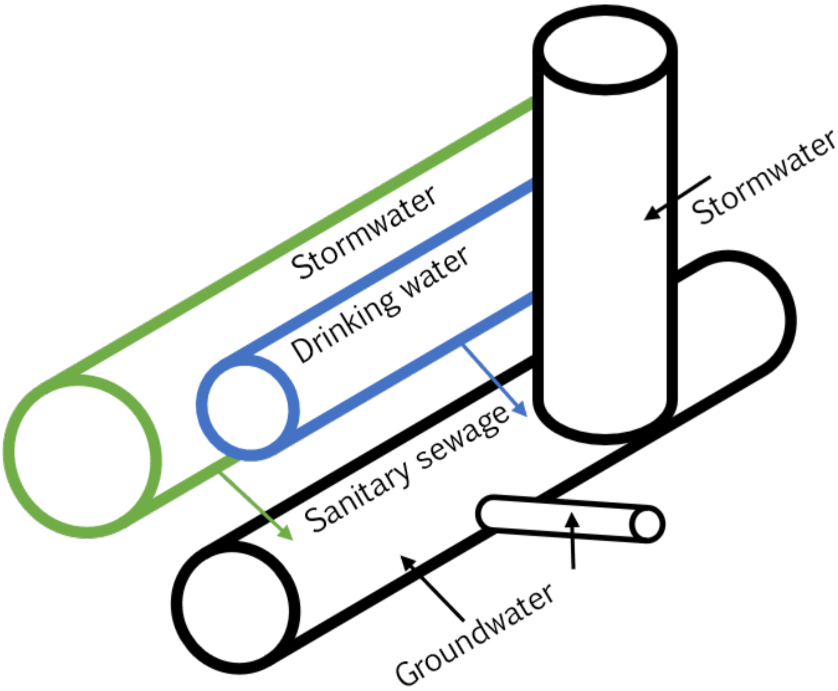

Infiltration and inflow to wastewater sewer systems

A literature review on risk management and decision support

ANNA OHLIN SALETTI

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
DIVISION OF GEOLOGY AND GEOTECHNICS

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2021
www.chalmers.se

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ANNA OHLIN SALETTI

Department of Architecture and Civil Engineering
Division of Geology and Geotechnics
031 368 71 15, 073-529 15 19
anna.ohlin.saletti@chalmers.se

Chalmers University of Technology
412 96 Gothenburg, Sweden
www.chalmers.se

Summary

Wastewater sewer systems are one of our largest infrastructural assets. By transporting the sewage from our homes and other facilities to the wastewater treatment plants, the sewer systems protect public health, properties, and the environment. However, in addition to the sanitary sewage, there is an infiltration and inflow (I/I) of other water to the sewer system. This additional load can result in adverse effects such as basement flooding, combined sewer overflows, and larger pumping and treatment costs. I/I can originate from rainfall but also from sources such as groundwater, surface water or leaking drinking water pipes. Expected climate change effects include more intense rain events and periods of higher water levels which will increase the problem of I/I. Hence, it is important to manage I/I in a proper way by implementing efficient measures that provide the largest societal gain from a sustainability point of view.

This literature review was performed to form a basis for research on developing risk-based decision support models to evaluate I/I in wastewater sewer systems from a system perspective and with focus on sustainability. It reviews publications on I/I focusing on sources, impacts, quantification and mitigation measures, addresses risk definitions, and the risk management process. Further, common decision support methods are described and literature on decision support models to evaluate I/I are reviewed.

Important conclusions are that a vast amount of literature exists on finding and reducing I/I from a technical point of view and in several publications different decision support models are used to evaluate measures aiming at reducing I/I. However, existing models are focused on project internal and financial aspects and a need for future studies is identified, evaluating I/I from a broader societal and sustainability perspective, including project external, environmental, and social criteria.

Acknowledgement

This literature review was produced as part of the Mistra InfraMaint research programme with funding from the Department for Sustainable Waste and Water in the City of Gothenburg, Mistra, the Swedish Foundation for Strategic Environmental Research and Swedish Water & Wastewater Association.

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Abbreviations

AI	Artificial intelligence
AR	Augmented reality
CBA	Cost-benefit analysis
CCTV	Closed-circuit television
CEA	Cost-effectiveness analysis
CIP	Cured in place
COD	Chemical oxygen demand
CSO	Combined sewer overflow
DALY	Disability-adjusted life years
DTS	Distributed temperature sensing
I/I	Infiltration and inflow
IoT	Internet of things
LCCA	Life cycle cost analysis
NPV	Net present value
MCDA	Multi-criteria decision analysis
QALY	Quality-adjusted life years
SCADA	Supervisory control and data acquisition
SSO	Separate sewer overflow
VR	Virtual reality
WFD	Water framework directive
WTA	Willingness to accept
WTP	Willingness to pay
WWTP	Wastewater treatment plant

Glossary

Combined sewer system	A wastewater collection system that conveys domestic, commercial, and industrial wastewater and stormwater runoff through a single pipe system to a WWTP.
Combined sewer overflow	A discharge of untreated wastewater from a combined sewer system at a point prior to the WWTP.
Infiltration and inflow	The total quantity of water from both infiltration and inflow.
Infiltration	Stormwater and groundwater that enter a wastewater sewer system through such means as defective pipes, pipe joints, connections, or manholes.
Inflow	Water, other than sanitary flow, that enters a wastewater sewer system from sources such as roof leaders, area drains, manhole covers, cross connections or surface runoff.
Sanitary sewage	The spent or used water from a home, community, farm, or industry that contains dissolved or suspended matter. Does not include stormwater.
Sanitary sewer system	A wastewater collection system designed to convey domestic, commercial, and industrial wastewater to a WWTP.
Separate sewer overflow	A discharge of untreated wastewater from a sanitary sewer system at a point prior to the WWTP.
Stormwater	Stormwater runoff, snow melt runoff, and surface runoff and drainage; rainfall that does not infiltrate the ground or evaporate because of impervious land surfaces but instead flows onto adjacent land or watercourses or is routed into drain/sewer systems.
Sustainability	A holistic approach that considers environmental, economic, and societal implications in determining potential solutions to an issue.
Wastewater	The used water and solids from a community (including used water from industrial processes) that flow to a WWTP. Stormwater, surface water, and ground-water infiltration may also be included in the wastewater that enters a WWTP.
Wastewater sewer system	The combined sewer system and the sanitary sewer system.

1 Introduction

1.1 Background

Our modern world is facing many challenges such as climate change with effects like increased precipitation and rising sea levels as a result. With these changes, it is increasingly important that the infrastructure is constructed in a sustainable way in terms of environmental, social, and economic aspects. The wastewater sewer system, that is designed to transport sanitary sewage from our homes and other facilities to the wastewater treatment plants (WWTP) to protect public health and prevent flooding, is a giant hidden asset that already faces problems such as aging and suboptimal design (Diogo et al., 2018). Apart from the sanitary sewage in the wastewater sewer system, there is infiltration and inflow (I/I), which origins from e.g. rainwater and groundwater. I/I does in many cities take up more space than the sanitary sewage flow and leads to extra pumping and treatment as well as other adverse effects such as increased risks for basement flooding and combined sewer overflows (CSOs) (Sola et al., 2018).

The levels of I/I vary much from place to place depending on e.g. rain intensity and system design. Hey et al. (2016) present levels of I/I found in literature from 12 different countries where the I/I levels vary between eight and 75 percent. Sola et al. (2018) evaluated the levels and trends of I/I in the Nordic countries. The results showed that the average share of I/I for the studied plants were 66 percent in Norway, 49 percent in Sweden, 41 percent in Finland, and 30 percent in Denmark.

The European Union Water Framework Directive (2000/60/EC) (WFD) aims to protect the European Union water bodies by stopping the deterioration and achieve good status in lakes, rivers, and groundwater. Based on the interpretation of the WFD, the European Court ruled in 2015 that member states are obliged to refuse projects that would result in a deterioration of the water quality of the water bodies (e.g. Paloniitty, 2016; Söderasp and Pettersson, 2019). This case, C-461/13 Bund v Germany or more commonly called "The Weser case", affects what mitigation measures can be performed to reduce I/I, e.g. when it comes to treatment of disconnected stormwater. The Weser case has been criticised for being contradictive, e.g. by making large societally important projects impossible if it results in that one water quality parameter is deteriorated (Bjällås et al., 2015). Several other legal aspects affect the handling of I/I. One important aspect is the ownership of the wastewater piping system where the water utility only is responsible for the part of the system outside of the private properties (Lundblad and Backö, 2014). Measures performed by the municipality to reduce I/I do usually not include the private parts of the system which make holistic measures complex.

Since the resources in our society are limited, prioritisation of I/I measures is needed in order to reach the highest gain. I/I can be reduced using different kinds of approaches, to different levels as well as based on different delimitations of system boundaries and there is a need for decision support models to support which decisions to make regarding I/I management. Examples on decision support methods are multi-criteria decision analysis (MCDA), cost-benefit analysis (CBA), cost-effectiveness analysis (CEA), and life-cycle cost analysis (LCCA). When choosing between measures in infrastructure projects, more sustainable decisions can be made if all the aspects of sustainability as well as both internal and external factors are included (Ek et al., 2019).

This literature review is part of a PhD research project (From hidden wastewater networks to full access for smart decisions) that aims to develop a decision support model for choosing measures at the wastewater system to reach sustainable levels of I/I. There is an increasing interest in I/I and several other ongoing projects in Sweden exist where collaboration with the current PhD research project will take place. One example is *Future City Flow*, aiming at developing a decision support model to evaluate measures to decrease I/I (Future City Flow, 2020). In the Future City Flow project, a simplified sewage network model is used to monitor I/I in cities. Using the web-based tool, technical measures and their costs can be compared with the reduction of I/I. Another ongoing project is *Development of strategic decision support regarding I/I* performed by Research Institute of Sweden (RISE) in collaboration with Swedish Water.

1.2 Aim and specific objectives

The aim of this literature review is to form a basis for research on developing a risk-based decision support model to evaluate infiltration and inflow to wastewater sewer systems from a system perspective and with focus on sustainability. Specific objectives are to:

- Review the published literature on I/I with regards on sources and impacts as well as on detection, localisation, and quantification of I/I and uncertainties on these methods. Also, review of the published literature on measures to reduce I/I and the uncertainties of these methods.
- Describe the risk management process and common risk definitions and evaluate the risk of I/I based on these.
- Describe the decision support methods multi-criteria decision analysis, cost-benefit analysis, cost-effectiveness analysis, and life-cycle cost analysis.
- Review the published literature on decision support and I/I as well as goals and key indicators related to reducing I/I.

1.3 Terminology

Key terms used in this literature review are defined in the glossary in the beginning of the report. In this review the term *infiltration and inflow* with the abbreviation *I/I* is used to describe both the concept of water entering the wastewater sewer system as well as the water itself. These terms are commonly used in the reviewed literature. However, many alternative terms are also used for describing I/I and these are presented in Table 1.

Table 1. Terms used in this review and their synonyms.

Term used in this review	Used by e.g.	Synonyms	Used/mentioned by e.g.
Infiltration and inflow – I/I (concept)	(Diogo et al., 2018) (Davalos et al., 2019) (Staufer et al., 2012) (Panasiuk et al., 2019)	I&I II	(Cook et al., 2018) (Hey et al., 2016)
Infiltration and inflow – I/I (flow)	(Diogo et al., 2018) (Davalos et al., 2019) (Staufer et al., 2012) (Panasiuk et al., 2019)	Extraneous water I/I-water Infiltration/inflow Infiltration inflow Infiltration inflows Inflow/infiltration Parasite water Parasitic water Unwanted water	(Franz, 2007) (Sola et al., 2018) (Beheshti et al., 2015) (Weiss et al., 2002) (Weiss et al., 2002) (Lee et al., 2009) (Brombach et al., 2005) (Bareš et al., 2009) (Beheshti and Sægrov, 2018)

In Figure 1, a schematic overview of the terminology for the sewer system used in this review is presented. The term *wastewater sewer system* is used to describe the system in general when the situation applies to both the *sanitary sewer system* and the *combined sewer system*. The flow is in that case called *wastewater*. When referring to the sanitary system the term *sanitary sewage* is used and when referring to the combined sewer system the term *combined sewage* is used. The sanitary sewage has alternative names used in the literature, such as sewage, raw sewage, foul or wastewater.

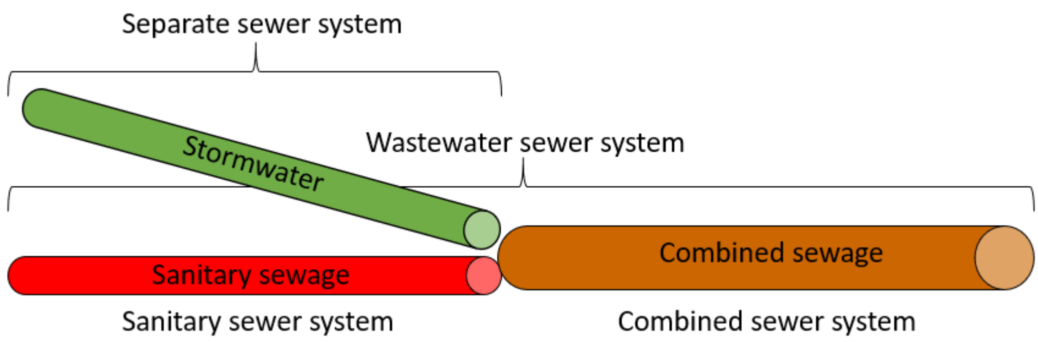

Figure 1. Schematic overview of the terminology used in this review to describe the sewer system.

