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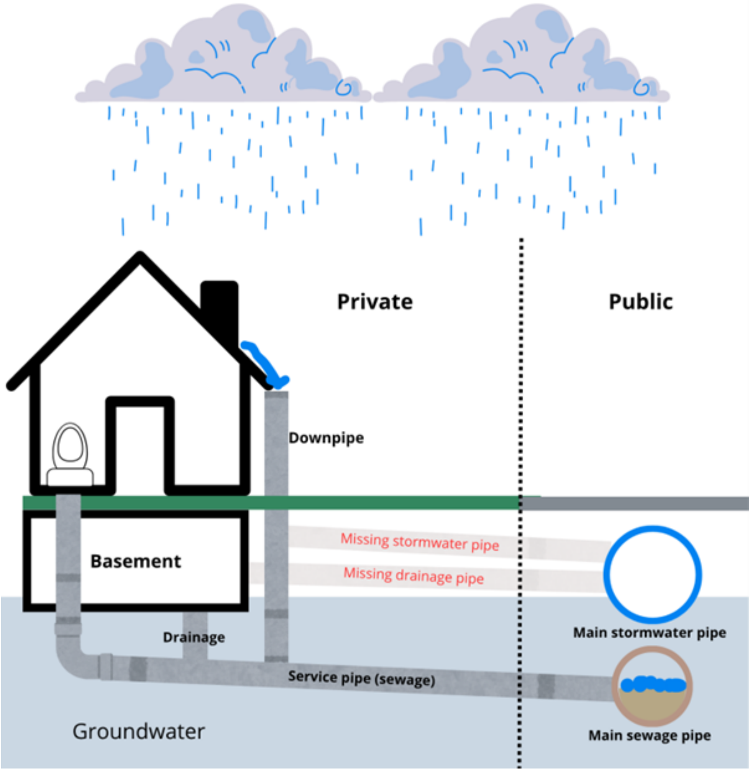

Value of Information Analysis for Improved Decisions on Infiltration and Inflow to Wastewater Systems

Master's thesis in the Master's Programme Infrastructure and Environmental Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
Master's thesis ACEX30
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Cover:
Incorrect downpipe and drainage connections, described in chapter 2.2.1.
Department of Architecture and Civil Engineering
Göteborg, Sweden, 2025

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ABSTRACT

Infiltration and inflow (I/I) of excess water into wastewater systems pose significant technical, economic, and environmental challenges. This Master's thesis explores the application of value of information (VoI) analysis as a decision-support tool to improve I/I-water management in private and separate sewer systems in Gothenburg. By combining cost-benefit analysis with probabilistic modeling and Bayesian updating, a VoI framework is developed to quantify the economic value of acquiring additional information. This is achieved by comparing optimal decisions before and after considering potential new data, to determine whether methods such as smoke and dye testing are economically justified. Using data from the Department of Sustainable Waste and Water at the City of Gothenburg (Kretslopp och vatten), the model assesses the viability of three decision alternatives: intervention, no intervention, or further investigation. The results show that interventions are recommended in 67% of analyzed subareas, while further investigation is justified in 20%. Sensitivity analysis highlights the influence of several parameters, such as costs for measures and film inspections, detection accuracy, and especially property owner compliance, which plays a decisive role in cost-effectiveness. While the model is applied to Gothenburg, its structure is generalizable and adaptable to other municipalities facing similar challenges. The thesis demonstrates that VoI analysis can enhance municipal decision-making by supporting more targeted, risk-aware, and cost-effective I/I-water management, ultimately contributing to more resilient and sustainable wastewater infrastructure systems.

Keywords: Infiltration and inflow, Wastewater systems, Value of Information analysis, Cost-benefit analysis, Decision support, Uncertainty analysis, Sensitivity analysis, Smoke testing, Dye testing

Informationsvärdesanalys för förbättrade beslut kring tillskottsvatten i avloppsystemet

Examensarbete inom masterprogrammet Infrastruktur och miljöteknik

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SAMMANFATTNING

Tillskottsvatten i avloppssystem innebär stora tekniska, ekonomiska och miljömässiga utmaningar. Denna masteruppsats utforskar hur en informationsvärdesanalys kan användas som beslutsstöd för att effektivisera hanteringen av tillskottsvatten i Göteborgs privata och separata avloppssystem. Genom att kombinera kostnads–nyttoanalys med probabilistisk modellering utvecklas en informationsvärdesmodell som kvantifierar värdet av ytterligare information från rökning och färgning för att avgöra om dessa undersökningsmetoder är ekonomiskt motiverade. Modellen bygger på data från Kretslopp och vatten och analyserar tre handlingsalternativ: åtgärd, ingen åtgärd eller vidare undersökning. Resultaten visar att åtgärder rekommenderas i 67% av de undersökta delområdena, medan vidare undersökning är motiverad i 20%. Känslighetsanalyser lyfter särskilt fram fastighetsägares efterlevnad av åtgärdskrav, åtgärdskostnader och detektionssäkerhet som avgörande parametrar. Resultaten visar att informationsvärdesanalys kan stärka kommunala beslut genom att möjliggöra mer träffsäkra, riskmedvetna och kostnadseffektiva insatser för en hållbar och resilient avloppsinfrastruktur.

Nyckelord: Tillskottsvatten, Avloppssystem, Informationsvärdesanalys, Kostnads–nyttoanalys, Beslutsstöd, Osäkerhetsanalys, Känslighetsanalys, Rökning, Färgning

Contents

Preface

This Master's thesis was conducted as the final part of the Master's Programme in Infrastructure and Environmental Engineering at Chalmers University of Technology during the spring of 2025. The work has been carried out in collaboration with the Department of Sustainable Waste and Water, in Swedish: Kretslopp och Vatten (KoV), in the City of Gothenburg and contributes to an ongoing PhD research initiative within the Mistra InfraMaint programme, focused on risk-based decision support in wastewater management.

Throughout the process, we have had the privilege of working with professionals from KoV and DHI, whose insights have greatly enriched our work. We would also like to thank the staff at IRG for their contributions to the expert workshop and the representatives from Gothenburg and Kristianstad municipalities, who shared their experiences in managing I/I-water issues.

Finally, we would like to express our sincere gratitude to our supervisor, Licentiate Anna Ohlin Saletti, for her invaluable guidance, and to our examiner, Professor Lars Rosén, for his constructive feedback and support. We also thank Associate Professor Andreas Lindhe for insights in risk-modeling.

Gothenburg, May 2025
Wilma Frostberg
Sofia Moberg

Notations

CBA	Cost benefit analysis
CSO	Combined sewer overflow
FRC	Fast runoff component
GWI	Groundwater impact
I/I	Infiltration and inflow
KoV	Department of sustainable waste and water (Kretslopp och vatten
NPV	Net present value
SCC	Social cost of carbon
SDR	Social discount rate
SRC	Slow runoff component
SRCC	Spearman rank correlation coefficient
VoI	Value of information
WWTP	Wastewater Treatment Plant

1 Introduction

Population growth, climate change, and urbanization are widely recognized as key forces driving the continuous functional shift and adaptation of wastewater systems (Jia et al., 2021) (Fletcher et al., 2013). Wastewater systems, including their sewer networks, play a critical role in urban infrastructure, transporting and treating sanitary sewage to safeguard both public health and the environment (Ohlin Saletti, 2022). The driving forces, along with stricter regulations, create substantial obstacles that must be addressed to prevent suboptimal management and ensure the efficient operation of wastewater systems (Jia et al., 2021).

