THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Risk-based management of the cost to society from infiltration and inflow to wastewater systems

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Cover:
Schematic figure showing common effects of infiltration and inflow, see page 27.

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ABSTRACT

The wastewater system is an important part of our infrastructure as it protects public health and the environment. Well-functioning maintenance is essential to sustain the functionality of the system. Insufficient maintenance in combination with the complexity of the system often results in problems related to water from infiltration and inflow (I/I-water). I/I-water is all water in the wastewater sewer system that is not sanitary sewage and can originate from, e.g. groundwater, stormwater, and surface water. Common effects of I/I-water are the need of additional treatment at the wastewater treatment plants and pumping of water. After large rains, basement flooding events and discharge of untreated wastewater into streams and rivers are also common. To enable a more efficient management of I/I-water, the problem is comprehensively mapped in this thesis. Furthermore, a risk-based framework for decision support is presented that emphasises the need of considering economic, social, and environmental effects of I/I-water, as well as uncertainty throughout the decision-making process. Based on the framework a model is set up to calculate the cost to society from I/I-water. Important effects of I/I-water are monetised and the present value for a longer time horizon is calculated. Further, a case study in central Gothenburg, Sweden, is used to illustrate the applicability of the model. It is concluded that a comprehensive model for decision support is needed to handle I/I-water in a more sustainable way and that the result of this thesis can work as a basis for this.

Keywords: infiltration and inflow (I/I), wastewater, sewer system, risk management, decision support, uncertainty

LIST OF PUBLICATIONS

This thesis includes the following papers, referred to by Roman numerals:

I. Ohlin Saletti, A., Rosén, L. & Lindhe, A. (2021). Framework for Risk-Based Decision Support on Infiltration and Inflow to Wastewater Systems. *Water*, 13, 2320. https://doi.org/10.3390/w13172320

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Paper I: Conceptualisation, A.O.S., A.L., L.R.; methodology, A.O.S., A.L., L.R.; writing—original draft preparation, A.O.S.; writing—review and editing, A.O.S., A.L., L.R.; visualisation, A.O.S.; supervision, A.L., L.R.; funding acquisition, A.L., L.R.

Paper II: Conceptualisation, A.O.S., A.L., L.R.; methodology, A.O.S., A.L., T.S., L.R.; formal analysis, A.O.S., writing—original draft preparation, A.O.S.; writing—review and editing, A.O.S., A.L., T.S., L.R.; visualisation, A.O.S.; supervision, A.L., L.R.; funding acquisition, A.L., L.R.

Other work and publications not appended to this thesis:

- Ohlin Saletti, A., Rosén, L., Lindhe, A., Blom L. B., Nivert, G. (2021). *Managing infiltration and inflow to wastewater systems – Key aspects in a risk-based approach* (Abstract). Presentation at the digital NORDIWA wastewater conference 2021, September 28 – October 1.
- Ohlin Saletti, A., Rosén, L., Lindhe, A., Blom L. B., Malm, A., Wilson, A. (2021). *Presenting a framework for risk management and decision support for infiltration and inflow to wastewater systems* (Abstract). Digital poster presentation at the Digital World Water Congress 2021, May 24 – June 4.
- Ohlin Saletti, A. (2021). *Infiltration and inflow in wastewater sewer systems - A literature review on risk and decision support.* Chalmers University of Technology. Parts of this review serve as a basis for the theoretical background covering I/I-water, risk, and decision support, in this thesis.

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Gothenburg, May 2022
Anna Ohlin Saletti

TABLE OF CONTENTS

1. INTRODUCTION

1.1 Background

Our world is facing serious problems connected to climate change, environmental issues, and conflicts. In 2050 around 70% of the world's population is expected to live in urban areas (UNDESA, 2018) and a key challenge is how to provide everyone with sufficient services. The wastewater system is an important part of the infrastructure and exists mainly to decrease the risk of disease and flooding. In developed areas, the wastewater sewer system is usually located underground and consists of pipes, pumps, manholes, and other components. To sustain the functionality of the system, continuous maintenance is needed which often requires large reinvestments. The pace of the maintenance has, in most countries, including Sweden, not been fast enough and reinvestments are lacking behind, creating an enormous maintenance debt (Swedish water, 2020). Deterioration of the wastewater system can lead to different problems, of which the increase of water from infiltration and inflow (I/I-water) (e.g., Bäckman, 1985; USEPA, 1970) is substantial. I/I-water is all water in the wastewater sewer system that is not sanitary sewage and can either be stormwater connected to combined systems or, e.g. groundwater leaking into the system. The levels of I/I-water vary depending on the local conditions but it is not uncommon with wastewater treatment plants (WWTPs) that on a yearly scale receive more I/I-water than sanitary sewage (e.g., Hey et al., 2016; Sola et al., 2018). I/I-water can lead to various adverse effects such larger volumes to be treated at the WWTP, basement flooding, and discharge of untreated wastewater into recipients. However, I/I-water can be reduced, e.g., by rehabilitation of pipes or separation of combined systems, but the measures are often resource-demanding and do not always lead to the expected results (e.g., Sola et al., 2021). Moreover, several legal perspectives have to be taken into account performing measures to reduce I/I-water, one being that the outermost parts of the wastewater system, which in total make up a substantial share, is privately owned (Lundblad & Backö, 2014; NEIWPCC, 2003). In those parts, the water utilities have limited responsibility and limited possibilities to perform measures. Moreover, the possibility to implement measures to reduce I/I-water is in the European Union affected by the "Weser case" (C-461/13 Bund v Germany). This ruling is in accordance with the European Union Water Framework Directive (2000/60/EC) and states that any project that would result in a deterioration of the quality of the water bodies must be refused (e.g., Paloniitty, 2016; Söderasp & Pettersson, 2019). Since the ruling can make projects impossible if only one water quality parameter is deteriorated, even though the project is important for society, the Weser case has been criticised for being contradictive (Bjällås et al., 2015). When taking decisions regarding handling of I/I-water, legal requirements must be fulfilled but also balanced against other needs in society and resources put where most beneficial.

1.2 Aim and objectives

The overall aim of this thesis is:

> *to develop a framework and model that facilitate risk-based management of water from infiltration and inflow to wastewater systems through assessment of its costs to society*

To reach the overall aim, the thesis has the following specific objectives:

i. to evaluate existing decision support models focused on I/I-water and present a framework for risk management and decision support on I/I-water,
ii. to map effects of and possible measures to manage I/I-water, and
iii. to develop a model for assessing the cost to society from I/I-water and illustrate its applicability by means of a case study where some of the most important effects are monetised.

1.3 Scope of work

To achieve the overall aim of this thesis a multidisciplinary approach was used. A theoretical background (Chapter 2) is presented to establish important concepts and theories for the research. For a more extensive literature review on I/I-water and decision support, see Ohlin Saletti (2021). In the methodology section (Chapter 3), the concepts presented in the theoretical background are connected to the topic of this thesis to reach its objectives. The result section (Chapter 4) starts with a presentation of the results from Paper I which includes the framework and evaluation of previous decision support models on I/I-water. This is followed by results regarding various effects and measures related to I/I-water. The last part of the results section includes the outcomes from Paper II, i.e. a model for calculating the cost to society from I/I-water. In the final sections the work included in this thesis is discussed (Chapter 5) and the conclusions and further work are presented (Chapter 6).

1.4 Limitations

The following key limitations of this thesis have been identified and are further elaborated on in the discussion section.

- The presented research is focused on comprehensive decision support on I/I-water considering effects on the entire society. Therefore, emphasis is not put on the technical details (although parts are summarised in the theoretical background) and several simplifications have been made in the developed model.
- The case study included in Paper II has been performed in a discharge area in Gothenburg, Sweden. The case study is used to show the applicability of the model and the results are case study specific and dependent on the geographic location.

2 THEORETICAL BACKGROUND

This chapter provides a theoretical background introducing important concepts for the research. These concepts serve as a basis for the approaches used to develop the methodologies presented in this thesis.

2.1 Wastewater sewer systems

2.1.1 Conceptual description

Infrastructure provides our society with essential services and can consist of systems for transport, communication, energy, drinkingwater, and wastewater (Kaijser, 1994). The word *infrasystem* is used to include more characteristics of a technical system as it comprises its integration with organisations and people that develop, operate, and use the system.

The wastewater sewer system exists mainly to transport wastewater to avoid disease and flooding and is one of our most important infrasystems. In many urban areas the main parts of the wastewater sewer system are located underground with components such as pipes, valves, manholes, and pumps.

Two main types of wastewater systems are the separate system and the combined system (Figure 1). In the combined system the sanitary sewage is transported in the same pipe as the stormwater and in the separate system these flows are separated into two different pipes. Nowadays, separate systems are built to a large extent, but combined systems still exist, mainly in old and central parts of urban areas.

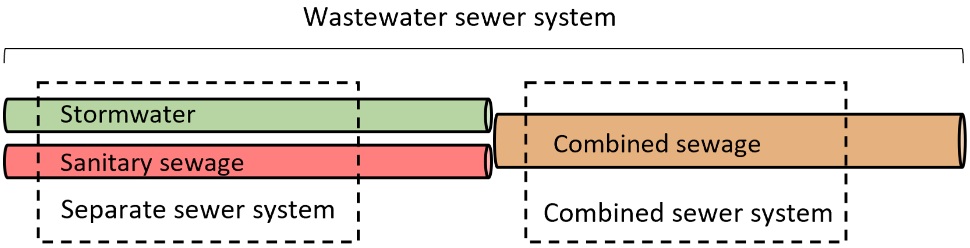

Figure 1. Schematic overview of a separate and combined wastewater system.

2.1.2 History

In order to understand an infrasystem it is, as stated by Blomkvist and Johansson (2016), important to be aware of its history. One of the first records of a wastewater system is found from the Mesopotamian Empire and later on, during the Roman period advanced sewer systems were constructed (Lofrano & Brown, 2010). From the Middle Ages to the industrial revolution followed the sanitary dark age and it was not until the recent decades that the wastewater sewer system got its current structure in industrialised regions.

To illustrate the recent development of the wastewater system the City of Gothenburg is used as an example. Between 1830–1850, approximately 15% of the city's population died in waterborne cholera pandemics (City of Gothenburg, 2013). In 1879 a plan for a large culvert leading the wastewater from the city to the river was finished. It was not until 1953 that a biologic treatment plant to treat wastewater from a newly exploited area was brought into operation. Until 1955 the wastewater system was built as a combined system but from then and onward, separate sewer systems were built to a larger extent. A decision on building a large WWTP was taken in 1957 and in 1972 the Rya WWTP was taken into operation. Since then, more strict regulations about nutrient release into recipients have been implemented and the WWTP has been rebuilt and upgraded in steps.

