this thesis is presented in Table 4.1. Papers I-IV provide practical examples of how established decision support methods can be further developed and applied to provide guidance on different water challenges. Papers I and II focus on how to evaluate the economic profitability and sustainability of water supply options in an inter-municipal setting, whereas Papers III and IV focus on how to evaluate the cost-effectiveness and risk reduction potential of water availability improvement measures. Paper V, on the other hand, focuses on providing necessary background data to better apply the methods developed in the other papers.

Table 4.1 Overview of the five papers included in this thesis.

PAPER	TITLE	SHORT TITLE	TYPE OF WORK
I	Cost-benefit analysis for supporting inter-municipal decisions on drinking water supply	Cost-benefit analysis	Method development and case study
II	Sustainability assessments of regional water supply interventions – combining cost-benefit and multi-criteria decision analyses	Sustainability assessment	Method development and case study
III	Marginal abatement cost curves for water scarcity mitigation under uncertainty	Cost-effectiveness analysis	Method development and case study
IV	Water supply delivery failures – a scenario-based approach to assess economic losses and risk reduction options	Risk assessment	Method development and case study
V	The value of water – estimating water-disruption impacts on businesses	Economic valuation	Survey data collection

4.2 Paper I: Cost-benefit analysis

Paper I presents a cost-benefit analysis approach to facilitate inter-municipal decisions on drinking water. Examples are given of how some key effects that may arise from regional water supply interventions can be valued economically. A special focus is given to the quantification of effects on consumers' health, water supply reliability, and operation and maintenance costs. The uncertainties of the quantified effects are represented by probability distribution functions and analyzed by means of Monte Carlo simulations. The CBA approach and economic valuation techniques are then used in a case study, the Göteborg region in Sweden, to illustrate their applicability. Paper I hence provides a detailed description of how the economic domain in the sustainability assessment model described in Paper II can be assessed.

4.3 Paper II: Sustainability assessment

Paper II presents a decision support model for assessing the sustainability of regional water supply interventions. The model is developed to meet the lack of generic decision-support adapted to the inter-municipal level that can assess economic profitability and environmental and social aspects of alternative interventions while facilitating for a structured handling of uncertainties. The model is based on multi-criteria decision analysis, with input from cost-benefit analysis. Sustainability is defined based on a set of criteria within the economic, social and environmental sustainability domains. Model results provide information on whether a specific alternative leads towards sustainable development or not, taking a reference alternative as a point of departure. Uncertainties about costs, benefits and sustainability criteria are handled by uncertainty distributions and calculations are performed by Monte Carlo simulations. The decision support model is exemplified by assessing five alternative interventions for the Göteborg region in Sweden, i.e. the same case study as in Paper I. The interventions are designed to meet the targets in the region's Regional Water Supply Plan and to illustrate decision situations regarding regionalization, (de)centralization, source water quality and redundancy.

4.4 Paper III: Cost-effectiveness analysis

Paper III presents a novel approach of constructing marginal abatement cost curves (MACC) for comparing water scarcity mitigation measures while taking the underlying uncertainties into account. The MACC is applied on the island of Gotland, one of the most water-stressed parts of Sweden, to provide the first marginal abatement cost curve in Europe for water scarcity mitigation in which municipal, agricultural, industrial and household measures are compared. The MACC shows the cost of adding or conserving water, i.e. increasing water availability by one unit, compared to a reference scenario. The measures are ranked and displayed as bars on the curve in order of cost to increase water availability, from the cheapest to the most expensive. Uncertainties in input variables are represented by probability distributions and calculations are performed using Monte Carlo simulations.

4.5 Paper IV: Risk assessment

Paper IV provides a quantitative risk assessment method for water supply disruption. A disruption in the water provision can lead to economic consequences for the water utility as well as for businesses and residential consumers, and may generate significant economic losses for society. In the paper, risk is expressed in terms of economic consequences to society arising from disruption events. The approach proposed in the paper integrates the full range of risk scenarios, from low to high probability events, to estimate the total risk of the water supply system. The purpose is to avoid sub-optimization, where risk reduction measures are prioritized based on individual events. The method is based on a combination of quantitative risk analysis and cost-benefit analysis, which enables the identification of the most economically profitable risk reduction alternatives. The paper applies a probabilistic approach with formal uncertainty analysis. The SHELF Framework is used to elicit information regarding uncertain quantities, such as the proportion of households affected in different scenarios and the frequency of events. Probability distributions are assigned to represent each uncertain quantity, and Monte Carlo simulations are used to calculate annualized risks, risk reductions and net present values. The method is exemplified by application on the island of Gotland, Sweden.

4.6 Paper V: Economic valuation

The purpose of Paper V is to gather data to improve our ability to analyze the economic consequences of short and long-term water supply disruptions, and thereby improve our assessments, comparisons and decisions on potential improvement measures. An online questionnaire is designed to gather qualitative and quantitative data on unplanned water outages from the following economic activity sectors in Sweden: A Agriculture, forestry and fishing; B Mining and quarrying; C Manufacturing; D Electricity, gas, steam and air; E Water, sewerage, waste and remediation; F Construction; G Wholesale, retail and repair of motor vehicles; H Transportation and storage; I Accommodation and food service; J Information and communication; K Financial and insurance activities; L Real estate activities; M Professional, scientific and technical activities; N Administrative and support service activities; O Public administration and defense; P Education; Q Human health and social work activities; R Arts, entertainment and recreation; and S Other service activities. The survey is distributed both by mail, to companies randomly singled out by Statistics Sweden to represent the above-mentioned economic sectors, and through trade associations' websites and newsletters. Time-dependent water resiliency factors are calculated for each of the sectors based on the survey data. The resiliency factor is defined as the ratio of maintained value added during and after a water disruption event to the value added during normal business activity.

5 RESULTS

In this chapter the results in terms of methods developed, data collected and case study applications are described.

I know that you believe you understand what you think I said, but I am not sure you realize that what you heard is not what I meant.

– Unknown

5.1 The sustainability assessment model

As described in section 2.1, the Swedish national inquiry of the public water supply system (SOU 2016:32) recommended a regionalization of the Swedish water sector, including an increase in inter-municipal cooperation. To address the lack of decision support tools adapted to the inter-municipal level, a decision support model for assessing the sustainability of regional water supply interventions was developed. Both the decision model itself and the model development, economic valuation examples and model application are important results from Papers I and II. The model, which is based on a combination of CBA and MCDA, is presented in detail in Papers I and II and a summary is presented here.

Framework and decision model structure

Figure 5.1 shows a schematic description of a framework for decision analysis where the developed decision support model for sustainability assessment is shown as the innermost (blue) parts. Sustainability is defined based on a set of criteria within the economic, social and environmental sustainability domains. Each alternative intervention is assessed relative to a reference alternative, and the decision model provides information on whether the analyzed alternative *leads towards* sustainable development or not, taking the reference alternative as a point of departure.

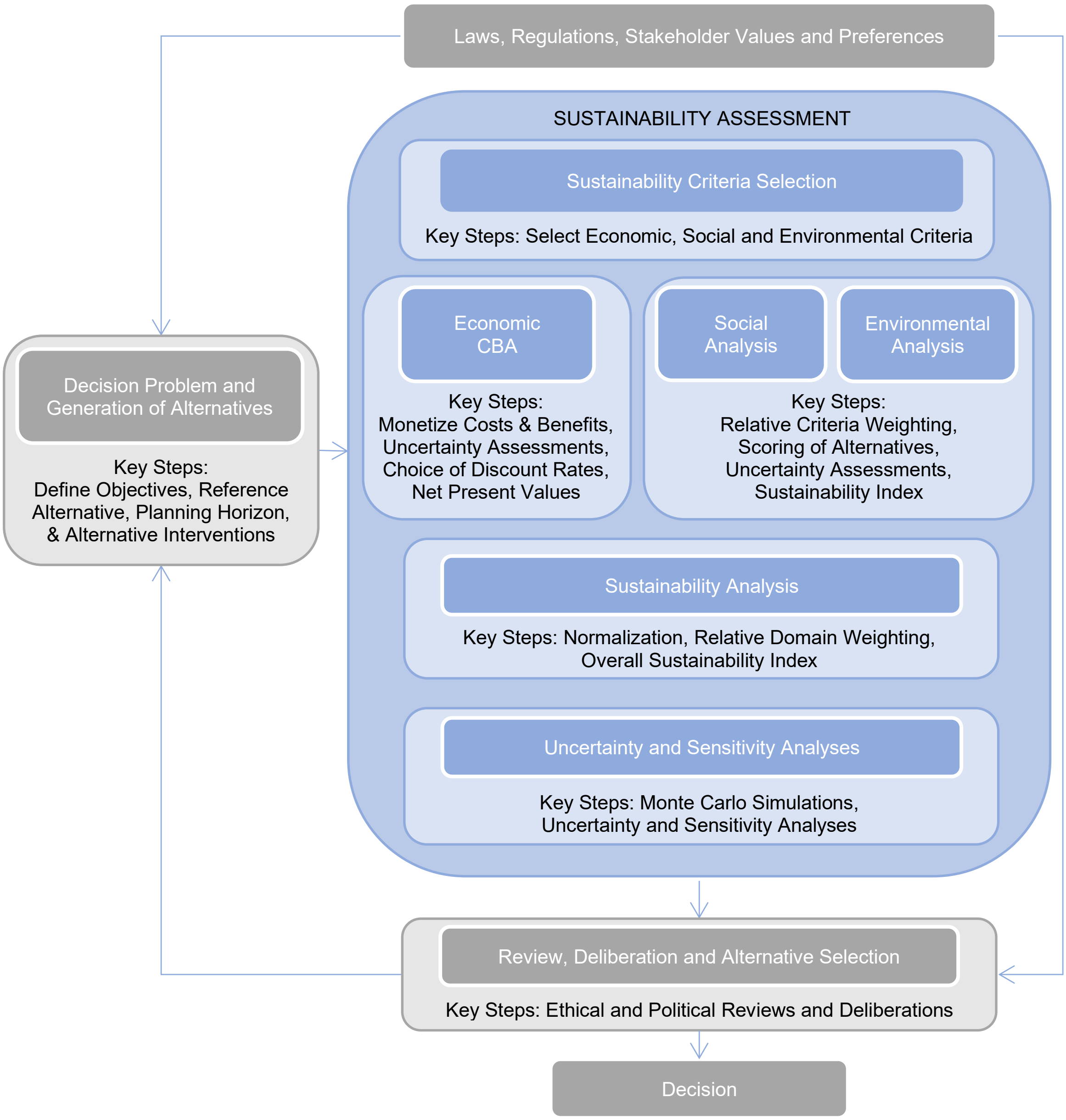

Figure 5.1 *Schematic description of a decision analysis framework, including the developed decision support model for sustainability assessment of regional water supply interventions.*

The first part of the sustainability assessment involves a selection of criteria, based on which the alternative interventions are to be evaluated. To aid in that selection, a generic list of sustainability criteria for regional interventions was developed in collaboration with stakeholders and experts from the Göteborg region in Sweden (Table 5.1).

Table 5.1 Generic set of sustainability criteria.

DOMAINS	CRITERIA	DESCRIPTION
Social	Equity	Effects on equity regarding if some consumers and/or municipalities are made worse off by the alternative.
	Health	Effects on human health due to insufficient source water quality, quantity, water treatment, distribution and/or emergency preparedness.
	Consumers' trust	Effects on consumers' trust in the water providers.
	Access and participation	Effects with regard to public access and participation in water supply planning and decision-making.
Environmental	Energy use at construction	Total energy use at construction.
	Energy use at production and distribution	Total energy use at production and distribution.
	Water use	Effects on water use in production and distribution, e.g. water reuse, alternative water use and leakage.
	Materials for construction	Use of non-renewable materials for construction.
	Chemical use	Effects on total chemical use in water production.
	Non-recyclable waste	Production of non-recyclable waste.
	Aquatic ecosystems	Effects on aquatic ecosystem viability due to quality and/or quantity changes in water resources.
	Terrestrial ecosystems	Effects on terrestrial ecosystem viability due to e.g. land use changes.
Economic	Economic profitability	Economic profitability assessed by means of CBA.

Effects in the social and environmental sustainability domains are assessed based on the MCDA procedures of scoring and weighting (see further description in Paper II and section 3.4). The assessment principles are based on stakeholders' involvement and value judgements followed by an aggregation of preferences across the criteria. A probabilistic approach is used to enable a structured handling of uncertainties regarding the performance of the alternatives. In relation to a reference alternative, the minimum, most likely (mode), and maximum scores are therefore estimated for each criterion on a scale from -10 to 10. These estimates are then input parameters in Beta PERT probability distributions (Malcolm et al., 1959) to represent the uncertainties of the scores. A simple scoring aid of guiding matrices was developed to facilitate uniform scoring. By using a linear additive model, a social and environmental sustainability index are calculated for each alternative as the weighted sum of the scores on all criteria of the specific sustainability domain.

To account for ethical pluralism, the economic effects are analyzed by use of CBA (see further description in Paper I and section 3.1). In a CBA, the benefits of an intervention are compared to its costs (again in relation to a reference alternative). Future costs and benefits are expressed in present values using specified discount rates, whereby net present values and thus economic profitability can be calculated for each alternative. In a similar way as the list of generic sustainability criteria was generated, a list of generic costs and benefits for regional interventions was also developed (Table 5.2). The provision of generic lists of criteria and costs and benefits, facilitates the identification of potential consequences so that effects that are normally overlooked in evaluation processes can be explicitly considered and openly addressed. It further reduces the risk of double counting effects when evaluating alternative interventions. Paper I provides examples of how some of the costs and benefits can be estimated in monetary terms. Uncertainties regarding cost and benefit estimates are expressed by lognormal probability distribution functions (Garvey et al., 2016).

Table 5.2 Potential costs and benefits of regional water supply interventions.

CRITERION	COST & BENEFIT ITEMS	EXAMPLES
Economic profitability	Water utility costs and benefits	Investments
		Operational and maintenance costs
		Other costs and benefits for water utilities
	Effects of water supply reliability	Lost value added in economic sectors
		Losses for residential consumers
	Water related health effects	Costs for healthcare
		Lost production
		Discomfort and loss of life
	Effects on ecosystem services	Drinking water
		Irrigation
		Hydropower
		Industrial water use
		Recreational activities
		Flood & erosion risk reduction
		Retention of contaminants
		Other ecosystem services
	Effects on agriculture, forestry and industry due to water protection restrictions	Agricultural, forestry and industrial production
		Other effects on agriculture, forestry and industry due to water protection restrictions

After assessments of the social, environmental and economic effects, the alternative interventions can be ranked within each sustainability domain by their sustainability indexes and *NPVs* respectively. In order to calculate an overall sustainability index, which takes all domains into account, the domains must first be comparable and assessed on a common scale. In the proposed decision model, this is done by normalizing the economic domain so that the *NPVs* are transformed to a similar unit-less scale as the social and environmental sustainability indexes, i.e. ranging from -10 to 10. The overall sustainability index *S* can then be calculated for each alternative (*a*) using a linear additive model:

$$S_a = W_{Env} S_{Env,a} + W_{Soc} S_{Soc,a} + W_{Eco} S_{Eco,a} \quad (5\text{-}1)$$

where *W* is the relative weight of each domain, S_{Env} and S_{Soc} are the environmental and social sustainability index, and S_{Eco} is the normalized *NPV* given by:

$$S_{Eco,a} = 10 \frac{NPV_a}{Max\ (|P05(NPV)|, |P95(NPV)|)} \quad (5\text{-}2)$$

Case study site

The sustainability decision model provided in Paper II and the economic valuation examples provided in Paper I were both exemplified by application in the Göteborg region in Sweden (Figure 5.2). The Göteborg region consists of 13 municipalities and has about one million inhabitants. The region's drinking water is supplied from 30 water treatment plants, of which 12 are supplied by surface water, 15 by groundwater and 3 by artificially recharged groundwater. About 75% of the source water in the region comes from the river Göta älv. Göta älv, which flows from Lake Vänern to the City of Göteborg, has a varying water quality and is considered particularly exposed to effects of climate changes, e.g. increased risks of flooding, landslides, erosion, increased sea levels and varying storm water quality. The large dependence on Göta älv together with the river's exposedness and the overall insufficient ability in the municipalities to replace their main source waters with supplementary water if necessary, contributes to making the region's water supply vulnerable (GR, 2014).

The five alternative interventions analyzed in Papers I and II were designed to meet the nine regional targets of the Göteborg region's Regional Water Supply Plan (GR, 2014) and to illustrate general decision situations regarding regionalization, (de)centralization, source water quality and redundancy, see Table 5.3.