2 Sources

I/I can be classified with respect to either its sources or the time scale (Bäckman, 1985). The timescale is usually related to the response time after rainfall and the I/I can then be classified as direct or indirect and rainfall-induced or dry weather related. The timescale classification can also be related to variations in the groundwater table. When classified related to the sources a differentiation is made between infiltration and inflow.

Infiltration and inflow originate from rainwater, groundwater, drinking water (e.g. Sola et al., 2018), water from snow melt (e.g. Bäckman, 1985; Kaczor et al., 2017), and surface water (e.g. Broadhead et al., 2013; Lundblad and Backö, 2012). The United States Environmental Protection Agency (USEPA) (1970) states that an important difference between infiltration and inflow is that infiltration takes place due to damages in the wastewater sewer system while inflow, with a few exceptions, depends of the design of the system.

2.1 Components

I/I can be divided into different components which can be especially useful when modelling the flows. In Figure 2, a division of I/I into components and their connection to the different parts of the drinking water and wastewater sewer systems are illustrated. This illustration is used by Swedish Water.

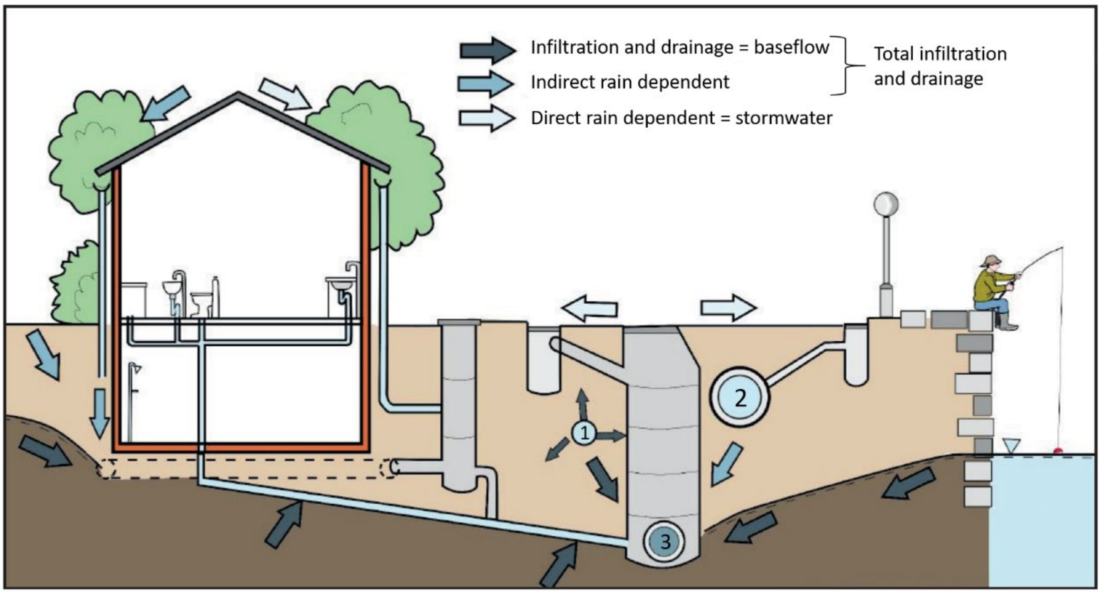

Figure 2. Sources and components of I/I. 1 = drinking water pipe, 2 = stormwater pipe, 3 = sanitary sewage pipe. Figure modified from Bäckman et al. (1997).

A few alternative divisions have been found in the literature and some examples of these are shown in Table 2. The I/I is divided into components based on the time it takes for it to reach the wastewater piping system. Changes in the groundwater table can affect the I/I level seasonably or yearly (Staufer et al., 2012) and are considered to be a slow response component. I/I that derives from rainfall is considered to be a fast response component, and after a rainfall inflow to the piping system can occur directly or in the matter of a few hours. Infiltration that occurs due to a rainfall usually takes longer but reaches the piping system within 24 hours. Tidal I/I can affect coastal areas (Woliner et al., 2002) and high surface water levels can similarly also cause I/I even though the variations might not be as regular. The different components can cause different effects, which is addressed in Chapter 3.

Table 2. Components of I/I, examples of classifications.

(Staufer et al., 2012)	(Davalos et al., 2019)	(Metelka et al., 1998)
Groundwater infiltration (GWI)	Base I/I	Slow response components (FRC)
Rain induced infiltration (RDII)	Rain Dependent I/I	Fast response components (SRC)
Rain-derived inflow (RDI)		
	Tidal I/I	

2.2 Infiltration

Infiltration is a physical factor (USEPA, 1970) which happens unintentionally because of damages in the wastewater sewer system (Sola et al., 2018). The infiltration typically takes place at defective joints, pipes, connections, and manholes (USEPA, 1970). Defects in the pipe system can be caused by, e.g. overloading, hydrogen sulphide attacks, and root intrusion (Malm and Svensson, 2011). If the system is damaged and the groundwater table located higher than the defected pipe, infiltration will take place (Fenner, 1990). Hence, infiltration is dependent on the status of the sewer system, the hydrogeologic conditions, and possible sources of infiltration water.

In Sweden, the sanitary sewer pipe is usually located as the lowest pipe in the trench which makes it possible for leaking water from the higher located drinking water and stormwater pipes to enter a defected sanitary sewer pipe (Bäckman et al., 1993), see Figure 3. While cross-leakage from drinking water pipes is independent of rainfall, the cross-leakage from stormwater pipes and groundwater infiltration can happen either during dry weather or be rain induced (Bäckman, 1985). An example is that cross-leakage from a stormwater pipe may occur directly after a rainfall, but it can also occur independent of the rain if the stormwater system leaking to the sewer system is supplied with groundwater.

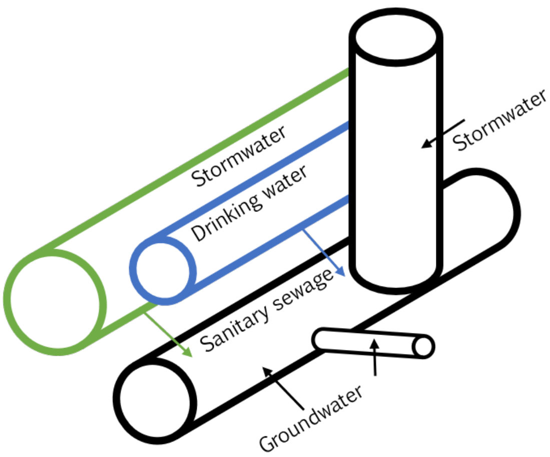

Figure 3. Schematic illustration of sources of infiltration.

Several factors affecting infiltration are reported in literature. These factors are either related to external conditions like precipitation, the groundwater table, and soil material or related to the system itself and the way it was constructed (USEPA, 1970). Franz (2007) are listing and describing factors influencing the structural deterioration of wastewater sewer systems divided into the categories construction features, local external features, and other factors. Some of the most important factors are addressed below.

Rain induced infiltration is dependent on the precipitation and it is thus possible to notice a large difference in the infiltrations volumes when comparing a wet year with a dry (e.g. USEPA, 1970). Rainfall can also affect the groundwater table, which in turn affects the infiltration, since groundwater infiltration only can happen when groundwater surrounds the pipe. Dirckx et al. (2016) showed that groundwater infiltration is more likely in flat areas with a natural shallow groundwater table than in more hilly areas and Karpf and Krebs (2011) identified groundwater influence as a useful indicator for estimating the infiltration potential of sanitary sewer pipes.

The geological material around the pipe also affects the infiltration (USEPA, 1970). Water movement is easier when permeable granular material surrounds a pipe in the bedding (Indiketiya et al., 2017). Moreover, the level of infiltration is also depending on the size of connected impermeable surface areas (Bäckman, 1985). Subsidence, i.e. lowering of the land surface in response to geologic or man-induced causes (Encyclopaedia Britannica, 2020), can affect the stability of the pipes and joints and also increase infiltration (Malm et al., 2011).

The possibility for infiltration to happen is also dependent on the pipe and joint material and quality (USEPA, 1970). Over 60 percent of the Swedish sewer network is made of concrete pipes (Malm and Svensson, 2011) and concrete is the most common sewer pipe material in most countries (Kuliczkowska, 2016). The usage of plastic pipes, mostly PVC and PE, has however increased during the past years (Malm et al., 2011) and nowadays plastic pipes are mostly used when installing new sewer systems (Malm and Svensson, 2011). The life span of plastic pipes of today's quality is estimated to be more than 100 years and mainly dependent on the characteristics of the material and the amount of loading (Malm et al., 2011).

It is less common with leakage to plastic pipes compared to concrete pipes (Malm et al., 2011) and in concrete pipes corrosion is a more frequent problem. Corrosion can be internal or external and can among other factors be caused by hydrogen, sulphide or micro-organisms (e.g. Kuliczkowska, 2016). For concrete pipes, structural failures can depend on the pipe diameter as well as how it is installed e.g. the burial depth (Malm et al., 2011). Examples of other factors that can affect the risk of structural failures caused by internal corrosion are geological material, whether the sewer is combined or separate, and access for repair (Kuliczkowska, 2016). When a concrete pipe has started to be defect, it is likely that the degradation process will increase (Malm et al., 2011). The lifespan of a concrete pipe of today's quality is estimated to be more than 100 years but shorter if it must be leakproof.

The quality of wastewater sewer systems and thereby the problem with infiltration is also highly dependent on the system's age and the quality is generally decreasing with age (Malm et al., 2011). Fenner (1990) states that the defect rate is not linear to the age of the pipe but rather depends on the method of construction and design used in different periods. Further, Indiketiya et al. (2017) state that according to Kuwano et al. (2006), pipe defects are more common for pipes that are older than 25 years. Malm et al. (2011) state that the risk of infiltration in Swedish wastewater sewer systems is higher for pipes constructed before 1970 when the rubber sealing was started to be used. Additionally, pipes constructed before 1950 have more defects and are changing to a higher degree compared to pipes constructed later in time.

The use of the excavator, which was introduced in the end of the 1940s in Sweden, affected the way pipes were installed and resulted in broader trenches and that other material than the original could be used for backfilling (Malm et al., 2011). Compared to when the backfilling was done by hand it was now often done less carefully which increased the risk of subsidence and other damages. Bäckman (1985) states that the quality of the constructed wastewater sewer system in general is highly dependent on the craftsmen's skills.

2.3 Inflow

Inflow is caused by intentional or unknown connections of stormwater to the wastewater sewer system or by surface water (USEPA, 1970), see Figure 4. The rainfall induced inflow can either be categorised as direct or indirect depending on the response time.

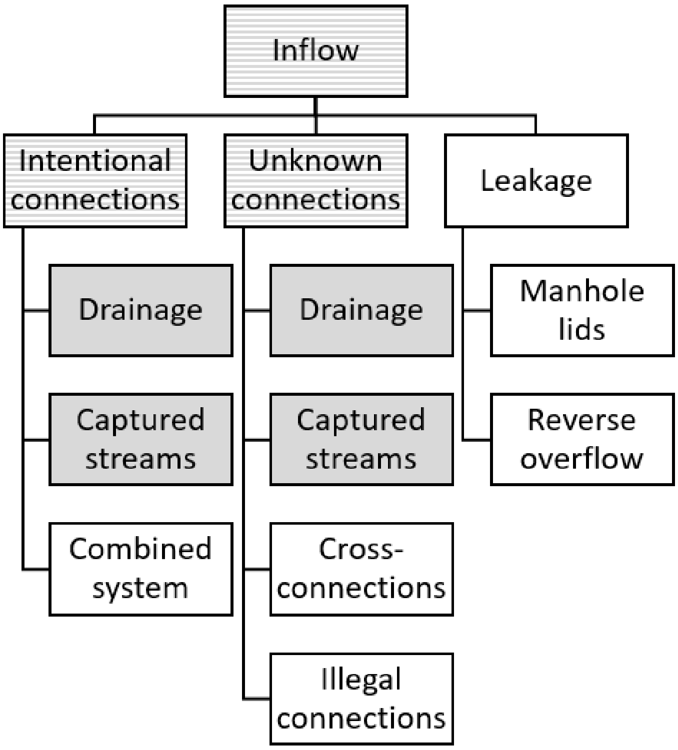

Figure 4. Sources of inflow divided into intentional connections, unknown connections and leakage. Grey boxes indicate indirect inflow and white boxes indicate direct inflow.

The construction of the first combined sewer systems in modern sense started during the second half of the 19th century to decrease the health impacts caused by poor sanitation (Bäckman, 1985; Tibbetts, 2005). It was not until decades later the separate sewer systems for sanitary sewage and stormwater were introduced (Bäckman et al., 1997). Some cities have been able to reduce their proportion of combined sewer systems by separating it while others still have a large share of combined sewer systems. The average rate of combined system in Sweden in relation to the wastewater system was in 2005 12 percent (SWWA, 2007). The effects related to separating the sewer systems are further addressed in section 5.2.

Since the purpose of the combined sewer system is to transport both sanitary sewage and stormwater, the result of inflow from this kind of system can be considered deliberately planned for (USEPA, 1970). However, part of the sources of the inflow can be unknown, e.g. when documentation of cross-connections between the stormwater network and the combined network is missing (Lundblad and Backö, 2012).