2.1.3 Technological change

In this section concepts related to innovation and technical systems are presented. These concepts in relation to possible changes in the wastewater system are discussed later in this thesis.

The characteristics of an infrasystem can be described from a technical, geographic, economic, and institutional perspective (Kaijser, 1994). How it is organised depends on whether the connection between flow and system is weak or strong. A system where the flow is led in a pipe or line which it should not deviate from, e.g., the wastewater-, railway or electricity system, has a strong connection between flow and system. These can be compared to more weakly connected systems like the road-, or postal service system. Implementing a strongly connected system usually requires large initial investments and gradual extensions are difficult.

The wastewater system can be seen as a large technical system (LTS) which is a complex socio-technical system with a wide geographical spread (e.g., Mayntz & Hughes, 2019). When applying an LTS approach, not only the technical system is referred to but also parts related to relations and organisational structure. In relation to technical systems and technological change Hughes (1992) introduces the concepts of salients and reverse salients and states that these can help us understand industrial revolutions. A salient is defined as a bulge in an advancing front and can in this context be a more efficient innovation in a system, comparable to the engine in an aeroplane system. A reverse salient is the opposite, something that lags after the front, e.g. the transmission system in a power system where the system goal is expansion to a low cost.

To describe how technological transitions can appear, a multi-level perspective (MLP) can be used (e.g., Geels, 2002). Using this perspective three different levels are described which are technological niches, sociotechnical regimes, and sociotechnical landscape. If a new radical innovation is present at the technological niche-level its further success is also depending on the developments at the sociotechnical regime-level, regarding, e.g. infrastructure, market and policies, and at the sociotechnical landscape-level regarding, e.g. environmental problems, economic growth, and war. Destabilisation at the landscape- and regime levels can hence facilitate an innovation break-through (e.g., Geels, 2005).

What design choices that are made, or which dominant design that is established, also play a large role in the further development of that technology since the established design is improved and elaborated, and other technologies hence fall behind (e.g., Henderson & Clark, 1990). This may be a problem, especially if the dominant design is not the most suitable for society.

2.2 Infiltration and inflow to wastewater systems

An inevitable consequence of having a traditional wastewater system is that I/I-water to varying degree also is transported in the sewer system. I/I-water is defined as all water apart from sanitary sewage in pipes transporting sanitary sewage and can hence be present in both separate and combined systems.

2.2.1 Sources and components

Even though some overlaps exist a way to classify I/I-water is by distinguishing if it is coming from either infiltration or inflow. Infiltration happens due to damages in the wastewater system (e.g., Sola et al., 2018) and is dependent on the status of the system, the hydrogeologic conditions, and possible sources of infiltration water (Fenner, 1990) such as leaking drinking water, groundwater, or stormwater (Figure 2).

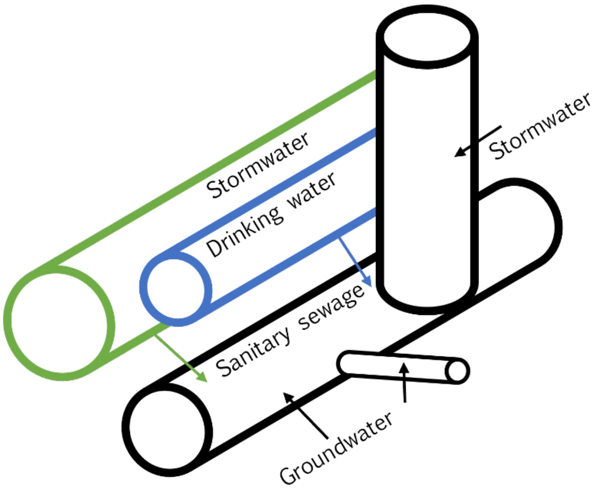

Figure 2. Schematic illustration of sources of infiltration (Ohlin Saletti, 2021).

While the contribution of I/I-water from infiltration often is unintentional I/I-water from inflow can come from both intentional and unintentional sources (e.g., USEPA, 1970). An important intentional source of I/I-water is through the combined system which was designed to transport this water to the WWTP. This is a design choice that probably would not have been chosen today, however the consequences must still be handled. I/I-water from inflow can also originate from unknown connections or from leakage and be either direct or indirect (Figure 3).

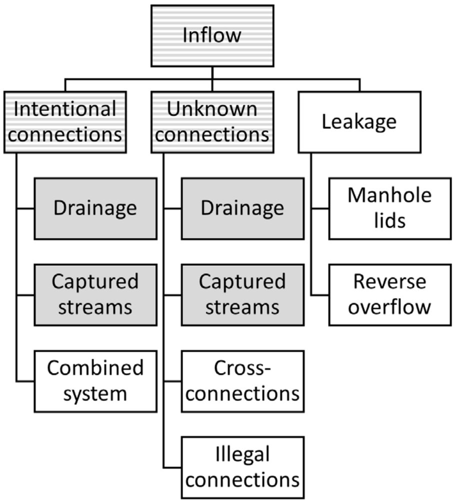

Figure 3. Sources of inflow divided into intentional connections, unknown connections, and leakage. Grey boxes indicate indirect inflow and white boxes indicate direct inflow (Ohlin Saletti, 2021).

Direct or indirect impact of I/I-water also relate to other classifications of I/I-water which instead of the source focus on the time it takes for the water to reach the system. A common classification is to divide the I/I-water into groundwater infiltration (GWI), rain-induced infiltration (RDII), and rain-derived inflow (RDI) (e.g., Staufer et al., 2012). The terms fast response components (FRC), slow response components (SRC), and groundwater induced components are also used to classify a rain (e.g., Clementson et al., 2020; Metelka et al., 1998). FRC often derive from runoff from impermeable surfaces being connected to the sewer system and its effect can be measured in hours, while SRC reach the system days after a rainfall and usually derive from rain that run off from permeable surfaces (Figure 4). The groundwater impact changes more slowly, and the effect can be seen on a yearly or seasonal scale.

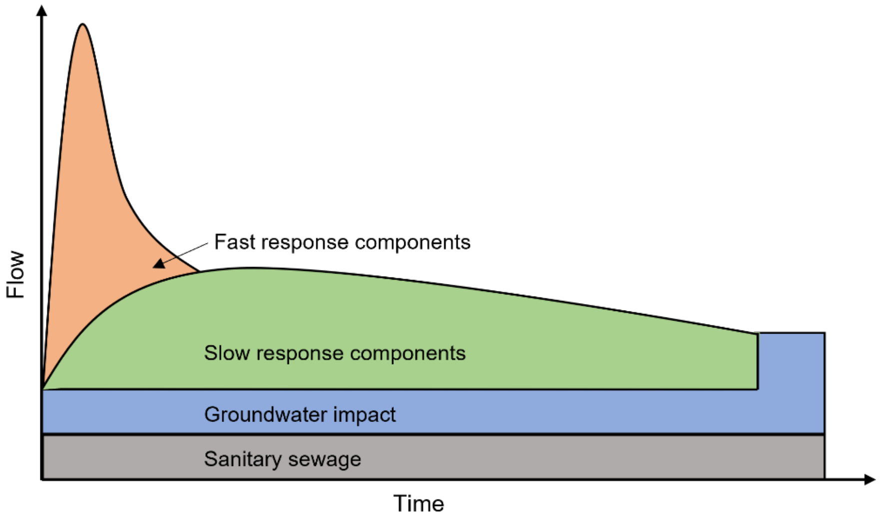

Figure 4. Components of flow to a WWTP. Adapted from Clementson et al. (2020).

2.2.2 Effects

Various effects of I/I-water are reported in the literature and a short overview of the most commonly described effects are presented here. I/I-water results in more water to the wastewater system which requires more energy for pumping and a higher use of chemicals at the WWTPs (e.g., USEPA, 1970). Moreover, I/I-water dilutes the sanitary sewage resulting in less efficient treatment (e.g., Bäckman, 1985; Diogo et al., 2018). Apart from the direct effects of I/I-water, it can indirectly affect the society due to the consumption of labour, energy, and costs needed to replace and extend wastewater systems because of I/I-water (USEPA, 1970). A wastewater system with no capacity for new connections can also affect planned urban development projects.

Exceeding the capacity of the wastewater system can also lead to other kinds of effects. To avoid flooding elsewhere wastewater is sometimes by-passed into recipients (e.g., USEPA, 2004). This is called combined sewer overflow (CSO) if occurring from a combined system and separate sewer overflow (SSO) if occurring from a separate system. Wastewater can also, when required, by-pass one or several treatment steps in the WWTP. Since there are pollutants such as microbial pathogens, toxics, and trash in the wastewater these also reach the receiving water during a CSO, SSO, or by-pass which can have negative environmental and health effects. Another possible effect of excessive volumes of wastewater in the system is basement flooding events that occur due to backflow into houses after large rains (e.g., Bäckman, 1985). Other kinds of urban flooding events can also occur due to I/I-water (USEPA, 1970).

Many other possible adverse effects of I/I-water are mentioned in the literature, such as blockage because of sediment and debris transported by I/I-water (USEPA, 1970), street and road damages due to undermining (Karpf & Krebs, 2011; Weil, 1995), and subsidence due to lowered groundwater tables (Bäckman, 1985). Positive possible effects of I/I-water are less commonly stated in the literature. However, less I/I-water could result in a higher methane concentration in the wastewater which can lead to increased greenhouse gas emissions (Sun et al., 2015), blockages could be more common due to a decreased frequency of self-cleaning velocities (Karpf & Krebs, 2011; Parkinson et al., 2005), and CSOs and SSOs would (if still occurring) contain a higher concentration of pollutants. It is also likely that the groundwater levels in many cities are controlled by the drainage effect caused by infiltration to the wastewater system (Kracht & Gujer, 2006) and that sealing of all pipes hence could result in surface flooding (Gustafsson, 2000; Karpf & Krebs, 2011). There is evidence that wastewater sewage pipes historically were designed to be leaky to avoid flooding by draining the land and lowering the groundwater table (Broadhead et al., 2013). Moreover, the action of culverting streams can also have been performed historically to better manage surface flooding.

2.2.3 Detection, localisation, and quantification

There are many reviews and publications on the different methods to detect, localise, and quantify I/I-water. In this thesis the methods have been divided into the categories of sensory methods, tracer methods, flow-based methods, models, and digital water as done by Ohlin Saletti (2021) (Figure 5).