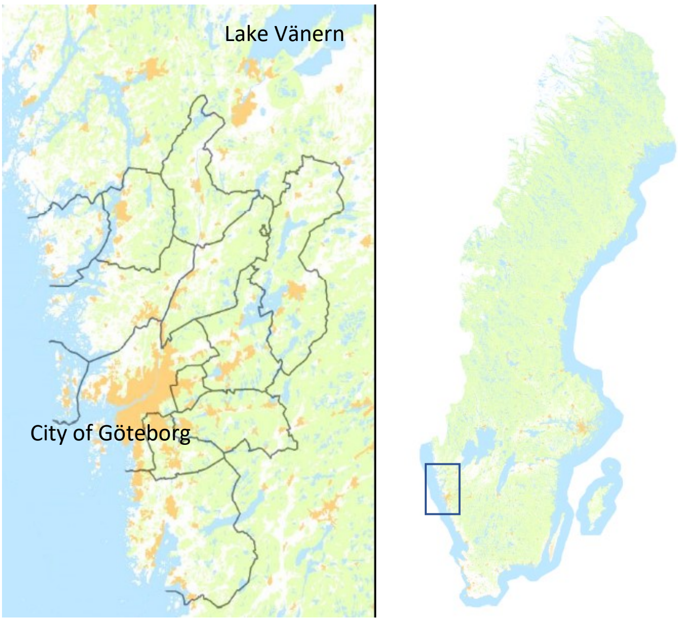

Figure 5.2 *The 13 municipalities of the Göteborg region (left) and their position in Sweden (right), © Lantmäteriet.*

Table 5.3 *Description of alternative interventions evaluated for the Göteborg region.*

ALTERNATIVE INTERVENTIONS	DESCRIPTION
A1: Regionalized governance & centralized production from lake Vänern	Sweden's largest lake, Vänern, is the main source water for the entire region. Water is led in a tunnel from Vänern, which is located outside the region, to the City of Göteborg where it is treated and then distributed throughout the region. One single drinking water organization operates the production. Water protection areas and restrictions for prior source waters cease to exist.
A2: Regionalized governance & centralized production from the river Göta älv	The river Göta älv is the main source water for the entire region. The water is treated in the City of Göteborg from which it is distributed throughout the region. One single drinking water organization operates the production. Water protection areas and restrictions for prior source waters cease to exist.
A3: Regionalized governance & maintained semi decentralized production	Current water treatment plants, source waters and water protection areas are maintained. One single drinking water organization operates the production within the different municipalities.
A4: Maintained governance & decentralized groundwater dependent production	Current water treatment plants, water protection areas and source waters, except Göta älv, are maintained. The source waters are supplemented with increased/new withdrawals from several groundwater resources as well as some lakes. New water protection areas and restrictions are established for the new source waters.
A5: Maintained governance, with additional source waters and treatment plants	Current water treatment plants, source waters and water protection areas are maintained. The current system is expanded with two new water treatment plants and an increased proportional use of the region's largest lakes.

Case study results

Monte Carlo simulations were used to calculate the identified cost and benefit items for the alternative interventions, as well as the alternatives' *NPVs*, social and environmental sustainability indexes and overall sustainability indexes. The simulations were based on 10,000 iterations, which was considered a sufficient number to achieve robust results since the variation between repeated simulations was small and did not affect the interpretation of the results. Monte Carlo simulations were also used for sensitivity analysis. Since the interventions were assessed relative to a reference alternative, the alternatives performing worse than the reference alternative have a negative sustainability index/*NPV* and alternatives performing better than the reference alternative have a positive index/*NPV*.

The CBA outcome is presented in Figure 5.3, indicating that the two alternatives with a regionalized water utility and centralized drinking water production (A1 and A2) were the least economically profitable alternatives. The alternative with highest average *NPV* (A3) was that of a maintained production and regionalized utility. However, as discussed in Papers I and II, alternative A3 may have benefited from the model for estimating operating and maintenance costs compared to the other options. As also shown in Figure 5.3, there is a large difference between the alternatives on how certain (or uncertain) the information used to estimate the net present values are.

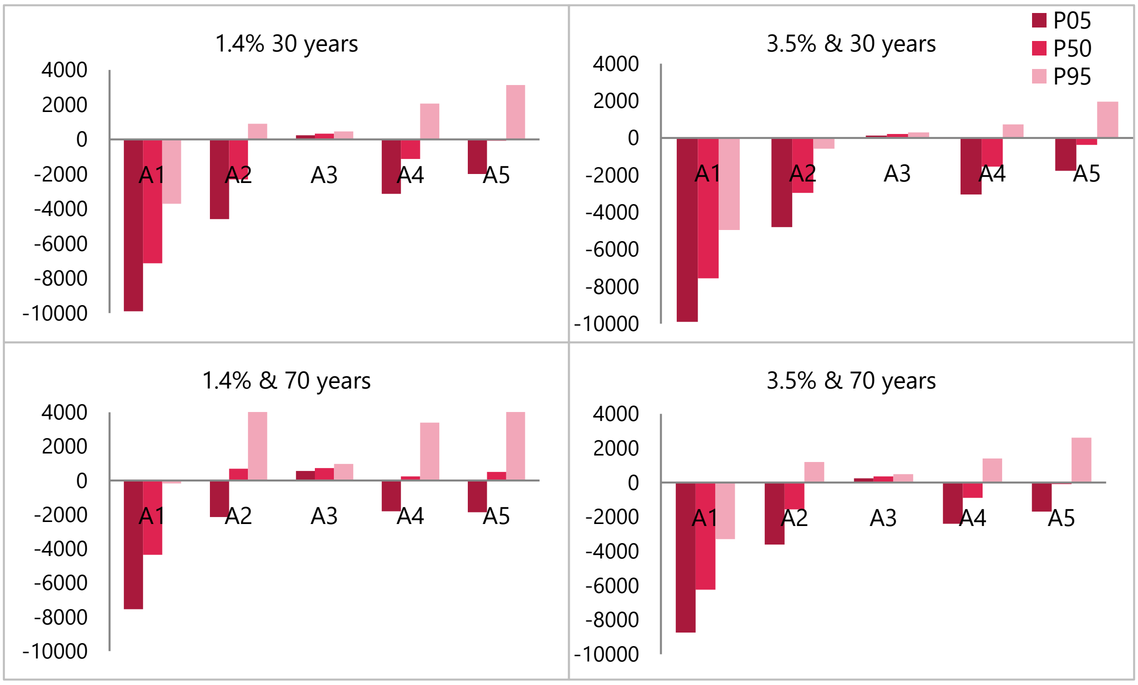

Figure 5.3 P05, P50 and P95 net present values of the five alternatives evaluated for the discount rates 1.4% and 3.5%, and the time horizons 30 years and 70 years (MSEK).

The results from the criteria weighting shows that health and consumers' trust were seen as most important among the social criteria, whereas aquatic and terrestrial ecosystems along with water use and energy use at production and distribution were seen as most important among the environmental criteria. As shown in Figure 5.4, all alternatives were expected to contribute to an increased social sustainability. This was mostly due to an expected increase in consumers' trust for the regionalized alternatives (A1-A3), and a slightly expected increase within the health criterion in the other two alternatives (A4 and A5). Within the environmental domain, the groundwater based alternative (A4) was expected to lead to the highest increase in sustainability, and the centralized alternative with a long source water tunnel (A1) was expected to lead to largest decline in environmental sustainability. This was in large part due to positive and negative effects, respectively, on aquatic ecosystems.

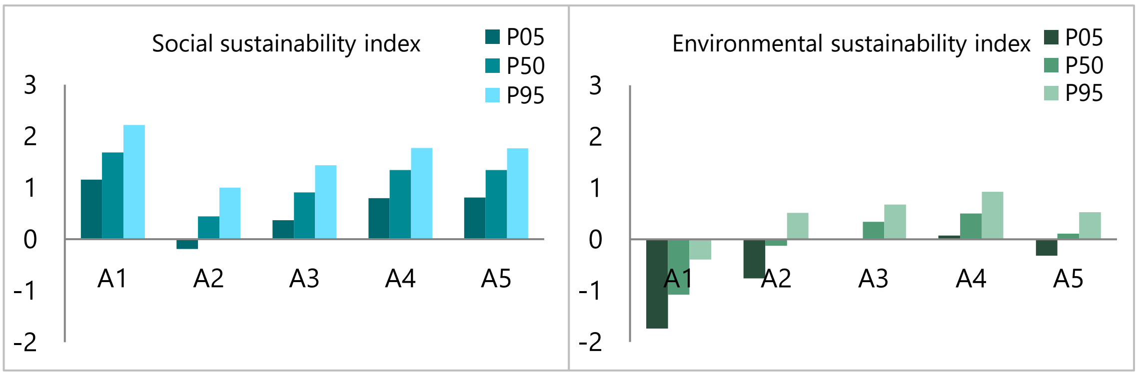

Figure 5.4 P05, P50 and P95 of social (left) and environmental (right) sustainability indexes.

As shown above, the results from the decision model can be used to rank alternative interventions from the most preferred to the least preferred within each sustainability domain and, as shown in Paper II, with regards to all domains combined. The probabilistic approach used in the model enables a structured handling of the uncertainties in all three domains, facilitating calculations of e.g. probabilities that alternatives exceed certain cost limitations or environmental threshold values. Another valuable feature of the probabilistic approach is that it enables calculations of the probability that each measure will perform best within each sustainability domain and with respect to all domains. Figure 5.5

As shown in Figure 5.5, the centralized and regionalized alternative A1 has the highest probability of being the best solution with respect to the social criteria whereas the groundwater dependent alternative A4 has the highest probability of being best solution with respect to the environmental criteria. However, when combining all the three sustainability domains (with equal weight), the regionalized alternative with maintained production (A3) shows the highest probability of being the overall best solution.

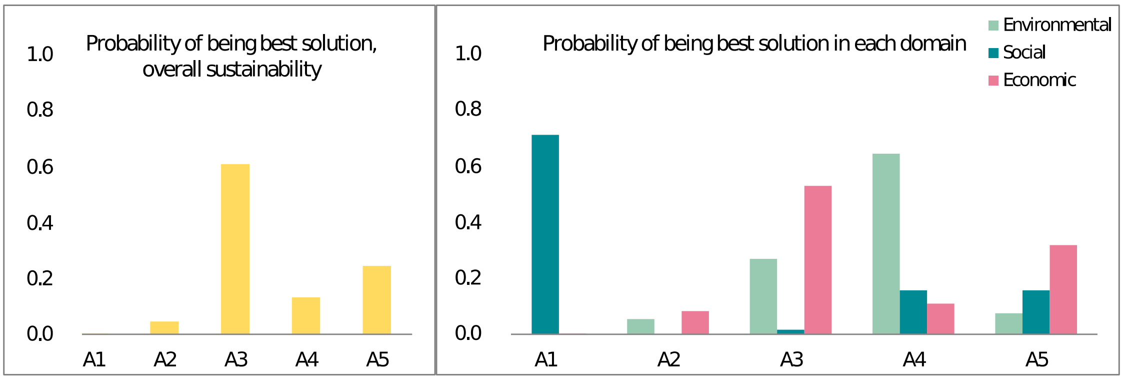

Figure 5.5 *Probability that each alternative is the best solution in each sustainability domain (left) and in all domains combined (right).*

The decision model provides a novel way of presenting monetized benefits and costs with non-monetized social and environmental effects, capturing both utilitarian aspects of the alternative interventions as well as aspects based in the deontological theories of moral ethics. The model can be used by decision-makers to develop coherent preferences within economic, environmental and social sustainability so that decisions on regional water supply interventions can be taken with a higher degree of confidence. In addition, communication between decision-makers, stakeholders and the community is facilitated by the organized and transparent treatment of uncertainties. By integrating stakeholders in the decision-making process, the likelihood of viable and accepted decisions is increased.

5.2 Marginal abatement cost curves

As pointed out in section 2.3, large attention has been given to water scarcity and drought in Sweden in recent years. Among other things, discussions have focused on how we can be better prepared for the next dry periods, how we should use and manage our water resources, and which measures to prioritize in the effort to increase water availability.

As improved water availability can be reached in many different ways, by contribution from several societal sectors, there was a need for a shared starting point for cross-sectoral dialogue. To address this need, a decision support tool for comparing cost-effectiveness and potentials of municipal, agricultural, industrial and household mitigation measures was developed in Paper III. The tool is based and on the marginal abatement cost curve (MACC) approach (see further description in section 3.3), and the main focus in the development was to provide a systematic handling of the uncertainties involved.

Case study site

The MACC was applied on the island of Gotland, one of the most water-stressed areas of Sweden. Gotland is with its 3,000 km^2 Sweden's largest island. It is located in the Baltic Sea about 100 km from the mainland and it is one of the most popular tourist summer destinations in the country. The number of people who live on Gotland all year round is about 58,000, just a fraction of the vast number of visitors each year. The peak season for tourism is during the summer, resulting in a large seasonal variation in water demand and with the highest demand occurring when water supplies are at their lowest.

The large variation in water demand is coupled with a generally low water availability and high precipitation run-off due to thin soil layers, extensive agricultural drainage, and lack of coherent reservoirs in the sedimentary limestone bedrock. The water supply system has a large proportion of private solutions, with only 67% of the households connected to the public water supply system. In addition to an already constrained water supply situation, the total water demand on the island is predicted to increase by more than 40% through to 2045 (Eklund, 2018), see Table 5.4.

Table 5.4 Recent and forecasted water demand on the island of Gotland (Eklund, 2018).

SECTOR	WATER USE IN 2015 (Mm^3/year)	PREDICTED CHANGE TO 2045	PREDICTED DEMAND IN 2045 (Mm^3/year)
Households			
• Municipal water	2.5	+20%	3
• Private water	1.2	+20%	1.4
Animal keeping			
• Municipal water	0.2	+100%	0.4
• Private water	1.3	+5%	1.4
Tourism etc.			
• Municipal water	1.3	+30%	1.7
• Private water	NA	NA	NA
Industry			
• Municipal water	0.3	+100%	0.6
• Private water	5.8	+10%	6.4
Irrigation	5.0	+100%	10
Total	17.6		24.9

Case study results

A multidisciplinary expert workshop was held to find a relevant subset of measures to be analyzed and compared for the island of Gotland. The final list of measures included in the study is provided in Table 5.5. The measures aim to either increase the water supply or to decrease the water demand.

Table 5.5 List of measures, aimed at increasing supply (S) and decreasing demand (D), included in the study.

SECTOR	MITIGATION MEASURE	SHORT DESCRIPTION
Municipality	Leakage detection (S)	Extended active leak detection efforts using district-metered areas, in which the flow is univocally measured.
Municipality	Desalination (S)	Reverse osmosis desalination and transport of treated water to demand centers.
Municipality	Surface water extraction (S)	Increased surface water extraction.
Municipality	Groundwater extraction (S)	Increased groundwater extraction.
Municipality	Artificial recharge (S)	Artificial groundwater recharge in existing water supplies.
Municipality	Wastewater for irrigation (S)	Improved wastewater treatment with UV for irrigation.
Household	Rainwater harvesting (S)	Collection and treatment of rainwater to drinking water quality at single household units.
Household	Small scale desalination (S)	Collection and treatment of seawater to drinking water quality at single household units.
Household	Vacuum toilets (D)	Installation of vacuum toilets in single households.
Household	Greywater reuse (D)	Installation of greywater treatment techniques for non-potable reuse in single households.
Agriculture	Sub irrigation (large scale) (S)	Implementing controlled drainage and sub irrigation by regulating the riser in the drain outlet. Permit required.
Agriculture	Sub irrigation (small scale) (S)	The same measure as above but without permit requirement.
Agriculture	Irrigation dams (S)	Collection of precipitated water in irrigation dams.
Agriculture	Ramp irrigation (D)	Conversion from traditional irrigation methods to water-saving irrigation techniques.
Industry	Reuse of mining drainage water (S)	Treatment of mining drainage water to drinking water quality and use within the municipal water supply system.
Industry	Saltwater pools and toilets at campsites (D)	Conversion from freshwater to seawater in campsite pools and toilets.
Industry	Retrofit showers and taps at hotels (D)	Retrofitting showerheads and bathroom faucets with water saving devices.

In Figure 5.6, the marginal costs of increasing water availability are presented for the analyzed measures along with the water availability potential of each measure. As described in section 3.3, the measures in a MACC are ranked in order of marginal costs with the most cost-effective measures displayed to the left. Hence, as shown in the MACC below, the analyzed household measures were the least cost-effective for Gotland. The most cost-effective measure, retrofitting showerheads and faucets at hotels, was financially beneficial due to the energy savings that came with reducing warm water usage. However, it is important to point out that the marginal costs are based on site-specific conditions and the investments required on those specific sites in order for the improved water availability to reach its intended use. For example, if new pipelines are needed for desalinated water to reach intended towns, the costs of piping are included in the marginal costs. The largest water availability potential was associated with increasing the number of irrigation dams on the island. Of the municipal measures, an increased groundwater extraction and desalination had the largest potential.