Drainage water is also a source of inflow (USEPA, 1970). When the only available pipe was the combined sewer pipe, the drainage from houses was normally connected to that (Bäckman et al., 1997). However, the drainage has still often been connected to the sanitary sewer pipe even when a separate stormwater pipe exists, this since the sanitary sewer pipe is located lower which make connections there more convenient because of height and gravity.

Surface water can also enter combined and sewage systems as inflow. This can happen due to reverse overflowing from surface water via CSOs when non-return valves are lacking or malfunctioning (Dirckx et al., 2016). When the water level rises over a critical level, water from e.g. streams, lakes, and the sea can flow into the system (Lundblad and Backö, 2012). This kind of inflow is expected to increase in the future because of climate change leading to more rain and rising surface water levels.

Streams and springs have been captured deliberately in history to maximise development space and to sanitise polluted watercourses (Broadhead et al., 2013). The knowledge of a captured watercourse is often lost, and the source of the inflowing water can thereby be unknown. According to Broadhead et al. (2013) the source of inflow from captured streams and springs in combined sewers has not been much discussed in literature.

The source of the inflow can also be unknown if connections of stormwater or drainage water from public and private areas exist but are either forgotten, unintentional, or made without authorisation (USEPA, 1970). Inflow can also occur through leaky manhole lids, especially when they are located at low points (Lundblad and Backö, 2012).

3 Effects

This chapter provides an overview of the effects by I/I reported in the literature. The chapter is divided into continuous and temporary effects. The different components of I/I usually result in different effects, the continuous effects are mostly related to infiltration while the temporary are related to inflow and are rain dependant. Although most emphasis in the existing literature is on negative effects, both positive and negative effects caused by I/I are presented here. An overview of the effects explained below is presented in Table 3.

Table 3. Overview of effects caused by I/I found in literature.

	Continuous	Temporary
Negative	Larger energy consumption Larger need for maintenance Reduced life span of components Larger use of chemicals Need for expansion of WWTP (e.g. energy, labour, land take) Less capacity for more connections Less efficient treatment in WWTP	CSO affecting water quality SSO affecting water quality By-passing WWTP affecting water quality Basement flooding Flooding Blockage Faster aging Undermining of roads Subsidence
Positive	Lower need for chemicals for sulphide mitigation Drainage Control of groundwater level Decrease of methane concentration due to dilution	More self-cleaning velocities Lower concentration of pollutants in CSOs and SSOs Less odour and corrosion

3.1 Continuous effects

I/I results in more water in the wastewater sewer system and to the WWTP (e.g. Bäckman, 1985; USEPA, 1970; Dirckx et al., 2016; Kaczor et al., 2017; Sola et al., 2018). The additional volumes of water lead to a larger energy consumption in terms of pumping as well as a larger need for maintenance and a reduced life span for the components (USEPA, 1970). More water in the WWTP also results in a higher use of chemicals for the treatment processes (Bäckman, 1985). On the other hand, a decrease of I/I would lead to a higher concentration of sanitary sewage which significantly would increase the chemical cost for sulphide mitigation per unit (Sun et al., 2015). However, the total treatment cost would still decrease because of the decreased flows.

The larger volume of water in the systems also impact the society. To replace sewer systems that have reached their capacity because of I/I, new ones must be constructed which consume energy, labour, and generates costs (USEPA, 1970). Further, I/I can lead to effects regarding increased required land take for larger WWTPs and increased engineering efforts to build larger systems (Broadhead et al., 2013). It can also affect new urban developments if the existing wastewater systems do not have any spare capacity (USEPA, 1970).

I/I contributes to dilution of the wastewater which leads to less efficient treatment in the WWTPs (e.g. Bäckman, 1985; Parkinson et al., 2005). The I/I volumes can affect the removal rates, and this result in higher total pollutant loads in the effluent which can affect the aquatic environment (Hey et al., 2016).

Broadhead et al. (2013) refer to The Manufacturer and Builder (1880) and state that wastewater sewer pipes historically were designed to be leaky to help draining land and lowering the groundwater table. Further, the authors state that it is found in literature that culverting of streams originally was made to manage surface flooding. Kracht and Gujer (2006) also state that there are increasing evidence that the groundwater levels in many European cities are controlled by the drainage effect caused by infiltration in the wastewater sewer systems. Hence, without the effect of infiltration, there are areas that would be flooded due to rising groundwater levels (Gustafsson, 2000; Karpf and Krebs, 2011).

Sun et al. (2015) state that the methane concentration in the wastewater sewer system would increase with a lower water consumption. This implies that removing I/I could lead to increased greenhouse gas emissions from the wastewater sewer system. Cook et al. (2018) present a methodology to determine if water conversation measures have a positive or negative impact on wastewater utilities. They conclude that systems with high levels of infiltration, defined as more than 30 percent of the total dry weather flow, will benefit the most from water conservation practices. Negative effects from implementing water conservation measures are more likely to occur for systems with an infiltration level less than five percent of the dry weather flow.

3.2 Temporary effects

When the capacity of the wastewater system is exceeded, the wastewater can be by-passed into receiving waters to avoid flooding elsewhere (USEPA, 2004b). When the by-pass takes place from a combined sewer, the phenomenon is called combined sewer overflow (CSO) and when it takes place from the separate sewer it is called separate sewer overflow (SSO). Combined sewer systems are designed to overflow to the receiving waters when the capacity of the pipes is exceeded (Wennberg et al., 2017; USEPA, 2004b). This can also happen during dry weather if the groundwater levels are high (Ellis, 2001). The sanitary sewer systems are not designed to divert water at any flow but there are emergency pipes to divert flows during e.g. mechanical failures (Wennberg et al., 2017). According to USEPA (2004b) overflow from the sanitary sewer system can also occur during wet weather due to I/I.

By-passing can also be necessary from WWTP at peak-flows caused by I/I. The wastewater can then by-pass some or all the treatment processes which also results in more pollutants to the receiving waters (USEPA, 1970).

Microbial pathogens, oxygen depleting substances, total suspended solids, toxics, nutrients, floatables, and trash are the principal pollutant present in CSOs and SSOs and can thereby reach the receiving waters (USEPA, 2004b). Wennberg et al. (2017) state that by-passing has a limited environmental effect even though CSOs can stand for a large share of the phosphorus pollutants in some receiving waters. Single CSOs can also have a large impact regarding contamination of the bath water quality as well as on the drinking water supplies. USEPA (2004b) estimated that approximately 4 000 persons in the Unites States get gastrointestinal illnesses every year because of swimming in waters where CSOs and SSOs have taken place. Pathogens from CSOs and SSOs reaching the drinking water system can cause disease outbreaks which can result in substantial costs and suffering (Bergion, 2019).

When the capacity of the wastewater sewer system is exceeded because of I/I, basement flooding may take place (USEPA, 1970; Bäckman, 1985). Basement flooding usually occur in conjunction with large rains when a backflow takes place into the pipe of the house (Bäckman et al., 1993). Flooding due to I/I can also occur at other locations, e.g. at streets and roads (USEPA, 1970).

Several other effects of I/I can be found in literature. Sediment and debris that enter the system together with the I/I may cause blockage (USEPA, 1970) and lead to faster aging of the pipes (Karpf and Krebs, 2011). Sand and soil entering the wastewater system can also lead to street and road damages due to undermining (Weil, 1995; USEPA, 1970; Karpf and Krebs, 2011). Additionally, subsidence can occur because of lower groundwater tables due to infiltration (Bäckman, 1985). On the other hand, less I/I in the system may lead to a reduction of the frequency of self-cleaning velocities which leads to accumulation of sediments in the wastewater sewer system (Parkinson et al., 2005; Karpf and Krebs, 2011). Less I/I may also cause higher concentrations of pollutants in CSOs and SSOs if they would occur. An increased concentration of pollutants in the wastewater sewer system due to decreased flows may also lead to problems with odour and corrosion (Marleni et al., 2015; Sun et al., 2015; Karpf and Krebs, 2011).

4 Detection, localisation and quantification

There exists a vast amount of publications on the numerous ways to detect, localise and quantify I/I. This section aims to provide a summary of identified methods and references are provided to more comprehensive reviews and descriptions. In the literature, different methods for detecting, localising, and quantifying I/I are reported and categorised depending on the specific application e.g. in Franz (2007) and Beheshti et al. (2015). In this review, the methods have been divided into the following categories: sensory methods, flow-based methods, tracer methods, I/I-models and digital water. Figure 4 gives an overview of the used categorisation and corresponding methods addressed in this review.

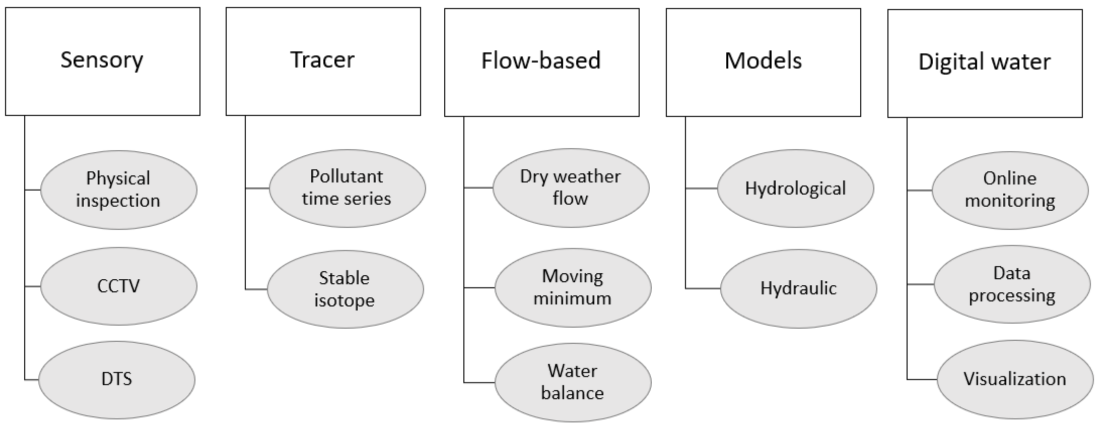

Figure 5. Examples of methods to detect, localise and quantify I/I.

4.1 Sensory methods

Sensory methods aim to assess the status of the wastewater sewer system and can be used for detection and localisation of I/I. These methods are usually performed on site, do not include any calculations and can focus on different aspects e.g. detecting illicit connections or groundwater leaking into the system. According to Eiswirth et al. (2000) sensory methods, or inspection methods, must fulfil a few criteria such as being efficient, relatively uncomplicated to use, and provide accurate information. They must also cause minimum disruption to the surrounding environment, be non-destructive, and have a wide range of possible applications.

There is a very large amount of technologies to assess the status of the wastewater system described in the literature. Overviews of the various available technologies have been made by e.g. Wirahadikusumah et al. (1998), Rizzo (2010) and USEPA (2010). It should, however, be noted that all technologies that assess the status of the wastewater sewer system not always detect or localise I/I.

Physical inspection methods are described in the literature by e.g. Lundblad and Backö (2012), Beheshti et al. (2015), and Eiswirth et al. (2000). A very basic way to detect I/I is by following the wastewater sewer grid downstream while opening the manholes to get a perception of the flows (Lundblad and Backö, 2012). These inspections are performed during dry weather and when the groundwater levels are high. If the inspections are done during night, the sanitary sewer flows are also assumed to be minimised. A sewer periscope, that consists of a spotlight and a mirror can be used as an aid during visual inspections (Bäckman, 1985).

Physical inspection can also involve the procedure of a person entering a larger pipe system, not in service, to inspect it (Wirahadikusumah et al., 1998). CSOs and SSOs can be detected by both visual inspection or by using technical devices such as flow meters (Lundblad and Backö, 2012). By adding a substance to the wastewater sewer system, unknown connections and cross-leakages can be discovered. The substance is added in one part of the system and it is visually inspected if it reaches another location. Commonly used substances are dye, smoke, and water (Beheshti and Sægrov, 2019; Lundblad and Backö, 2012; Bäckman, 1985). The methods of adding a substance to the water are related to the Tracer methods described in 4.2 where inherent substances in the water are monitored.

Closed-circuit television (CCTV) is a very well-established and the most commonly used method of inspection of wastewater sewer systems (USEPA, 2010; Wirahadikusumah et al., 1998). The method involves putting a camera in the sewer system and filming of the surroundings by using e.g. a pushrod cameras or remote controlled robot crawlers (USEPA, 2010). During the real-time visual inspection faults and sources of I/I can be found (Beheshti and Sægrov, 2019). The technology is described more in detail by e.g. Rizzo (2010).

In a large amount of studies evaluating I/I, CCTV is used as an inspection method e.g. Beheshti and Sægrov (2019), Martire et al. (2019), O'Sullivan et al. (2018) and Varghese et al. (2018). Several studies have also compared CCTV to other methods as CCTV can be considered to be slow, costly, and with limited accuracy e.g. Huynh et al. (2016), Romanova et al. (2013), and Harris and Dobson (2006).

Distributed temperature sensing (DTS) has become an increasingly popular method of detecting I/I during the recent years. By putting a fibre-optic cable at the bottom of a wastewater pipe the temperature can be continuously measured using laser methods (Panasiuk et al., 2019). Because of the temperature difference between sanitary sewage and I/I, the latter can be detected and localised. A more detailed information about the method is provided by Hoes et al. (2009).