One significant obstacle is the issue of excess water in the pipes that is not sanitary sewage, here defined as water from infiltration and inflow (I/I-water). This issue is multidimensional and can negatively affect both the efficiency of the wastewater treatment processes and the hydraulic capacity of the system (Diogo et al., 2018). There are several I/I-water sources, with a considerable volume originating from private properties due to damaged pipes or connected stormwater pipes (Alenius et al., 2020).

As much of the vital infrastructure of wastewater systems is located underground, uncertainties surrounding rehabilitation and maintenance further complicate efforts to upgrade and optimize the system for long-term sustainability (Diogo et al., 2018). Addressing these uncertainties is crucial to ensure resilient and sustainable urban wastewater systems. However, a common ground for many municipalities in Sweden is that the work to mitigate the effects of I/I-water is neither consistent nor strategic (Alenius et al., 2020). To ensure cost-efficiency and environmental protection, it is necessary to make more informed and deliberate decisions about wastewater system management. A key aspect of this is having relevant information, which requires a careful assessment of what data should be collected and to what extent.

A possible way to evaluate available and potential information is to implement a type of cost-benefit analysis (CBA) called value of information (VoI) analysis (Zhang et al., 2021). Today, VoI analysis is not widely recognized or applied in the context of wastewater management. However, it has played a key role in civil and infrastructure engineering since 1970s regarding efficient planning of operation and maintenance (Zhang et al., 2021). The VoI model used in this thesis includes prior analysis, Bayesian updating, and preposterior analysis. Together, the three steps support the decision-making process, particularly in complex situations where uncertainty is high and new information must be incorporated.

In this thesis, a previously developed probabilistic VoI model will be applied to the issue of I/I-water in separate wastewater systems originating from private properties. The model will be tested using data from the Department of sustainable waste and water (in Swedish: Kretslopp och vatten (KoV)), a municipal department in the City of Gothenburg, to act as a tool providing a decision-making framework for mitigating I/I-water issues. The result of the VoI analysis, from an economic perspective, is a selection of the most appropriate information collection alternative. This thesis will investigate whether further investigation, such as smoke testing or dye testing, will change the decision of whether or not to implement a certain measure, or if the outcome will remain the same.

This work is directly related to an ongoing PhD research initiative focused on risk-based decision support for I/I-water in wastewater systems, part of the Mistra InfraMaint research program. By adopting a holistic perspective, the research aims to contribute to the development of more sustainable strategies for managing I/I-water and wastewater systems, identified as an urgent need in Sweden and globally. Conducted in collaboration with KoV, this master's thesis will help enhance decision-making processes and improve infrastructure resilience in wastewater management in Gothenburg.

1.1 Aim and objectives

The aim of this thesis is to support decision-makers at KoV in identifying and prioritizing subareas in Gothenburg for further investigation of private properties contributing to I/I-water in the separate wastewater system.

To achieve this, the following objectives are identified:

- Develop a consistent and reliable method for estimating the proportion of private properties contributing to I/I-water, using data provided by KoV.
- Evaluate the detection accuracy of smoke and dye testing methods.
- Apply a VoI analysis to selected subareas to determine when further investigations (e.g., smoke and/or dye testing) are economically justified.
- Provide cost-effective recommendations for action: intervention, no intervention, or further investigation.

1.2 Research questions

To be able to achieve the aim, key questions to answer are:

- How should the available data be assessed for adequate estimations of the probability that a private property in the separate system contributes with I/I-water?
- What subareas in Gothenburg would benefit from being investigated with smoke and/or dye testing?
- What subareas in Gothenburg should be prioritized for mitigation of I/I-water impact?
- How do uncertainties in the data impact the results of suggested decisions?
- What is required to apply the VoI model effectively in a municipal decision-making context?

1.3 Limitations

- The research is focused on the Gothenburg area.
- Only private properties in subareas with separated wastewater and stormwater systems are included in the study.
- The work is based on available data provided by KoV. No further flow measurements or modeling has been executed.
- In the VoI model, only benefits related to cost-reduction for treatment and pumping are considered.

2 Theory

This chapter outlines the theoretical background for analyzing water from infiltration and inflow (I/I) in wastewater systems and evaluating decision strategies using value of information (VoI). It explains the concepts and challenges of combined and separate sewer systems, with focus on Gothenburg. I/I-water from private properties in separate systems is discussed, including its sources, consequences, mitigation strategies, and common detection methods. The chapter also presents current decision-making challenges and introduces VoI analysis as the theoretical basis for assessing the value of acquiring additional information before taking action.

2.1 Wastewater systems

Wastewater systems consist of underground sewer networks that transport sewage to wastewater treatment plants (WWTPs) where it is treated (Jia et al., 2021). Typically, sewer networks include pipes, manholes, pumping stations, overflow structures, and other hydraulic installations. However, the design and function vary depending on whether they operate as a combined or separate system.

2.1.1 Combined and separate systems

Combined sewer systems were developed in the 19th century as part of the sanitary movement and the industrial revolution (Lofrano & Brown, 2010). These systems were designed to efficiently remove both sanitary sewage and stormwater using a single pipe network. As a result, they are the dominant solution in many older urban areas. While combined sewer systems simplified infrastructure planning at the time, they also introduced significant challenges, such as combined sewer overflows (CSOs) (Joseph-Duran et al., 2015). CSOs are a form of bypassing which can occur during heavy rainfall, when stormwater overwhelms the system, and untreated sewage is discharged into water bodies, causing environmental and public health risks. Consequently, the stormwater contribution in combined sewer systems is an example of I/I-water entering the sewer network.

To address the challenges of combined sewer systems, many cities have transitioned to separate sewer systems (Jia et al., 2021). This means that wastewater and stormwater are conveyed through separate pipe networks where sanitary sewage is connected to the WWTP, and stormwater is directed elsewhere. This separation mitigates the risk of bypassing and basement overflows and leads to more even flows to the WWTPs, which are easier to predict and treat more efficiently. As cities continue to modernize their wastewater infrastructure, the switch from combined systems to separate systems remains an essential strategy to mitigate pollution, improve resilience to climate change, and strengthen overall urban water management.

While separating wastewater and stormwater systems greatly reduces the amount of water entering the wastewater network, some excess water still infiltrates and flows into the sewer network even after separation due to different types of faults and damages (USEPA, 1970). Hence, even with separate systems, managing I/I-water remains critical. Problems such as separate sewer overflows, which have triggers and consequences similar to those of CSOs, can still occur (Ohlin Saletti, 2021). Furthermore, there are some cases where the separate system is not the most effective option in terms of treatment, as combined sewer systems in some cases can manage pollutants such as heavy metals, total organic carbon, and chemical oxygen demand more efficiently (Brombach et al., 2005).