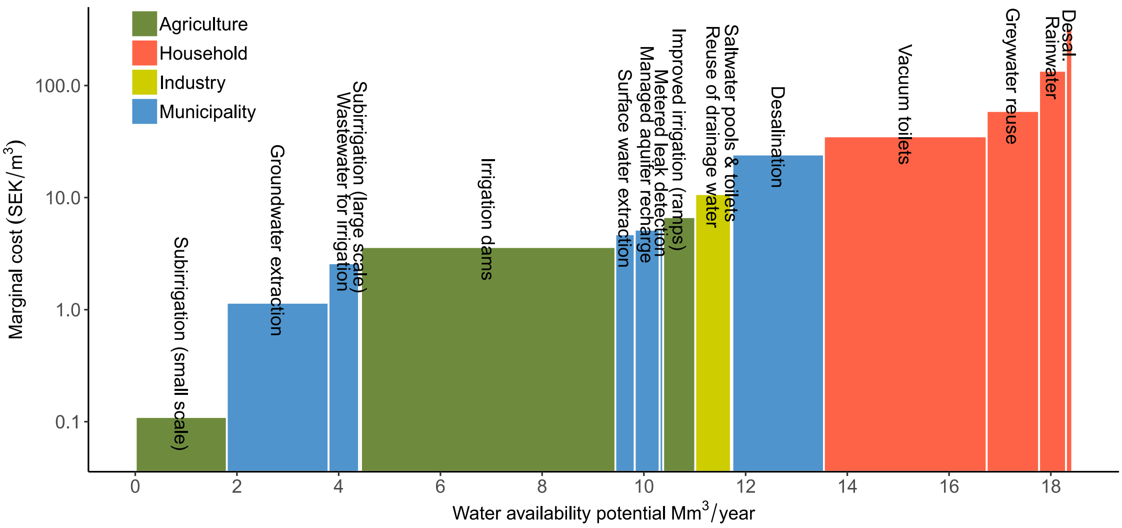

Figure 5.6 *Marginal abatement cost curve for agricultural, household, industrial and municipal measures based on mean values at a 3.5% discount rate (note the logarithmic scale on the y-axis).*

Uncertainties associated with cost items, water availability potentials and other input data were represented by probability distributions, and calculations were performed by Monte Carlo simulations (10,000 iterations). As mentioned in Paper III, uncertainties are commonly not considered in MACCs and there is no commonly applied approach for uncertainty and sensitivity analysis. The probabilistic approach proposed in Paper III enables a thorough uncertainty analysis where the variation in estimated water availability and cost can be assessed and thus the robustness of the measures evaluated. The range of uncertainties associated with the marginal costs is shown in Figure 5.7 by the 5th, 50th and 95th percentiles.

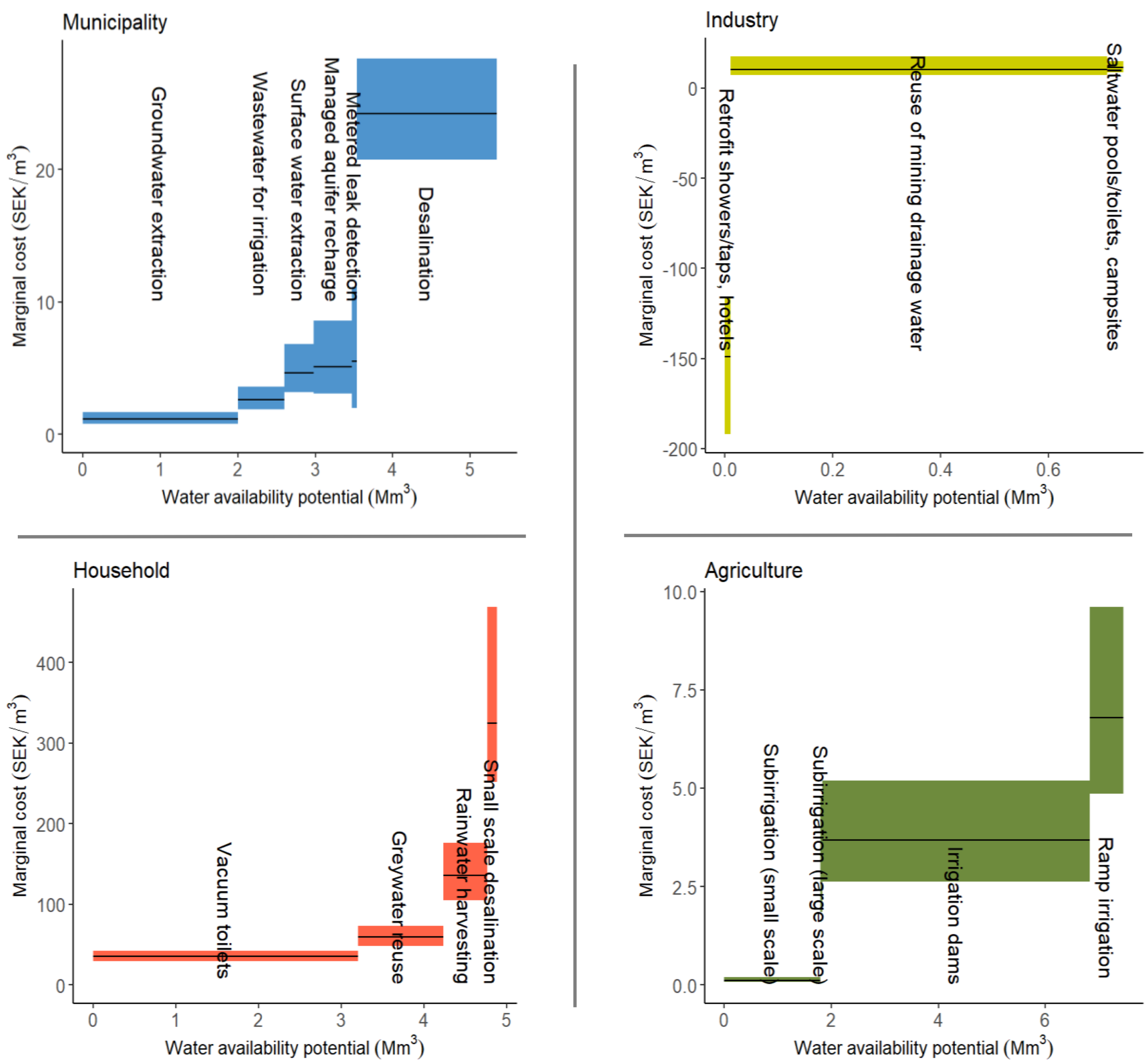

Figure 5.7 *Marginal, agricultural, household and industrial measures, percentiles P05, P50 and P95 with a 3.5% discount rate.*

The coefficient of variation (CV), i.e. the ratio of the standard deviation to the mean, was used to compare the uncertainties associated with each measure, independent of their marginal cost, see Figure 5.8. The CVs for the analyzed measures are between 0.10 and 0.74. Of the municipal measures, metered leak detection with a CV of 0.49 was associated with the largest uncertainties. In the household, industry and agriculture sectors, small-scale desalination (0.74), reuse of mining drainage water (0.32), and small-scale sub-irrigation (0.34), respectively, were the measures associated with the greatest uncertainties. Furthermore, correlation coefficients of the measures were used to assess which input variables had the greatest effect on the outcome uncertainty.

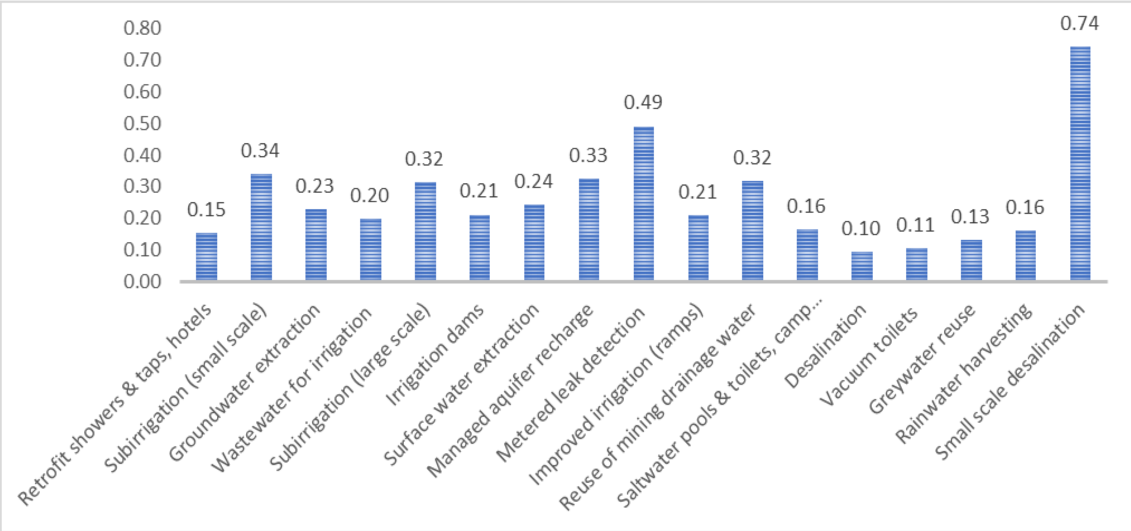

Figure 5.8 *Coefficient of variation for all analyzed measures.*

As shown in the results above, a MACC for water scarcity mitigation provides an informative tool that can be used to guide municipalities, households, farmers and businesses as well as regional and national authorities. Improving previous MACC formats by incorporating a systematic handling of uncertainties, offers the public and private managers an opportunity to attain a higher level of water security and to do so cost-effectively in a well-informed manner. A MACC can set the scene for targeted measures and strategic investments, along with a better decision-making basis on the societal level for determining which measures and sectors to prioritize from a cost-effectiveness perspective. In addition to guidance on measures, the results can also enable identification of areas in which policy instruments are needed to facilitate implementation.

5.3 Scenario-based risk assessment

As discussed in section 2.1, the water supply systems are subject to a wide range of threats which may affect their ability to provide water to society. Disruptions in water provision may for example occur due to events related to the raw water systems, the treatment systems and/or the distribution systems. Paper IV presents a scenario-based risk assessment approach that enables estimates of the total risk of water supply disruption, by integrating the full range of possible outcomes from low to high probability events (see further in section 3.5). The purpose is to avoid sub-optimization when prioritizing between risk reduction measures. The same case study site as used in Paper III, i.e. the island of Gotland in Sweden, is also used in Paper IV.

Case study results

The risk is defined as a function of a set of scenarios, the frequency with which they occur and the economic consequences if they occur. To capture the range of low and high probability events, six risk scenarios were identified around the question *What can pose a challenge to maintain a continuous municipal water supply provision on Gotland?*, see Table 5.6. The scenarios were identified together with the municipality's water supply strategists.

Table 5.6 Scenario summaries.

SCENARIO	SUMMARY
Scenario 1	One of the smaller towns (with approximately 400 inhabitants) experiences failure in the water supply provision. This can be caused by failures in either the distribution system, the raw water system or the treatment system. The municipality transports water by truck to the town.
Scenario 2	The water availability on the small, adjacent island of Fårö is too low during summers to meet demand. The municipality transports water to the island. The amount of water trucked varies over the summer months with the number of tourists on the island.
Scenario 3	Due to low precipitation, the raw water quantity is insufficient going towards the summer months. The municipality prohibit urban irrigation and call for careful use of the drinking water.
Scenario 4	A failure in connection to the municipality's desalination plant makes it unable to provide water to consumers. The nearby groundwater resource is used as a backup. The amount of available groundwater is however not sufficient, and households, summer tourists and businesses in that region have to make due with a reduced water quantity.
Scenario 5	One of the larger towns (with approximately 1,500 inhabitants) experience failure in the water supply provision. Again, this can be caused by failures in either the distribution system, the raw water system or the treatment system. The municipality transports as much water as possible to the town, but households and businesses in that town have to make due with a reduced water quantity.
Scenario 6	Due to a severe drought, neither the groundwater nor the surface water resources are sufficiently replenished. Households and businesses on the whole of Gotland have to make due with a significantly reduced water quantity.

By use of formal expert elicitation, using the Sheffield Elicitation Framework SHELF (Oakley and O'Hagan, 2016), frequencies and consequences of the risk scenarios could be estimated. Figure 5.9 shows the estimated annual risk for the reference alternative R_0 in the form of staircase to the left and as a risk curve to the right, showing the mean and P05 and P95 frequency percentiles. The low-frequency events were generally associated with larger economic consequences than the high-frequency events.

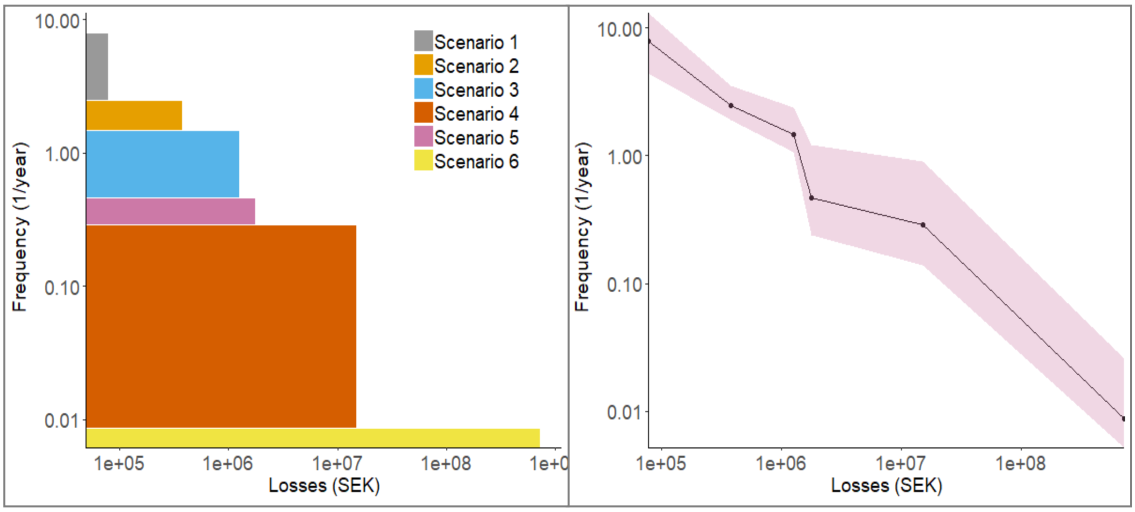

Figure 5.9 *Estimated annual risk of the reference alternative for analyzed scenarios in the form of staircase (left), and in the form of a risk curve showing the mean values and frequency percentiles P05 and P95 (right). Note that the curves are plotted on log-log scales with cumulative frequencies.*

Four alternative measures were analyzed for their potential to reduce the estimated annual risk of the reference alternative (Table 5.7). The top three measures in the table were also part of Paper III, in which their cost-effectiveness and water availability potential were estimated. However, it should be noted that the measures analyzed in Paper IV focused on reducing risks associated with the raw water system, and little attention was given to improving the treatment system or the distribution system.

Table 5.7 *Alternative risk reduction measures.*

MEASURE	SUMMARY
MAR	Managed aquifer recharge (MAR) in nine of the municipality's existing well fields. In total, an additional 490,000 m^3 is made available annually.
GW	Increased groundwater extraction (GW) from three groundwater resources on Gotland. In total, an additional 2 million m^3 is made available annually.
SW small	Increased surface water extraction (SW small) from one of the surface water resources on the island. In total, an additional 380,000 m^3 is made available annually.
SW large	Increased surface water extraction (SW large) from one of the surface water resources on the island. In total, an additional 4.7 million m^3 is made available annually.

In Figure 5.10, the risk curves of the alternative measures are shown alongside the risk curve of the reference alternative. The potential risk reduction of the measures is the difference between the risk curve of the reference alternative and those of the measures. The large-scale surface water measure (SW large) was shown to reduce the total annual risk the most, suggesting a potential reduction of approximately 6 million SEK annually compared to 965,000 SEK for groundwater, 785,000 SEK for MAR, and 307,000 SEK for the small surface water measure (mean values).

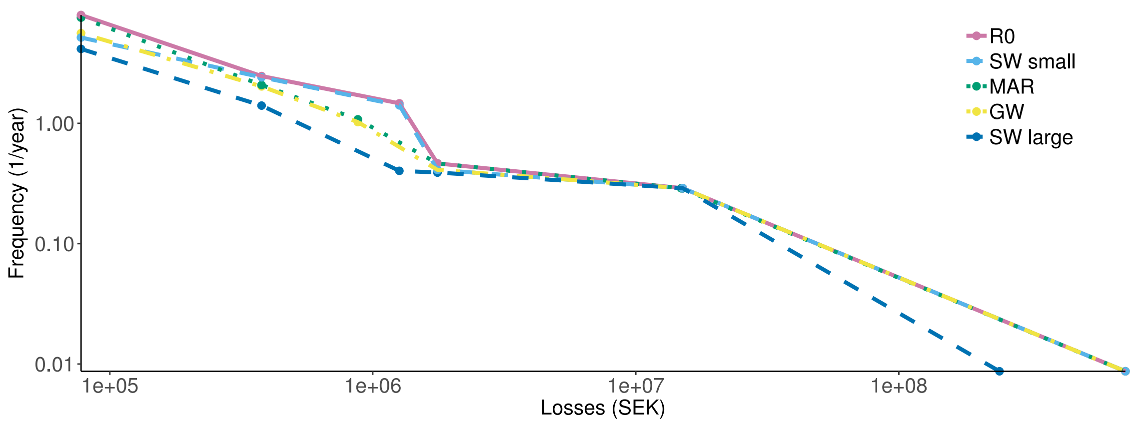

Figure 5.10 *Risk curves for analyzed risk reduction measures over all scenarios (mean values). Note that the curves are plotted on log-log scale with cumulative frequencies.*

As the purpose of the study was to address the topic of optimizing measures based only on individual threats, the following two figures present results both broken down into single risk scenarios and for all scenarios combined. In Figure 5.11, the probability that each measure will reduce the risk the most is shown for the respective scenarios. As noted above, the SW large measure has the highest probability to reduce the total risk the most. However, since the ranking of the measures differ between scenarios, a decision based only on threats related to e.g. scenario 1, 2 or 4 would not necessarily have prioritized that measure.