DTS have been used to detect and localise I/I in combined or separate sewer systems in studies by Schilperoort and Clemens (2009), Schilperoort et al. (2013), Kessili et al. (2018), Beheshti and Sægrov (2018), and Beheshti and Sægrov (2019). Moreover did Langeveld et al. (2012) investigate the performance of stormwater separating manifolds in house connections in the Netherlands using DTS. Panasiuk et al. (2019) used the method for localisation and characterisation of I/I in the sanitary sewage system before, during and after a snowmelt period in Sweden.

Many more technical inspection methods for assessing the status of the wastewater sewer system are described in the literature. Examples of methods presented by e.g. Wirahadikusumah et al. (1998), Eiswirth et al. (2000) and USEPA (2010) are infrared thermography, ultrasonic methods, and ground penetrating radar techniques. Studies that have been found to apply some of these technical inspection methods for finding I/I are presented by e.g. Lepot et al. (2017) who detected I/I using an infrared camera and by Yap and Ngien (2017) who used ultrasonic sensors to collect data to quantify I/I.

4.2 Tracer methods

Tracers are commonly used in hydrology and can be described as substances that can be detected and observed in water (Leibundgut and Seibert, 2011). I/I tracer methods are described in literature by e.g. De Bénédittis and Bertrand-Krajewski (2005), APUSS (2005), and Kracht et al. (2008). Tracer methods can be divided into the two categories;

pollutant time series methods and stable isotope methods (Kracht et al., 2008). These methods can be related to those described in 4.1 under Physical inspection methods where a substance is added and followed in the wastewater.

Pollutant time series methods, or chemical methods, are based on analysis of dilution of pollutants (De Bénédittis and Bertrand-Krajewski, 2005). The idea of these methods is to choose a pollutant that is assumed only to be present in the sanitary sewage and not in the I/I (Kracht et al., 2008). By measuring or estimating the concentration of the pollutant it can be calculated how much the sanitary sewage has been diluted and the volume of I/I can be obtained. Several different substances can be used as tracers. Sola et al. (2018) used the input data of total phosphorus concentration (TOT-P). Kracht et al. (2008) and Bareš et al. (2009) measured the chemical oxygen demand (COD) and the total suspended solid (TSS) to calculate the amount of I/I. Methods using ammonia as a tracer to indicate I/I is described by e.g. Uusijärvi (2013). In a study by Mattsson et al. (2016), 14 chemical elements were measured in the wastewater entering a WWTP and it was concluded the level of dilution correlated closest with the levels TOT-P and total nitrogen (TOT-N). Zhang et al. (2017) evaluated which of the parameters ammonia, phosphate, COD, and conductivity that was most suitable to use as indicators for rain induced I/I in sanitary sewer systems and concluded that conductivity was the most reliable.

Stable isotopes methods or natural tracer methods, are based on the assumption that characteristics of inherent components in the wastewater differ depending on the source (Kracht et al., 2007). It is crucial that the components of drinking water and groundwater sources do not interact and that the local groundwater and the I/I have different characteristics (APUSS, 2005). Examples where these methods are used to detect infiltration in wastewater sewer systems are in studies by Kracht et al. (2007), Kracht et al. (2008), and De Bénédittis and Bertrand-Krajewski (2005). They all analysed differences in stable isotopes to distinguish how much of the wastewater that originated from fresh water and how much that originated from drinking water (sanitary sewage). In these approaches, measurements are performed during dry weather when the inflow is assumed to be zero.

4.3 Flow-based methods

In flow-based methods, or statistical methods, flow measurements are used together with knowledge about e.g. drinking water consumption and sanitary sewage production (Franz, 2007). Assumptions that some flow components can be neglected during specific flow conditions are made to measure I/I and the components of the wastewater can then be balanced over a certain period. Several of the assumptions that are used in flow-based methods are also used in some of the sensory and tracer methods.

Many flow-based methods to estimate I/I exist and are presented in literature, e.g. by Franz (2007) and Weiss et al. (2002). Some of the methods and the assumptions that they are based on are briefly described below.

A common assumption is that the sanitary sewage flow is minimal during the night and that thereby all the flow consists of I/I (Lundblad and Backö, 2012). Another common assumption is that there is no impact from rain induced I/I during dry weather. In the method *Dry weather flow*, described by e.g. USEPA (2014) the flow is measured after a period of dry weather and when the seasonal groundwater table is high. The flow is then assumed to consist of only infiltration and sanitary sewage. In the similar method, called *Moving minimum*, described by e.g. Weiss et al. (2002) and Franz (2007) the sum of the infiltration and the sanitary sewage is assumed to be the lowest daily inflow to the WWTP during the past 21 days.

The *triangle method*, described by e.g. Weiss et al. (2002) and Franz (2007), is used to estimate how much of the I/I that is direct rain induced. This is done graphically by drawing curves in a spread sheet including the information of daily flow to the WWTP, the sanitary sewage flow, and the number of days with storm events. The assumption that the sanitary sewage flow is constant is made.

In the *Water Balance Method*, described by e.g. Sola et al. (2018), the I/I-volume is considered to be the total volume of wastewater reaching the WWTP except the drinking water consumption of the connected people. It is assumed that the sanitary sewage flow is the same as the water consumption and that the consumption is constant.

Mitchell et al. (2007) describe empirical methods to determine the seasonal groundwater infiltration. In all the methods equations including daily average total wastewater production, average daily flow rate, and minimum daily flow rate are set up. In the *Wastewater production method*, it is estimated that the minimum daily flow rate is 88 percent of the average daily flow rate, in the *Minimum flow factor method* the relationship between the flowrates and the basin size is used and, in the *Stevens-Schutzbach method* a curve fitting technique to increase the reliability of the groundwater infiltration is used.

4.4 I/I-models

The word model is in this context referring to the definition as "a representation of something in words on numbers that can be used to tell what is likely to happen if particular facts are considered as true" (Cambridge Dictionary, 2020). I/I models can be used to, by using a reasonable number of measurement points in the sewer system, estimate and assess the distribution of I/I (Karpf and Krebs, 2011). I/I-modelling does however require much labour for set-up and calibration. An overview of I/I-modelling principles and method developments is presented by Franz (2007) who states that two types of models can be used, *hydrological models* and *hydraulic models*. A hydrological model is a simplification of the system at a catchment scale, aiming to predict the precipitation's formation to runoff. A hydraulic model is a mathematical model describing the wastewater sewer system's hydraulic behaviour.

Gustafsson et al. (2010) present a study where rainfall dependent I/I was modelled in a separate sewer system. In the study, one model describing the geohydrology of the case area and one describing the pipe flow the sanitary sewer system were coupled in a hydrologic-hydraulic model. The system calculated the water movement from groundwater, watercourses, and pipe network. After calibration, the model could be used to give an understanding of the groundwater flows and the runoff in the area and the effect of suggested measures could be evaluated.

Karpf and Krebs (2011) developed a multiple model approach for quantification of I/I. Models for each component of the dry-weather flow was set up and combined in a quasi-linear model, and parameters were identified by least-square optimisation. Other examples of publications presenting I/I models are Wittenberg and Aksoy (2010) that used a nonlinear reservoir algorithm to separate groundwater flow from measured influents to WWTPs and Belhadj et al. (1995) that modelled rain induced infiltration into a separate sewer system.

4.5 Digital water

The term *Digital Water* refers to the digitalisation of the whole water system and the use of data in the water context can also be called Smart Water, Internet of Water or Water 4.0 (IWA, 2019). While digitalisation has already started to some extent in the water sector through the use of sensors, geographic information system etcetera, the potential for further development is large. IWA (2019) states that digitalisation of the water system has the possibility to bring benefits for communities, operation, finance, and resilience.

Development of *online monitoring* capabilities such as SCADA (Supervisory Control And Data Acquisition) and IoT (Internet of Things) is classified as part of the basic phase of adaption to digital water (IWA, 2019). A SCADA system receives data from field sensors, process the information, and may take action to avoid a hazard or to optimise the performance (Upadhyay and Sampalli, 2020). Smith et al. (2017) state that a low cost, low tech data acquisition systems have been used by municipalities for manhole monitoring since the early 2000s. Several publications have been found to use SCADA systems to monitor I/I. In a study by Pereira et al. (2019), several flow measurement devices, integrated with a SCADA system, were installed within the wastewater sewer network to measure discharges along the entire network to reduce water inflows. Davalos et al. (2019) present a methodology to analyse and quantify I/I through SCADA Flow Data analysis and Li et al. (2008) used a SCADA system in their model to monitor illicit connections.

IoT is a paradigm in which physical, digital, and virtual objects are connected and can communicate on the Internet (Diène et al., 2020). IoT networks can use different communication technologies which are described by e.g. Sabry et al. (2019). One example of a communication technology used for wastewater networks is LPWAN (Low Power Wide Area Network) that can have the connectivity track LoRa (Long- Range) and the LoRa-based protocol LoRaWAN (Long-Range Wide Area Network). In a study by Drenoyanis et al. (2019) an IoT based LPWAN was implemented to improve the wastewater network management. The authors also present a comprehensive review of wastewater monitoring networks. Limitations and possible development of LPWAN used for underground infrastructure are covered by Ebi et al. (2019).

Another category of digital water consist of *data processing* where machine learning and artificial intelligence (AI) can be used (IWA, 2019). With these technologies the algorithms can be updated over time as new data is presented. In the literature several examples of studies, such as by Shehab and Moselhi (2005) and Huang et al. (2017) are found where defects in the sewer pipes are detected after performing CCTV using machine learning or AI. Kumar et al. (2020) argue that previous approaches focus on defect classification more than localisation and present a deep learning-based framework for the classification and localisation of sewer defects. They state that the models at the current state can classify and localise defects such as root intrusion and deposits but not fractures or cracks since these require a higher accuracy of detection. AI or machine learning can also be used for other purposes such as in a study by Ratnaweera et al. (2018) where unsupervised learning algorithms are used to prioritise control locations in sub-catchments. IWA (2019) also state that the AI technology can be used for services such as always available chat bots.

Visualisation is another category of digital water where virtual reality (VR), augmented reality (AR), and twin city technology are included. VR is a technology where the user is put in an artificial environment whereas the user in AR is in a mixed world where the physical attributes of the real world is present together with virtual content (Behzadan et al., 2015). An example of use for the VR technology in the context of wastewater systems is for education purposes such as scenario based training for employees (IWA, 2019). AR can be used to give field workers a "X-ray vision" to be able to localise the underground infrastructure in order to avoid damages during excavation (Schall et al., 2009). A digital twin is a realistic digital representation of something physical (Bolton et al., 2018) that can be used for purposes such as monitoring current conditions and predicting real-world scenarios (IWA, 2019). In a study by Whyte et al. (2019) the aim was to investigate system relationships and independences found by using digital twins and included a major new sewer tunnel though the centre of London.

4.6 Uncertainties

In this section some uncertainties associated with the methods presented above are addressed. The uncertainties mostly correspond to assumptions, sampling, and measurements.

An overall uncertainty regarding visual inspection such as CCTV and physical inspection is that the methods are dependent on subjective opinions regarding the status and damages in the wastewater network. Eiswirth et al. (2000) state that the reliability of the image when performing CCTV can depend on the experience of the operator as well as the fact that misjudgements can be done regarding the damages. Wirahadikusumah et al. (1998) also note that the quality of the information from CCTV is dependent on the experience and skill of the technician as well as the reliability of the TV picture. Lundblad and Backö (2012) state that it is difficult to choose the right time to perform the physical inspections and the CCTV-inspection. To draw the right conclusions, it is important that the rain induced I/I does not take place if it is assumed to be dry weather flow. Moreover, the CCTV should be performed right after the physical inspections for best results.

Beheshti et al. (2015) mention simplified assumptions as a limitation that can generate inaccurate results when performing flow-based methods. De Bénédittis and Bertrand-Krajewski (2005) also state that there are considerable uncertainties in flow-based methods and chemical tracer methods due to underlying assumptions and general principles. The assumption that the sanitary sewage flow is constant and estimated based on the annual drinking water consumption or by a reference value of discharge per inhabitant brings with it large uncertainties. The same applies to the assumption that the infiltration is the same as the night flow where no regard is taken to sources like groundwater pumping or drinking water leakages. De Bénédittis and Bertrand-Krajewski (2005) further state that the assumption of a permanent and constant infiltration rate during the day can be questioned.

Regarding sampling and measurements, the uncertainties are depending on how the sampling and measurements are performed but also on how many samples or measurements that are taken and when. De Bénédittis and Bertrand-Krajewski (2005) state that the uncertainties for the traditional methods, such as flow-based and chemical methods, can be decreased by developing an improved sampling strategy. They further state that sampling during the night decreases the uncertainty since the infiltration fraction then is higher and that more sampling lead to less uncertainty. Similarly, Bäckman (1985) addresses that consideration must be taken to the balance between many measurements with a low accuracy and high cost per unit and few measurements with a high accuracy and a high cost per unit.

Bäckman (1985) further presents potential sources of error for flow measurements in sanitary sewers. The author states that a possible uncertainty is that the conditions in a sewer system do not meet the specific hydraulic conductions which the measurement methods are based on. Errors can also occur because of faults in the instrument installation, signal interpretation, and conversion and the author stress the importance of knowing the sensitivity of the method used in a specific sewer. Further, the practical experience of the staff performing the measurement is also stated as important.