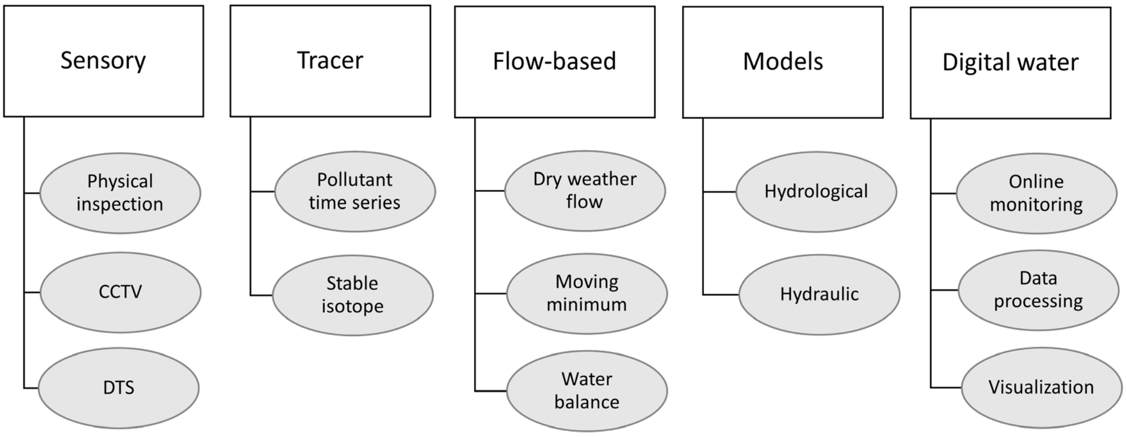

Figure 5. Categories and examples of methods to detect, localise, and quantify I/I-water (Ohlin Saletti, 2021).

To detect and localise I/I-water, e.g. by finding leakages into the system or illicit connections, sensory methods can be used. A category of the sensory methods are the *physical inspection* methods described by, e.g. Beheshti et al. (2015) and Eiswirth et al. (2000). A common way to perform physical inspection is to add smoke or dye to the system to visually observe how the pipes are connected (e.g., Bäckman, 1985; Lundblad & Backö, 2012). The most common method to inspect wastewater networks is *closed-circuit television (CCTV)*. CCTV is described more in detail by Rizzo (2010) and involves filming the surroundings in the wastewater system by inserting a camera on a pushrod or installed to a remote controlled robot (Tuccillo et al., 2010). Further, an increasingly popular sensory method is *distributed temperature sensing (DTS)*, described by, e.g. Hoes et al. (2009). The method involves continuous measuring of the temperature of the water using a fibre-optic cable at the bottom of the wastewater pipe (Panasiuk et al., 2019). I/I-water can then be detected and localised because of the temperature difference between sanitary sewage and I/I-water. Other methods that can be categorised as sensory methods are to use infrared sound, ultrasonic methods, and ground penetrating radar techniques (e.g., Eiswirth et al., 2000; Tuccillo et al., 2010; Wirahadikusumah et al., 1998).

I/I-water tracer methods aim at monitoring substances that can be detected and observed in the wastewater and are described by, e.g. De Bénédittis and Bertrand-Krajewski (2005) and Kracht et al. (2008). *Pollutant time series methods*, or chemical methods, are tracer methods where the concentration of a pollutant that is assumed to only be present in sanitary sewage and not I/I-water is estimated (Kracht et al., 2008). The share of I/I-water can be obtained by calculating its dilution in the wastewater. Examples of pollutants used as tracers are the total phosphorous concentration (TOT-P) (e.g., Sola et al., 2018), the chemical oxygen demand (COD) (e.g., Bareš et al., 2009; Kracht et al., 2008), the total suspended solids (TSS), and ammonium (Uusijärvi, 2013). In the similar *stable isotopes methods*, or natural tracer methods, it is assumed that the inherent components in the wastewater differ depending on sources like drinking water and groundwater (Kracht et al., 2007). Differences in stable isotopes in the wastewater are then monitored to distinguish how much of the water consists of I/I-water.

Flow-based methods, or statistical methods, are used to quantify I/I-water by studying the wastewater volumes and making assumptions regarding, e.g. the drinking water consumption and sanitary sewage production. Flow-based methods are described in the literature by, e.g. Franz (2007) and Weiss et al. (2002). Two examples of methods are *dry weather flow* (USEPA, 2014) where the flow is measured after a dry period and all the flow is considered to consist of sanitary flow and infiltration and *moving minimum* (e.g., Franz, 2007; Weiss et al., 2002) where the lowest flow to the WWTP during the past 21 days is assumed to only consist of sanitary sewage and infiltration. Another example of a flow-based method is the *water balance method* (e.g., Sola et al., 2018) in which the I/I-water volume is assumed to be all water reaching the WWTP minus the drinking water consumption of the connected people. The water consumption is in this method assumed to be equivalent to the sanitary sewage flow.

Models can be used to quantify I/I-water after being calibrated with measurement points in the wastewater system (Karpf & Krebs, 2011) and an overview of I/I-water modelling principles is presented by Franz (2007). *Hydrological models* aim to predict the runoff in a catchment area while *hydraulic models* describe the hydraulic behaviour in a wastewater system.

The umbrella term *digital water* refers to the digitalisation of the water system which to some extent already has started but still has a large potential to transform the water sector in the close future (IWA, 2019). In the I/I-water context, a basic step towards a more digital operation is using *online monitoring*. Two examples are using SCADA (Supervisory Control And Data Acquisition) systems where data from field sensors are processed and used to take action or optimise performance (Upadhyay & Sampalli, 2020) or IoT (Internet of Things), where objects are connected and can communicate with each other on the Internet using technologies as LPWAN (Low Power Wide Area Network). In literature several publications present methods to use SCADA systems to monitor I/I-water (e.g., Davalos et al., 2018; Li et al., 2008; Pereira et al., 2019). Examples where IoT technology is used to monitor wastewater networks are presented by Drenoyanis et al. (2019) and Ebi et al. (2019). Another category of digital water is *data processing methods* where machine learning and artificial intelligence (AI) are two examples (IWA, 2019). A common application of these technologies is using the systems to detect defects in sewer pipes in data from CCTV (e.g., Huang et al., 2017; Shehab & Moselhi, 2005). *Visualisation* using virtual reality (VR) or augmented reality (AR) technologies can also be used in an I/I-water context. VR technology, where the user is put in an artificial environment can be used for scenario based training for employees (IWA, 2019) and AR technology, where the real world is mixed with the digital world, can be used to give workers “X-ray vision” to localise the pipes during excavation (Schall et al., 2009).

2.2.4 Measures to reduce and control infiltration and inflow

The various methods to reduce the effects of I/I-water can be divided into rehabilitation methods and methods to control the flow (Figure 6).

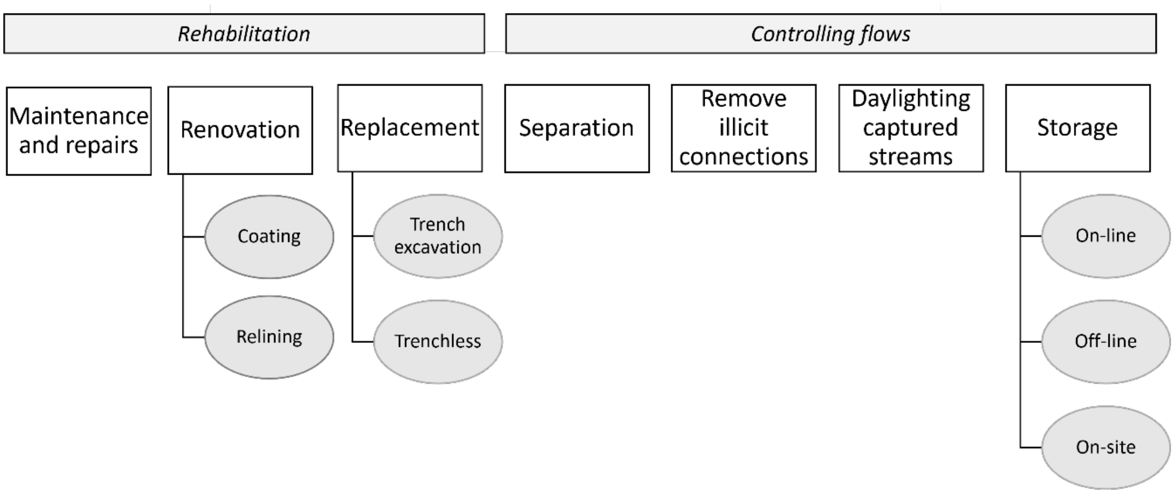

Figure 6. Overview of measures to reduce I/I-water or the impacts caused by I/I-water (Ohlin Saletti, 2021).

The structural state and functional efficiency of a sewer system are maintained by performing rehabilitation actions (Staufer et al., 2012). Sterling et al. (2009) and Abraham and Gillani (1999) present overviews of different rehabilitation methods. Sewer rehabilitation can be divided into the three categories *maintenance and repair*, *renovation*, and *replacement* (Tomczak & Zielinska, 2017) and the actions are performed either to prevent failure, or more commonly, as a reaction to an already occurred failure (Rizzo, 2010). Maintenance and repair involve cleaning and point repairing in the sewer system and an example of an efficient and cost-effective method is using chemical grouting for point repairs (e.g., Abraham & Gillani, 1999). The two most common renovation methods are coating and pipe relining (Tomczak & Zielinska, 2017). Coating can be done using, e.g. cement mortar coatings or resin coatings while relining means improving a pipe's structural state by inserting a lining (Abraham & Gillani, 1999). Two examples of relining methods are sliplining and cured-in-place (CIP) lining. Wastewater system replacement can be performed either by using open cut trench excavation or trenchless methods (Tomczak & Zielinska, 2017). Open cut trench excavation has been used traditionally for replacement but due to its disruptive nature, e.g. due to traffic disturbances and the need for disposal of soil it is today usually used only when the pipe is seriously in need of a total replacement. Trenchless replacement is usually a more convenient choice which can be done, e.g. through pipe bursting where the existing pipe is broken open and a new pipe inserted (e.g., Rameil, 2007). Pipe bursting has a similar result as relining but with the difference that pipe bursting does not decrease the diameter of the pipe.