Therefore, separating wastewater and stormwater does not solve all challenges alone. Additional measures, such as stormwater treatment, may be necessary. Moreover, separate systems require strategic investments in wastewater infrastructure, since both stormwater and wastewater systems must be carefully designed and maintained to handle their respective flows efficiently (Diogo et al., 2018) (Jia et al., 2021). A robust network design and efficient maintenance, including strategic investments, are needed to manage the issue of I/I-water in separate systems.

2.1.2 The wastewater system in Gothenburg

Gothenburg has a long history with a city center dating back to the 17th century. For a long time, the city lacked an organized wastewater system, which led to sanitary issues and groundwater contamination (Andersson et al., 2007). In 1866, a plan was introduced to divert wastewater directly into the Göta river to reduce pollution in the inner canals of the city. The sewer network was gradually expanded, where combined sewer pipes were the predominant solution, since installing a single pipe was more cost-effective than constructing two. From the late 1950s onward, separate sewer systems became the standard for reconstruction and new developments. However, many older areas of the city still depend on the combined system, particularly the central parts of the city and the area around Hisingen.

Today, the total length of the sewer network in Gothenburg is approximately 1,650 km, of which about 400 km consist of combined sewer systems (Kretslopp och vatten, 2024). The separation process of the systems is ongoing; however, because of the high cost, it is often economically unfeasible compared to the benefits. Consequently, separation is typically performed in conjunction with other infrastructure projects. In terms of pipe material choice, concrete has been dominant for both systems, but in recent years the use of plastic has increased significantly (Malm et al., 2011). This shift is mainly due to older concrete pipes often having leaky joints that allow substantial infiltration, making them unsuitable for wastewater systems where I/I-water mitigation is crucial. Additionally, concrete is more vulnerable to damage from ground settlement and hydrogen sulfide corrosion. At the same time, plastic materials and joints have improved, resulting in plastic pipes designed for very long service life, with better long-term sealing performance compared to older concrete joints, and strong resistance to corrosion.

KoV is responsible for the sewer network, while another company, Gryaab, is in charge of the wastewater treatment processes (Gryaab, n.d.). Gryaab owns and operates the Ryaverket WWTP, which was commissioned in 1972. The facility treats and handles wastewater not only from Gothenburg, but also from six other smaller municipalities in the Gothenburg region. The presence of I/I-water in Gothenburg has an impact with consequences across society and on the environment, resulting in increased costs for inhabitants, KoV, and Gryaab (Tanskanen et al., 2024).

2.2 Water from infiltration and inflow in private separate sewer systems

As defined previously for this thesis, I/I-water is any water entering the wastewater system that is not sanitary sewage (Sola et al., 2018). Infiltration refers to the unintended entry of water into the sewer system through cracks, pipe defects, or faulty joints, which can originate not only from groundwater but also from leaking water mains or other underground sources (USEPA, 1970). Inflow, on the other hand, describes the direct entry of larger volumes of, i.e., precipitation, snowmelt, or even industrial discharges. Both inflow and infiltration put strain on the system, but they differ in terms of their source and triggers.

2.2.1 Sources and triggers

For combined sewer systems, the proportion of I/I-water is large due to the design of the system (Weiß et al., 2002). For separate sewer systems, I/I-water is not intended to exist in the sewage pipe; however, it is still present due to faults and damages (Ohlin Saletti, 2021). A common error for the private separate sewer network is the direct connection of downpipes or yard gullies to the sewage service pipe, illustrated in Figure 2.1 (Jia et al., 2021) (Ohlin Saletti, 2021). This issue is directly related to weather fluctuations, as stormwater ends up in the network as soon as the rain begins to fall or the snow begins to melt, contributing to peak flows in the wastewater system (Alenius et al., 2020). Such faults are widespread in many cities with separate sewer systems (Jia et al., 2021).

A similar issue is faulty connected drainage systems, also portrayed in Figure 2.1. In contrast to the incorrectly connected downpipes, drainpipes often affect the system at a slower pace (Alenius et al., 2020). This occurs when foundation drains and sub-surface drainage pipes, or other groundwater management systems, are incorrectly connected to the foul sewer instead of the stormwater pipe. Unlike direct stormwater connections, these drainage systems continuously allow water to infiltrate the sewer, leading to a persistent increase in base flow. Faulty connected drainage systems have a significant correlation with the prevalence of basements (Lundblad & Backö, 2012).

Another significant issue, across the entire wastewater system, is defective pipes and joints, as illustrated in Figure 2.2 (Lundblad & Backö, 2012). These defects, such as cracks, misaligned joints, or deteriorated seals, can allow water to enter the wastewater system in two different ways; in-leakage and cross-leakage. In-leakage typically involves groundwater or other external water sources infiltrating the sewer system, often resulting in a slow but persistent increase in flow. In areas with high groundwater levels, in-leakage can lead to substantial infiltration, placing a heavy burden on the sewer system. Furthermore, cross-leakage refers to water entering the sewer network from adjacent pipes, such as stormwater or drinking water pipes. It can result in both slow and fast flow increase, depending on the magnitude of the defects. This is a common error since stormwater and drinking water pipes are positioned above wastewater pipes; if both systems are damaged, water can intrude downward into the wastewater network.

The prevalence and magnitude of the I/I-water issue depends on various factors. In addition to the presence of basements, factors such as soil material, hydrogeology, pipe materials, and the age and depth of the wastewater pipes also have an impact (Lundblad & Backö, 2012). To be able to make fully accurate estimations, thorough measurements are required.

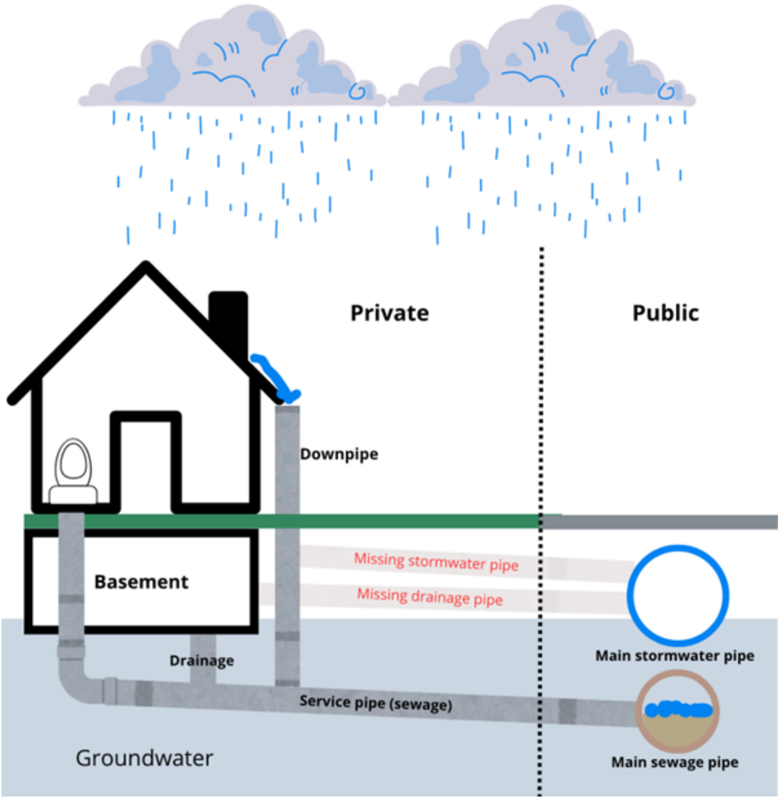

Figure 2.1: Incorrect downpipe and drainage connections in a separate sewer system.