Beheshti and Sægrov (2018) compared the wastewater flow calculated by DTS with flow measured with a flowmeter and got a 72 percent correlation and the relative error from the calculated flow was approximately 12 percent which the authors state can be because of instrumental measurement errors of the flowmeter. However, the authors further express that the application of flowmeters in low and shallow flows can have high uncertainty and inaccuracy.

Bareš et al. (2009) included an uncertainty analysis in their study where the I/I was monitored using a pollutant time series method based on daily variation of pollutant mass flux. It was assumed that the discharge measurements had an error of 10 percent of measured flow rate and the uncertainty of the pollutant concentration in the wastewater was given by the calibration curves of the measuring device. The authors also refer to the Standard Methods (1998) that present that the uncertainty of the concentration of surface and infiltration water is assumed to be nine percent of measured value. Using Monte Carlo simulations, Bareš et al. (2009) finally conclude that the application of their method did not significantly increase the uncertainty compared to a simple method measuring the night flow.

Since models are simplifications of reality, it is important to consider the uncertainties when interpreting the results. Korving et al. (2009) state that uncertainties exist in sewer models due to the fact that some parameters often are omitted and that the physical phenomena are not exactly known. Moreover, the input data can include data errors. In their publication, Cantone and Schmidt (2009) express concerns about the danger of simplifications in urban catchment models. They give the two simplification techniques skeletonization and sub catchment aggregation as examples and show that these techniques can lead to underestimation of the peak of the outfall hydrograph. Kumar et al. (2020) state that uncertainties in the deep-learning detection of sewer defects can arise due to limitations in the training sets of images as well as due to lack of three-dimensional information.

5 Measures

This chapter provides an overview of the large amount of literature on how to remove or reduce I/I after it has been detected, localised, and/or quantified. The possible measures are here divided into rehabilitation and redirection of flows, and an overview is presented in Figure 5.

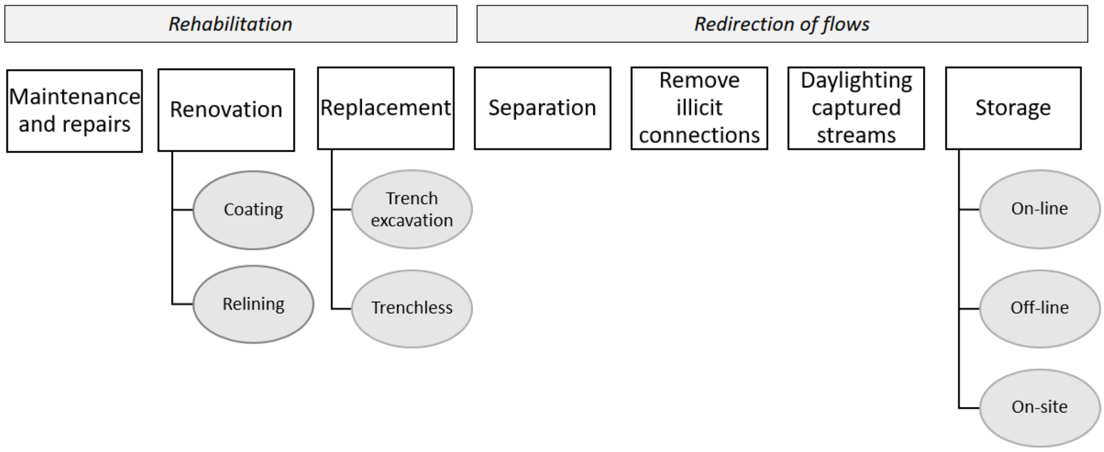

Figure 6. *Overview of measures to reduce I/I or the impacts caused by I/I.*

5.1 Rehabilitation

Sewer rehabilitation is performed to maintain the structural state and functional efficiency of sewer systems (Staufer et al., 2012). To perform the rehabilitation a wide variety of techniques exists and more detailed overviews of these are presented by e.g. USEPA (2009) and Abraham and Gillani (1999). Not only the piping system should be part of the rehabilitation but also faults in other components such as manholes and manhole lids.

The rehabilitation can, in general, be based on two types of failure management (Rizzo, 2010). Either the rehabilitation is done to prevent failure or, more commonly, when a failure has already occurred. In their publication, Tomczak and Zielinska (2017) divide the rehabilitation methods into the three categories: maintenance and repair, renovation, and replacement. *Maintenance and repair* include cleaning and point repairs. One example of a point repair is chemical grouting which involves injection of a chemical grout into cracks and defective joints (USEPA, 2009; Abraham and Gillani, 1999). The grout is applied to leaking structures like pipeline joints and manhole walls. Abraham and Gillani (1999), referring to Vipulanandan et al. (1997), state that chemical grouting in a healthy sewer system is better than all other rehabilitation technologies when it comes to efficiency and cost-effectiveness.

Renovation can be performed either by application of coating materials or by pipe relining (Tomczak and Zielinska, 2017). *Coating* is performed by application of a material to the pipe and it is important to consider factors like bonding between material and resistance to e.g. corrosion when choosing coating material (Abraham and Gillani, 1999). Examples of coating methods are cement mortar coatings, resin coatings, and reinforced gunite or shotcrete. *Relining* involves inserting a lining into the pipe in order to improve its structural state. There exists a large amount of relining methods, see e.g. USEPA (2009) and Abraham and Gillani (1999) where sliplining and cured-in-place (CIP) lining are two examples. When performing sliplining a new pipe of smaller diameter is inserted into the existing pipe. CIP lining involves putting a resin-saturated tube is inserted into the existing pipe. The tube is expanded using air or water pressure and then cured within the pipe.

When applying a replacement method, existing pipes are replaced by new ones (Yang et al., 2007) using open cut trench excavation or trenchless methods (Tomczak and Zielinska, 2017). Problems with open cut *trench excavation* can be disruption in traffic and other activities and that old pipes and soil need to be disposed somewhere (Abraham and Gillani, 1999). Because of the many problems arising from open cut trench excavation it is usually performed only when the pipe is seriously damaged and renovation is not a possible option (Tomczak and Zielinska, 2017). *Trenchless replacement* can be done using the method pipe bursting where the existing pipe is broken open and a new pipe simultaneously pulled into the location, e.g. (Rameil, 2007). An advantage with pipe bursting compared to relining is that the diameter of the pipe remains the same or becomes larger when performing pipe bursting whereas it is decreased after relining.

5.2 Redirection of flows

By redirecting flows that are intentionally or unintentionally connected to the wastewater or sewage system, the volumes of I/I can be decreased. The methods of redirecting flows addressed in this review are implementing separate sewer systems, removing illicit connections, daylighting captured streams, and using storage. Flows can also be redirected by e.g. preventing inflow from and streams lakes from entering CSOs locations (Bäckman et al., 1997).

One method of redirecting the flows is to change the combined sewer system to a *separate sewer system*. A stormwater pipe is then added, and the stormwater is led into that pipe instead of to the WWTP together with the sanitary sewage. The stormwater is either released into the receiving water without treatment or directed to a stormwater treatment facility (Brombach et al., 2005).

The separate sewer system is usually seen as the most preferable sewer system and is often uncritically implemented (Brombach et al., 2005). According to Toffol et al. (2007) it has still been heavily discussed whether the separate or the combined sewer system is the best. In theory, separate sewer systems should not be affected by large rains but it has been shown that the flow characteristics in these systems are similar to the ones in the combined (Bäckman et al., 1993). In several studies such as by Brombach et al. (2005), Toffol et al. (2007), and Mannina and Viviani (2009) it is also indicated that a separate sewer system not always is preferable due to the fact that it can lead to more pollution load in the receiving waters due to release of untreated stormwater. Brombach et al. (2005) state that the choice between separate and combined sewer systems must be done from case to case, with regards to the local conditions. It is also an option to keep the combined system but to disconnect areas that contribute to much inflow (City of Gothenburg, 2010). Moreover, it should be kept in mind that climate change effects will affect the sewer systems performances and the choice between separate and combined sewer systems, something that is investigated by e.g. Kleidorfer et al. (2009).

Another way of redirecting flows is *removing illicit connections* e.g. stormwater laterals from private housing that are connected to the sewer system. When an illicit connection has been identified it can be disconnected and directed to the stormwater pipe instead. The procedure of elimination of illicit connections is explained in detail by e.g. USEPA (2004a). Removing illicit connections often involves extensive interaction and cooperation with property owners (Lundblad and Backö, 2014).

When it comes to streams captured in combined sewers, these can be redirected by *daylighting*, i.e. restoring the waterway in the open air by removing it from the piping system. This concept is addressed more in detail by e.g. Buchholz et al. (2016), Broadhead et al. (2013), and Broadhead et al. (2015). Apart from removing I/I, daylighting of streams can lead to social and ecological benefits.

An alternative to removing the I/I from the sewer system is to use *storage* facilities to even out the peak flows, something that is addressed by e.g. Eisenbath (2008) and USEPA (2004b). Storage can take place within the existing system, which is called *in-line storage* (USEPA, 2004b). By using flow regulators, advantage can be taken to the volumes potentially available in the sewer system. *Off-line storage* consists of facilities, such as tanks, basins or tunnels located adjacent to the sewer system that can be used during wet weather and then emptied back to the system using pumps. Storage can also take place at the WWTP and is then called *on-site storage*. Storage does not remove I/I but helps regulating the peak flows which can lead positive benefits such as decreased risks of CSOs, SSOs, and flooding.

5.3 Uncertainties

According to Lundblad and Backö (2014), it is common that measures aiming to reduce I/I conducted by the water departments do not show any effects. According to the authors this can happen since infiltrating water comes from the pipes within the private properties that are not affected by rehabilitation on the public system. However, the infiltrating water can also find new ways after a rehabilitation action and instead of entering at the rehabilitated location infiltrate somewhere else in the system (Lundblad and Backö, 2014). A rehabilitation action may thereby not be effective unless the whole system is rehabilitated to the highest groundwater level and Bäckman et al. (1997) state that the measure that is most suitable to perform is completely dependent on the local conditions. Furthermore, actions involving redirection of flows may not have the intended results, e.g. a separate system may still be affected by inflow (Bäckman et al., 1993).

Staufer et al. (2012) state that quality assurance often is lacking for rehabilitation projects aiming to reduce I/I and that this can be because of not taking account of variability caused by e.g. climate and hydrologic conditions. They recommend using monitoring results from a reference catchment instead of only monitoring the reviewed catchment before and after the rehabilitation.

6 Risk

When working with risk assessments it is important to have established clear definitions of the used concepts. The first part of this chapter provides information about risk definition and the concepts of probability, consequence, and uncertainty. In the reviewed literature, not much have been found regarding risk definition in relation to I/I and the second part of this chapter therefor aims to evaluate how risk associated with I/I should be defined. Then follows a section about the risk management process.

6.1 Risk definition

The word *risk* can have many meanings and can in non-technical contexts refer to a wide range of situations (Hansson, 2002). It is important to differentiate between a hazard and a risk, where a hazard is a source of danger and a risk typically seen as the likelihood of conversion of that source into any form of damage (Kaplan and Garrick, 1981). The International Organization for Standardization (ISO, 2018) states that risk usually is expressed in terms of risk sources, potential events, their consequences and their likelihood (or probability). Before going deeper into other definitions of risk the concepts consequence, probability, and uncertainty will be addressed. It should be noted that there exist several definitions of these concepts whereas only a few are mentioned here. The focus here is on the concepts most relevant from the perspective of I/I.

Aven (2012) defines *consequence* as "outcome of an event". A consequence can be both positive and negative and be expressed qualitatively or quantitatively. Moreover, one event can lead to more than one consequence. Bedford and Cooke (2001) describe a consequence as a "new state of the world" and is also referring to Savage (1972) who use the definition "state of the acting subject".

ISO (2018) defines *probability* as an "extent to which an event is likely to occur" and it is defined by Aven (2012) in a similar way as "a measure of uncertainty of an event". Three common conceptual interpretation of probability are the classical interpretation, the frequency interpretation and the subjective interpretation (e.g. Bedford and Cooke, 2001; Aven, 2012). Using the classical interpretation, the probability is the sum of a finite set of equally possible outcomes of one experiment i.e. throwing a dice or tossing a coin (Bedford and Cooke, 2001). The frequency interpretation describes the frequency as the sum of a finite set of outcomes of an experiment that can be repeated indefinitely under identical conditions. An example is tossing a coin 10 000 times to see what the frequency for heads would be (Kaplan and Garrick, 1981). In that case it is also possible to assign a probability for the frequency. Finally, the subjective interpretation, or Bayesian probability, that is widely applied in risk analysis, state that probability is the sum of a set of possible worlds or set of possible states of the world (Bedford and Cooke, 2001). Using the Bayesian approach the probability is expressed as a degree of belief. An example of using the subjective interpretation is when answering the question if it will rain tomorrow.

Aven (2012) is defining *uncertainty* as "lack of knowledge about the performance or a system (the world), and observable quantities in particular". Bedford and Cooke (2001) state that it is important to distinguish between uncertainty and ambiguity. Ambiguity, or inexactness can be reduced e.g. by using careful definitions and only after that it is meaningful to discuss uncertainty. Two types of uncertainties are aleatory and epistemic uncertainty. The aleatory, or stochastic, uncertainty, arises from variability in a system and represent randomness in samples (Aven, 2012; Bedford and Cooke, 2001). The epidemic uncertainty regards the lack of knowledge in the system and the fundamental phenomena. Moreover, uncertainty can exist at different levels such as parameter uncertainties, that regards the uncertainty about the "true" value and model uncertainties, that regards the truth of the model.