The effects of I/I-water can also be decreased if flows that are intentionally or unintentionally connected to the wastewater or sewer system are redirected or controlled. The addition of I/I-water in the combined system can be reduced by *separation* of the system where an additional pipe only for stormwater is added leading the stormwater to the recipient, either with or without treatment (Brombach et al., 2005). *Removing illicit connections* is another method to reduce the I/I-water to the system, e.g. by disconnecting private stormwater laterals from the sewer system. The procedure is explained more in detail by Brown et al. (2004) and requires that faulty connections have been localised as well as extensive interaction and cooperation with private property owners (Lundblad & Backö, 2014). *Daylighting of captured streams* is another method of redirecting the flows and involves restoring old waterways which have been connected to the wastewater or sewer system (e.g., Broadhead et al., 2015; Buchholz et al., 2016). Further, instead of being removed, I/I-water can be regulated to avoid effects related to peak flows. This is done by using *storage* facilities which can be located in-line, i.e. within the existing system, off-line, i.e. in tanks and basins adjacent to the system, or on-site, i.e. at the WWTP (USEPA, 2004).

It should not be assumed that a measure to reduce I/I-water always has the intended effect. When it comes to rehabilitation it has been shown that the effect on I/I-water is very limited if not all pipes and manholes in an area are rehabilitated (Bäckman, 1985; Lundblad & Backö, 2014; Sola et al., 2021). Regarding the choice of separation of combined systems, the separate system is nowadays usually preferred over the combined and uncritically implemented (Brombach et al., 2005). However, it has been shown that the flow characteristic in a separate system often is similar as in a combined system even though it theory should contain no rain induced I/I-water (Bäckman, 1985).

2.3 Sustainability and ethical principles

Sustainable development can be defined in various ways, but one of the most established definitions is from the Brundtland report which states that “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987). A way of reaching sustainable development is to fulfil goals related to different dimensions of sustainability. Although several additional dimensions have been suggested, e.g. a moral, legal, technical and political dimension (e.g., Pawłowski, 2008), the three dimensions of economic, social, and environmental or ecological sustainability (Barbier, 1987) are those traditionally used. The economic dimension concerns the distribution of resources between current and future generations (Hedenus et al., 2018). Resources can include both finite natural resources (e.g., fossil fuels and metals), but also capital created by humans, such as buildings and education. Definitions regarding the social dimension of sustainability vary. Often included factors are health, well-being, equity, and participation (e.g., Harris, 2009; Torjman, 2000), but some argue that these are the goals or means of sustainability. According to this view the social dimension should instead include prerequisites to achieve the goals and concern vertical relations, e.g. trust between people and horizontal relations, e.g. well-functioning social institutions (Hedenus et al., 2018). The environmental dimension includes the conservation of nature and landscape, e.g. by avoiding over-exploitation, maintaining biodiversity, and creating resilience (e.g., Barbier, 1987; Harris, 2009; Pawłowski, 2008).

There are different ways of illustrating how the three dimensions of sustainable development relate to each other (Figure 7). A common way is using a Venn diagram as done by, e.g. Barbier (1987). Sustainability then means maximising the goals of all three dimensions and is illustrated by the common space shared by all three circles. In the Bull's eye model (see e.g., Scott Cato, 2012) it is, on the other hand, illustrated that the boundaries for the economy is set by social relationships which in their turn depend on the environment which make up the outer border. The two presented models on how the dimensions relate to each other can be connected to the concepts of weak and strong sustainability, described by, e.g. Turner et al. (1993) and Neumayer (2003). Weak sustainability relates to the Venn diagram and assumes perfect substitutability between different forms of capital. Hence, it is possible to compensate for the loss of natural capital by introducing man-made capital since it is the sum of these capitals that should not decrease over time to reach a sustainable development. Strong sustainability is more related to the bull's eye diagram and claims that it is not possible to compensate between the dimensions and to reach a sustainable development neither of the capitals should decrease over time.

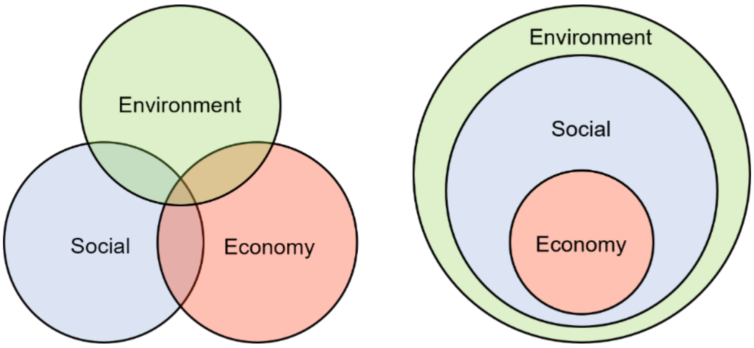

Figure 7. Two examples of how the three dimensions of sustainable development can be related. To the left: Venn-diagram. To the right: bull's eye diagram.

In recent years the definitions of and tools for assessing sustainability have been further developed and expanded. An example of this is the sustainable development goals formulated by the United Nations (United Nations, 2015). The 17 goals include themes related to, e.g. poverty, energy, and peace, and it is acknowledged that different kinds of progress must be synchronised to reach sustainable development. Goal number 6: Clean water and sanitation and goal number 11: Sustainable cities and communities are the most strongly related to this thesis.

To define what sustainable development is, one must determine who or what has an intrinsic value, e.g. only humans (anthropocentrism), also animals, all living things (biocentrism), or ecosystems (ecocentrism) (Brennan & Norva, 2021). These views can to different extent correlate to other ethical theories. Utilitarian ethics are related to anthropocentrism and it is believed that the action that leads to the maximum total happiness of people should be chosen (Bentham, 1789; Mill, 1863). Using this perspective, ecosystems do not have intrinsic values but should be evaluated based on how they directly and indirectly contribute to human welfare, i.e., by ecosystem services. Costanza et al. (1997) listed 17 ecosystem services that can be divided into provisioning, regulating, cultural, and supporting services. A classification of ecosystem services has been performed by the Common International Classification of Ecosystem Services (CICES) (Haines-Young & Potschin, 2018). A different ethical theory is the deontological, which is more related to ecocentrism. Moral norms, duty and, ethical values here distinguish if an action is good or not and it is hence not related to which consequences of the action that arise (Broad, 1930).

2.4 Risk and decision support

2.4.1 Risk definitions and uncertainty

There are many ways to define risk, both in technical and more social-science related contexts (Hansson, 2002). A risk should not be confused with a hazard which is a source with the potential to cause harm, whereas a risk is the likelihood of harm caused by the hazard (e.g., Kaplan & Garrick, 1981). ISO (2018) presents the risk definition “effect of uncertainty on objectives”, but also states that risk usually is expressed in terms of risk sources, potential events, consequences, and likelihood. The latter can, from an engineering perspective, be derived from the classical risk definition by Kaplan and Garrick (1981) who use the three questions “What can go wrong?”, “How likely is it that that will happen?”, and “If it does happen, what are the consequences?” as a basis for expressing risk.

Probability is defined by ISO (2018) as “an extent to which an event is likely to occur” and the concept can be interpreted in thee ways (Bedford & Cooke, 2001). The classical interpretation involves seeing probability as the outcome after repeating an experiment, e.g. throwing a dice a limited number of times whereas in the frequentist interpretation it is assumed that the experiment can be performed an infinite number of times. The third interpretation, the subjective or Bayesian interpretation, in which probability is expressed as a degree of belief, is widely used in risk analysis (Bedford & Cooke, 2001). The probability is then seen as the sum of a set of possible worlds or a set of possible states of the world and this interpretation could be used, e.g. when answering the question "Will it rain tomorrow?". ISO (2018) defines consequence as the "outcome of an event affecting objectives" and states that a consequence can have both positive and negative direct or indirect effects.

Using probability and consequences to quantify risk is widely established in engineering contexts but some argue that the definition should be developed or broadened, e.g. by adding a dimension of time (Haimes, 2009) or replacing the probability component with uncertainty (Aven, 2010).

Uncertainty is by Aven (2012) defined as "lack of knowledge about the performance of a system (the world), and observable quantities in particular". Uncertainties can be either *aleatory*, arising from randomness in samples, or *epistemic*, due to lack of knowledge of the system. In risk assessment both types of uncertainties are common, and it is thus important to consider them in a suitable manner to obtain a good understanding of the risk.

2.4.2 Risk management and decision support

A risk management process is suggested by ISO (2018) (Figure 8) which aims to show how risks can be handled in a structured way.

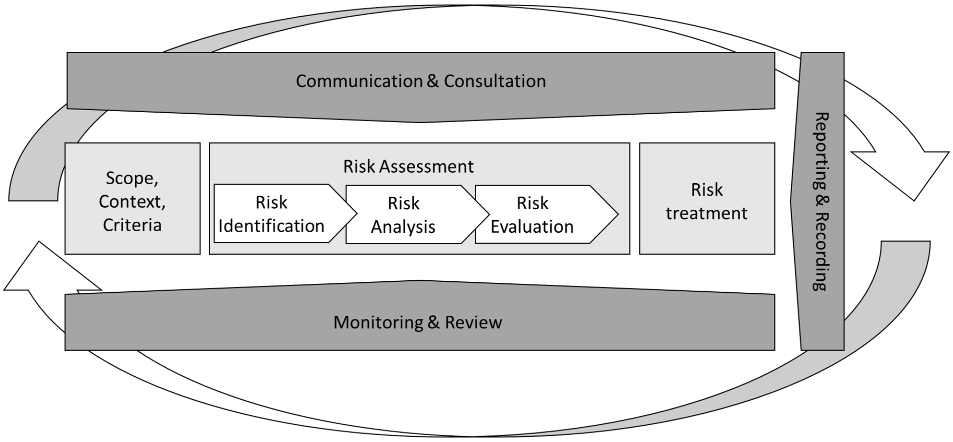

Figure 8. Risk management process adapted from ISO (2018) (Ohlin Saletti, 2021).

After defining a scope and risk criteria, e.g. to reduce the risk of CSOs or basement flooding events to a specific level, a risk assessment is performed which involves identification, analysis, and evaluation of the risks. In the risk analysis step parameters such as risk sources, consequences, likelihood, and uncertainties are estimated and then used in the risk evaluation step where different decision support methods can be used. The results are compared with the risk criteria to see if additional actions to reduce or eliminate the risks should be performed. In the risk treatment step these actions are selected and implemented.

To involve and create understanding among stakeholders, improving the process and define clear responsibilities, the steps Communication and Consultation and Monitoring and Review take place throughout the process. Additionally Reporting and Recording are performed to and document important outcomes. When new information becomes available the process is updated and is thus iterative rather than linear.