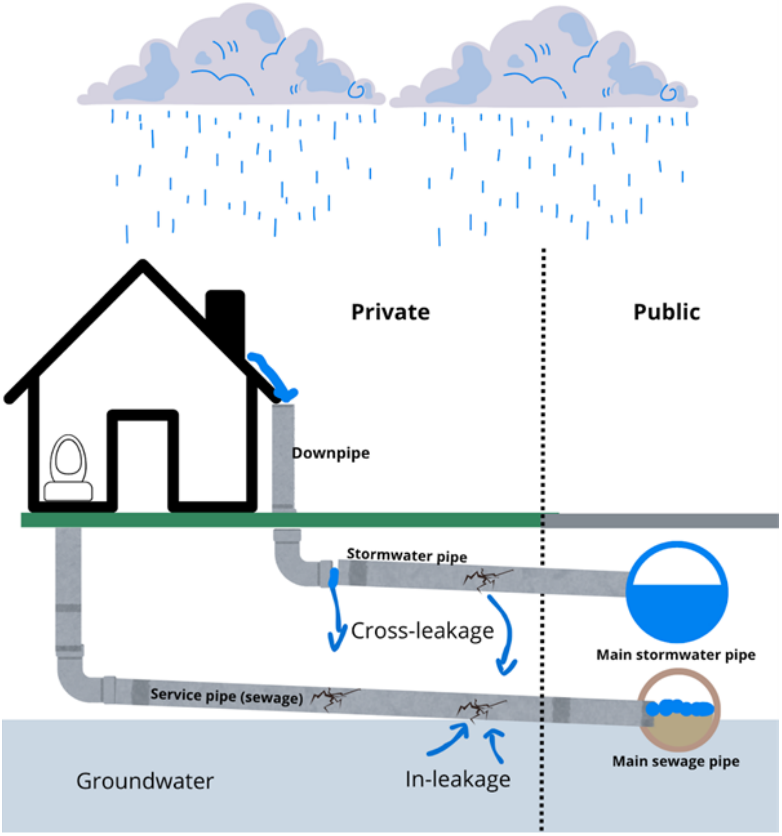

Figure 2.2: Cross- and in-leakage due to defect pipes and joints in a separate sewer system.

2.2.2 Consequences

The consequences of I/I-water vary over time and space (Ohlin Saletti, 2021). For example, increased rainfall during certain seasons, as stated above, as well as regions with aging or deteriorating infrastructure, can lead to higher loading. The types of consequences are similar for both separate and combined systems, as well as within municipal and private networks; only the severity or magnitude differs depending on the specific context.

I/I-water significantly compromises the efficiency of the wastewater system by overloading pump stations and WWTPs, leading to increased energy consumption, higher maintenance demands, and ultimately rising operational costs (Sola et al., 2018). Since both pumping and treatment require substantial energy input, I/I-water contributes to the overall climate impact of wastewater management. Furthermore, the dilution effect of I/I-water reduces pollutant concentrations (Ohlin Saletti, 2021), making biological and chemical treatment processes less efficient. This inefficiency requires increased chemical dosing, additional aeration, and prolonged retention times, driving up the costs, resource use and emissions associated with chemical production and transport.

In the long term, persistent I/I-water can force municipalities to expand the capacity of WWTPs to handle peak flows, requiring costly investments in land acquisition, infrastructure expansion, and new treatment technologies (Ohlin Saletti, 2021). In addition, infiltration accelerates the deterioration of the pipes, leading to higher repair and replacement costs. Consequently, I/I-water not only imposes an immediate economic burden but also has long-term sustainability implications and contribute to a higher climate impact and greater financial strain on wastewater utilities and society.

2.2.3 Mitigation strategies

To mitigate I/I-water originating from private properties, certain corrective measures are typically required at the property level. There are two main strategies available: rehabilitating the sewer infrastructure or redirecting incorrectly connected flows (Ohlin Saletti, 2021).

Rehabilitation on private properties involves repairing, renovating, or replacing damaged sewer pipes to restore their structural integrity and function. This can include measures such as chemical grouting to seal cracks, applying coatings or relining to reinforce pipe walls, or complete pipe replacement. Among these, replacement is the most common approach on private land, as property owners often opt for excavation and substitution of old pipes, especially when access allows and the existing infrastructure is in poor condition.

Alternatively, redirection focuses on eliminating I/I-water caused by incorrect connections. This often involves disconnecting roof downpipes, yard gullies, or foundation drainage systems that have been mistakenly connected to the wastewater pipe instead of the stormwater system. This type of mitigation is particularly relevant in areas with high rainfall or elevated groundwater levels, where such misconfigurations can significantly contribute to peak flows.

It is the legal responsibility of the property owner to implement corrective measures on their own land when informed. The choice of mitigation strategy depends on the type and extent of the problem. Municipalities may identify faults and issue notices, but actual execution is borne by the property owner. The public sewer network is only owned and maintained by the municipality up to the boundary of the property (Sveriges riksdag, n.d.).

2.2.4 Detection methods

There are several methods for identifying, tracking, and quantifying I/I-water in general (Ohlin Saletti, 2021). When it comes to detecting I/I-water sources in private properties in Sweden (Lundblad & Backö, 2012), the conventional detection methods include:

- Smoke testing
- Dye testing
- Filming

These qualitative methods are illustrated in Figure 2.3, Figure 2.4, and Figure 2.5. The capacity and performance vary depending on the chosen method (Lundblad & Backö, 2012). Smoke testing can cover 15 properties per day, dye testing can be performed on 10–15 properties per day, and filming can inspect up to five properties per day (typically in combination with dye flushing). Filming is the most costly method, while smoke and dye testing are more affordable (Beheshti et al., 2015). Smoke and dye testing can identify problematic properties, whereas filming can confirm the presence of faults, determine their exact nature, and accurately locate them (Ohlin Saletti et al., 2025).