Kaplan and Garrick (1981) were the first to define risk by using the concept of "sets of triplets" consisting of scenarios and their corresponding probabilities and consequences. The questions "What can go wrong?", "How likely is it that that will happen?", and "If it does happen, what are the consequences?" are posed. The first question is answered by listing the scenarios, or categories of scenarios that can be caused by the hazard. Except for listing the scenarios that can be thought of, an additional scenario is added which includes all unknown outcomes. The second two questions are answered by assigning a probability and consequence for each scenario and as an additional level, uncertainty is added. The authors argue that a single number is not enough to communicate a risk, but it should be communicated as a curve or as a family of curves.

The risk definition of using probability and consequence when quantifying a risk is widely established and used by e.g. Aven (2012) and Bedford and Cooke (2001). Further, it is also argued by e.g. Aven (2010) that the probability component in the risk definition should be replaced by uncertainty. ISO (2018) defines risk as "effect of uncertainty on objectives" and this definition shows that everything affecting how targets are achieved should be considered which involves various kinds of uncertainties. The classic risk definition has been further developed by e.g. Haimes (2009) who adds the fourth question "Over what time frame?". He states that a risk is a vector that is a function of time, the probability of the threat, the probability of the consequence, the vector of the states of the system, and the vector of the resulting consequences. The vector of the state of the system includes its performance capability, vulnerability, and resilience.

Among the various existing risk definitions not all take a technical approach, aiming to quantify the risk. An example of a more social science related risk definition is the relational theory of risk presented by Boholm and Corvellec (2011). The authors argue that risks are culturally informed and a semantic creation that occurs within the communication context. In this theory a risk emerges between a risk object and an object at risk and is dependent of the relationship between the two objects.

6.2 Defining risk in relation to I/I

In this section the conventional risk definition by Kaplan and Garrick (1981), the extended risk definition by Haimes (2009), and the relational theory of Boholm and Corvellec (2011) are used to describe the risk from the perspective of I/I the risks of I/I. The suitability of the definitions in the context of I/I is discussed in the discussion chapter of this report. When analysing risks associated with I/I based on the definitions earlier in this chapter, it is clear that I/I is a *hazard*, a source of danger, that pose a risk. To describe the risk, I/I must be considered in combination with the probability and consequences of resulting outcomes such as basement flooding and CSOs.

In Table 4, a summary of how the risk associated with I/I can be described based on definitions by Kaplan and Garrick (1981) and Haimes (2009) is presented. When applying the definition by Kaplan and Garrick (1981), the first question "What can happen?" is answered by a list of scenarios caused by I/I in the wastewater system. The list will include scenarios corresponding to the outcomes such as basement flooding and CSOs. A final scenario should be added to include all unknown outcomes. Probability and corresponding uncertainty can be obtained by gathering data on flooding, CSOs, precipitation etc. When identifying the consequences for each scenario the environmental, social, and economic effects should be considered.

When using the risk definition by Haimes (2009) most remains as in the previous definition, but some additional parameters are added, see Table 4. The added time vector affects the description of the I/I related risks in that sense that it is acknowledged that the water volumes in the sewer systems vary over time and thus also the risk. The peaks in the sanitary sewage flow are e.g. in the mornings and in the evenings and the precipitation varies based on the seasons. The state of the system is also added as an additional parameter and it is divided into state of the internal system and state of the external system. When it comes to I/I, the state of the internal system can represent the status of the wastewater system and can include aspects such as year of construction, level of maintenance, number of faulty connections, and capacity of system. External states can be groundwater table or water level in receiving waters.

Haimes (2009) divides the probability parameter into two, one for the probability of the threat and one for the probability of the consequence. In the context of I/I this division is very relevant. The probability of the threat represents the probability of I/I in the system and the probability of the consequence represents the probability of outcomes, such as basement flooding. Since there must be I/I in the system for the outcomes to occur the consequence will be conditioned on the occurrence of the I/I. However, there can be a lot of I/I in the system without any outcomes if the wastewater sewer system is dimensioned to take care of large volumes of water. Both probability parameters are dependent on the status of the system.

Table 4. Description of I/I based on two risk definitions.

Questions used to define risk (Kaplan and Garrick, 1981)	**Application to I/I**	**Extended risk definition (Haimes, 2009)**	**Application to I/I**
What can go wrong?	Scenarios caused by I/I, e.g. basement flooding, CSOs and additional pumping. Including unknown scenarios.		
How likely is it that that will happen?	Probability of occurrence for each scenario including uncertainties.	The probability of the threat	Probability of I/I occurring.
		The probability of the consequences, given the threat	Probability of outcomes such as basement flooding, CSOs and additional pumping when I/I has occurred.
If it does happen, what are the consequences?	Consequence for each scenario, including uncertainties.	Resulting consequences	Consequence of hazard.
		Over what time frame?	Variations in flow depending on season and time of day.
		States of the system	State of internal system, e.g. state of wastewater pipes and number of faulty connections State of external system, e.g. water levels in receiving water.

When describing the risks associated with I/I using the relational risk definition by Boholm and Corvellec (2011), the three outcomes basement flooding, CSOs, and additional pumping were chosen as illustrative examples, see Table 5. Regarding the basement flooding, the object that is exposed for a risk is the basement itself and what is threatening the basement is the I/I. The event of the flooding then becomes the relationship of risk between the object at risk in the form of a basement and the risk object in the form of the I/I. Looking at CSOs, the receiving waters are threatened, not by the I/I itself but by the pollutants in the I/I and the sanitary sewage it is mixed with. The risk object is in this case therefore considered to be the pollutants in the I/I and the object at risk the receiving waters. The relationship of the objects is the event of the CSO. Finally, the outcome additional pumping because of I/I is evaluated. The object at risk is in this case not a physical object but the city's economy since additional pumping will lead to larger costs. What is threatening the city's economy is the I/I and the additional pumping then becomes the relationship.

Table 5. Three outcomes of I/I evaluated based on the relational risk theory by (Boholm and Corvellec, 2011).

[Risk object]	(Relationship of risk)	[Object at risk]
I/I	Flooding	Basement
Pollutants in I/I	CSO	Receiving waters
I/I	Additional pumping	City's economy

6.3 The risk management process

This section aims to give a short summary of the risk management process described by ISO (2018) and showed in Figure 6. The risk management process, even though it is often illustrated as sequential, is iterative. The step *scope, context and criteria* involves defining a clear scope and understanding the external and internal environment. The step also involves defining risk criteria to specify what risk, relative to the objectives, that is acceptable as well as defining criteria to evaluate the meaning of the risk. *Risk assessment* includes the three steps: risk identification, risk analysis, and risk evaluation. The *risk identification* step aims to find, recognise, and describe risks with sources both under and not under control. The *risk analysis* step includes estimation of parameters such as risk sources, consequences, likelihood, uncertainties, and if needed also the effect of control measures. In the *risk evaluation* step, the important parts of the needed decision support is provided and examples of decision support methods are presented in Chapter 7. It involves comparing the results of the risk analysis with the risk criteria to see if additional actions must be performed. If the risk must be reduced, possible actions may have been analysed and the results of this provides additional decision support. The aim of the *risk treatment* step is to select and implement options for addressing risk and the step is guided by the results from the risk assessment step. The most appropriate risk treatment option should be selected by balancing potential benefits of the option against disadvantages which should be broader than solely economic considerations. The treatment step also involves preparation and implementation of treatment plans.

Throughout the whole process, communication and consultation, monitoring and review, and recording and reporting should take place. *Communication and consultation* aims to involve stakeholders in the risk assessment process to create understanding and involvement. *Monitoring and review* should be a planned part of the risk management process with clearly defined responsibilities and aims to assure and improve the process and the outcomes. The process is updated when new information becomes available. Finally, in the step *recoding and reporting* the risk management process and the outcomes are documented and reported. This is done to communicate the activities and outcomes, provide information for decision-making, interact with stakeholders, and improve risk management activities.

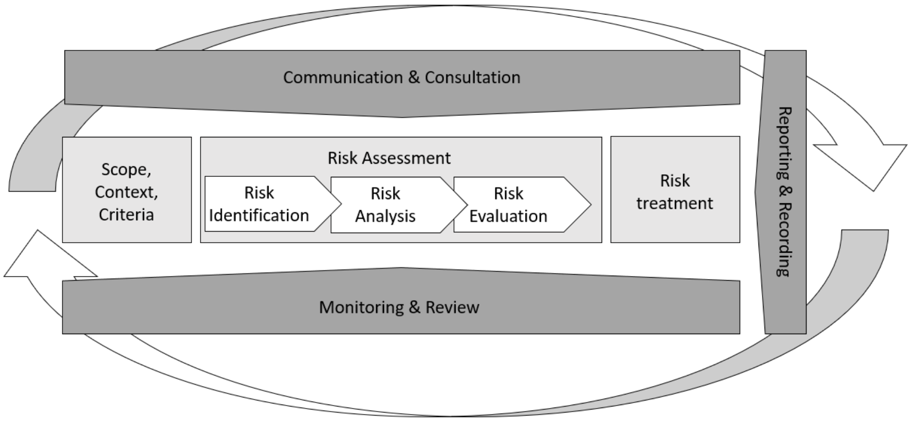

Figure 7. *Risk management process adapted from ISO (2018).*

7 Decision support

Aven (2003) describes a basic structure of the decision-making process, see Figure 8. According to the author, the decision-making should mainly be seen as a process to provide decision support that should be followed by informal managerial judgement instead of a process of choosing an alternative. The process consists of several steps, whereas all are based on the stakeholder's values. The methods multi-criteria decision analysis (MCDA), cost-benefit analysis (CBA), cost-effectiveness analysis (CEA), and life-cycle cost analysis (LCCA) that will be described in this chapter are applicable in the analysis step, upper circle of Figure 8, as well as in the risk evaluation step in the risk management process presented in the previous chapter (see Figure 7).

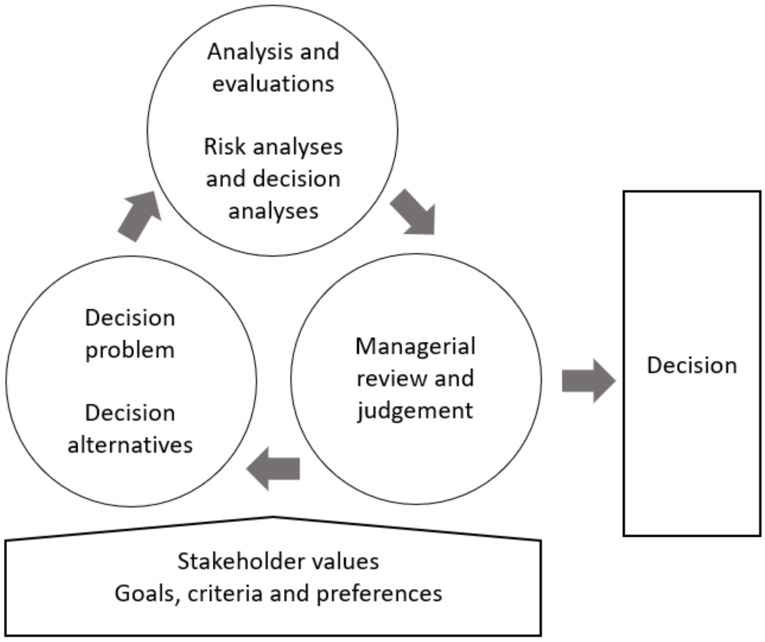

Figure 8. Basic structure of the decision-making process, adapted from (Aven, 2003).

7.1 Multi-criteria decision analysis

A multi-criteria decision analysis (MCDA) aims to provide decision support for complex problems with both monetary and non-monetary objectives (DCLG, 2009). The problem is broken down into smaller pieces to be able to evaluate the parts before putting them together again to receive an overall picture. Figure 9 shows the basic steps of a MCDA. The steps are described more in detail below based on DCLG (2009).

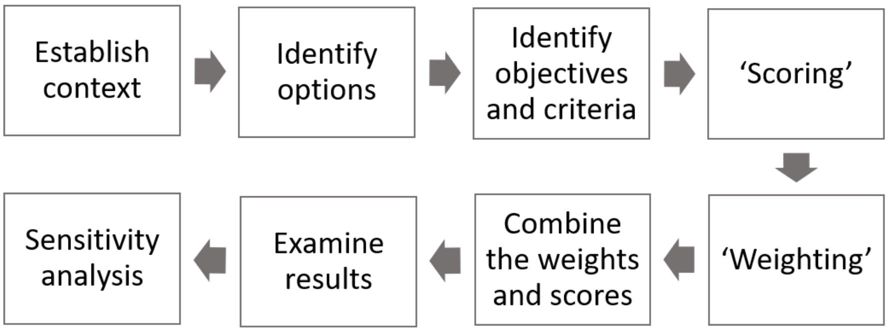

Figure 9. Basic steps of the MCDA, adapted from DCLG (2009).

When performing a MCDA the decision context must be established (DCLG, 2009). This includes formulating the aim of the analysis as well as identifying the stakeholders and additional key players. It also includes design of the socio-technical system to formulate when and how the stakeholders and key players will contribute to the MCDA, deciding what form of MCDA that will be used and how it will be implemented. Moreover, it is important to consider the context of the appraisal and establish the discrepancy between now and the vision for the future.