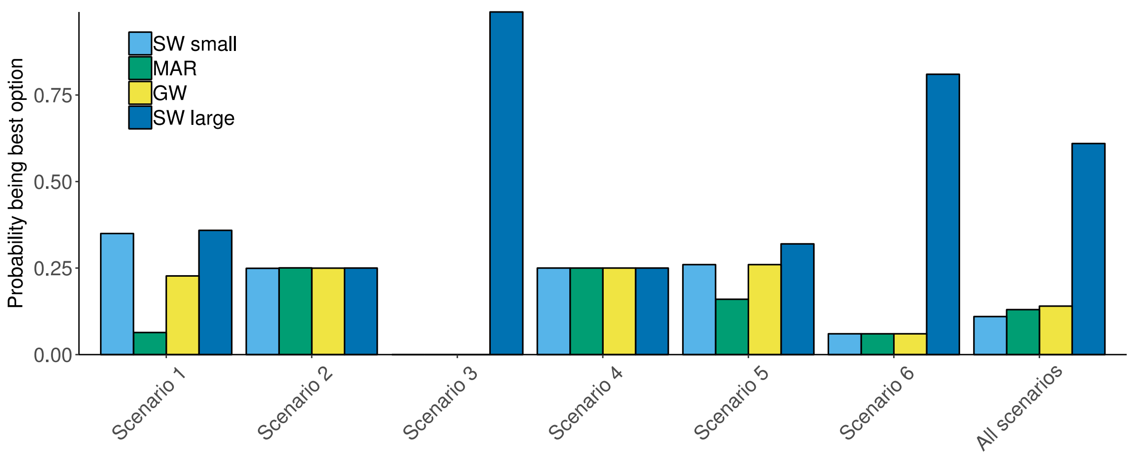

Figure 5.11 *Probability that each measure is the best option with respect to risk reduction for each individual scenario and combined for all scenarios.*

The same reasoning goes for the results provided in Figure 5.12, in which the net present values of the measures are provided with respect to each individual scenario and to all scenarios combined. Here it is shown that SW large is the least economically beneficial measure if only addressing threats related to scenario 1, 2, 3, 4 or 5. However, by taking all risks (and potential risk reductions) into account, this measure proves to be the most economically beneficial measure. This is due to the measure's high implementation cost in and its large risk reduction effect on several of the scenarios. The combined effect of these risk reductions creates a large benefit when analyzing all scenarios together. It is worth noting that the net present values are based only on implementation costs and the benefits of risk reduction. The *NPV* results can therefore be improved by inclusion of other relevant costs and benefits, but the present result is sufficient to highlight the importance of a holistic view when prioritizing between risk reduction measures.

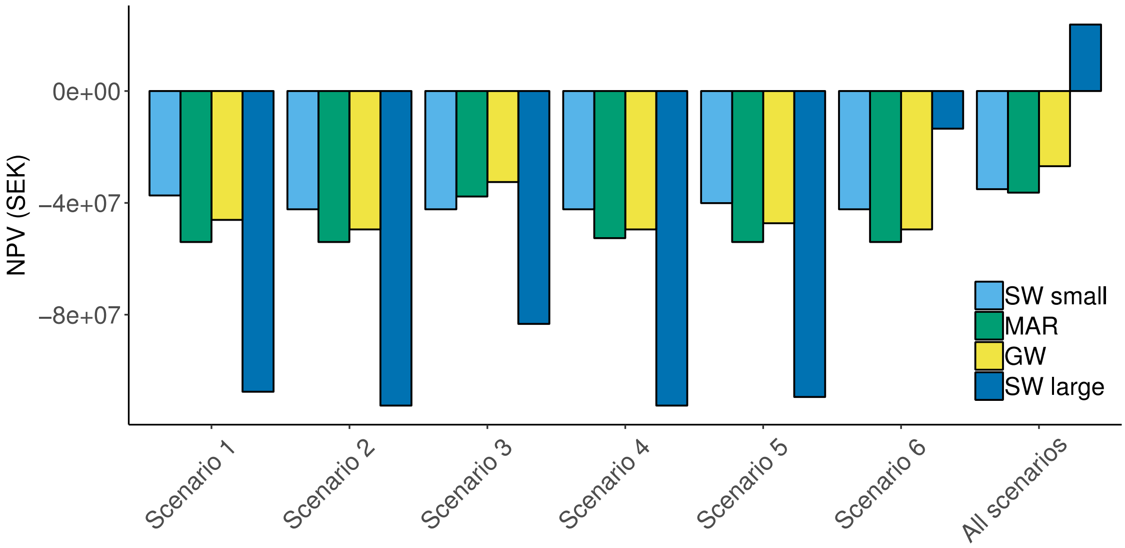

Figure 5.12 *Net present values for measure implementation with the annual benefit of risk reduction for each individual risk scenario and for all scenarios combined, over a 50-year time horizon and with 3.5% discount rate (mean values).*

In Figure 5.13, the degree to which input variables co-vary with the calculated total risk is expressed using Spearman rank correlation coefficients between −1 and 1. Only the eight most strongly correlated input variables are provided. The figure reveals that input variables related to the return periods and duration of the risk scenarios contributed more to the outcome uncertainty than input parameters related to the economic consequences of the scenarios. This type of analysis is valuable to help decision-makers prioritize which variables to be aware of and which needs more data gathering to reduce uncertainties. Similar assessments are made in each of Papers I to IV.

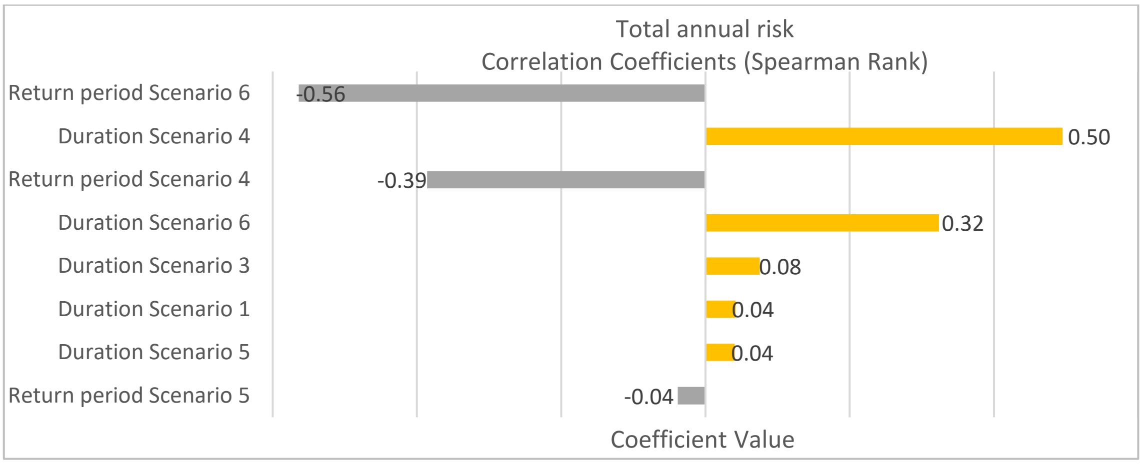

Figure 5.13 *Correlation coefficients (Spearman rank) of the eight most strongly correlated input variables for the total annual risk.*

In the risk-based approach proposed in Paper IV a range of scenarios can be evaluated, thus helping decision-makers become aware of the strengths and weaknesses of their water supply system. An increased knowledge of the risks allows for an understanding of how to address the threats and can be used as a starting point for identifying risk reduction measures. Alternative measures can then be compared based on their risk reduction capacities, demonstrating whether they reduce the frequencies and/or the consequences of identified risk scenarios. The approach highlights the importance of considering the full range of possible outcomes. Some advantages of evaluating the total risk based on the full spectrum of scenarios relate to the risk-based decision making, as the ranking and prioritization of risk reduction measures may vary depending on whether the measures are evaluated with respect to single or multiple low and/or high probability events.

5.4 Water-disruption impacts on businesses

Paper V focused on estimating changes in value added due to short and long-term water supply disruption for Swedish economic activity sectors. The purpose was to provide data to improve assessments, comparisons and decisions on measures aiming to reduce the risk of future water disruption events. The paper made use of an online questionnaire, in which companies were asked to estimate potential changes in value added during and after water disruptions lasting for 2 hours, 4 hours, 12 hours, 24 hours, 1 week, and 1 month respectively.

Figure 5.14 shows the average reduction in value added in the non-manufacturing sectors and Figure 5.15 shows the results for the manufacturing sectors. Food, beverage and tobacco along with Accommodation and food services proved to be the two most affected manufacturing and non-manufacturing sectors, respectively, based on mean values. The Forestry sector was the overall least affected.

A fairly large proportion of the companies answered that they can maintain a normal business activity (100% value added) throughout a water outage: 48% of all companies during a 2-hour disruption; 26% during a 12-hour disruption; and 16% of all companies during a one-month disruption. However, there were also several companies responding that they could not recover at all from the longer disruptions and would have to file for bankruptcy.

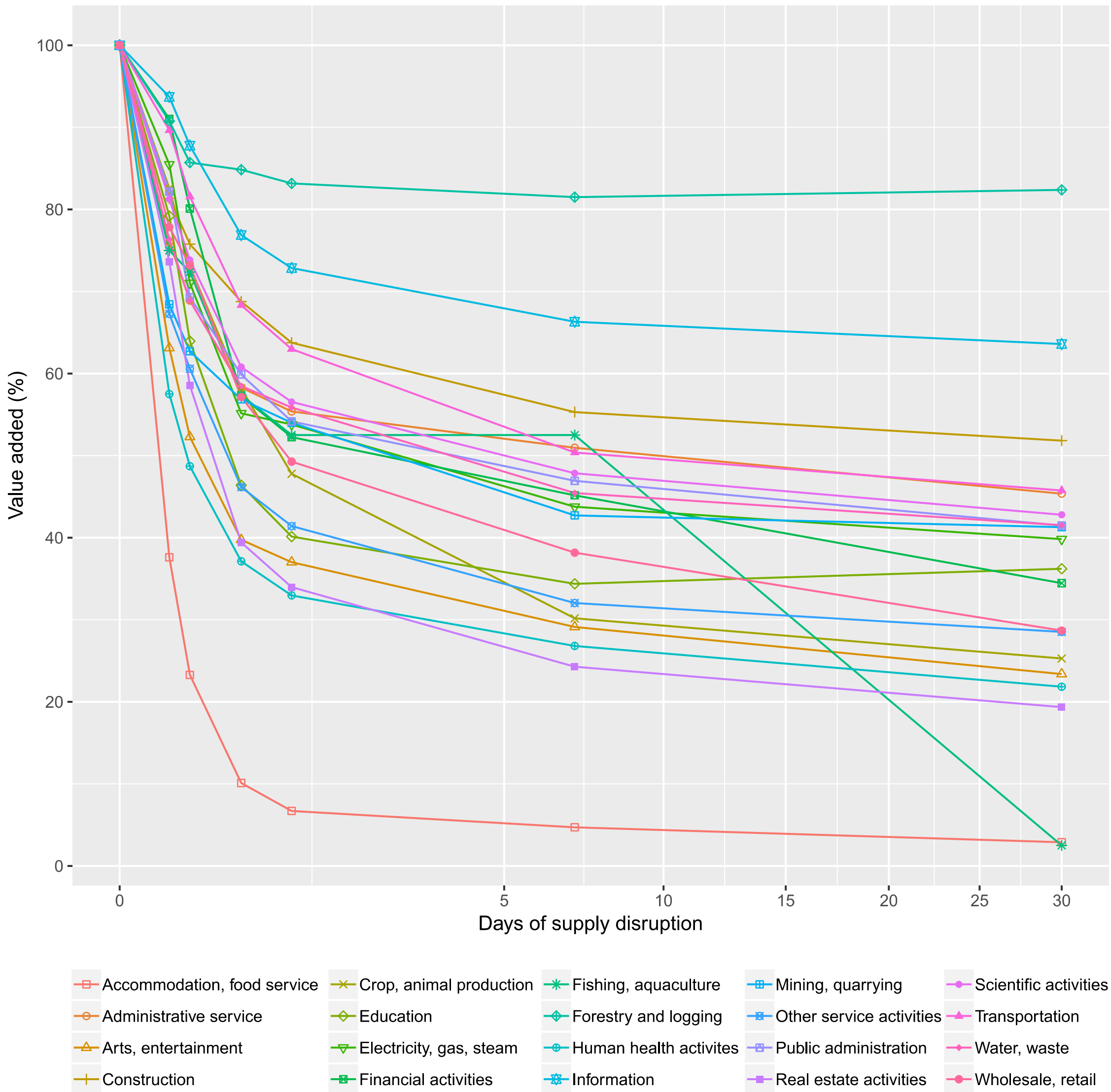

Figure 5.14 Maintained value added for the non-manufacturing sectors, expressed as a percentage of normal business activity during water supply disruptions of different durations.

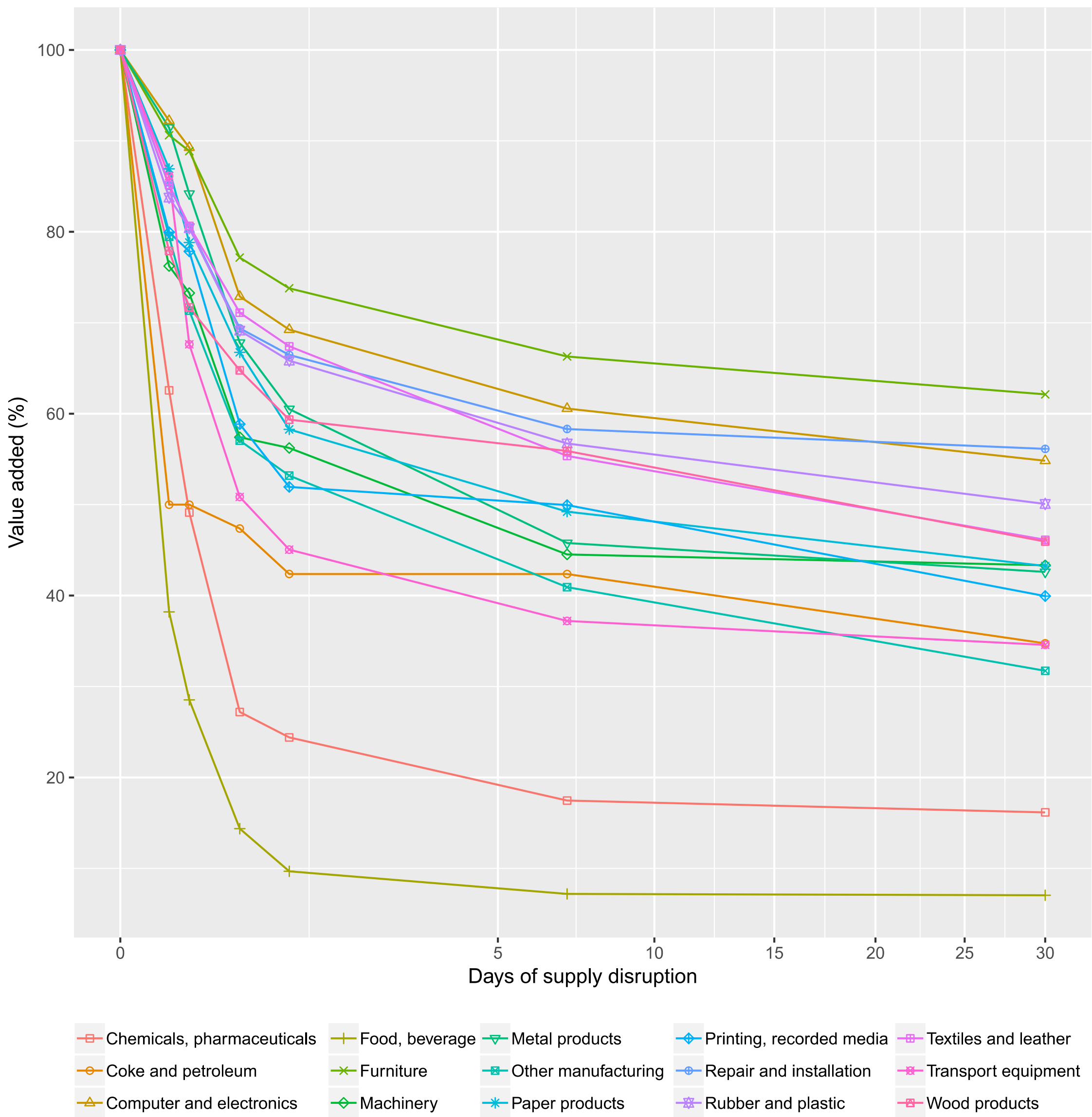

Figure 5.15 Maintained value added for the manufacturing sectors, expressed as a percentage of normal business activity during water supply disruptions of different durations.

Based on survey result, water resiliency factors were calculated as the ratio of maintained value added over time to the value added of normal business activity for each economic activity sector and water disruption duration, see results in Table 5.8. The business resilience estimates can be used for better economic impact assessments and evaluations of mitigation strategies, hence facilitating the managing of risks at the least cost to society. By illustrating the economic benefit of a reliable water provision, the results can thus be used to justify measures aimed at strengthening water security, by e.g. infrastructure renewals, and ensuring a long-term sustainable use of our water resources.