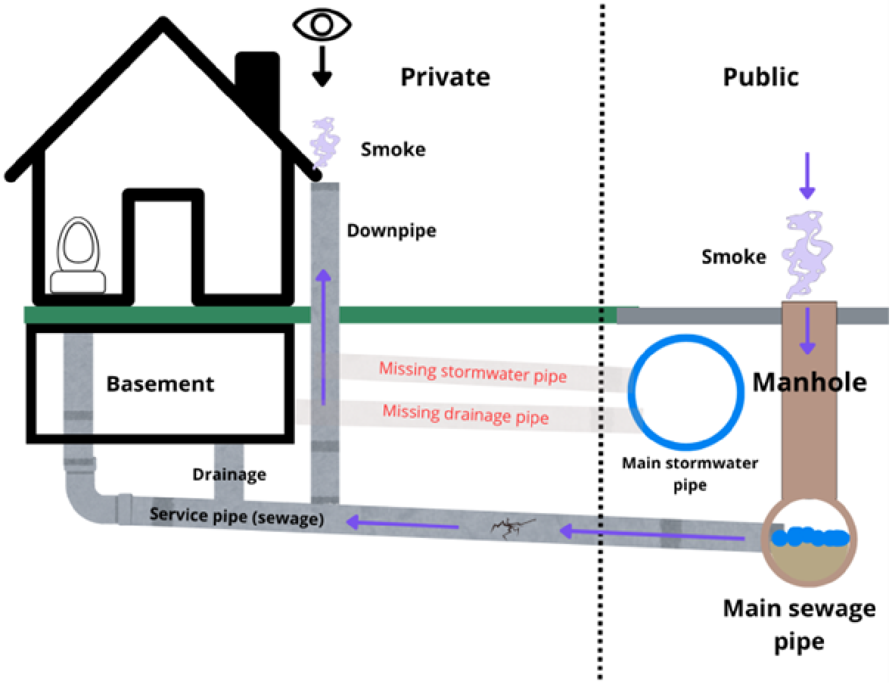

Figure 2.3: Schematic presentation of the concept of locating, identifying, and tracing I/I-water sources using smoke testing in a separate sewer system.

The smoke testing procedure involves pumping in non-toxic smoke into the sewer system through a manhole, and then observe where it escapes (Beheshti et al., 2015), as illustrated Figure 2.3. In best case, it can identify unintended openings, leaks, and faulty connections (Lundblad & Backö, 2012). Normally, smoke should escape through the roof vent of the sewer system, indicating a proper connection between the foul sewer and the manhole. If smoke escapes through stormwater system components, such as roof drain connections, this indicates a faulty connection. In theory, other I/I-water sources can be identified if the smoke escapes in unintended locations. Compared to filming, smoke testing cannot precisely locate the I/I-water source; it can only indicate a potential origin. Additionally, smoke testing may sometimes require additional investigation due to uncertainties.

When performing dye testing, a fluorescent, non-toxic dye is introduced into the stormwater system, often through a roof drain connection (Lundblad & Backö, 2012), as illustrated in Figure 2.4. The inspection is conducted visually by observing a manhole to determine whether the dye has entered the sewer system. This method allows for tracing faulty connections but does not enable precise localization of the I/I-water source (Beheshti et al., 2015). Compared to smoke testing, dye testing is typically carried out on one sewage service pipe at a time, whereas smoke testing can be applied simultaneously to service pipes connected to a given manhole.

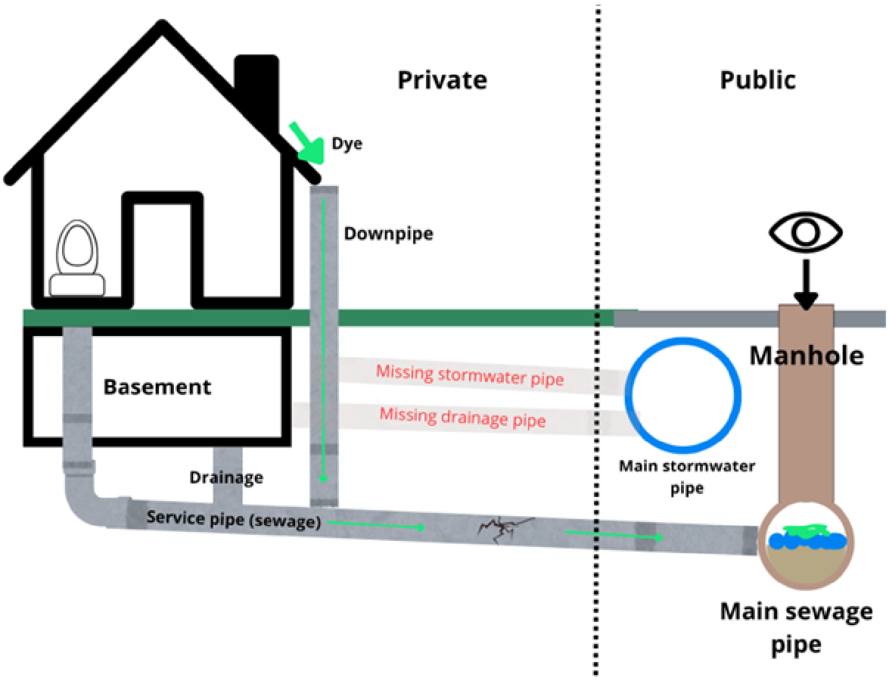

Figure 2.4: Schematic presentation of the concept of locating, identifying, and tracing I/I-water sources using dye testing in a separate sewer system.

Filming, or film inspection, is used to assess pipe conditions, detect cracks and leaks, and locate faulty connections (Lundblad & Backö, 2012). The method involves inserting a camera directly into the pipe to visually inspect its condition, as shown in Figure 2.5. Film inspection is typically performed before selecting mitigation strategy, as understanding the I/I-water source and the severity of the issue is essential for choosing an appropriate measure (Beheshti et al., 2015). While filming can be conducted independently to evaluate the condition of the pipe, it is often combined with dye to trace the I/I-water source. The same fluorescent, non-toxic dye as described earlier is used, but with a camera inside the service pipe. The presence of the camera can help pinpoint the exact location of the fault.

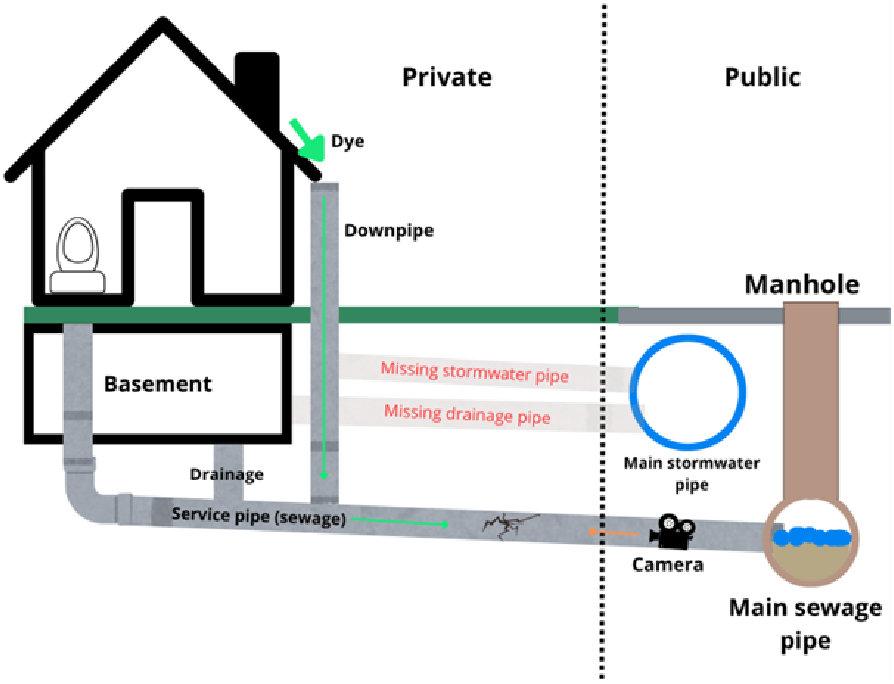

Figure 2.5: Schematic presentation of the concept of locating, identifying, and tracing I/I-water sources using film inspection in a separate sewer system.