A basic structure for decision support is presented by Aven (2012) which suggests that after formulating the decision problem or decision alternatives and performing the risk and decision analyses, a managerial review and judgement process should be done (Figure 9). The review aims to see if a decision can be taken or if the problem should be updated. The whole process is governed by stakeholder goals, criteria, and preferences.

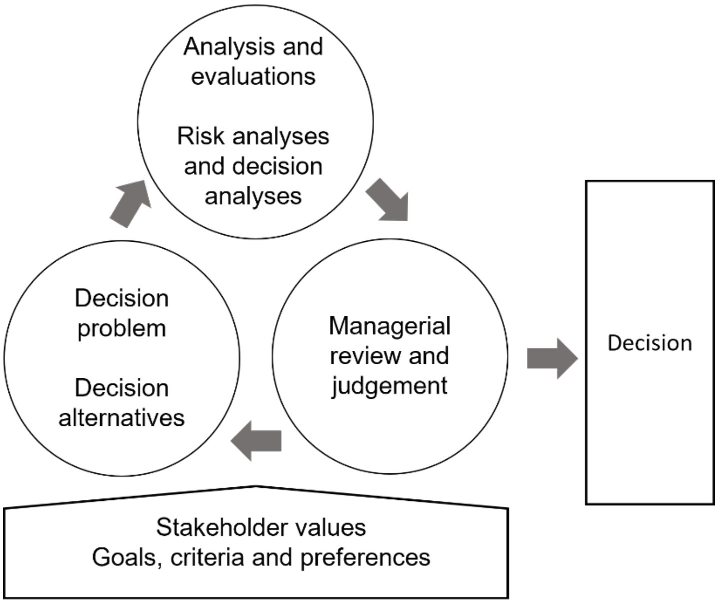

Figure 9. Basic structure of the decision-making process, adapted from (Aven, 2012) (Ohlin Saletti, 2021).

Several different decision support methods can be used for managing risks, e.g. multi-criteria decision analysis (MCDA) and cost-benefit analysis (CBA). In a MCDA a complex problem is broken into smaller pieces that can be either monetised or not (DCLG, 2009). The different alternatives are evaluated using scoring based on identified criteria which are weighted in relation to each other. After combining the weights and scores for each alternative together, overall weighted scores are obtained which can be used as a basis for decision support. In a MCDA, different effects can be evaluated in relation to each other, e.g. a reduced risk due to a specific measure can be evaluated against negative impacts caused by the measure.

In a CBA all costs and benefits for a project alternative are monetised from a societal perspective (Hanley et al., 2009). A reduced risk associated with a project alternative is considered a benefit and can be combined with other benefits and costs to achieve the particular risk reduction. The Net Present Value (*NPV*) for each alternative is:

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

where T is the project time including the years t $(t=0 \ldots T)$, B_t the benefits for year t, C_t the costs for year t, and r the discount rate.

To make costs and benefits that arise at different years comparable discounting is performed (e.g., Boardman et al., 2017; Johansson & Kriström, 2018). Using a discount rate, the value of future costs and benefits are assumed. A discount rate close to zero means that the future costs and benefits are valued similar as today whereas a higher discount rate lower the present value of the future costs and benefits. It is also possible to let the discount rate decline along the project time which can make up for intergenerational inequality (Arrow et al., 2014). After calculating a *NPV* for each project alternative they can be compared and the alternative with the highest *NPV* is considered to be the most preferable.

In both a MCDA and a CBA, sensitivity analyses should be performed to examine how changes in the used parameters and different boundary conditions for the model set-up affect the final results.

2.5 Expert elicitation

Information needed to perform an analysis is not always easily available, due to the complex nature of the problem or since the answer is subjective. In those cases elicitation, defined by Dias et al. (2018) as the “facilitation of the quantitative expression of subjective judgements” can be used. Expert elicitation is extensively described in literature by, e.g. Cooke (1991), O'Hagan et al. (2006), and O’Hagan (2019). Exactly how the elicitation process should be performed is debated. However, based on a review of method descriptions, Jenkinson (2005), suggests six steps which most models have in common. The steps are: (1) Background and

Preparation, (2) Identify and recruit experts, (3) Motivating the experts, (4) Structuring and Decomposition, (5) Probability Training, and (6) The Elicitation.

Within the elicitation process persons representing different roles should be present, however one person can represent more than one role (Jenkinson, 2005). The roles are the decision maker or the one that will use the result, the experts that have knowledge about the variables, a statistician that can train the experts and validate the results, and a facilitator to lead the exercise. The process can follow different protocols whereas The Cooke protocol, The SHELF protocol, and the Delphi method are three most applied protocols for elicitation with multiple experts (O'Hagan, 2019).

Disregarding what protocol is used for the elicitation it is essential that biases that can lead to systematic errors in the judgement are avoided (see e.g., Montibeller & Winterfeldt, 2018). Principles for heuristics and biases have been formulated by Tversky and Kahneman (1974) and four important biases to avoid in the elicitation process are *anchoring*, *availability*, *range-frequency*, and *overconfidence* (O'Hagan, 2019).

3 METHODOLOGY

This chapter describes the approaches being applied in the thesis and the appended papers.

3.1 I/I-water and system boundaries

The I/I-water situation can be analysed using different system perspectives. In an analysis, different effects will be included depending on how the system boundaries are set (Figure 10). Commonly, boundaries are set around the assets of the project owner resulting in a financial analysis. In the I/I-water case this can be around the piping system or around the WWTP. However, the system boundaries can be extended, e.g. to include the city or be set regional or globally. In this thesis a broader system perspective is applied with the aim to include all effects of I/I-water which can affect society.

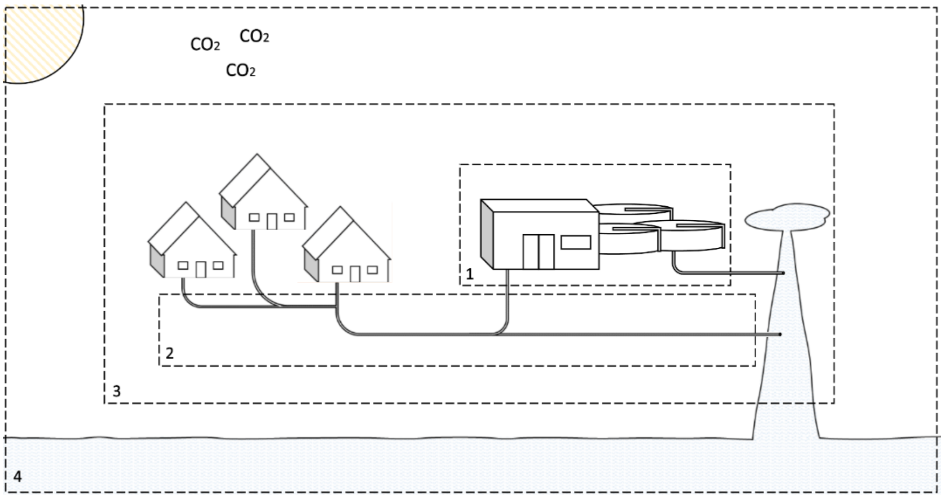

Figure 10. Example of possible system boundaries (1: WWTP, 2: Piping system, 3: City, 4: Global) (Paper I).

Paper I deals with sources, effects, detection and quantification, and measures relating to I/I-water in general terms. In Paper II, the I/I-water is not divided into sources but in the case study the different components of FRC and SRC are at times handled separately. Apart from that, the total flow of I/I-water, disregarding the component or source, is considered. Regarding effects, four categories of effects are included in the model and monetised in the case study. These are effects at the WWTP and effects from pumping, basement flooding events, and CSOs. Regarding quantification of I/I-water for the case study in Paper II, data from hydraulic models, calibrated using measurement points at the system, are used. The models were not set up as part of the research project but are already existing models belonging to the City of Gothenburg. Measures to reduce I/I-water are not a part of Paper II.

All cost and benefits to society related to I/I-water are in this thesis classified as internal or external effects. The internal effects are defined as those affecting the project owner. In this thesis, also external effects, which can affect the environment, human health, or other aspects are included to provide a calculation of the full expected cost to society. Effects are monetised as far as possible given the time and budget constraints of the analysis.

To further identify effects of I/I-water and measures to reduce I/I-water a workshop was held with representatives from the water utility in the City of Gothenburg, the WWTP in the Gothenburg region, and researchers. The participants were divided into two groups and asked to identify positive, negative, continuous, and temporary effects of I/I-water. The groups then presented their effects to each other, and these were compared to effects found in the literature. In the next step the participators were asked to discuss and list measures to reduce I/I-water. After the workshop the effects and measures were compiled, grouped into categories, and sent to the participants. The participants were asked to value the significance of each effect, from a Gothenburg context and a socio-economic perspective (1 = no significance to 5 = very large significance). They were also asked to evaluate how interesting they found each measure to be included in a CBA (1 = not interesting at all to 5 = very interesting).

3.2 Sustainability and ethical principles

In this thesis the definition of sustainability using the three dimensions (economy, social, and environmental) is applied. The dimensions are valued as equally important according to the Venn diagram (Figure 7). Moreover, well-being, health, and happiness of people are included as factors in the social dimension.

In Paper I both utilitarian and deontological perspectives for decision support methods are acknowledged in relation to the decision support models MCDA and CBA. The approach in paper II takes a stand in a CBA perspective and is hence based on a utilitarian and anthropocentric perspective.

3.3 Risk

Since several of the effects from I/I-water are connected to events which can occur with different probability, a risk-based approach is applied in this thesis. The applied risk definition is based on an engineering perspective and in accordance with the description by Kaplan and Garrick (1981) using events, consequences, and probabilities. Moreover, the concept of using uncertainty in accordance with Aven (2010) is applied.

An important point is that I/I-water does not constitute a risk in itself but should be considered a *hazard* as it may pose a risk but not always do. Goals relating to I/I-water should therefore be set based on the effects and not the hazard. An example of commonly set goals based on the hazard are goals related to the yearly share of I/I-water reaching the WWTP. Instead, goals should be set relating to the effects of I/I-water, as previously advocated by, e.g. Bäckman et al. (1997) and applied in this thesis. Goals set based on the effects from I/I-water can, e.g. relate to a maximum allowed number of CSOs or basement flooding events, or to how the WWTP is allowed to be affected of I/I-water.