Table 5.8 *Resiliency factors for economic activity sectors, categorized according to the European statistical classification of economic activities (NACE) (European Parliament, 2006).*

NACE code	Economic activity	Water disruption duration 2 h	4 h	12 h	24 h	1 week	1 month
A 01	Crop and animal production	0.91	0.89	0.74	0.65	0.44	0.32
A 02	Forestry and logging	0.95	0.93	0.89	0.87	0.84	0.83
A 03	Fishing and aquaculture	0.88	0.81	0.70	0.63	0.54	0.34
B 07-09	Mining and quarrying	0.84	0.78	0.65	0.61	0.51	0.44
C 10-12	Food, beverage and tobacco	0.69	0.68	0.40	0.32	0.18	0.11
C 13-15	Textiles and leather	0.93	0.88	0.81	0.76	0.65	0.55
C 16	Wood products	0.89	0.83	0.73	0.68	0.59	0.53
C 17	Paper products	0.93	0.95	0.80	0.73	0.58	0.51
C 18	Printing and recorded media	0.90	0.84	0.73	0.65	0.55	0.49
C 19	Coke and petroleum	0.75	0.78	0.62	0.58	0.47	0.44
C 20-21	Chemicals and pharmaceuticals	0.81	0.82	0.53	0.45	0.32	0.23
C 22-23	Rubber and plastic	0.92	0.91	0.80	0.75	0.65	0.57
C 24-25	Metal products	0.96	0.93	0.82	0.74	0.57	0.47
C 26-27	Computer and electronics	0.96	0.94	0.85	0.78	0.67	0.60
C 28	Machinery	0.87	0.82	0.69	0.63	0.53	0.47
C 29-30	Transport equipment	0.93	0.86	0.67	0.57	0.41	0.34
C 31	Furniture	0.95	0.93	0.86	0.81	0.72	0.66
C 32	Other manufacturing	0.90	0.87	0.72	0.65	0.52	0.40
C 33	Repair and installation	0.93	0.88	0.79	0.74	0.64	0.60
D 35	Electricity, gas, steam and air	0.93	0.92	0.74	0.69	0.54	0.45
E 36-39	Water, sewerage, waste	0.88	0.85	0.72	0.66	0.56	0.48
F 41-43	Construction	0.91	0.86	0.77	0.72	0.64	0.57
G 45-47	Wholesale and retail	0.92	0.86	0.72	0.62	0.46	0.36
H 49-53	Transportation and storage	0.95	0.91	0.81	0.73	0.59	0.51
I 55-56	Accommodation and food service	0.69	0.61	0.35	0.28	0.17	0.10
J 58-63	Information and communication	0.97	0.95	0.87	0.81	0.72	0.67
K 64-66	Financial and insurance activities	0.96	0.92	0.76	0.66	0.52	0.42
L 68	Real estate activities	0.87	0.78	0.59	0.50	0.33	0.26
M 69-75	Scientific and technical activities	0.91	0.86	0.74	0.67	0.56	0.48
N 77-82	Administrative and support service	0.89	0.83	0.72	0.66	0.55	0.50
O 84	Public administration and defense	0.91	0.86	0.72	0.65	0.53	0.46
P 85	Education	0.89	0.83	0.64	0.55	0.40	0.37
Q 86-88	Human health and social work	0.79	0.71	0.53	0.46	0.35	0.29
R 90-93	Arts, entertainment and recreation	0.82	0.77	0.58	0.51	0.38	0.31
S 94-96	Other service activities	0.84	0.78	0.62	0.54	0.41	0.34

The surveyed companies were asked to state the reason why they would experience a reduction in value added during water disruptions, see their responses in Figure 5.16. Most companies stated that a reduced value added was due to either their production being dependent on water or that they chose to slow down production due to lack of water for sanitary and hygienic purposes.

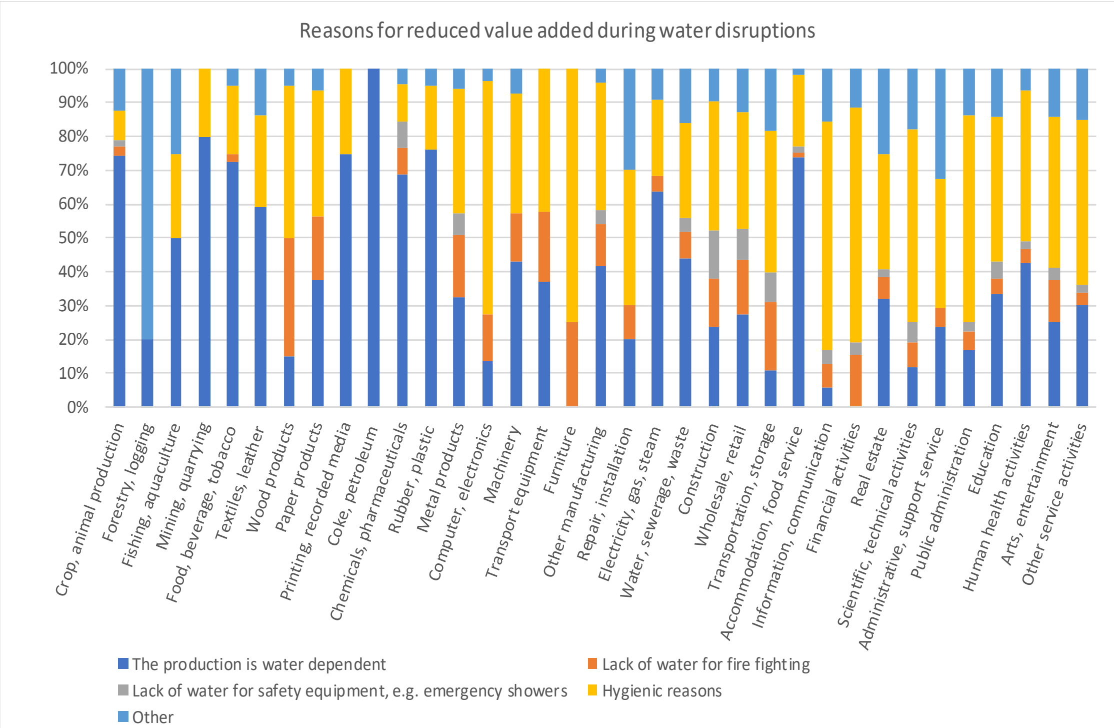

Figure 5.16 Reasons for reduced value added during water disruptions.

6 DISCUSSION

In this chapter the content of the thesis is discussed. Strengths and weaknesses of the methods and tools used are presented along with implications and recommendations regarding practical application.

6.1 Combination of decision support methods

Better information cannot guarantee improved decisions, but it is a prerequisite for sound decision-making.

– Millennium Ecosystem Assessment (2003)

The decision support methods and tools developed in this thesis are based on the well-established analytical processes of risk management, cost-benefit analysis (CBA), marginal abatement cost curves (MACC) and multi-criteria decision analysis (MCDA). Figure 6.1, along with the following text, provides examples of inputs and results from the different methods, how they relate to each other, and how the methods have been combined in Papers I to IV.

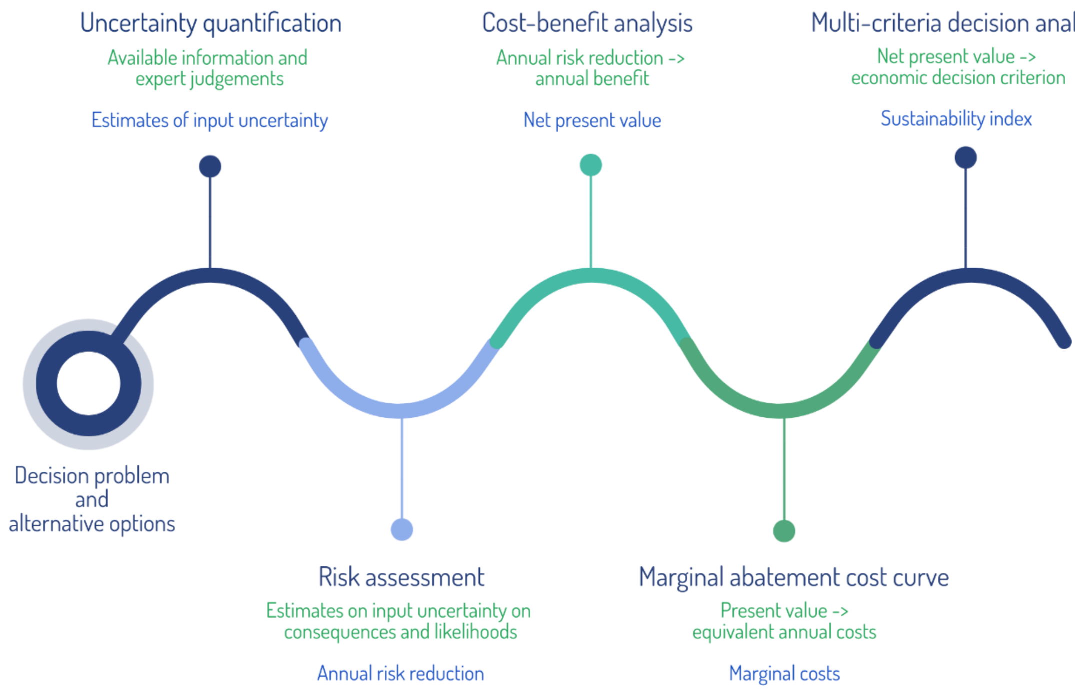

Figure 6.1 Examples of how presented methods can be combined when evaluating alternative options (green text: examples of input in the analysis; light blue text: examples of output).

Starting to the left in Figure 6.1, with uncertainty quantification. All methods described in Papers I to IV have been developed using a probabilistic approach to provide estimates of how likely each outcome is. Thus, great emphasis has been placed on the quantification of various uncertainties associated with input data, e.g. by use of expert judgements and formal expert elicitation frameworks. For example, Paper I focused on quantifying uncertainties associated with societal costs and benefits, while Paper II focused on uncertainties related to the scoring of alternative options. In Paper III, uncertainties associated with implementation costs and water availability potentials were quantified, whereas Paper IV focused on consequences and likelihood of occurrence of unwanted events. The quantified uncertainties were represented by probability distributions and Monte Carlo simulations were used to quantify uncertainties in the various assessment results.

Moving a step further to the right in Figure 6.1, to risk assessment. The scenario-based risk assessment approach presented in Paper IV, used the quantified uncertainties described above as input variables. One of the assessment results was the potential risk reduction of evaluated measures. The benefit of risk reduction was then, in turn, input to a CBA where it was weighed against the cost of measure implementation.

Moving on to the three last steps in Figure 6.1, CBA, MACC and MCDA. When evaluating measures through CBA, as described in Papers I, II, III and IV, the net present value (*NPV*) of each alternative constitutes one of the assessment results. The *NPV* can then, in turn, be used as input in the other described methods, MCDA and MACC. For example, the *NPV* is the economic decision criterion in the sustainability assessment model described in Paper II, which is based on MCDA. And in Paper III, the present value (*PV*) of costs constitutes input to calculations of the measures' cost-effectiveness, which is presented in the MACC.

Hence, the presented methods in this thesis can be combined in many different ways and they will consequently provide different types of decision support depending on how they are used and which challenges they are applied to. Papers I through IV provide examples of how the methods can be applied to address challenges with respect to water supply and demand management. The papers thus give examples of how the methods can be used to guide, inform and support decision-makers on the road to an improved water security.

6.2 Cost-benefit analysis

The nation behaves well if it treats the natural resources as assets which it must turn over to the next generation increased and not impaired in value.

– Theodore Roosevelt (1907)

One of the main efforts in CBA lies in applying suitable economic valuation techniques to quantify identified costs and benefits into monetary terms. Of the different types of costs and benefits identified in appended papers, financial implementation costs along with operation and maintenance costs are often the easiest to estimate. These costs can generally be estimated based on information from water utility managers, benchmarking data, literature, and similar previous projects. However, monetization of costs and benefits not related to existing markets is difficult, and often time-consuming, expensive and requiring a high level of economic knowledge (Ding et al., 2011). To facilitate the economic analysis of the sustainability assessment model developed in Paper II, Paper I provides examples of how some key costs and benefits can be estimated and integrated in a CBA. Health effects are, for example, valued on the basis of the avoided cost method, in which costs for medical care, lost production and discomfort are estimated. Although the avoided cost method is often used in risk analysis and health economics (Hanley and Barbier, 2009), it is important to be aware that there is also criticism of its use. For example, Freeman et al. (2014) point out that potential behavioral changes are not taken into account in the method. Moreover, as there is a lack of both primary valuation studies and standard economic values for water-related effects in Sweden to use for the estimations, the examples in Paper I relies mostly on international literature and benchmarking data. To address the lack of reliable background data and facilitate future economic analyses of water supply reliability in Sweden, Paper V focused on estimating water resiliency factors for Swedish economic sectors.

In the same way that there are advantages and disadvantages to all valuation methods, the decision support method CBA is also both praised and criticized. It is for example considered attractive for enabling a holistic analysis, in which *all* gains and losses of well-being are to be counted. It is also appreciated as it can show the decision-makers *who* the beneficiaries and losers of the analyzed options are over time. Further, a CBA is based on individuals' preferences. This is argued to be both an advantage, as it makes the method democratic, and a weakness, as the individuals' preferences count no matter how badly informed they are. Another valuable feature comes from expressing the costs and benefits in the same units (money), which facilitates decisions on whether something should be done at all or whether it is actually better to do nothing. This can e.g. be compared to cost-effectiveness analysis (CEA), in which the effectiveness indicator and cost are measured in different units. A CEA can therefore be used to evaluate which alternative that reaches a defined goal at the lowest cost, but not to evaluate whether the alternatives are worth undertaking or not (OECD, 2018). In some cases, e.g. due to legal requirements, measures need to be implemented regardless of whether they are economically viable or not. A CBA (and a CEA) can be useful also in those cases, providing valuable decision support. Moreover, using the familiar unit of money (instead of a unitless scale) facilitates comparisons that are more informative for the decision-makers as we all have a lifetime of experience of the monetary scale.

Discounting has a theoretical justification in the welfare economics of CBA, and the literature on the choice of discount rate is extensive. Nevertheless, there is no consensus on either its definition, its size or even its sign (Johansson and Kriström, 2018). The choice of discount rate is important as it has a large effect on the resulting net present values, and thus also on resource allocations. If the discount rate is set too high, it risks hindering the implementation of desirable measures. However, if the rate is set too low, it can encourage investments in ineffective measures. Different magnitudes of discount rate results in different weights attached to costs and benefits occurring over time. The higher the discount rate, the lower the weight given to costs and benefits occurring in the distant future, which favors measures with early benefits. Low discount rates, on the other hand, favors measures with benefits that occur at a later date. Hence, the choice of discount rate reflects how we value today's well-being versus wellbeing in the future, and is thus a question of intergenerational equity (Zhuang et al., 2007). Whatever discount rate is chosen, it is important to be aware of its ethical and moral implication and that it has large effect on the resulting net present values. To account for different views and prioritizations, and to assess the sensitivity of the outcomes, the cost-benefit analyses performed in the appended papers was conducted under different discount rates.

6.3 Multi-criteria decision analysis

If we work together, a secure and sustainable water future can be ours.

– Kofi Annan (2002)

Multi-criteria decision analysis (MCDA) provides a framework for solving problems as characterized with multiple (conflicting) actors, objectives and criteria. MCDA has become popular as it allows decision-makers to consider all criteria and objectives simultaneously and make appropriate decisions as per the priority. Numerous previous studies have proposed MCDA for evaluating sustainability of water supply interventions, see for example Scholten et al. (2017). However, even though MCDA often involves criteria valued in monetary terms, cost externalities are rarely included in sustainability assessments (Rathnayaka et al., 2016). By combining MCDA with CBA, as proposed in Paper II, valuations based on welfare economics of private costs and benefits as well as externalities can be included in the sustainability assessments. This also creates an opportunity to assess economic profitability in addition to sustainability.

Much of the MCDA literature focus on well-structured problems using already defined sets of criteria and alternatives as starting points (Belton and Stewart, 2010). However, as Dewey (1938) points out *a problem well put is half solved*, and it is not an easy task to arrive at the point of a well-structured problem. When identifying and defining the criteria, which serve as performance measures in the decision problem, emphasis must be placed on ensuring that they are soundly based. To begin with, they need to be operationally meaningful, i.e., it must be possible to measure or judge how well an option performs on each criterion. According to DCLG (2009), the criteria should also be assessed against a range of qualities, such as *completeness* – ensuring that all important criteria are included; *redundancy* – judging whether the criteria are necessary or not; *mutual independence* – ensuring that preferences associated with the consequences of the options are independent of one another from one criterion to the next; *double counting* – ensuring that consequences are not counted more than once; *size* – ensuring that the number of criteria is no larger than it needs to be; and *impacts occurring over time* – ensuring that attention is drawn to time-differentiated consequences. In order to minimize the risk of double counting and to ensure that the other criteria qualities are met, a generic list of sustainability criteria was co-developed with a multisectoral stakeholder group in an iterative process in Paper II. The criteria from this list were later weighted in large stakeholder workshops in both the Göteborg region and Gotland, the two case study sites used in this thesis. Interestingly, the two workshops resulted in almost exactly the same criteria weightings, despite major differences in water availability, geological conditions and population density.

The sustainability assessment model was applied to five alternative interventions for the Göteborg region in Paper II. The assessment results provided information regarding both positive and negative economic, social and environmental aspects related to the different interventions. Discussions have since been held about generating new alternatives based on combinations of the positive consequences from the old alternatives. To facilitate future application of the sustainability assessment model, a user-friendly calculation tool with an associated guiding manual is currently under development.