Investing in these detection methods and systematically addressing I/I-water sources through targeted efforts has been a growing priority for wastewater infrastructure management in recent decades (Diogo et al., 2018). However, the cost and accuracy of these methods differ considerably. Given that the wastewater infrastructure system is public and complex with some private networks, a comprehensive and holistic approach including technical, environmental, social, and economic aspects are needed in the decision-making process, which can be described as a "multi-objective optimization problem".

2.3 Decision-making in infiltration and inflow water management

A study has shown that many water utilities in Sweden make decisions regarding I/I-water issues at random, where the implemented measures are not always the most effective way to address the problem (Alenius et al., 2020). One reason for this is that one of the most common key indicator of how much I/I-water that is present in a municipality, "share of I/I-water", is insufficient, as it is heavily dependent on the number and magnitude of rain events, which varies from year to year. The share of I/I-water is often presented on a yearly basis, which makes it difficult to identify the source of the I/I-water, and hence track results of implemented measures. Instead, other key factors are better suited for analysing the origin of I/I-water.

2.3.1 Contributing areas

One suggested approach is to use "contributing areas" to analyse the I/I-water levels, where three components are identified: fast response component (FRC), slow response component (SRC), and groundwater impact (GWI) (Alenius et al., 2020).

- FRC addresses the impact that occurs almost immediately after the rain begins and stops after the time corresponding to the duration of runoff within the area once the rain has stopped. This component causes short-term but intense flow peaks.
- SRC addresses the increased flow over the first three days following a rainfall event.
- GWI does not show a clear direct change in flow magnitude during individual rainfall events but gradually increases during wet periods.

When dividing each component with the total I/I-water volume, a contributing area is received, which is independent of annual rainfall variations (Alenius et al., 2020). In the other way around; when the contributing area is multiplied with the precipitation, the volume of I/I-water is obtained. By relating contributing areas to system parameters such as service area, pipe length, and population equivalents, key performance indicators can be calculated to provide a better understanding of the problem of I/I-water. These provide information on which type of issue is most common in a specific area, and they can be calculated after a measure has been implemented, unlike the share of I/I-water, which historically been the conventional method.

2.3.2 Infiltration and inflow modeling in Gothenburg

An important decision-support system at KoV is the software Future city flow (FCF). FCF integrates real-time data, hydrological modeling, and predictive analytics to simulate different scenarios. FCF uses contributing areas, where GWI is incorporated in SRC. The current data set that FCF is based on is developed by KoV and DHI in collaboration. This data set categorizes Gothenburg into four larger areas; north, east, west, and central. These areas are then divided into 258 subareas that vary in population and area-size, where 97 of them have a separate system running to a significant degree. Each subarea is presented with a number of attributes, including total area, number of properties, FRC and SRC area, and proportions of separate and combined system, respectively.

The contributing areas are calibrated from a relatively small number of measurements around the city. Furthermore, the estimated number of incorrectly connected drainage systems is listed, with the general assumption that 30% of all properties have incorrectly connected drainages. In Gothenburg, the total number of properties that contribute to I/I-water is unknown, and the current estimations have a general perspective where local variations are not taken into account. An extraction of the data set, with anonymized areas, can be seen in Figure 8.1 in Appendix A.

The existing data of the contributing areas are theoretically useful, and of significant value in this thesis. However, it needs to be noted that there are complications with using contributing areas in practice. Altimiras Granel (2023) at KoV investigated the use of contributing areas for FCF and found that practical application is hindered by data quality issues, natural variability, and the specific characteristics of the system. It is stated that meaningful results depend on long-term data collection and thorough validation, however "there are currently shortcomings in the availability of high-quality rainfall data in Gothenburg". Contributing areas in FCF can be a useful analytical tool and part of the decision-making basis, but they require complementary analyses and professional interpretation to be effectively used in decision-making.

2.4 Value of information analysis

A VoI analysis is a specialized type of cost-benefit analysis (CBA), which is a support tool for decision-making (Zhang et al., 2021). CBA is used to evaluate whether a certain decision is worth implementing by comparing the associated benefits and costs (Mishan & Quah, n.d.). A key principle is that it is conducted from a societal perspective, where the costs and benefits for both the project owner and the society as a whole should be included to the greatest extent possible. Like a traditional CBA, a VoI analysis compares expected benefits and costs. However, instead of assessing the value of implementing a specific action, it assesses the value of acquiring information to reduce uncertainty and improve the quality of the decision (Fenwick et al., 2020).

A fundamental part of the CBA involves calculating the net present value (NPV), given by Equation 2.1, where B_t and C_t denote the benefits and costs that occur at time t, and SDR is the social discount rate (Mishan & Quah, n.d.). A positive NPV indicates that the benefits of a decision outweigh its costs, justifying its implementation from a societal perspective.

CBA is a flexible framework that can be tailored to specific decision-making contexts (Mishan & Quah, n.d.). In the context of the VoI analysis conducted in this thesis, a risk term, $P_f C_f$, is introduced, with P_f being the probability of failure and C_f the cost incurred if failure occurs. By isolating the risk component, the model more transparently illustrates how uncertainty impacts decision-making and how VoI analysis can reduce expected losses through improved information.

$$\text{NPV} = \sum_{t=0}^{T} \frac{B_t - C_t - P_f C_f}{(1 + SDR)^t} \tag{2.1}$$

Furthermore, the focus in this thesis lies solely on cost reduction. This simplification does not imply that benefits are ignored entirely. Rather, it reflects the analytical choice to keep them constant between options. In doing so, differences in NPV can be attributed solely to differences in cost. This method remains consistent with the comparative logic of CBA. It should be noted that referring to this result as NPV might seem misleading, as it does not involve the traditional subtraction of costs from benefits, as presented above.

The concept of a VoI analysis is based on Bayesian decision theory (Zhang et al., 2021). It uses probabilities to represent uncertainty, and compares the most optimal decision before and after assumed collection of additional relevant information, but before the information is actually collected. The VoI is determined by the difference in the expected outcomes. The VoI determines whether existing data are sufficient to make an informed decision or if investing time and money in gathering more information would be more beneficial (Fenwick et al., 2020). As emphasized by Zetterlund et al. (2015), the core principle of VoI analysis is to "assess the economic value of an investigation before the investigation has actually taken place". In other words, it forecasts the economic justification of gathering extra information, providing decision-makers with more knowledge. Since collecting information implies costs, there is a limit to how much is needed, excessive data collection may be unnecessary and result in wasted resources.