The concepts associated with risk correlate to each other in a “risk chain” (Figure 11) which is introduced in Paper I. In this risk chain sources of I/I-water, such as groundwater, faulty connected stormwater, or water from combined systems, transform to I/I-water which can result in effects, such as basement flooding events or CSOs. The consequences of these effects in combination with uncertainties corresponding to all previous steps make up the risk.

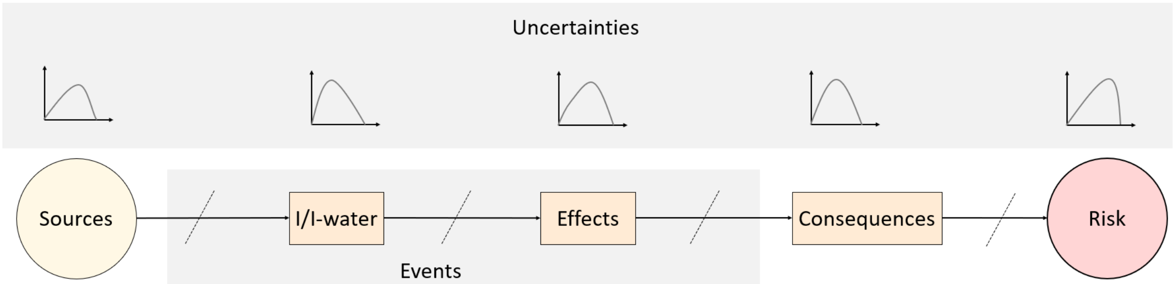

Figure 11. Risk-chain showing the relation of used concepts (Paper I).

3.4 Uncertainty

A substantial number of different uncertainties are associated with the different steps in the “risk chain” of I/I-water (Figure 11). Concerning the sources there are uncertainties, e.g. related to how much, often and for how long it will rain, and if a drinking water pipe is leaking. Further, there are uncertainties regarding if these sources will become I/I-water, e.g. related to the state of the wastewater system and its leakiness. There are also uncertainties connected to if a specific effect, e.g. a CSO, will occur and further if specific consequences will happen due to that, e.g. if specific pollutants will affect the ecosystem. Both aleatory and epistemic uncertainties are represented, e.g. the variation in the rain intensity and duration are aleatory and the uncertainty regarding the status of the system is epistemic.

To account for the uncertainties associated with I/I-water a probabilistic risk approach (Bedford & Cooke, 2001) is applied. Instead of using point values as variables, probability distributions are assigned to perform an uncertainty analysis. Using Monte Carlo simulation (see e.g., Metropolis & Ulam, 1949), a large number of iterations can be performed to sample values from the probability distributions and conduct repeated calculations (Figure 12). Therefore, the final result can be represented by a probability distribution where, e.g., the expected value and its uncertainty interval can be obtained. This approach also enables the performance of a sensitivity analysis where the contribution of each input variable to the total uncertainty is calculated. To evaluate the impact of variables where it is not possible or suitable to assign a probability distribution, sensitivity analysis can also be performed as a scenario analysis. Scenarios are then set up, e.g. using different discount rates or climate factors, and the difference in the final result between the different scenarios is evaluated.

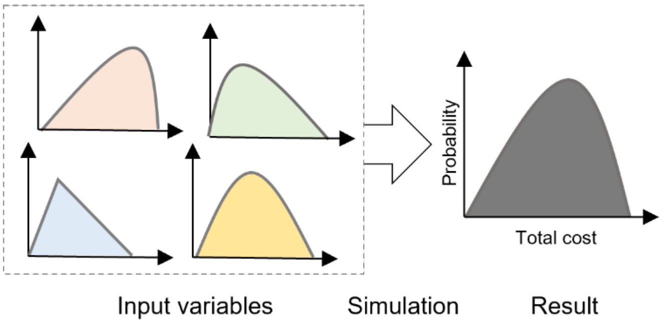

Figure 12. Schematic illustration showing the concept of a Monte Carlo simulation (Paper II).

3.5 Economic analysis

In Paper II, an economic analysis is performed to calculate the cost for society of I/I-water. This analysis is, as mentioned before, based on a CBA perspective although only costs and no benefits of I/I-water effects are included. The included costs comprise both internal and external costs. The time horizon used is 100 years and to be able to compare and summarise costs occurring in different years, discounting is performed (Boardman et al., 2017). The present value (PV) is:

$$PV = \sum_{t=0}^{T} C_t \frac{1}{(1+r)^t}$$

where T is the time horizon including the years t $(t=0...T)$, C_t the cost for year t, and r the discount rate.

In Paper II a discount rate of 3.5% is used in accordance with the Swedish transport administration (2020), but the rates of 1.5% and 6.0% are used in a sensitivity analysis as recommended by Johansson and Kriström (2015). Valuation of the effects of I/I-water is performed by monetisation into Swedish kronor (SEK) where 1 SEK corresponds to approximately 0,1 EUR (April 2022).

3.6 The Sheffield Elicitation Framework

Expert elicitation was performed to obtain input data for the case study in Paper II. The elicitation protocol The Sheffield Elicitation Framework (SHELF) was used (Oakley & O'Hagan, 2019). This protocol follows a 10-step process (Figure 13) which is an elaboration of the common steps presented by Jenkinson (2005).

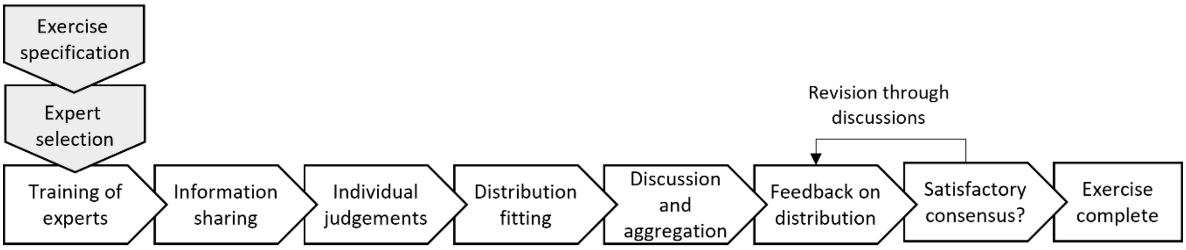

Figure 13. The steps of an elicitation exercise following the SHELF protocol. Grey background (Exercise specification and Expert selection) means that the steps are performed before the workshop. Figure adapted from Gosling (2018).

The steps of the SHELF-protocol are described more in detail, e.g. by Gosling (2018). All material needed to perform the elicitation process is available through open access by Oakley and O'Hagan (2019).

During the four different workshops one quantity of interest (QoI) was elicited at a time using individual judgements and group judgements. To perform the judgments the tertile, quartile, or roulette method can be used and the quartile method was chosen in Paper II. All individual judgements were used for fitting probability distributions using free web tools provided by Oakley (2022). The experts were then allowed to discuss their distributions before performing a group judgement to agree on an aggregation of their views. After fitting this joint judgement to a probability distribution, it was discussed and modified until consensus was reached. The next QoI was then elicited using the same process with individual and group judgements.

4 RESULTS

In this chapter, a summary of the key findings in the appended papers of this thesis are presented.

In Figure 14, the included results are related to the different parts of the generic framework presented in Paper I. A summary of Paper I is presented in section 4.1. Paper II is focused on the calculation of risk- and base costs and the results are presented in section 4.3. In section 4.2, the results from the workshop about effects and measures related to I/I-water are presented and serve as a link between the two papers.

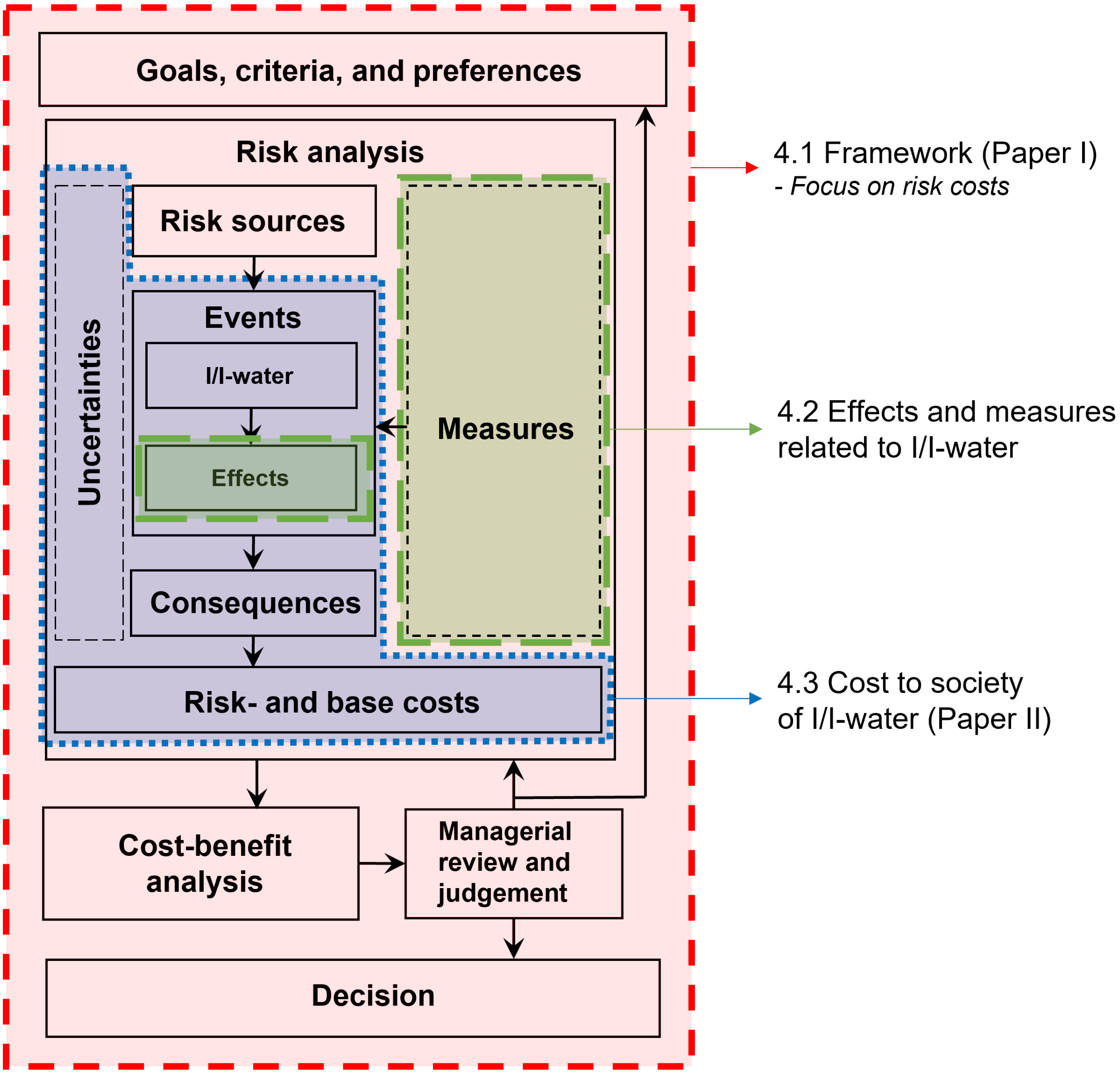

Figure 14. Adjusted framework from Paper I to demonstrate how the results in this thesis relate to each other.