6.4 Marginal abatement cost curves

Water resource management is complex, and that complexity must be recognized.
– Prof Elinor Ostrom, Nobel Laureate

MACC is an attractive decision support tool as it provides an easily understandable format for comparing a range of complex measures. The cost curves specify the marginal cost of abatement for each analyzed measure while enabling assessments to be made of the total abatement costs through the integral of the curve (Kesicki, 2012). However, the limited representation of uncertainty in MACC studies has led to concerns that the cost curves give a false impression of robustness, thus reducing their usefulness (Eory et al., 2018b). Paper III presents a probabilistic approach for inclusion of uncertainties in MACCs for water scarcity mitigation. The approach enables thorough uncertainty and sensitivity analyses where the variation in estimated water availability and cost can be assessed along with the relative uncertainty of the measures. This information provides an informed picture of the robustness, financial risks and water potentials associated with each measure and could thus affect the perception of which measure is most beneficial. It also facilitates decisions regarding which variables ought to be investigated further in order to reduce uncertainties. However, it can be difficult to show all uncertainties in the same cost curve. In Paper III, the MACC shows the range of uncertainties associated with the cost per unit calculation of each measure, illustrated by error bars based on the 5th, 50th and 95th percentiles. The water availability uncertainties are thus included in the cost per unit calculations shown on the y-axis, whereas the x-axis is limited to showing the annual mean value of water availability. Information about the water availability uncertainties are provided in separate graphs.

MACCs usually (as in this thesis) present the theoretical maximum potential, i.e. if all measures were to be implemented by all possible actors, instead of showing the most likely level of implementation. The most likely level of implementation can be hard to estimate in cost curves since it may in fact change as a result of the cost curves themselves and the subsequent policy development (Eory et al., 2018a). A simple sensitivity analysis of low, medium and high implementation levels could be included to highlight how different implementation levels may affect the total outcome. Alternatively, it can be included as an uncertain input variable and a full uncertainty analysis performed by means of Monte Carlo simulations.

In Paper III, 17 municipal, industrial, agricultural and household water scarcity mitigation measures were evaluated and compared for the island of Gotland. The most cost-effective measure analyzed for Gotland was retrofitting showerheads and faucets in the hotel industry, which highlights the potentially large cost savings when reducing hot water use. However, even though some measures are shown to be highly cost-effective in a MACC, there may be e.g. financial, legal or social barriers that could hinder implementation and hence the possibility of improving the situation. In that case, MACCs may also be used to identify which measures need an extra push by policy intervention. For example, a low degree of implementation of cost-effective measures may be due to a lack of awareness and could in that case be incentivized by improved information. The expensive measures, on the other hand, may only be incentivized by financial support (Eory et al., 2018a). However, it is important that MACCs and other decision support methods are not misused to promote interventions that may be illegal or unethical.

6.5 Risk assessment

Managing climate risk and uncertainty requires better governance and a more integrated and sustainable water resources management approach.

– UNESCO (2019)

Quantitative risk assessments are essential tools for guiding both public and private decision-making. They support decisions by providing estimates on consequences and probabilities of hazardous events and alternative decision options, while weighting the predicted consequences and risks against presumptive values and preferences (Aven, 2012). The risk assessments can aid decision-makers in e.g. knowing which events and losses that can occur and their likelihood of occurrence; the design of risk reduction measures; risk reduction financing and budgeting; and in comparing the presumptive risk reduction with the cost of measure implementation. However, as risk is not the only information required for making decisions on risk reduction, risk assessment results must often be combined with other information to provide useful decision support (Lindhe et al., 2011).

Paper IV presents a scenario-based risk assessment approach that is combined with CBA to assess the total risk of water supply disruptions on Gotland, as well as risk-reduction potentials and net present values of four alternative risk reduction measures. In the paper, risk is expressed in terms of expected economic consequences for households, industry and municipality from disruption events included in a set of risk scenarios. The scenarios are defined to capture a range of possible events, such as failures in the distribution system, the raw water system and the treatment system. By quantifying the probability of losses caused by the scenarios, an economic risk curve is produced showing the relationship between frequency and its associated losses. Each point of the curve represents the actual return period of losses, and the curve can hence be used to provide information on how to address the different levels of risk. The four analyzed measures are site specific measures to enhance the raw water supply. There are of course other potential solutions that could contribute to reduce identified risks, e.g. improvements in the treatment system and in the distribution systems. Such options were however not included in Paper IV as focus was on the raw water system. The aim of the study was to highlight the importance of considering all risks when prioritizing risk reduction measures. This was clearly demonstrated by the case study, in which the net present value of a large-scale surface water measure was negative when analyzed for individual scenarios but positive when analyzed for all scenarios combined.

Dealing with risks and economic consequences are important components in water resources management. It is therefore good to be aware of some challenging aspects when integrating risk in economic theory. Welfare economics is based on the behavioral assumption that individuals try to maximize their wellbeing (utility). When choosing between risk reduction measures, this motivates a search for the measure that would give the greatest utility improvement. To value such improvements as monetized benefits makes it possible to assess the measures through cost-benefit analysis (Johansson and Kriström, 2018). This valuation can be performed either *ex ante* or *ex post*. An *ex ante* analysis is based on monetizing the change in individuals' expected utility of risk reduction. An *ex post* analysis, on the other hand, is based on first monetizing the utility change of avoiding a consequence as if it occurs with certainty, and subsequently transforming this to a monetary value of risk reduction through multiplication with the relevant probability. (Freeman et al., 2014).

By use of stated preference (and in some cases revealed preference) methods, the option price, i.e. the *ex ante* willingness to pay (WTP) for avoiding a risky situation can be estimated as the monetary value of the associated change in expected utility. The consumer sovereignty principle of mainstream welfare economics (Friedman, 2002) suggests that this is the preferred way of valuing changes in risk as it takes into account individuals' preferences with respect to the risky situation as a whole, i.e. both consequences and associated probabilities. However, it is not necessarily true that people have good information about the adverse event and the available alternatives. With no previous experience about the event (or alternatives) in question, the task of assessing what changes in probabilities and consequences implies for their wellbeing can be somewhat difficult.

The alternative *ex post* valuation is rather straightforward as it only requires information based on people's preferences related to consequences. However, by definition this approach does not take the individuals' risk preferences into full account, contributing to differences in estimated *ex ante* and *ex post* values (Freeman et al., 2014). As stated preference methods are rather time and cost consuming, various *ex post* analyses such as estimations of expected avoided damage costs are often used in practice in risk assessments (Hanley and Barbier, 2009), and in this thesis. When using *ex post* analysis for valuation of changes in risk, it is important to bear in mind that the general public's risk perception often differ from the risk perception of experts (Johansson-Stenman, 2008).

6.6 Recommendations

The best way to predict the future is to create it.

– Peter F. Drucker

Most real-world decision problems take place in complex environments characterized by various forms of incompleteness, such as uncertainty, imprecision and vagueness (De Baets and Fodor, 2010). To meet such complexity and to provide structure and transparency to the decision-making process, a suitable step is to use appropriate decision support methods. This thesis has presented various decision support methods which can aid in complex decision situations. When applying the presented methods and tools in real-world applications, the following recommendations may be useful:

- To facilitate viable and accepted decisions, it is important to make sure that relevant stakeholder groups are included and represented as widely as possible in the assessment and decision-making processes. This can be done through e.g. workshops or focus group meetings, in which objectives, preferences and values, decision criteria, decision alternatives, and alternative performances and consequences are discussed and assessed.
- As discussed above, the choice of discount rate has large effects on CBA results and has intergenerational implications. To account for different views and prioritizations, and to assess the sensitivity of the outcomes, a CBA should preferably include a sensitivity analysis with respect to different discount rates.
- The results from the case study applications provided in this thesis are site specific. For example, both the prioritized set of measures and the marginal costs of a MACC depend on site-specific conditions. A MACC is hence unique to every region for which it is performed. It is therefore difficult to draw general conclusions from the case study results, and it is not possible to transfer the results from one region to another. In fact, this is also one of the reasons for using decision support methods, i.e. to provide information tailored to the specific problem, region and situation at hand rather than using standard solutions.

- MACCs are often used to reveal the cumulative potential of all the measures, i.e. in this case the cumulative water availability potential. If this is to be calculated, it is important to remember that account must be taken to possible interactions between measures, e.g. when the implementation of one measure changes the water availability potential of another measure.
- When relevant hard data to support assessments is lacking, the only sound option may be to elicit the information needed using expert judgements. The typical way is to elicit judgement from more than one expert and represent the uncertainties by probability distributions. This is preferably done by the use of a formal expert elicitation process, e.g. the Sheffield Elicitation Framework (Oakley and O'Hagan, 2016).
- It is practically impossible to cover all risks of real systems (Kaplan et al., 2001). Hence, risk assessment results are conditioned on several assumptions and simplifications. For assumptions and simplifications not to be overlooked in the risk management or decision-making processes, these variables should preferably be included in the analysis using a qualitative uncertainty analysis as exemplified in Paper IV and suggested by e.g. Aven (2010).
- The same reasoning as above also applies to the economic valuation of costs and benefits. It is usually practically impossible, or too expensive, to quantify all economic consequences that may arise as a result of a proposed alternative (DCLG, 2009; National Research Council, 2005). Hence, a prioritization is recommended regarding which effects are reasonable and possible to quantify and monetize in a CBA, and to what degree of certainty.
- Finally, the decision can only be as good as the best alternative. If there are only weak alternatives, even the best analysis will only identify a weak alternative. It is therefore important to remember that assessment results can be used to provide insights on how to create even better alternatives. By evaluating values in the original alternatives, new alternatives can be created in which the good properties of the original alternatives are combined to better meet our objectives (Parnell et al., 2013).

7 CONCLUSIONS AND FUTURE RESEARCH

In this final chapter the main conclusions of the thesis are summarized. Possible further development and application of the described methods is also presented.

7.1 Conclusions

What is needed, along with fresh water, is fresh thinking. We need to learn how to value water.

– Kofi Annan (2003)

Water managers of today have to deal with an increasing number of complex challenges, threats and future unknowns, and are faced with difficult decision situations on resource allocation and prioritizations of improvement measures. The challenges include balancing variable and uncertain water supplies with changing and uncertain demands, while handling challenges related to e.g. ageing infrastructure, urbanization, and climate change effects.

The overall aim of this thesis was to contribute to an increased understanding of how decision support methods based on risk, cost-benefit and multi-criteria decision analyses can be used to enhance water security through sustainable water management. The aim was hence to facilitate our collective action towards a sustainable access to adequate quantities and quality of water by helping decision-makers identify efficient and sustainable water management choices when faced with complex and uncertain decision situations. The overall aim and the specific objectives of this thesis have been met in accordance with the following main conclusions:

- The presented sustainability assessment model was developed to help water supply decision-makers identify sustainable water management choices. The case study application shows that the model is practically useful to rank alternative options from the most preferred to the least preferred within each of the social, environmental and economic sustainability domains and with regards to all domains. The model provides a novel way of presenting monetized benefits and costs with non-monetized social and environmental effects of water supply interventions, capturing both utilitarian aspects of analyzed options and aspects based in the deontological theories of moral ethics.

- A marginal abatement cost curve (MACC) was developed to provide a common starting point for cross-sectoral dialogue on water scarcity mitigation. The MACC enables a comparison of the cost-effectiveness and water availability potential of alternative mitigation measures, providing guidance for businesses, households, farmers and authorities on which measures and sectors to prioritize from a cost-effectiveness perspective. The easily understandable format facilitates stakeholder communication and proactive discussions on how to improve our community preparedness and resilience to the challenges posed by water scarcity and droughts.
- The presented scenario-based risk assessment approach was developed to enable a comprehensive view on risk when evaluating water supply infrastructure systems and risk reduction options. The approach allows for thorough analyses of economic losses and associated uncertainties under a range of possible water supply disruption scenarios, facilitating prioritizations on measures that aim to reduce the overall risk rather than individual risks. By combining quantitative risk analysis with cost-benefit analysis, identification of the most economically viable risk reduction options is made possible.
- The presented business resilience estimates provide information that can help decision-makers in both the private and public sectors respond to challenges arising from water disruption risks. With a better understanding of the value of water to all water users, a good, effective and efficient water governance is made possible.
- The probabilistic approach used throughout the thesis allows for a structured and transparent handling of uncertainties involved. The approach is beneficial since it not only provides information regarding the magnitude of the results but also regarding how likely each outcome is, facilitating calculations of probabilities that alternatives exceed certain cost limitations or environmental threshold values. Thus, the approach help decision-makers make a more informed decision on which alternative to choose. It also enables analysis of the sensitivity of the results to uncertainties in input variables, thus providing a basis for prioritization of efforts to increase the reliability of model calculations if necessary.
- The presented methods and tools are all exemplified by practical case study applications, providing examples of stakeholder participation approaches. Stakeholder involvement in the decision-making process is demonstrated through different types of workshops where representatives for relevant stakeholder groups are involved in: the identification and definition of decision objectives and criteria; the weighting of decision criteria; the identification of alternative options; the identification and quantification of effects of alternative

options along with their associated uncertainties; and the quantification of probabilities and consequences of identified risk scenarios.

- Finally, it should be mentioned that the structured process of conducting the different assessments often are as valuable as the final result. The process usually necessitates the involvement of many stakeholders and encourages communication between water providers, farmers, industry, public authorities and other parts of society. It also necessitates considerations of aspects that could easily otherwise have been overlooked. It thus improves the overall awareness of the challenges ahead and possible ways to address and overcome them.

In conclusion, the work has led to an increased understanding of how decision support methods and tools based on risk, cost-benefit and multi-criteria decision analyses can be used to enhance water security through sustainable water management. The provided methods offer different ways of evaluating and comparing management responses to the water-related challenges we face. They can help us reduce the water-related risks and identify the most cost-effective, socio-economic profitable or sustainable options while providing structure and transparency to decision-making. Thus, the work will help strengthening the ongoing discussions regarding our water-related challenges and opportunities, and by that contribute to an enhanced water security.

7.2 Future research

Effective water resources management needs more and better data.

– UN (2018)

Provided methods, tools and estimates offer possibilities for further development and application:

- As municipalities, businesses and communities place greater importance to ensuring efficient and sustainable water management, it becomes increasingly important to have reliant data and estimates as basis for the analysis of mitigation options. Moving forward, it would therefore be useful to carry out research that focus on estimating standard economic values for a variety of water-related effects in society.
- The MACC provided in Paper III was limited to estimations of financial costs and did not allow for inclusion of any ancillary effects, such as environmental improvements or other externalities. Such additional effects may be substantial and could change the marginal costs and ranking order if included. Inclusion of

externalities would therefore be a valuable next step in the development of the MACC.

- Even if a measure is shown to be e.g. cost-effective, environmentally beneficial or socio-economic profitable, existing barriers can hinder measure implementation. To remove barriers and facilitate implementation of desired measures, more information is needed on both drivers and barriers and on appropriate mixes of policy instruments.
- In the case study examples, the effects of alternative future measures were analyzed to guide decision-makers in different decision situations. It would be useful to also perform *ex post* evaluations of already implemented measures, as a validity check of evaluations made and to minimize the risk of mistakes in future decision-making.
- To be effective, the decision-support methods developed and presented in this thesis should preferably be implemented in the early stages of the decision-making process, as indicated in the suggested framework structure in Section 5.1. It should therefore be further studied how the methods can be practically implemented into the planning-process of responsible authorities to be most effective in providing relevant decision-support.

REFERENCES

A Camp. (2009). *Golden Teeth and Silver Medals*: Colonia.

Abbott, M., & Cohen, B. (2009). Productivity and Efficiency in the Water Industry. *Utilities Policy, 17*(3-4), 233-244. doi:10.1016/j.jup.2009.05.001

Addams, L., Boccaletti, G., Kerlin, M., & Stuchtey, M. (2009). *Charting Our Water Future - Economic Frameworks to Inform Decision-Making*: 2030 Water Resources Group.

Ang, F., & Van Passel, S. (2012). Beyond the Environmentalist's Paradox and the Debate on Weak Versus Strong Sustainability. *BioScience, 62*(3), 251-259. doi:10.1525/bio.2012.62.3.6

Annan, K. (2002). *Quote from the World Water Day 2002: Water for Development*: United Nations.

Annan, K. (2003). *Message by Secretary-General Kofi Annan for World Environment Day, 5 June 2003*.

Anscombe, G., E., M. (1958). Modern Moral Philosophy. *Philosphy, 33*(124), 1-19.

Aquastat. (2015). Aquastat - Fao's Global Information System on Water and Agriculture.

Arriola, L., & Hyman, J. M. (2009). Sensitivity Analysis for Uncertainty Quantification in Mathematical Models. In G. Chowell, J. M. Hyman, L. M. A. Bettencourt, & C. Castillo-Chavez (Eds.), *Mathematical and Statistical Estimation Approaches in Epidemiology*. Netherlands: Springer

Ashley, R., Blackwood, D., Butler, D., & Jowitt, P. (2004). *Sustainable Water Services: A Procedural Guide*: IWA publishing.

ATC. (1991). *Atc-25. Seismic Vulnerability and Impact of Disruption of Lifelines in the Conterminous United States*. FEMA Federal Emergency Management Agency.

Aven, T. (2010). On How to Define, Understand and Describe Risk. *Reliability Engineering & System Safety, 95*(6), 623-631. doi:10.1016/j.ress.2010.01.011

Aven, T. (2012). *Foundations of Risk Analysis, 2nd Edition*. West Sussex, UK: John Wiley & Sons, Ltd.

Aven, T., & Kørte, J. (2003). On the Use of Risk and Decision Analysis to Support Decision-Making. *Reliability Engineering and System Safety, 79*, 289–299.