The VoI analysis can be categorized into three different steps: prior analysis, Bayesian updating, and preposterior analysis. A prior analysis assesses a situation before new data collection (Freeze et al., 1992). It evaluates different options based on current knowledge, using CBA. This approach helps identify the most advantageous strategy when decisions must be made before further investigations. Bayes' theorem (Equation 2.2), or Bayesian updating, refines the probabilities, transitioning from prior to preposterior estimates (C.F Wilson, 2015) (Zhang et al., 2021). A preposterior analysis assesses the value of planned or potential data collection before it occurs, estimating how much uncertainty can be reduced (Freeze et al., 1992). It helps determine whether the benefits of data collection justify the cost.

$$P(A \mid B) = \frac{P(B \mid A)P(A)}{P(B)} \tag{2.2}$$

It is important to note that the Bayesian updating is not used to update probabilities to a posterior distribution based on newly collected data. Instead, it is used to estimate a preposterior distribution, updating prior information with the estimations of the expected reliability and usefulness of future data, before the data have been collected. The Bayesian updating is fundamentally the same as prior decision analysis, except that it improves the probabilistic modeling of uncertainty (Zhang et al., 2021). In this thesis, $P(A)$ represents the probability of failure, and $P(B)$ is the probability of detection.

3 Value of Information Model

This chapter details the risk-based value of information (VoI) model utilized in this thesis, which has been developed and refined as part of an ongoing PhD project focusing on risk management related to infiltration and inflow (I/I) (Ohlin Saletti et al., 2025). The model serves as a decision-support tool, prioritizing cost-efficiency to identify subareas where collecting additional information (such as smoke or dye testing) is economically justified before potentially implementing measures. It does not explicitly incorporate direct benefits of reduced I/I-water volumes (such as avoided basement flooding or overflows), but rather reflects these indirectly through cost reductions achieved by making the most cost-efficient decision alternative. The primary focus remains on minimizing overall societal costs and resources while effectively managing the risks and impacts of I/I-water.

The VoI analysis follows a structured approach comprising three main phases: prior analysis, preposterior analysis (which incorporates Bayesian updating), and decision support. This process allows for the evaluation of different decision alternatives under uncertainty and determines the potential value of reducing that uncertainty through further investigation, see Figure 3.1. The subsequent sections of this chapter outline the model structure, parameters, and cost components, describe the underlying cost-benefit analysis (CBA) framework, and explain each phase of the VoI analysis. The application of this model to the specific Gothenburg case study, along with the data assessment methods, is presented in section 4.2.

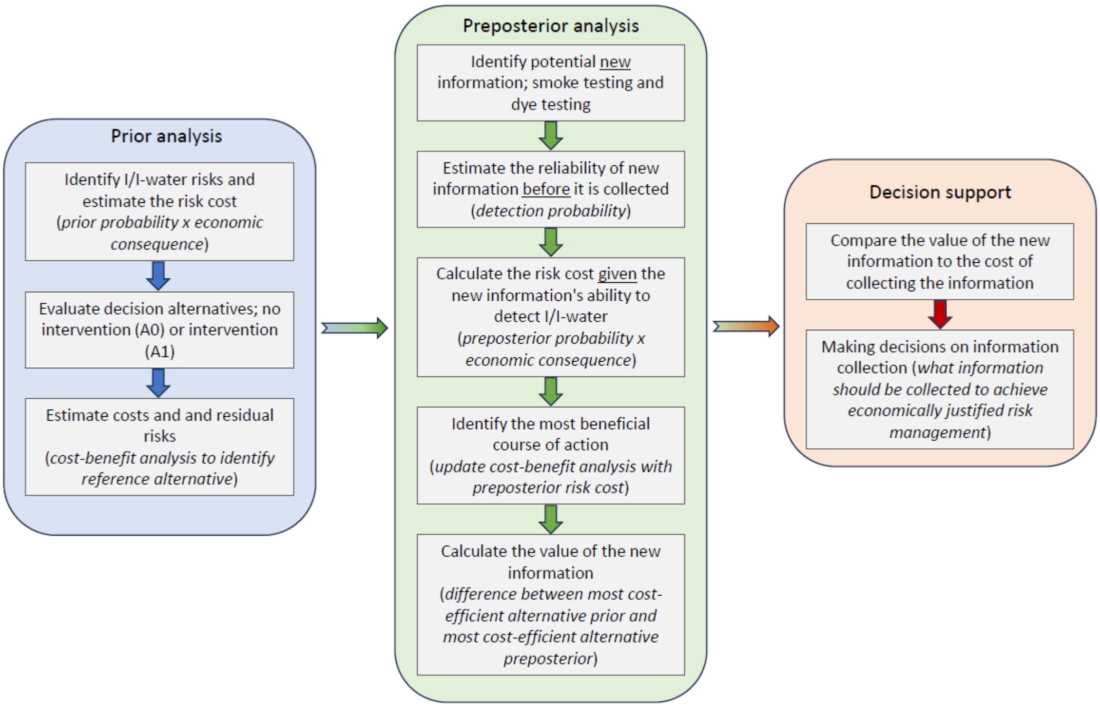

Figure 3.1: Overview of the value of information analysis process.

The decision alternatives used in this thesis are defined below. The costs associated with different decision alternatives vary depending on the information available, distinguishing between prior and preposterior analyses. In this context, intervention refers to implementing a corrective measure for mitigating the I/I-water impact on a private property, often conducted in combination with film inspection to locate the failure. Although multiple mitigation strategies, including different types of measures as outlined in subsection 2.2.3, could theoretically be applied in the VoI analysis, this thesis limits itself to one (A1).

- A0: A scenario in which no intervention is made to mitigate the impact of I/I-water from a private property.
- A1: A scenario in which an intervention, specifically, film inspection and a selected rehabilitation measure, is made to mitigate the impact of I/I-water from a private property.
- Further investigation: A scenario where further investigation using additional detection methods, including smoke and/or dye testing is recommended.

3.1 Model parameters and cost components

Several parameters are assessed in the model, categorized as either direct inputs or derived components, see Table 3.1. The cost of I/I-water per property forms the foundation for evaluating decision alternatives within the VoI analysis, encompassing prior analysis, Bayesian updating, and preposterior analysis. Another fundamental parameter is the share of properties with I/I-water, denoted as $P(F)$, which represents the probability that a randomly selected private property within the separate system has I/I-water impact. This parameter is defined for each subarea under consideration. See the Methodology section for further details on data assessment.

Table 3.1: Model parameters and cost items.