The next step is identifying the options to be appraised. The options can be pre-specified or developed during the process, but space should always be given to modify and adding new options along the way. In the following step, objectives and criteria are identified. Criteria are specific, measurable objectives, and express the many ways that options create value. The criteria are in this step first identified for assessing the consequence of each option and then organised in higher-level and lower-level objectives.

The scoring step starts with a description of the consequences e.g. in a performance matrix where the performance for each option is noted for each criterion (DCLG, 2009). To make the performances comparable, a value associated with the consequence is set for each option for each criterion.

In the following weighting step, weights are assigned for each of the criteria to reflect its relative importance to the decision. Both the scoring and the weighting can be done using different methods where two examples are direct scoring or weighting where the scores or weights are assigned based on an explicit scale (Antov, 2018) and Analytical Hierarchy Process (AHP) where the different alternatives are compared in pairs (Ossadnik et al., 2016). Preferably the scoring is performed based on facts or made by individuals that are both experts and not bias in the project (DCLG, 2009). The weighting should be performed by the decision maker to get a representation of the relative importance of the criteria taken from a broad perspective.

The nest step in a MCDA aims to combine the weights and the scores (DCLG, 2009). This is done by first calculating the overall weighted score. Different approaches can be used for this calculation but the most common one is the linear additive method, that is a basic application of the Multi attribute utility theory (MAUT) (Keeney and Raiffa, 1993). For these methods to be valid, all criteria must be mutually preference independent. Meaning that the scoring and weighting of one criterion is independent of the other criteria.

In the linear additive method, the different option's score is multiplied by the weighting and the overall weighted score for each option (S_i) is calculated as:

$$S_i = \sum_{j=1}^{n} w_j s_{ij} = w_1 s_{i1} + w_2 s_{i2} + \cdots + w_n s_{in} \qquad (1)$$

where s_{ij} is the preference score for option i on criterion j and w_j the weight for each criterion.

Using the MCDA results, the analysed options can be compared and prioritised. When examining the results, a key aspect is to explore the discrepancies between the MCDA results and people's intuitions to make sure that the future decisions are taken with full awareness of possible consequences. An important and last step of the MCDA process is to perform a sensitivity analysis. It should be examined if changes in preferences or weights affect the overall result and what the advantages and disadvantages of selected options are. If needed, more options can be added, and the steps repeated until a good model is obtained.

7.2 Cost-benefit analysis

Hanley et al. (2009) describe cost-benefit analysis (CBA) as "a technique for measuring whether the benefits of a particular action are larger than the costs, judged from the viewpoint of society as a whole". The CBA has been used for a very long time and can have many different applications (Johansson and Kriström, 2018). CBAs can be applied on projects with the aim to improve the environment and are in these cases called environmental CBAs (WHO, 2003). Figure 10 displays the basic steps of a CBA.

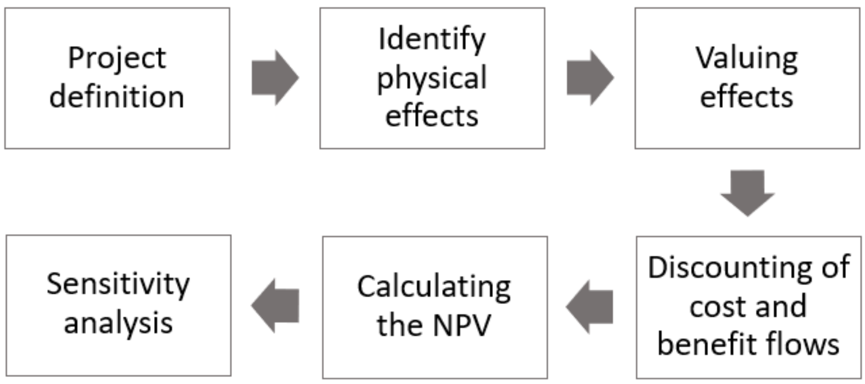

Figure 10. Basic steps of a CBA, adapted from Hanley et al. (2009).

The first step in a CBA is defining the project, including exactly what to analyse, whose welfare that is considered and over what time frame (Hanley et al., 2009). In the next step, all physical effects of the project are identified and quantified. It is then decided which of the effects that are relevant to the CBA. Effects can be anything which affects the quantity, quality or price of resources and can be linked to the well-being of the relevant population, e.g. man-hours of labour, amount of electricity or pollution, effects on global warming, or improved air quality.

Johansson and Kriström (2018) discuss whose cost and benefits that should be included when performing a CBA. The CBA can be undertaken at different levels such as globally, national or regional. Additionally, it must be decided whose preferences to be included inside the chosen system. CBA is insensitive to distributional concerns meaning that a project is recommended if the costs exceed benefits even if some of the induvial are worse off (Adler, 2013). Therefore, there is a need to handle distributional concerns in a CBA in cases where the distribution in the society is not optimal or where unlimited distributions are costly (Johansson and Kriström, 2018). Distribution can be done in different ways e.g. using the social welfare function or distributional weights. Additionally, a distributional analysis where the benefits and costs are assigned to different groups, can be performed during the sensitivity analysis.

Some effects, especially the financial, are relatively easy to value and monetarise, however it is more complicated to value nonmarket goods and services. To estimate these goods and services, it is common to use the willingness to pay (WTP) or willingness to accept (WTA) approaches (Johansson and Kriström, 2018). WTP and WTA are estimates of what a person is willing to pay or accept for an increase or decrease of his or her utility. It can be assessed using e.g. stated-preference methods where individuals state their preferences in interviews or questionnaires or in revealed-preference methods where information about the individuals' behaviour related to their choices are used. Previous studies can also be used in new studies to value non-market goods and services, called value transfer. When performing a value transfer either single values or aggregates of values can be transferred (Boutwell and Westra, 2013). It is important to take physical and demographic differences between the sites into consideration and to pay attention to errors such as measurement errors and transfer errors.

One agent's consumption or production can affect other agents in positive or negative ways (Johansson and Kriström, 2018). These effects are called externalities and can e.g. consist of pollution of air and water from a coal-fired power station or pollination from a honeybees. Johansson and Kriström (2018) state that the externalities could be treated as a public good or a public bad and that the aggregate willingness to pay (WTP) should be added in the CBA.

Effects on human health can be quantified using time-based measures of health, such as quality-adjusted life years (QALYs) or disability-adjusted life years (DALYs) (WHO, 2003). QALY is used to adjust a person's life expectancy based on the quality of the life (Sassi, 2006). One DALY is one lost year of healthy life since it expresses years of life lost to premature death and years with a disability with a specified severity (Murray et al., 1996).

The fourth step in the CBA consists of calculating the Net Present Value (*NPV*). The *NPV* is calculated using:

$$NPV = \sum_{t=1}^{T} \frac{B_t - C_t}{(1+r_1)^t} \qquad (2)$$

where T is the project time, B the benefits for year t, C the costs for year t, and r the discount rate. Discount rates are used to make benefits and costs that occur at different time stages comparable (Johansson and Kriström, 2018). With a zero discount rate the future costs and benefits are valued as today whereas a positive discount rate means that future costs and benefits are valued lower than today. It is also possible to use a discount rate that varies over time, e.g. a reduced discount rate over time to provide for intergenerational equality (see e.g. Johansson and Kriström, 2018). If the benefits exceed the costs, the project is efficient and would result in an improvement in the social welfare. The last step when performing a CBA is to do a sensitivity analysis (Hanley et al., 2009). This, to take uncertainties into account and to examine how changes in the input data changes the result.

7.3 Cost-efficiency analysis and life cycle cost analysis

A different decision support method that in many senses is similar to the CBA is the cost-effectiveness analysis (CEA). The aim of a CEA is comparing an indicator of effectiveness with a cost (OECD, 2018). This can be applied by setting up an environmental requirement and then finding the alternative that fulfils this requirement to the lowest cost as in Gren et al. (2013). CEA is useful when comparing or ranking several alternatives but it does not give the answer if the action is worth doing since the comparison is made using indicators with different units (OECD, 2018). The effectiveness indicator can be measured using individuals' preferences as in the CBA but is more often chosen by experts. Intangible costs should preferably also be added in the CEA.

A similar method to the CEA, is the life cycle cost-analysis (LCCA) that is commonly used for infrastructure projects. The idea of a LCCA is to include all cost that can occur for a product, such as an infrastructural asset from its design to the decommissioning (Rahman and Vanier, 2004). In the LCCA the NPV, or the end of year expenses, of all life cycle cost including initial costs, maintenance, repair and renewal costs over the whole life cycle are calculated and compared for different project alternatives.

LCCA is performed for projects where the project alternatives fulfil the same performance requirements, the benefits are thereby assumed to be similar and are therefore not included (e.g. Swärdh and Pyddoke, 2017). The project alternatives can, however differ in costs such as initial and maintenance costs as well as in the used technology (Fuller, 2010). As an example, LCCA can be suitable when building a road or a sewage pipe where the criteria for the performance of the final project are the same among the alternatives but the way of getting there differs in cost and technology.

Rahman and Vanier (2004) argue that social as well as user costs should be included in the LCCA. By social costs they refer to all intangible costs that arise for the public by disruption of services generated from e.g. physical stress and environmental costs. Social and hidden costs are however often omitted from the LCCA (Arditi and Messiha, 1999).

7.4 Decision support and infiltration and inflow

Eight publications have been found that present models for decision support in relation to I/I. In addition, many publications have been found that present models for decision support regarding sewer rehabilitation more in general e.g. by Vladeanu (2018), Yang et al. (2007), Berardi et al. (2009), and Ward and Savic (2012). Models on decision support and other measures to reduce I/I as well as models on decision support and effects of I/I have also been found e.g. by Korving et al. (2009), Dusenbury et al. (2019) and Sadr et al. (2020). This review will focus on the publications regarding I/I and decision support which are presented in Table 6. After the table follows more detailed information about each of the eight publications. Several of the publications listed in Table 6 use CBA as a method. Other decision support methods used are MCDA, genetic algorithm, and Benders decomposition model. Genetic algorithms are computational models inspired by evolution and often used as optimisation tools (Whitley, 1994). Benders decomposition is also a method for large-scale optimisation problems but where the problem is divided into smaller parts (Taskın, 2010).

Table 6. Summary of publications found regarding models to optimise reduction of I/I.

Title	Reference & Method*	Aim	Criteria
Analysing consequences of infiltration and inflow water (I/I-water) using cost-benefit analyses	(Sola et al., 2020) CBA	To reflect on the impacts of I/I and how the consequences may be limited	• Project costs • Operation costs • WTP for water quality • WTP to avoid basement flooding • Cost of basement flooding
Cost effective infiltration and inflow analysis and remediation efforts in Miami-Dade County	(Davalos et al., 2019) CBA	To present a methodology for assessing I/I and provide recommendations to remediate excessive I/I	• Pumping, treatment and construction cost savings • Cost of I/I evaluation and repair
An effective and comprehensive model for optimal rehabilitation of separate sanitary sewer systems	(Diogo et al., 2018) Genetic algorithm multi-objective model	To develop a cost-benefit approach for optimisation of I/I reduction for rehabilitation decision	• Project cost • Cost of operation and maintenance • I/I before and after rehabilitation • Treatment and transportation
Eliminating sewer infiltration within the region of Halton	(Moskwa et al., 2018) LCCA	To find the most suitable technology for infiltration reduction in a specific trunk sewer	• Infiltration elimination • Corrosion resistance • Availability • Hydraulic capacity • Cost • Design life • Full pipe structural rehabilitation
Evaluation of multi criteria analysis as a tool for spatial resource allocation of stormwater measures for inflow and infiltration to the sewage water system	(Vallin, 2016) Multi-criteria analysis	To investigate whether multi-criteria analysis can be used as an appropriate tool to allocate stormwater measures to the most beneficial areas for reducing I/I	• Project cost • Cost for treatment • Risk of CSOs/SSOs • Risk of basement flooding
Development of a decision making support system for efficient rehabilitation of sewer systems	(Lee et al., 2009) Genetic Algorithm	To present a model for prioritising of sub-areas for minimising I/I during the rehabilitation process	• I/I before and after rehabilitation • Cost of treatment
Benefit/cost analysis report – Regional infiltration and inflow control program King County, Washington	(King County, 2005b) CBA	To examine the benefits and costs of implementing I/I reduction measures	• Capital facility cost reduction (pipes, pumping stations, storage and treatment) • Project cost
A Benders decomposition model for sewer rehabilitation planning for infiltration and inflow planning	(DeMonsabert and Thornton, 1997) Benders Model	To demonstrate a model to optimise the repair and replacement strategy for reducing I/I	• I/I before rehabilitation • I/I after rehabilitation • Possible repairs • Treatment and transportation cost • Project cost

* The decision support methods stated in the table correspond to the terms used by the authors of each publication. In some cases, these terms differ from how the decision support methods are described in this report. Each model and the used methods are described more in detail below.

Sola et al. (2020) present a model comparing four project alternatives related to I/I. The project alternatives are located in the municipality of Asker in Norway and involve full restauration of all pipes, increasing pump capacity, using local retention basins, and business as usual. In the model, project internal financial costs of performing the different project alternatives including operation costs were compared to the benefits of improved bathing water quality and the avoidance of basement flooding translated into financial terms using WTP. In the case study, benefits for avoiding basement flooding were excluded and all project alternatives were considered to result in the same improvement in water quality. The comparation of the project alternatives was hence based on the costs for performing the measures and the model resemble how a CEA is described in this review.