AWWA. (2015). Regional Collaboration by Water Utilities. Retrieved from http://www.awwa.org/about-us/policy-statements/policy-statement/articleid/213/regional-collaboration-by-water-utilities.aspx

Azqueta, D., & Montoya, Á. (2017). The Social Benefits of Water and Sanitation Projects in Northern Colombia: Cost-Benefit Analysis, the Water Poverty Index and Beyond. *Development Policy Review, 35*, O118-O139. doi:10.1111/dpr.12285

Bacon, F. (1605). *The Advancement of Learning*. New York, 1901: P.F. Collier and Son.

Beaumont, N. J., & Tinch, R. (2004). Abatement Cost Curves: A Viable Management Tool for Enabling the Achievement of Win-Win Waste Reduction Strategies? *J Environ Manage, 71*(3), 207-215. doi:10.1016/j.jenvman.2004.03.001

Bedford, T., & Cooke, R. (2001). *Probabilistic Risk Analysis: Foundations and Methods*. Cambridge, UK: Cambridge University Press.

Belton, V., & Stewart, T. (2010). Problem Structuring and Multiple Criteria Decision Analysis. In M. Ehrgott, J. R. Figueira, & S. Greco (Eds.), *Trends in Multiple Criteria Decision Analysis* (pp. 209-239). New York, Dordrecht, Heidelberg, London: Springer.

Bentham, J. (1789). *An Introduction to the Principles of Morals and Legislation*. Oxford: Clarendon Press.

Berger, J. O., & Bayarri, M. J. (2004). The Interplay of Bayesian and Frequentist Analysis. *Statistical Science, 19*(1), 58-80. doi:10.1214/088342304000000116

Bergion, V., Lindhe, A., Sokolova, E., & Rosen, L. (2018). Risk-Based Cost-Benefit Analysis for Evaluating Microbial Risk Mitigation in a Drinking Water System. *Water Res, 132*, 111-123. doi:10.1016/j.watres.2017.12.054

Bouma, J. A., & van Beukering, P. J. H. (2015). *Ecosystem Services: From Concept to Practice*. Cambridge, UK: Cambridge University Press.

Brealey, R. A., Myers, S. C., & Allen, F. (2010). *Principles of Corporate Finance* (10th Edition ed.). New York: McGraw-Hill/Irwin.

Brown, A., & Matlock, M. D. (2011). *A Review of Water Scarcity Indices and Methodologies*. Arkansas: The Sustainability Consortium.

Brozović, N., Sunding, D. L., & Zilberman, D. (2007). Estimating Business and Residential Water Supply Interruption Losses from Catastrophic Events. *Water Resources Research, 43*(8), 14p. doi:10.1029/2005wr004782

Burek, P., Satoh, Y., Fischer, G., Kahil, M. T., Scherzer, A., Tramberend, S., Nava, L. F., Wada, Y., Eisner, S., Flörke, M., Hanasaki, N., Magnuszewski, P., Cosgrove, B., & Wiberg, D. (2016). *Water Futures and Solution: Fast Track Initiative (Final Report)*. Laxenburg, Austria: International Institute for Applied Systems Analysis (IIASA).

Caradonna, J., L. (2014). *Sustainability a History*. New York: Oxford University Press.

Carvalho, P., & Marques, R. C. (2016). Estimating Size and Scope Economies in the Portuguese Water Sector Using the Bayesian Stochastic Frontier Analysis. *Sci Total Environ, 544*, 574-586. doi:10.1016/j.scitotenv.2015.11.169

Cha, S., Cho, Y., Kim, S. J., Lee, Y., Choi, S., Asuming, P., Kim, Y., & Jin, Y. (2018). Cost-Benefit Analysis of Water Source Improvements through Borehole Drilling or Rehabilitation: An Empirical Study Based on a Cluster Randomized Controlled Trial in the Volta Region, Ghana. *Glob Health Action, 11*(1), 1523303. doi:10.1080/16549716.2018.1523303

Chukalla, A. D., Krol, M. S., & Hoekstra, A. Y. (2017). Marginal Cost Curves for Water Footprint Reduction in Irrigated Agriculture: Guiding a Cost-Effective Reduction of Crop Water Consumption to a Permit or Benchmark Level. *Hydrology and Earth System Sciences, 21*(7), 3507-3524.

Cooke, R. M. (1991). *Experts in Uncertainty: Opinion and Subjective Probability in Science*. New York, US: Oxford University Press, Incorporated.

Damkjaer, S., & Taylor, R. (2017). The Measurement of Water Scarcity: Defining a Meaningful Indicator. *Ambio, 46*(5), 513-531. doi:10.1007/s13280-017-0912-z

Dawoud, O., Ahmed, T., Abdel-Latif, M., & Abunada, Z. (2020). A Spatial Multi-Criteria Analysis Approach for Planning and Management of Community-Scale Desalination Plants. *Desalination, 485*, 114426. doi:10.1016/j.desal.2020.114426

DCLG. (2009). *Multi-Criteria Analysis: A Manual*. London: Department for Communities and Local Government.

De Baets, B., & Fodor, J. (2010). Preference Modelling, a Matter of Degree. In M. Ehrgott, J. R. Figueira, & S. Greco (Eds.), *Trends in Multiple Criteria Decision Analysis* (pp. 123-156). New York, Dordrecht, Heidelberg, London: Springer.

Dekay, M. L., Small, M. J., Fischbeck, P. S., Scott Farrow, R., Cullen, A., Kadane, J. B., Lave, L. B., Granger Morgan, M., & Takemura, K. (2002). Risk-Based Decision Analysis in Support of Precautionary Policies. *Journal of Risk Research, 5*(4), 391–417. doi:10.1080/1366987021016620

Dewey, J. (1938). *Logic: The Theory of Inquiry* New York: H. Holt and company.

Ding, Y., Hayes Michael, J., & Widhalm, M. (2011). Measuring Economic Impacts of Drought: A Review and Discussion. *Disaster Prevention and Management: An International Journal, 20*(4), 434-446. doi:10.1108/09653561111161752

Donoso, M. C. (2019). Foreword *Water Security and the Sustainable Development Goals*. Paris: UNESCO Publishing.

Döll, P., Jiménez-Cisneros, B., Oki, T., Arnell, N. W., Benito, G., Cogley, J. G., Jiang, T., Kundzewicz, Z. W., Mwakalila, S., & Nishijima, A. (2014). Integrating Risks of Climate Change into Water Management. *Hydrological Sciences Journal, 60*(1), 4-13. doi:10.1080/02626667.2014.967250

EC. (2012a). *Commission Staff Working Document on the Implementation of the Water Framework Directive. Cwd-2012-379.* Brussels: European Commission.

EC. (2012b). *Report on the Review of the European Water Scarcity and Droughts Policy. Com/2012/0672 Final*. Brussels, Belgium: European Commission.

EEA. (2005). *The European Environment – State and Outlook 2005*. Copenhagen, Denmark: European Environmental Agency.

EEA. (2019). *Use of Freshwater Resources in Europe*. Copenhagen, Denmark: European Environment Agency.

Eklund, F. (2018). *Regional Water Supply Plan of Gotland* Visby, Sweden: County Administrative Board of Gotland

Eory, V., Pellerin, S., Carmona Garcia, G., Lehtonen, H., Licite, I., Mattila, H., Lund-Sørensen, T., Muldowney, J., Popluga, D., Strandmark, L., & Schulte, R. (2018a). Marginal Abatement Cost

Curves for Agricultural Climate Policy: State-of-the Art, Lessons Learnt and Future Potential. *Journal of Cleaner Production, 182*, 705-716.
Eory, V., Topp, C. F. E., Butler, A., & Moran, D. (2018b). Addressing Uncertainty in Efficient Mitigation of Agricultural Greenhouse Gas Emissions. *Journal of Agricultural Economics, 69*(3), 627-645.
EU. (2013). *Decision No 1386/2013/Eu of the European Parliament and of the Council of 20 November 2013 on a General Union Environment Action Programme to 2020 'Living Well, within the Limits of Our Planet'*. Luxemburg: European Union.
European Parliament. (2006). Regulation (Ec) No 1893/2006 of the European Parliament and of the Council of 20 December 2006 Establishing the Statistical Classification of Economic Activities Nace Revision 2 and Amending Council Regulation (Eec) No 3037/90 as Well as Certain Ec Regulations on Specific Statistical Domains
Eurostat. (2017). Water Statistics. Retrieved from https://ec.europa.eu/eurostat/statistics-explained/index.php/Water_statistics
Eurostat. (2018). Water Exploitation Index by Type of Water Source. Retrieved from https://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&language=en&pcode=sdg_06_60&plugin=1
Falkenmark, M., Lundqvist, J., & Widstrand, C. (1989). Macro-Scale Water Scarcity Requires Micro-Scale Approaches. Aspects of Vulnerability in Semi-Arid Development. *Nat. Res. Forum 13*, 258–267.
Farley, H. M., & Smith, Z. A. (2014). *Sustainability: If It's Everything, Is It Nothing?* London and New York: Routledge Publishing.
FEMA. (2011). *Fema Benefit-Cost Analysis Re-Engineering (Bcar). Development of Standard Economic Values*. Washington: Federal Emergency Management Agency (FEMA).
Figueira, J., Greco, S., & Ehrogott, M. (2005). *Multi Criteria Decision Analysis: State of the Art Surveys*. New York, NY, USA: Springer.
Franklin, B. (1746). *When the Well Is Dry, We Know the Worth of Water*. Poor Richard's Almanac.
Freeman, A. M., Herriges, J. A., & Kling, C. L. (2014). *The Measurement of Environmental and Resource Values: Theory and Methods*. New York: RFF Press.
French, S., & Insua, D. R. (2000). *Statistical Decision Theory*. London: John Wiley & Sons Inc.
Friedman, L. S. (2002). *The Microeconomics of Public Policy Analysis*. Princeton, NJ: Princeton University Press.
Frone, S. (2008). Factors and Challenges of Regionalization in the Water and Wastewater Sector. *Romanian Journal of Economics, 27*(2), 185-200.
Garvey, P. R., Book, S. A., & Covert, R. P. (2016). *Probability Methods for Cost Uncertainty Analysis: A Systems Engineering. Second Edition.* . Boca Raton: CRC Press.
German Bundestag. (2006). Report by the German Government on the Modernization Strategy for the German Water Industry and for a Stronger International Involvement by the German Water Industry (Bericht Der Bundesregierung Zur Modernisierungsstrategie Für Die Deutsche Wasserwirtschaft Und Für Ein Stärkeres Internationales Engagement Der Deutschen Wasserwirtschaft) Retrieved from http://dipbt.bundestag.de/extrakt/ba/WP16/4/480.html
Godskesen, B., Hauschild, M., Albrechtsen, H. J., & Rygaard, M. (2018). Asta - a Method for Multi-Criteria Evaluation of Water Supply Technologies to Assess the Most Sustainable Alternative for Copenhagen. *Sci Total Environ, 618*, 399-408. doi:10.1016/j.scitotenv.2017.11.018
Golfam, P., Ashofteh, P.-S., Rajaee, T., & Chu, X. (2019). Prioritization of Water Allocation for Adaptation to Climate Change Using Multi-Criteria Decision Making (Mcdm). *Water Resources Management, 33*(10), 3401-3416. doi:10.1007/s11269-019-02307-7
González-Gómez, F., & García-Rubio, M. Á. (2008). Efficiency in the Management of Urban Water Services. What Have We Learned after Four Decades of Research? *Hacienda Pública Española / Revista de Economía Pública, 185*(2), 39-67.
Gorbachev, M. (2001). Foreword. In P. Swanson (Ed.), *Water, the Drop of Life*. Minnetonka, MN: NorthWord Press.
GR. (2014). *Water Supply Plan for the Gothenburg Region (Vattenförsörjningsplan För Göteborgsregionen)*. Göteborg: The Göteborg Region Association of Local Authorities.
Grahn, L., Ruderfelt, L., Wolsing, J., Sköld, N. P., & Hammar, S. (2020). *Drought and Water Scarcity - Identification and Prioritization of Preventive Measures to Deal with Drought and Water Scarcity (Torka Och*

Vattenbrist - Identifiering Och Prioritering Av Förebyggande Åtgärder För Att Hantera Torka Och Vattenbrist): Sweco Environment AB.
Greco, S., Ehrgott, M., & Figueira, J. R. (2016). *Multiple Criteria Decision Analysis*. New York: Springer.
GWP-TAC. (2000). *Integrated Water Resources Management*. Stockholm, Sweden: Global Water Partnership
Hall, J., & Borgomeo, E. (2013). Risk-Based Principles for Defining and Managing Water Security. *Phil Trans R Soc A, 371:20120407*. doi:10.1098/rsta.2012.0407
Hanel, M., Rakovec, O., Markonis, Y., Maca, P., Samaniego, L., Kysely, J., & Kumar, R. (2018). Revisiting the Recent European Droughts from a Long-Term Perspective. *Sci Rep, 8*(1), 9499. doi:10.1038/s41598-018-27464-4
Hanley, N., & Barbier, E., B. (2009). *Pricing Nature. Cost–Benefit Analysis and Environmental Policy*. Cheltenham, UK; Northampton, USA: Edward Elgar Publishing Limited.
Hasanbeigi, A., Morrow, W., Sathaye, J., Masanet, E., & Xu, T. (2013). A Bottom-up Model to Estimate the Energy Efficiency Improvement and Co2 Emission Reduction Potentials in the Chinese Iron and Steel Industry. *Energy, 50*, 315-325. doi:10.1016/j.energy.2012.10.062
Hedenus, F., Persson, M., & Sprei, F. (2015). *Sustainable Development - History, Definition & the Role of the Engineer*. Gothenburg: Chalmers University of Technology.
Howarth, R., B. (1995). Sustainability under Uncertainty: A Deontological Approach. *Land economics, 71*(4), 417-427.
ICWE. (1992). *The Dublin Statement on Water and Sustainable Development.* Paper presented at the International Conference on Water and the Environment, Dublin, Ireland.
Imran, S., Alam, K., & Beaumont, N. (2014). Reinterpreting the Definition of Sustainable Development for a More Ecocentric Reorientation. *Sustainable Development, 22*(2), 134-144. doi:10.1002/sd.537
ISO. (2018). *Iso 31000:2018 Risk Management– Guidelines*. Geneva: International Organization for Standardization.
IWA. (2004). *The Bonn Charter for Safe Drinking Water*. London: IWA Publishing.
Jiménez Cisneros, B. E., Oki, T., Arnell, N. W., Benito, G., Cogley, J. G., Döll, P., Jiang, T., & Mwakalila, S. S. (2014). Freshwater Resources. In C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, & L. L. White (Eds.), *Climate Change 2014: Impacts,Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group Ii to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 229-269). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.
Johansson-Stenman, O. (2008). Mad Cows, Terrorism and Junk Food: Should Public Policy Reflect Perceived or Objective Risks? *J Health Econ, 27*(2), 234-248. doi:10.1016/j.jhealeco.2007.04.004
Johansson, M. V., & Forslund, J. (2009). *Climate Adaptation in Sweden. Socioeconomic Values of Health Effects (Klimatanpassning I Sverige. Samhällsekonomiska Värderingar Av Hälsoeffekter)*. Stockholm, Sweden: The National Institute of Economic Research.
Johansson, P.-O., & Kriström, B. (2013). *Evaluating Water Projects - Cost-Benefit Analysis Versus Win-Win Approach*. New York: SpringerBriefs in Economics.
Johansson, P.-O., & Kriström, B. (2016). *Cost-Benefit Analysis for Project Appraisal*. Cambridge, UK: Cambridge University Press.
Johansson, P.-O., & Kriström, B. (2018). *Cost–Benefit Analysis*. Cambridge, UK: Cambridge University Press.
Johnston, R., J., Rolfe, J., Rosenberger, R. S., & Brouwer, R. (2015). *Benefit Transfer of Environmental and Resource Values. A Guide for Researchers and Practitioners* (Vol. 14). Dordrecht, Heidelberg, New York and London: Springer.
Kant, I. (1785). *Groundwork of the Metaphysics of Morals (Grundlegung Zur Metaphysik Der Sitten)*. Riga: Johann Friedrich Hartknoch.
Kaplan, S., & Garrick, B. J. (1981). On the Qualitative Definition of Risk. *Risk Analysis, 1*(1), 11-27.

Kaplan, S., Haimes, Y. Y., & Garrick, B. J. (2001). Fitting Hierarchical Holographic Modeling into the Theory of Scenario Structuring and a Resulting Refinement to the Quantitative Definition of Risk. *Risk Analysis, 21*(5), 807-819.

Keeney, R. L. (1982). Decision Analysis: An Overview. *Operations Research, 30*(5), 803-838.

Kesicki, F. (2010). *Marginal Abatement Cost Curves for Policy Making – Expert-Based Vs. Model-Derived Curves*. Paper presented at the the 33rd IAEE International Conference, Rio de Janeiro, Brazil.

Kesicki, F. (2012). *Decomposing Long-Run Carbon Abatement Cost Curves - Robustness and Uncertainty.* (Doctor of Philosophy), UCL University College London, London.

Ki-moon, B. (2015). Foreword. In WWAP (Ed.), *The United Nations World Water Development Report 2015: Water for a Sustainable World*. Paris: UNESCO.

Kiureghian, A. D., & Ditlevsen, O. (2009). Aleatory or Epistemic? Does It Matter? *Structural Safety, 31*(2), 105-112. doi:10.1016/j.strusafe.2008.06.020

Kriström, B., & Bonta Bergman, M. (2014). *Socio-Economic Analyzes of Environmental Projects - a Guide (Samhällsekonomiska Analyser Av Miljöprojekt - En Vägledning)*. Stockholm: Naturvårdsverket.