4.1 Framework and evaluation of previous models

A framework was developed based on established theories on risk assessment and decision making (e.g., Aven, 2010; Aven, 2012; ISO, 2018). Important aspects of the framework are that it is risk-based and that uncertainties are included as well as economic, social, and environmental aspects of sustainability.

Eight published models which focus on I/I-water and decision support were found and evaluated based on the important aspects of the framework (Table 1). The result of the evaluation showed that only one of the models was risk-based and that two included uncertainty to some extent. All models include project internal, economic effects of I/I-water. Two of the models also include social and environmental aspects of I/I. The results show that from a sustainability perspective there is a need to develop a new model including all aspects presented in the framework.

Table 1. Evaluation of models based on framework. ✓ = Criterion included but not monetised. € = Criterion included and monetised. A: Sola et al. (2020), B: Davalos et al. (2018), C: Diogo et al. (2018), D: Moskwa et al. (2018), E: Vallin (2016), F: Lee et al. (2009), G: King County (2005), H: DeMonsabert and Thornton (1997).

Evaluation criterion	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Risk-based					✓			
Uncertainty					✓		(✓)	
Sustainability								
Economic								
Internal	€	€	€	✓	€	€	€	€
External	€							
Social	€				✓			
Environmental	€				✓			

4.2 Effects and measures related to I/I-water

During a workshop, generic effects related I/I-water were identified (Figure 15). The effects where then divided into the categories *consumption of resources, maintenance*, *undersized facilities*, *impact on surroundings*, *dilution*, and *additional effects.* The five effects that the participants valued as most significant from a socio-economic perspective (in the Gothenburg context) are increased risk of basement flooding events, increased risk of CSOs to sensitive recipients, less capacity for new connections, less effective treatment, and more stormwater pollutants in sludge at WWTP.

Consumption of resources

- Increased pumping
- Increased use of chemicals

Maintenance

- Increased need for maintenance (due to wear)
- Increased need for maintenance (due to decreased life-span)
- Difficulties to maintain (due to more water)

Undersized facilities

- **Increased risk of basement flooding events**
- Increased risk of surface flooding events
- **Increased risk of CSOs to sensitive recipient**
- Increased risk of CSOs to recipient
- **Less capacity for new connections**

Impact on surroundings

- Lowered groundwater levels
- Increased drainage
- Increased risk of subsidence
- Increase risk of undermining of roads

Dilution

- **Less effective treatment**
- Lower concentration of pollutants in CSOs
- Lower concentration of pollutants in pipes (less smell and corrosion)
- Deteriorated biogas production at WWTP
- Increased frequencies of self-cleaning velocities in piping system

Additional

- **More stormwater pollutants in sludge at WWTP**

Figure 15. Generic effects related to I/I-water identified during a workshop. The five effects valued to have the highest significance in a Gothenburg context in bold.

During a workshop, generic measures to reduce or control I/I-water were identified (Figure 16). The measures were then divided into measures before and after I/I-water reaches the wastewater system The three measures that the participants valued as most interesting to include in a future CBA are relining of the piping system, disconnection of combined surfaces, and influencing inhabitants and property owners to connect less stormwater to the piping system.

Measures before I/I-water reaches the wastewater system

- Maintenance and repair at piping system
- **Relining of piping system**
- Replacement of piping system
- Separate combined systems
- Build stormwater systems where missing
- **Disconnection of combined surfaces (separation already performed downstream)**
- Disconnect stormwater laterals
- Disconnect culverted water courses
- Build cut-off trenches to disconnect nature surfaces
- Lower the groundwater table to prevent infiltration
- Chose materials which causes less stormwater pollutants in city
- Perform more street cleaning to decrease stormwater pollution
- **Influence inhabitants and property owners to connect less stormwater to piping system**
- Decrease leakage from drinking water piping system

Measures after I/I-water reaches the wastewater system

- Build larger piping systems and larger WWTPs
- Adjust the WWTP to handle higher flows
- On-line storage (equalisation of flows)
- Off-line storage (equalisation of flows)
- Steering of CSOs
- Treatment of water from CSOs
- Treatment of stormwater before connection to combined system
- Check valves to protect properties from basement flooding
- Perform compensation measures

Figure 16. Generic measures to reduce I/I-water identified during a workshop. The three effects values to be most interesting to add in a CBA in the Gothenburg context in bold.

4.3 Cost to society of I/I-water

To calculate the cost to society of I/I-water a model was developed in which consequences of important effects of I/I-water are monetised. The effects are divided into base effects and risks (Figure 17). Base effects, such as increased treatment or pumping, occur continuously throughout a year and risks occur occasionally, such as CSOs or basement flooding events, and are calculated using the probabilities and consequences of large rains.

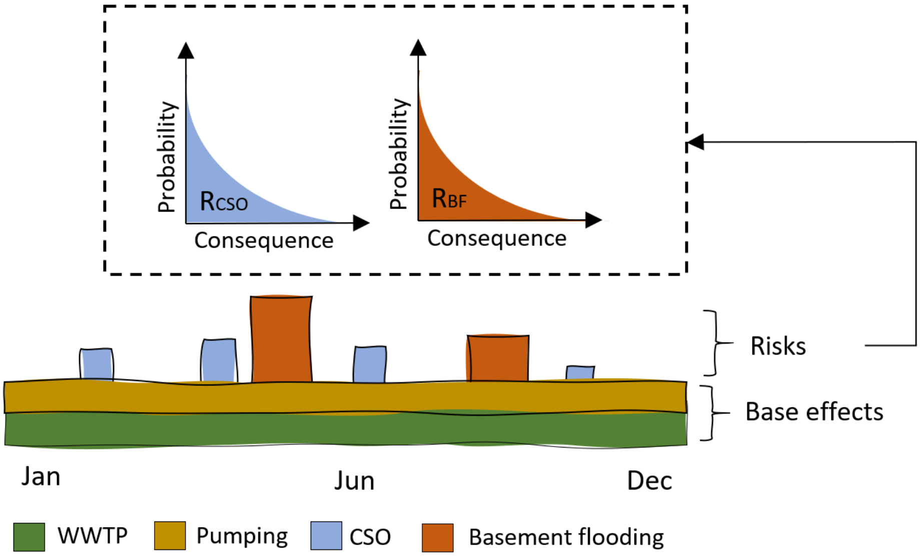

Figure 17. Schematic figure showing effects included in Paper II. Base effects occur continously thoughout a year whereas risks occur occasionally. The risks are expressed using probability of rainfall and cost ofconsequences (Paper II).

After calculating the yearly costs of each effect, the total *PV* is calculated for the chosen time horizon and discount rate. To account for uncertainties, probability distributions are assigned for the input variables.

The model was shown to be applicable in real world contexts by applying it on a case study area in the central parts of Gothenburg. Included effects were treatment and investment at the WWTP, internal and environmental effects due to pumping, environmental effects because of CSOs, and restoration and inconvenience due to basement flooding events (Figure 18). Results from hydraulic modelling and expert elicitation were used to obtain most of the needed input variables. Further, Monte Carlo simulations as well as scenario analyses were performed as part of the case study to investigate the uncertainties.

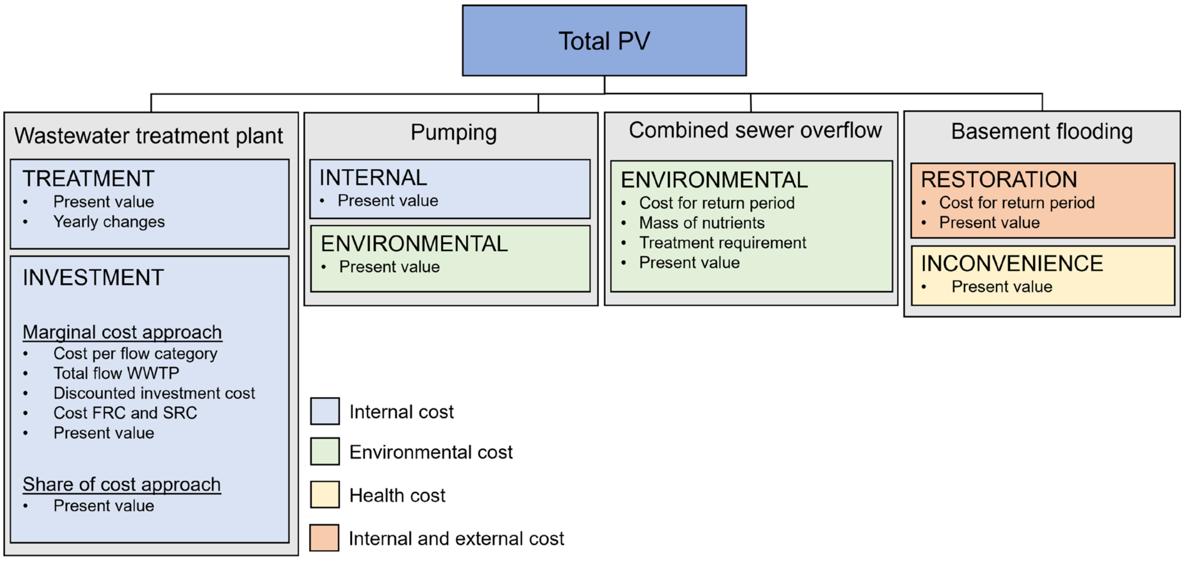

Figure 18. Overview of effects included in case study (Paper II).

The result from the case study showed that the median total *PV* of I/I-water from the area for a time horizon of 100 years was 687 million SEK. The *PV* mostly consisted of costs at the WWTP, mainly investments, and costs due to restoration after basement flooding. In Figure 19 the 10th, 50th, and 90th percentile of the *PV* for the total cost and the individual effects that were monetised are presented.