Davalos et al. (2019) present a model performed prior to the upgrade or rehabilitation of wastewater pump stations in the Miami-Dade County. The aim was to prioritise cost-efficient I/I reduction projects. In the study, prioritised pump station basins were selected to be evaluated based on their percentage of excess I/I. The benefits consisted of the savings of removing I/I in terms of costs of saved pumping, treatment, capital construction, and short-term construction. The capital construction cost benefits were related to not having to construct new capacity in the WWTP and at other downstream facilities. The sum of the benefits was compared to the cost in terms of I/I evaluation and repairs. However, the costs and benefits are not discounted. In the end of the article it is stated that I/I can result in social, economic, and environmental issues and a few examples are listed. However, only internal, financial criteria are included for the costs and benefits in the actual model.

Diogo et al. (2018) present a function to minimise the net rehabilitation cost reducing I/I. The function is divided into three different parts which regard infiltration through links, infiltration through nodes (manholes and stations), and inflow caused by inappropriate/wrong connections. In the parts regarding infiltration, the cost after rehabilitation for operation and maintenance to sustain the desired level of infiltration is included. The cost parameters include yearly updates and interest rates but are not discounted and are limited to project internal, financial costs. The difference of the cost for rehabilitation (and maintenance) and the cost savings for having to treat and transport less water after rehabilitation for each component (link, node, and wrong connections) for the lifespan of the system is summed. Another function is added that considers the structural condition. A genetic algorithm is used to get the result from the two-objective optimisation rehabilitation model. Diogo et al. (2018) present result from three case studies where simplified functions were used on real-word sewer systems.

The study by Moskwa et al. (2018) was performed to find the most suitable method to rehabilitate a large trunk sewer in which a lot of infiltration took place. The model is stated to be a LCCA but resembles how a MCDA is described in this review. The chosen project alternatives were full length CIP lining, spot repair by CIP lining, chemical grouting, and using a mechanical repair sleeve. For the project alternatives scores were assigned for the eight criteria: infiltration estimation, corrosion resistance, reduction in hydraulic capacity, availability locally and of pipe size, design life, and full pipe structural rehabilitation. The criteria were weighed giving extra weight to infiltration estimation and availability and a total score for each alternative was calculated using the linear additive approach described in Eq. 1. Initially it was concluded that full length CIP lining was the most favourable option. However, after receiving the information that the trunk sewer was going to be decommissioned within the next 10-15 years the project alternative of chemical grouting was chosen even though this alternative received the lowest score in the MCDA.

In her Master's thesis, Vallin (2016) examines the suitability of using a multi-criteria analysis for reducing I/I. Vallin focuses on measures to reduce inflow by disconnection of stormwater from surfaces and drainage to the wastewater piping system. The criteria used to analyse the need for measures in each sub-area are risk of large flows of I/I (treatment cost), risk of basement flooding, and risk of CSOs. For the three criteria, probability scores and consequence scores are assigned, and the criteria are weighted using the Analytical Hierarchy Process (AHP). The rehabilitation cost is then included to rank the sub-areas using both a linear additive method and a CBA. Vallin (2016) also performs sensitivity analyses of all parameters as well as a total sensitivity analysis using a Monte Carlo simulation. The result of the sensitivity analysis shows large uncertainties which make the author questioning the robustness of the model.

Lee et al. (2009) present a decision-making support system for sewer rehabilitation that focuses on in which order sub-areas should be rehabilitated to minimise the I/I to the WWTP during the rehabilitation process. Using a genetic algorithm, it can be concluded in which order rehabilitation, that leads to the lowest I/I in total and thereby the lowest treatment cost, should be performed. The criteria used in the study are volumes of I/I before and after rehabilitation as well as the project internal, financial cost for treatment of I/I.

King County (2005b) describe a model performed to examine the benefits and costs of implementing I/I reduction measures in King County, Washington. In the study benefits in terms of capital facility cost reduction are compared to costs in terms of I/I rehab in order to prioritise selected rehabilitation projects. The benefits consist of costs saved from the reduction of I/I from the facilities including not having to build new pipes, new pumps stations, new storage facilities as well as savings in the WWTP in terms of energy and disinfection costs. The project costs include internal parameters but apart from project internal, financial costs of implementing measures it also includes parameters such as traffic control. It is also mentioned that project specific mitigation, such as environmental, land use, public disruption, and private property, is included in the project cost. Parameters concerning social or environmental factors cannot be found to be quantified or included in the analysis even though it is mentioned several times that costs for environmental or other concerns may need to be added (King County, 2005a). The costs and benefits were evaluated based on the three approaches; reaching a 30-percent I/I reduction goal, finding the cost-effective projects based on a region-wide evaluation and finding the cost-effective projects based on a project specific evaluation. The study also includes a sensitivity analysis (King County, 2005b).

DeMonsabert and Thornton (1997) aim to find the most effective method of repair for each defected manhole or pipe in a system and state that the optimal strategy generally lies between repairing all defects and ignore all repairs, treating all wastewater. Using a Benders decomposition model the optimal reduction of I/I, limited by the available funds for the proposed sewer rehabilitation, is found. Costs for project repair as well as treatment and transportation costs include project internal, financial costs.

7.5 Goals and key indicators

A common goal or key indicator is to set a maximum ratio or percentage of I/I of the total flow to the WWTP. Two examples are Norway where the County Governor of Oslo and Askerhus has claimed that the maximum acceptable level of I/I should be 30 percent (Sola et al., 2019), and Gothenburg were a goal was set to have a maximum of 50 percent

I/I (City of Gothenburg, 2010). Bäckman et al. (1997) present more examples of municipalities that set this kind of goal related to maximal accepted dilution.

In some cases, the number of CSOs and number of basement flooding are set as key indicators. Bäckman et al. (1997) refer to the Helsinki commission that in 1990 stated that CSOs should not occur more than 10 times per year. City of Gothenburg (2010) set a goal to not have more than 40 basement flooding per year. Goals regarding I/I can also be set based on the pollutants released in the receiving waters (Bäckman et al., 1997). These goals often defined based on nitrogen, phosphorus, and BOD, and the regulation sometimes depends on the quality of the receiving water. An example of this goal is from the Netherlands where the goal has been set to reduce the pollution loads from sewer systems by 50 percent compared to the situation 1985 (Korving et al., 2009). This goal has been translated into the guideline of the allowance of a maximum of 50 kg COD discharged to the receiving waters per hectare and year.

After having given many examples of goals and key figures, Bäckman et al. (1997) conclude that key indicators such as maximum allowance average of I/I are unreasonable. The authors state that local conditions greatly affect effectiveness of measures and that wrongly formulated goals can lead to measures and cost put at the wrong places.

In Chapter 6, it was concluded that I/I should be considered a hazard and not a risk. After having made this conclusion it can be argued whether the risk or the hazard should be reduced when deciding on a goal or a key indicator. Löfstedt (2011) is exploring this problem from the perspective of chemical regulation in the European Union. The author argues that hazards are easier to assess, and that the precautionary principle often is used when it comes to chemicals. This "better safe than sorry"-principle can result in the implementation of unnecessary and costly actions. The author also states that a common bias is that there is a greater value in eliminating a hazard than reducing a risk. The goals regarding percentage of I/I concerns decreasing the hazard of I/I while the CSOs, flooding, and pollutant goals aim on decreasing parts of the risk. Figure 12 summarizes the goals mentioned above divided into if they are aiming on reducing the hazard or the risk.

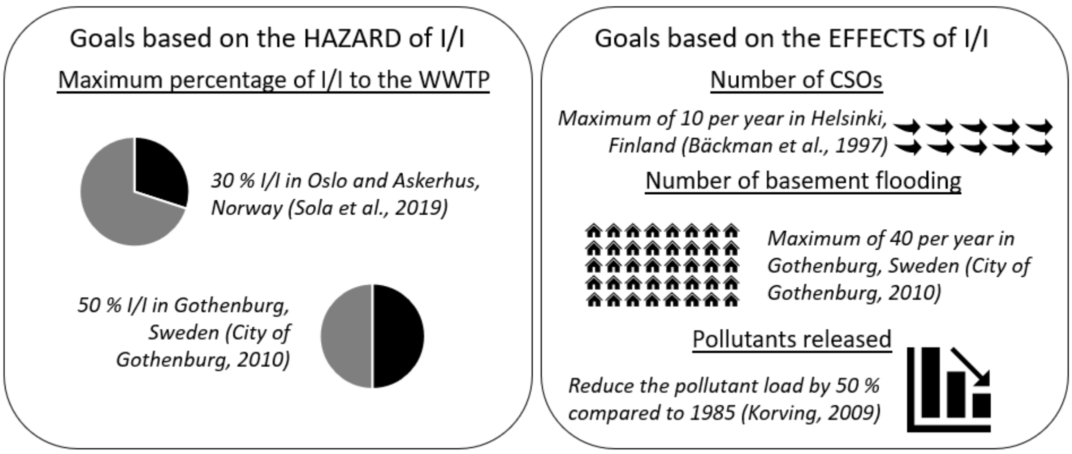

Figure 11. Examples of I/I goals based on the hazard or effect of I/I.

8 Discussion

Regarding the risk definition of I/I, both the definition by Kaplan and Garrick (1981) and the definition by Haimes (2009) provide important aspects useful when defining the risk of I/I. It is very relevant, in the context of I/I, as done by Haimes (2009), to divide the probabilities into probability of having I/I present and thus posing a situation that may cause negative effects and the probability of the final outcomes, e.g. the consequence that may occur due to the different effects. Moreover, it is useful to pay special attention to the time frame as well as the state of the system. However, Kaplan and Garrick (1981) also point out two important factors. These are that a scenario of unknown scenarios should be added, and uncertainty parameters should be defined for each probability and consequence. The definition by Boholm and Corvellec (2011) is less applicable in the I/I context since the risks in their approach are not quantified. However, the approach is still interesting and should be kept in mind since the relational risk theory can provide additional perspectives on the problems.

I/I should be considered a hazard and not a risk. Using this approach, the common goal of decreasing the I/I to a specific level may be unfeasible. The problem with I/I is distributed across a large and immense wastewater system and trying to reduce the hazard itself, i.e. the occurrence of I/I, might lead to very high costs as well as resulting in little effect on the actual risk. It should instead be carefully evaluated if there is a value in removing I/I volumes just to decrease the levels or if focus should be put on decreasing the actual outcomes.

In general, this literature review shows that a very large amount of publications on I/I exists. Especially when it comes to methods for finding and quantifying I/I as well as sewer rehabilitation, very immense technical knowledge is documented. However, few publications were found to present decision support models for I/I. Among the presented models most used the cost of treatment and transportation of I/I as the only criteria to measure the benefits of removing I/I. However, Vallin (2016) also added the parameters of risk of basement flooding and risk of CSOs. Vallin (2016) weighted the treatment cost as the least important criteria and even though she states error of sources in the weighting it can be assumed to be misleading to use treatment cost as the only cost parameter to value I/I as done in most of the other reviewed models.

In the reviewed models it was mostly assumed that the cost of treatment and transportation is proportional to the incoming flow. DeMonsabert and Thornton (1997) tackle this problem by assigning one cost for infiltration, representing the baseflow, and one for inflow, representing the peak flow. A similar approach is found in a report by I'Ons (2017) where the I/I is divided into categories with different costs depending on the size of the flow. A volume of I/I corresponding to a very high flow then gets a cost more than 40 times higher than a volume corresponding to a very low flow.

Criteria corresponding to environmental and social aspects are absent in most of the reviewed publications of decision support and I/I. Further, most existing publications only include internal effects. Only Vallin (2016) includes any of these criteria, but it is argued in several of the other publications that criteria like these are important. None of the reviewed publications apply a holistic approach including more than just a few aspects of the very complex issues regarding I/I. More research is therefore considered to be needed to, from a risk-based and system perspective, include environmental, social, and economic as well as both internal and external criteria to evaluate how I/I can be reduced in the most sustainable manner.

9 Conclusions

The following main conclusions were drawn from this literature review:

- I/I should be considered a hazard and not a risk where a hazard is a source of danger and a risk typically seen as the likelihood of conversion of that source into any form of damage. In the commonly used goal of reaching a specific percentage of I/I, the focus is on reducing the hazard which can result in implementation of unnecessary and costly actions. It might therefore be more efficient to set goals of decreasing the effects of I/I e.g. focus on CSOs, flooding or pollutant loads which aim at decreasing parts of the risk.
- When evaluating risks associated with I/I it is most suitable to use a risk definition including the probability of threat, the consequence and its probability, states of system, and timeframe for each outcome caused by the hazard. Unknown outcomes as well as uncertainties should also be included.
- I/I have many negative impacts such as increased pumping and treatment, flooding, and CSOs. However, several publications also address positive impacts such as less odour and corrosion as well as improved flushing of pipes.
- A very large amount of publications exists regarding methods of detecting, localising, and quantifying I/I. The same applies for methods on sewer rehabilitation, in general and with focus on I/I.
- Few publications present decision support models to evaluate measures to reduce I/I. Moreover, these do to a very large extent focus on project internal, financial effects i.e. costs for the project owner. Limited or no consideration is taken to external financial effects, inherent environmental values or social aspects.
- There is a need for future studies evaluating I/I from a broader system perspective, including positive and negative economic, social, and environmental effects both for the project owner and for external stakeholders.

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DEPARTMENT OF ARCHICTECTURE AND CIVIL ENGINEERING
DIVISION OF GEOLOGY AND GEOTECHNICS
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
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