Kurki, V., Pietila, P., & Katko, T. (2016). Assessing Regional Cooperation in Water Services: Finnish Lessons Compared with International Findings. *Public Works Management & Policy, 21*(4), 368-389. doi:10.1177/1087724x16629962

Lallana, C., & Marcuello, C. (2004). *Indicator Fact Sheet*. Copenhagen: European Environment Agency.

Langhans, S. D., & Lienert, J. (2016). Four Common Simplifications of Multi-Criteria Decision Analysis Do Not Hold for River Rehabilitation. *PLoS One, 11*(3), e0150695. doi:10.1371/journal.pone.0150695

Laslett, P., & Fishkin, J. S. (1993). *Justice between Age Groups and Generations*. New Haven: Yale University Press.

Lenton, R., & Muller, M. (2009). *Integrated Water Resources Management in Practice: Better Water Management for Development*. London: Earthscan.

Lieberherr, E. (2011). Regionalization and Water Governance: A Case Study of a Swiss Wastewater Utility. *Procedia - Social and Behavioral Sciences, 14*, 73-89. doi:10.1016/j.sbspro.2011.03.026

Lindhe, A., Rosen, L., Norberg, T., & Bergstedt, O. (2009). Fault Tree Analysis for Integrated and Probabilistic Risk Analysis of Drinking Water Systems. *Water Res, 43*(6), 1641-1653. doi:10.1016/j.watres.2008.12.034

Lindhe, A., Rosen, L., Norberg, T., Bergstedt, O., & Pettersson, T. J. (2011). Cost-Effectiveness Analysis of Risk-Reduction Measures to Reach Water Safety Targets. *Water Res, 45*(1), 241-253. doi:10.1016/j.watres.2010.07.048

Lindhe, A., Rosén, L., Norberg, T., Røstum, J., & Pettersson, T. J. R. (2013). Uncertainty Modelling in Multi-Criteria Analysis of Water Safety Measures. *Environment Systems and Decisions, 33*(2), 195-208. doi:10.1007/s10669-013-9442-9

Livernois, J. (2001). *The Economic Costs of the Walkerton Water Crisis*. Toronto: The Walkerton Inquiry

Malcolm, D. G., Roseboom, C. E., Clark, C. E., & Fazar, W. (1959). Application of a Technique for Research and Development Program Evaluation. *Operations Research, 7*, 646-649.

Malm, A., Moberg, F., Rosén, L., & Pettersson, T. J. R. (2015). Cost-Benefit Analysis and Uncertainty Analysis of Water Loss Reduction Measures: Case Study of the Gothenburg Drinking Water Distribution System. *Water Resources Management, 29*(15), 5451-5468. doi:10.1007/s11269-015-1128-2

Martins, R., & Fortunato, A. (2016). Critical Analysis of the Portuguese Water Industry Restructuring Plan. *Utilities Policy, 43*, 131-139. doi:10.1016/j.jup.2016.06.014

Matheson, D., & Matheson, J. (1998). *The Smart Organization*. Boston: Harvard Business School Press.

Mill, J., Stuart. (1863). Utilitarianism. Retrieved from the Library of Congress https://lccn.loc.gov/11015966

Millennium Ecosystem Assessment. (2003). *Ecosystems and Human Well-Being: A Framework for Assessment*. Washington DC: Island Press.

Mizzoni, J. (2010). *Ethics: The Basics*. Chichester, UK; Malden, MA Wiley-Blackwell.

Monat, J., P. . (2009). The Benefits of Global Scaling in Multi-Criteria Decision Analysis. *Judgment and Decision Making, 4*(6), 492–508.

Moran, D., Macleod, M., Wall, E., Eory, V., McVittie, A., Barnes, A., Rees, B., Pajot, G., Matthews, R., Smith, P., & Moxey, A. (2009). Marginal Abatement Cost Curves for Uk Agriculture, Forestry, Land-Use and Land-Use Change Sector out to 2022. *IOP Conf. Ser.: Earth Environ. Sci., 6*(24), 242002. doi:10.1088/1755-1307/6/24/242002

Morris, D. E., Oakley, J. E., & Crowe, J. A. (2014). A Web-Based Tool for Eliciting Probability Distributions from Experts *Environmental Modelling & Software, 52*, 1-4. doi:http://dx.doi.org/10.1016/j.envsoft.2013.10.010

Munda, G. (1995). *Multicriteria Evaluation in a Fuzzy Environment. Theory and Applications in Ecological Economics*. Heidelberg: Physica-Verlag.

Mysiak, J. E., Henriksen, H. J. E., Sullivan, C. E., Bromley, J. E., & Pahl-Wostl, C. E. (2010). *The Adaptive Water Resource Management Handbook*. London: Routledge.

National Research Council. (2005). *Valuing Ecosystem Services: Toward Better Environmental Decision-Making*. Washington, DC: The National Academic Press.

Nauges, C., & van den Berg, C. (2008). Economies of Density, Scale and Scope in the Water Supply and Sewerage Sector: A Study of Four Developing and Transition Economies. *Journal of Regulatory Economics, 34*(2), 144-163. doi:10.1007/s11149-008-9063-2

O'Hagan, A., Buck, C., E., Daneshkhah, A., Eiser, J., Richard, Garthwaite, P., H., Jenkinson, D., J., Oakley, J. E., & Rakow, T. (2006). *Uncertain Judgements: Eliciting Experts' Probabilities*. West Sussex, England: John Wiley & Sons.

Oakley, J. E., & O'Hagan, A. (2016). Shelf: The Sheffield Elicitation Framework (Version 3.0). Retrieved from http://tonyohagan.co.uk/shelf

OECD. (2018). *Cost-Benefit Analysis and the Environment* (G. Atkinson, N. A. Braathen, B. Groom, & S. Mourato Eds.). Paris: OECD Publishing.

Okun, D., A. (1975). Water Management in England: A Regional Model. *Environmental Science and Technology, 9*(10), 918-923.

Palaniappan, M., Cooley, H., Gleick, P. H., & Wolff, G. (2007). Water Infrastructure and Water-Related Services: Trends and Challenges Affecting Future Development *Infrastructure to 2030 (Vol 2). Mapping Policy for Electricity, Water and Transport*. Paris: OECD Publishing.

Parnell, G. S., Bresnick, T., Tani, S. N., & Johnson, E. R. (2013). *Handbook of Decision Analysis*. Hoboken, NJ, USA: John Wiley & Sons, Incorporated.

Pearce, D., & Atkinson, G. (1993). Capital Theory and the Measurement of Sustainable Development: An Indicator of "Weak" Sustainability. *Ecological Economics, 8*(2), 103-108.

Peng, B.-B., Xu, J.-H., & Fan, Y. (2018). Modeling Uncertainty in Estimation of Carbon Dioxide Abatement Costs of Energy-Saving Technologies for Passenger Cars in China. *Energy Policy, 113*, 306-319. doi:10.1016/j.enpol.2017.11.010

Peterson, M., & Sandin, P. (2013). The Last Man Argument Revisited. *The Journal of Value Inquiry, 47*(1-2), 121-133. doi:10.1007/s10790-013-9369-x

Rahaman, M. M., Varis, O., & Kajander, T. (2004). Eu Water Framework Directive Vs. Integrated Water Resource Management: The Seven Mismatches. *Water Resources Development, 20*(4), 565-575.

Rai, R. K., van den Homberg, M. J. C., Ghimire, G. P., & McQuistan, C. (2020). Cost-Benefit Analysis of Flood Early Warning System in the Karnali River Basin of Nepal. *International Journal of Disaster Risk Reduction, 47*, 101534. doi:10.1016/j.ijdrr.2020.101534

Rathnayaka, K., Malano, H., & Arora, M. (2016). Assessment of Sustainability of Urban Water Supply and Demand Management Options: A Comprehensive Approach. *Water, 8*(12), 595. doi:10.3390/w8120595

Rentz, O., Haasis, H. D., Jattke, A., Ruß, P., Wietschel, M., & Amann, M. (1994). Influence of Energy-Supply Structure on Emission-Reduction Costs*.*, *19*(6), 641-651.

Rosén, L., Back, P. E., Soderqvist, T., Norrman, J., Brinkhoff, P., Norberg, T., Volchko, Y., Norin, M., Bergknut, M., & Doberl, G. (2015). Score: A Novel Multi-Criteria Decision Analysis Approach to Assessing the Sustainability of Contaminated Land Remediation. *Sci Total Environ, 511*, 621-638. doi:10.1016/j.scitotenv.2014.12.058

Rygaard, M., Godskesen, B., Jorgensen, C., & Hoffmann, B. (2014). Holistic Assessment of a Secondary Water Supply for a New Development in Copenhagen, Denmark. *Sci Total Environ, 497-498*, 430-439. doi:10.1016/j.scitotenv.2014.07.078

Saal, D. S., Arocena, P., Maziotis, A., & Triebs, T. (2013). Scale and Scope Economies and the Efficient Vertical and Horizontal Configuration of the Water Industry: A Survey of the Literature. *Review of Network Economics, 12*(1), 93-129. doi:10.1515/rne-2012-0004

Sarica, A. (2018). Cost-Benefit Analysis of Water Production with Seawater Reverse Osmosis System: A Case Study for Mersin Free Zone and International Port. *International Journal of Economics and Financial Issues, 8*(5), 142-147.

Schlosser, C. A., Strzepek, K., Gao, X., Fant, C., Blanc, É., Paltsev, S., Jacoby, H., Reilly, J., & Gueneau, A. (2014). The Future of Global Water Stress: An Integrated Assessment. *Earth's Future, 2*(8), 341-361. doi:10.1002/2014ef000238

Schmidt, M. (2014). Regional Governance Vis-a-Vis Water Supply and Wastewater Disposal: Research and Applied Science in Two Disconnected Fields. *Water International, 39*(6), 826-841. doi:10.1080/02508060.2014.958796

Scholten, L., Maurer, M., & Lienert, J. (2017). Comparing Multi-Criteria Decision Analysis and Integrated Assessment to Support Long-Term Water Supply Planning. *PLoS One, 12*(5), e0176663. doi:10.1371/journal.pone.0176663

Sidgwick, H. (1874). *Methods of Ethics*. London: Macmillan.

Sjökvist, E., Abdoush, D., & Axén, J. (2019). *The Summer 2018 - a Glimpse of the Future?* Norrköping, Sweden: Swedish Meteorological and Hydrological Institute.

Sjöstrand, K. (2017). *Sustainability and Water Supply Governance - a Literature Review on Regional Water Governance, Multi-Criteria Decision Analysis, Cost-Benefit Analysis and Sustainability Assessments* Chalmers University of Technology.

Sjöstrand, K., Lindhe, A., Söderqvist, T., Dahlqvist, P., & Rosén, L. (2019). *Water Demand Management – Challenges and Possibilities (När Vattentillgången Brister)*. Lund: RISE Research Institutes of Sweden.

SMHI. (2019). *Water Availability in Sweden from the Perspective of Water Shortage and Droughts (Sveriges Vattentillgång Utifrån Perspektivet Vattenbrist Och Torka)*. Norrköping: Swedish Meteorological and Hydrological Institute.

SOU 2016:32. *A Safe Water Supply (En Trygg Dricksvattenförsörjning)*. (SOU 2016:32). Stockholm: Elanders Sverige AB.

Statistics Sweden. (2012). *Water Withdrawal and Water Use in Sweden 2010*. Stockholm, Sweden: Statistics Sweden.

Statistics Sweden. (2017). *Water Use in Sweden 2015*. Stockholm, Sweden: Statistics Sweden, Unit of Environmental Accounts.

Stern, N. (2006). *Stern Review: The Economics of Climate Change*. Government of the United Kingdom: Grantham Research Institute on Climate Change and the Environment.

Strosser, P., Dworak, T., Delvaux, P. A. G., Berglund, M., Schmidt, G., Mysiak, J., Kossida, M., Iacovides, I., & Ashton, V. (2012). *Gap Analysis of the Water Scarcity and Droughts Policy in the Eu*. Brussels: European Commission Tender ENV.D.1/SER/2010/0049.

SwAM. (2018). *Water Allocation as a Consequnce of Drought (Fördelning Av Vatten I Torkans Spår)*. Gothenburg: Swedish Agency for Marine and Water Management.

Swedish Food Agency. (2019). *Manual for Climate-Adapted Drinking Water Supply (Handbok För Klimatanpassad Dricksvattenförsörjning)*. Uppsala: Swedish Food Agency.

Swedish Transport Administration. (2018). Analysis Method and Socio-Economic Cost and Benefit Values for the Transport Sector: Asek 6.1. Retrieved from https://www.trafikverket.se/for-dig-i-branschen/Planera-och-utreda/Planerings--och-analysmetoder/Samhallsekonomisk-analys-och-trafikanalys/asek-analysmetod-och-samhallsekonomiska-kalkylvarden/

Sydvatten. (2019). *Climate-Safe Water - How Can We Ensure Enough Water for Everyone's Needs and Who Will Ensure That It Is Sufficient? (Klimatsäkert Vatten – Hur Räcker Vattnet Till Allas Behov Och Vem Ska Se Till Att Det Räcker?)*. Malmö, Sweden: Sydvatten.

TEEB. (2010). *The Economics of Ecosystems and Biodiversity - Ecological and Economic Foundations*. New York: Taylor & Francis Group.

The Dublin Prinicples. (1992). *The Dublin Statement on Water and Sustainable Development.* Paper presented at the The 1992 International Conference on Water and Environment Dublin, Ireland

Thomasson, A. (2013). *Organizing for Increased Sustainability – a Study of the Use of Different Organizational Forms within the Swedish Water and Sewage Sector*. Stockholm: Swedish Water and Wastewater Association.

Thomasson, A. (2015). *In-House Solutions for Water and Sewage Services – Experiences and Challenges in Small Municipalities*. Stockholm: Swedish Water and Wastewater Association.
UN-Water. (2013). *Water Security and the Global Water Agenda: A Un-Water Analytical Brief.* Hamilton: UN University.
UN. (2005). *60/1. 2005 World Summit Outcome* New York: The General Assembly
UN. (2018). *Sustainable Development Goal 6 Synthesis Report 2018 on Water and Sanitation*. New York: United Nations.
UN General Assembly. (2015). Transforming Our World: The 2030 Agenda for Sustainable Development, a/Res/70/1. Retrieved from https://www.refworld.org/docid/57b6e3e44.html
UNESCO. (2019). *Water Security and the Sustainable Development Goals (Series I)*. Paris: UNESCO Publishing.
Varouchakis, E. A., Palogos, I., & Karatzas, G. P. (2016). Application of Bayesian and Cost Benefit Risk Analysis in Water Resources Management. *Journal of Hydrology, 534*, 390-396. doi:10.1016/j.jhydrol.2016.01.007
Veldkamp, T. I. E., Wada, Y., Aerts, J. C. J. H., & Ward, P. J. (2016). Towards a Global Water Scarcity Risk Assessment Framework: Incorporation of Probability Distributions and Hydro-Climatic Variability. *Environmental Research Letters, 11*(2), 024006. doi:10.1088/1748-9326/11/2/024006
WCED. (1987). *Report of the World Commission on Environment and Development: Our Common Future (Brundtland Report)*. New York: Oxford University Press.
WEF. (2019). *The Global Risk Report 2019, 14th Edition*. Geneva: World Economic Forum.
Werner, C., Bedford, T., Cooke, R. M., Hanea, A. M., & Morales-Nápoles, O. (2017). Expert Judgement for Dependence in Probabilistic Modelling: A Systematic Literature Review and Future Research Directions. *European Journal of Operational Research, 258*(3), 801-819. doi:10.1016/j.ejor.2016.10.018
Williams, P., M. (2008). *University Leadership for Sustainability - an Active Dentric Framework for Enabling Connection and Collaboration.* (Doctor of Philosophy), Victoria University of Wellington, Wellington.
Worrell, E., Martin, N., & Price, L. (2000). Potentials for Energy Efficiency Improvement in the Us Cement Industry. *Energy, 25*(12), 1189–1214.
WWAP. (2009). *Integrated Water Resources Management in Action*. Paris: UNESCO.
WWAP. (2012). *The United Nations World Water Development Report 4: Managing Water under Uncertainty and Risk*. Paris: UNESCO.
WWAP. (2015). *The United Nations World Water Development Report 2015: Water for a Sustainable World*. Paris: UNESCO.
WWAP. (2016). *The United Nations World Water Development Report 2016 Report: Water and Jobs*. Paris: UNESCO.
WWAP. (2018). *The United Nations World Water Development Report 2018: Nature-Based Solutions for Water*. Paris: UNESCO.
WWAP. (2019). *The United Nations World Water Development Report 2019: Leaving No One Behind*. Paris: UNESCO.
Young, R. A., & Loomis, J. B. (2014). *Determining the Economic Value of Water - Concepts and Methods*. New York: RFF Press.
Zahedi, S., Azarnivand, A., & Chitsaz, N. (2017). Groundwater Quality Classification Derivation Using Multi-Criteria-Decision-Making Techniques. *Ecological Indicators, 78*, 243-252. doi:10.1016/j.ecolind.2017.03.015
Zhuang, J., Liang, Z., Lin, T., & De Guzman, F. (2007). *Theory and Practice in the Choice of Social Discount Rate for Cost-Benefit Analysis: A Survey*. Manila, Philippines: Asian Development Bank.