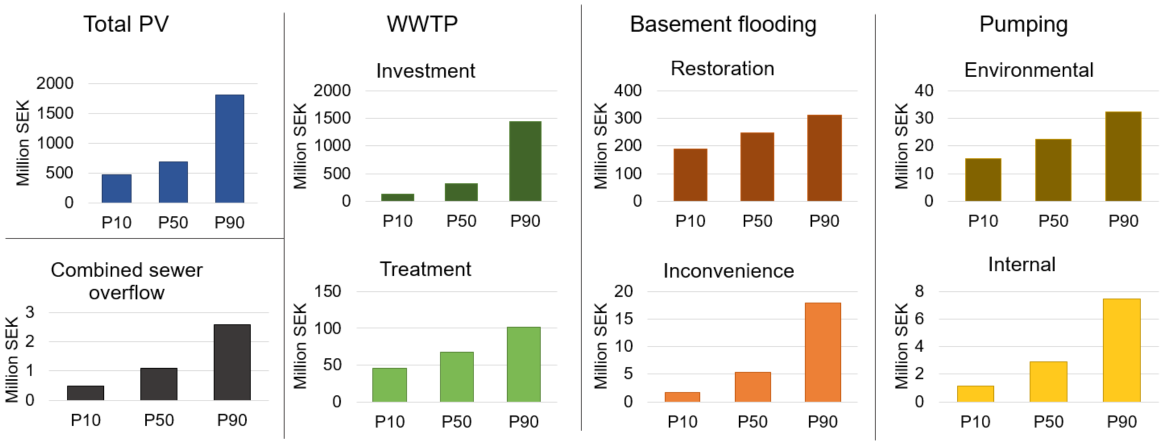

Figure 19. PV of 10th, 50th, and 90th percentiles for the effects included in the case study (Paper II).

The uncertainty and sensitivity analyses showed that the input variables that were most strongly correlated to the total *PV* mainly were related to the volume of I/I-water and the share of basements that can be flooded. Further, it was shown that the discount rate had a large impact on the result.

5 DISCUSSION

5.1 Development and application of the model

The theoretical background shows that there exists a vast number of publications about the technical aspects regarding identifying and reducing I/I-water. Although technical knowledge apparently is available, I/I-water still constitutes a substantial problem in many urban areas. This indicates that the I/I-water problems water utilities are facing are not due to lack of technical knowledge but to other factors. Uncertainties can be an important aspect since it is not always certain that methods that in theory should find or decrease I/I-water function as intended in practice. Moreover, it should not be forgotten that the I/I-water problem is of a very complex nature in large underground systems that have been built and rebuilt over centuries. It is very difficult to keep a complete track of status, flow, and changes everywhere in the system and the resources of water utilities are often limited.

In Paper II, important effects of I/I-water were monetised. However, many more effects exist as shown, e.g., in the theoretical background as well as in the result of the workshop about measures and effects. Of the five effects valued to have the highest significance during the workshop, basement flooding and CSOs were included in the model presented in Paper II. The effects regarding less capacity for new connections, less efficient treatment, and decreased quality of sludge were not included. These effects are more difficult to monetise, but it may be easier to value the cost of the change in these effects depending on which measure that is implemented. These effects, among others, are therefore planned to be included in future work using CBA to analyse how different measures impact the effects of I/I-water. The result from the workshop about effects and measures regarding which measures to be prioritised in a CBA will be considered when setting up scenarios combining different measures in this analysis. However, there was a limited number of participants in the workshop and all represented stakeholders. It might therefore be the case that other measures to reduce I/I-water could be identified and included in the planned CBA.

The results of the case study showed that effects at the WWTP and effects related to restoration after basement flooding events resulted in the largest costs in the case study area. It is important to note that the result could be different if a different case study area was used which is mentioned as a limitation of the thesis. However, the case study's main purpose is to illustrate the use of the developed model and although the results provide interesting insights more effects can be added, and the quantification of additional input variables can be supplemented in future projects.

As mentioned also in the limitations, this research, in which this thesis is a first part, focuses on developing a comprehensive decision-support method on I/I-water and several simplifications are made. An important factor related to this is on what level the I/I-water problems can and should be investigated and reduced. It is also important to acknowledge the different sources of I/I-water as well as how these sources are affecting the system at their specific location depending on the local conditions. At the same time more comprehensive analyses are also needed to get an overview and be able to take strategic decisions. The model presented in Paper

II can be used at different levels, both at a local and a larger scale and the result can serve as a basis for decision support. After identifying what effects lead to the largest cost for society focus can be put on removing the I/I-water that leads to these effects. However, this must be balanced against the cost to society of performing the measures, something that will be evaluated in the planned CBA.

Expert elicitation using the SHELF-method was an important data source for quantification of input variables for the case study in Paper II. The expert elicitation workshops turned out to be very useful to gather data but were also appreciated by the experts and many expressed that the SHELF method was new to them and that they were interested in using it in their future work. Application of the SHELF method was, however, time demanding which makes it important to prioritise which QoI to elicit according to the full SHELF-protocol and which to assess using more simple approaches. Choosing the most suitable experts to participate is also important to get a representative knowledge base for the quantification.

5.2 Technological change and ethical perspectives

The decision support tool that is being developed in this research project will, whether or not it is acknowledged, be based on normative assumptions. These assumptions can to a different extent relate to established views of sustainability and ethical aspects. Moreover, it is crucial what system boundaries are used and consequentially which stakeholders are included. Main stakeholders are, e.g. the water utility, the owner of the WWTP, other municipal organisations, operators, and the inhabitants of the city. These stakeholders, together with technical and sociological parts of the wastewater system are interconnected and connected with other systems such as the drinking water system and the waste management system. This makes the large technical system (LTS) approach useful for analysing how the system has developed and how changes can happen. Various reverse salients can be identified in the wastewater system where in a large perspective the piping system can be seen as a one when including also the WWTP. Extensive technology development and research have been performed regarding treatment processes at WWTPs. However less research has been performed on the piping system where the similar technologies are used as when they were invented. Possible reasons for the slow technology development may be the difficulties of monitoring the underground system and that the strong connection between the flow and the system making it difficult to perform gradual changes.

New investments in the piping system should consider that much of the infrastructure built today should last for at least 100 years. It is impossible to know for certain how society and the system will develop during this time horizon. Different factors, which can occur on different levels if using a multi-level perspective (MLP) may enable a technological change. Alternative technologies such as source separation, vacuum systems, and more decentralised systems (e.g., Larsen et al., 2013) exist on a niche level and can be enabled due to factors at the socio-technical level. These factors can be related to the problem with I/I-water which makes the whole system function less efficiently or to the large maintenance debt regarding the piping system, i.e., that renovation and maintenance have not been performed in the needed pace. Further, at the landscape level the most important transformation pressure is climate change which makes a system change more urgent due to, e.g. more precipitation and higher surface water levels. Using the MLP presented by, e.g. Geels (2002) to analyse the wastewater system it is hence not impossible that large system changes will take place in the near future. This should not be overlooked when taking decisions regarding investments that will affect the system and the society for a very long time ahead.

An important system choice is if the existing combined systems should be replaced with separated systems. Building combined systems was a design choice and we must now live with its consequences unless large system changes are made which would result in very large economic costs to society. But even if disregarding the economic costs, deciding to implement a large change in the wastewater system should be accompanied by investigating how the process of change should be made in the most sustainable way. We have inherited an imperfect system that has grown organically for more than a hundred years. The conversion to a more sustainable system may have to be done gradually where some parts at a time are replaced when there is a need also for other measures. That is, because changing systems that still function could lead to a waste of already spent resources. On the other hand, this incremental change might be too slow, and from a deontological perspective it can be argued that it is our duty to provide future generations with a better system. The aim is that the models that are presented in this thesis and those that are planned to be developed will help answering questions related to this dilemma by providing tools for comparing costs and benefits in society related to the different alternatives.

6 CONCLUSIONS

The following main conclusions are drawn from the work presented in this thesis:

- In the literature, comprehensive theoretical knowledge about water from infiltration and inflow (I/I-water) is reported. Information can, e.g. be found related to methods for detection and reduction of I/I-water. The problems related to I/I-water are, however, still widespread and extensive in many urban areas.
- To facilitate the overall handling of I/I-water, a framework for decision support is presented based on established approaches for risk management and decision support. The framework is risk-based and provides a structured approach for acknowledging uncertainty and the three dimensions of sustainability. No such framework has previously been described in the literature.
- The evaluation of previously published decision support models on I/I-water shows that none is fully in line with the proposed framework. Hence, there is a need to develop a decision support model to fully acknowledge uncertainty and sustainability in line with established standards and frameworks for risk management and sustainable development.
- Due to its characteristics the problem of I/I-water is complex and difficult to analyse. Possible effects of I/I-water includes positive and negative effects that can be both internal (to the problem owner) and external effects (e.g., environmental and health effects). In addition, there are various possible measures to reduce I/I-water which also lead to corresponding effects. To acknowledge all effects of I/I-water and possible measures, a structured approach for decision support is essential.
- Applying a CBA approach for decision support, many of the effects of I/I-water can be monetised. The presented model supports a more sustainable handling of I/I-water by including both internal and external effects, advocating analysis over a long time horizon, and letting the uncertainties of input variables be represented by probability distributions. By applying the model on a case study area is it shown to be applicable in practice. Moreover, expert elicitation is shown to be a valuable method of quantifying input data where hard data is lacking or insufficient.
- The developed model for calculating the costs of I/I-water to society provides a necessary input to a full CBA of alternative measures to reduce I/I-water and thereby an improved ability for a sound prioritisation of society's limited resources for wastewater system management.

The following steps are planned as part of the future work within the research project related to this thesis:

- Further extend the risk model by including measures to reduce I/I-water and its corresponding effects. After setting up scenarios the option with most benefits to society in relation to the costs can be identified using CBA.
- Simplify and generalise the CBA model to make it more applicable in practice and collect data from water utilities regarding costs of I/I-water and I/I-water measures.
- Evaluate how different system boundaries including different stakeholders and effects will affect the result of a CBA.
- Improve the method of monitoring I/I-water using IoT-meters and data processing.

- Develop a model for value of information analysis (VOIA) where the risk of not gathering enough data is balanced, using CBA, with the risk of gathering too much data in order to select a management option that is cost-efficient.
- Include aspects that cannot be monetised, applying a more deontological perspective that goes beyond the utilitarian perspective of CBA.

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