Parameter	**Description**
$r_{\text{flow}}(t)$	Flow parameter accounting for projected increases in precipitation over the next 100 years
$P(\text{film det.})$	Probability of I/I-water detection using filming method
C_{film}	Cost of film inspection (SEK/property)
C_{measure}	Cost of rehabilitation measure (SEK/property)
T_{horizon}	Time horizon (yr)
C_{WWTP}	Total cost for the WWTP handling I/I-water volume (SEK/m^3)
V_{property}	I/I-water volume per property (m^3/yr)
$C_{\text{I/I-water}}$	Cost of I/I-water per property (SEK/yr)
$P(F)$	Probability that a private property in the separate system has I/I-water impact
r_{change}	Change rate of property owners
C_{property}	Cost per property (SEK)
C_{prior,A_0}	Cost for no intervention (prior analysis) (SEK/property)
C_{prior,A_1}	Cost for intervention (prior analysis) (SEK/property)
$C^{\text{det.}}_{\text{prepost},A_0}$	Cost for no intervention (preposterior analysis, detection) (SEK/property)
$C^{\text{det.}}_{\text{prepost},A_1}$	Cost for intervention (preposterior analysis, detection) (SEK/property)
$C^{\text{no det.}}_{\text{prepost},A_0}$	Cost for no intervention (preposterior analysis, no detection) (SEK/property)
$C^{\text{no det.}}_{\text{prepost},A_1}$	Cost for intervention (preposterior analysis, no detection) (SEK/property)

A change rate, denoted as r_{change}, is incorporated into the calculation of intervention costs for decision alternative A1. This rate reflects the likelihood that private property owners will address I/I-water issues once identified. A low change rate presents a significant challenge to fully mitigating I/I-water because it indicates that even when problems are detected, many property owners may not take corrective action to fix them, thus limiting the effectiveness of any broader mitigation strategy. Hence, r_{change} serves as a bottleneck.

Since the VoI analysis in this thesis is a socio-economic analysis, the model does not differentiate between who the payer is, whether the municipality or the property owner, because, in theory, the cost is borne by society as a whole. However, these costs are directly influenced by property owners, as they are legally responsible for maintaining the network. Equation 3.1 accounts for the potential remaining I/I-water impact from and/or direct measure costs of the properties. These costs are linked to the r_{change}, identified above. If no measures are taken, the change rate remains at 0%, meaning the cost of I/I-water impact remains unchanged, and no measure costs are incurred.

$$C_{\text{property}} = C_{\text{measure}} \cdot r_{\text{change}} + (1 - r_{\text{change}}) \cdot C_{\text{I/I-water}} \tag{3.1}$$

3.2 Cost-benefit analysis

To calculate the cost of each decision alternative, the total cost for the wastewater system related to volume-based expenses is determined. These costs include energy costs, as well as costs for treatment, pumping, and investment. See Table 3.2 for all input parameters. The investment costs are linked to a fraction for the fast runoff component (FRC), which represents the proportion of water that exerts pressure on the WWTP during overloading or other operational challenges related to I/I-water.

A social cost of carbon (SCC) is related to the climate cost of pumping and treatment, with different weights assigned to assess the societal importance of carbon dioxide equivalents (CO_2-eqs). The SCC does not have a fixed value, as its assessment is influenced by climate sensitivity and future factors such as emission outlooks and ethical considerations in valuing consequences (Isacs et al., 2016). Serving as a key tool in evaluating climate change impact, SCC provides a monetary estimate of the long-term damage resulting from each additional ton of CO_2 emissions into the atmosphere.

The total volume cost is calculated based on three different scenarios for different values of SCC, representing different multiples of the cost of CO_2-eqs in $SEK/kg \cdot CO_2 - eq$. The model applies SCC values of 1, 4, and 7. See Equation 3.2 for the summarized volume costs for the wastewater system. This approach of using different weighting values acknowledges the inherent uncertainties and varying ethical perspectives associated with the SCC valuation.

Table 3.2: Input parameters for the CBA regarding WWTP volume-based costs.

Input Parameter	**Description**
T_{direct} (SEK/m^3)	Direct treatment cost per m^3
T_{climate} (kg $\cdot$ CO_2-eq/m^3)	CO_2 emissions from treatment
P_{energy} (kWh/m^3)	Energy use for pumping per m^3
P_{cost} (SEK/kWh)	Cost per kWh of pumping
E_{CO2} (CO_2-eq/kWh)	CO_2 emissions per kWh
I_{FRC} (SEK/m^3)	Investment for WWTP (FRC) per m^3
I_{SRC} (SEK/m^3)	Investment for WWTP (SRC) per m^3
F_{FRC} (%)	Fraction of FRC in WWTP

$$C^{\text{SCC}}_{\text{volume}} = T_{\text{direct}} + P_{\text{energy}} \cdot P_{\text{cost}} + SCC \cdot (T_{\text{climate}} + (P_{\text{energy}} \cdot E_{\text{CO2}})) + F_{\text{FRC}} \cdot I_{\text{FRC}} + (1 - F_{\text{FRC}}) \cdot I_{\text{SRC}} \tag{3.2}$$

NPVs are calculated for each year, incorporating different SDRs, see Equation 3.3. The NPV includes a flow parameter $r_{\text{flow}}(t)$ that accounts for projected increases in flow over the next 100 years. This parameter is integrated as a multiple to ensure that future flow variations are properly addressed. The NPVs are then summed over the chosen time period to assess the overall economic impact, see Equation 3.4. To calculate the cost of I/I-water per property, the total cost of handling the I/I-water load ($\sum$ NPV) is multiplied by the volume per property. The methodology chapter provides a detailed breakdown of the calculation and data assessment, including how subareas, precipitation levels, and fast and slow runoff coefficients (FRC and SRC) influence the volume per property.

$$\text{NPV}(t) = \frac{C^{\text{SCC}}_{\text{volume}} \cdot r_{\text{flow}}(t)}{(1 + SDR)^t} \tag{3.3}$$

$$\sum(\text{NPV}) = \sum_{t=0}^{T_{\text{horizon}}} \text{NPV}(t) \tag{3.4}$$

$$C_{\text{I/I-water}} = V_{\text{property}} \cdot \sum(\text{NPV}) \tag{3.5}$$

3.3 Prior analysis

In the prior analysis, existing knowledge in form of prior beliefs is evaluated regarding the choice between intervention and no intervention. Figure 3.2 illustrates the concept of the prior analysis. The cost of A0 in this analysis is calculated by multiplying the probability that a property has I/I-water impact with the cost of having it, see Equation 3.6. No change rate is applied here since no action is taken.

$$C_{\text{prior},A_0} = C_{\text{I/I-water}} \cdot P(F) \tag{3.6}$$

For A1, the cost includes the intervention cost of filming, the accuracy of the intervention strategy expressed as a risk cost of still having I/I-water impact, and the cost incurred by property owners, see Equation 3.7. The latter includes the r_{change} as explained above. Property-related costs are further tied to the probability of film detected I/I-water impact. Finally, a cost comparison between A0 and A1 is conducted to determine the reference alternative, the scenario with the lowest total cost.

$$C_{\text{prior},A_1} = C_{\text{film}} + (1 - P(\text{film det.})) \cdot P(F) \cdot C_{\text{I/I-water}} + C_{\text{property}} \cdot P(F) \cdot P(\text{film det.}) \tag{3.7}$$

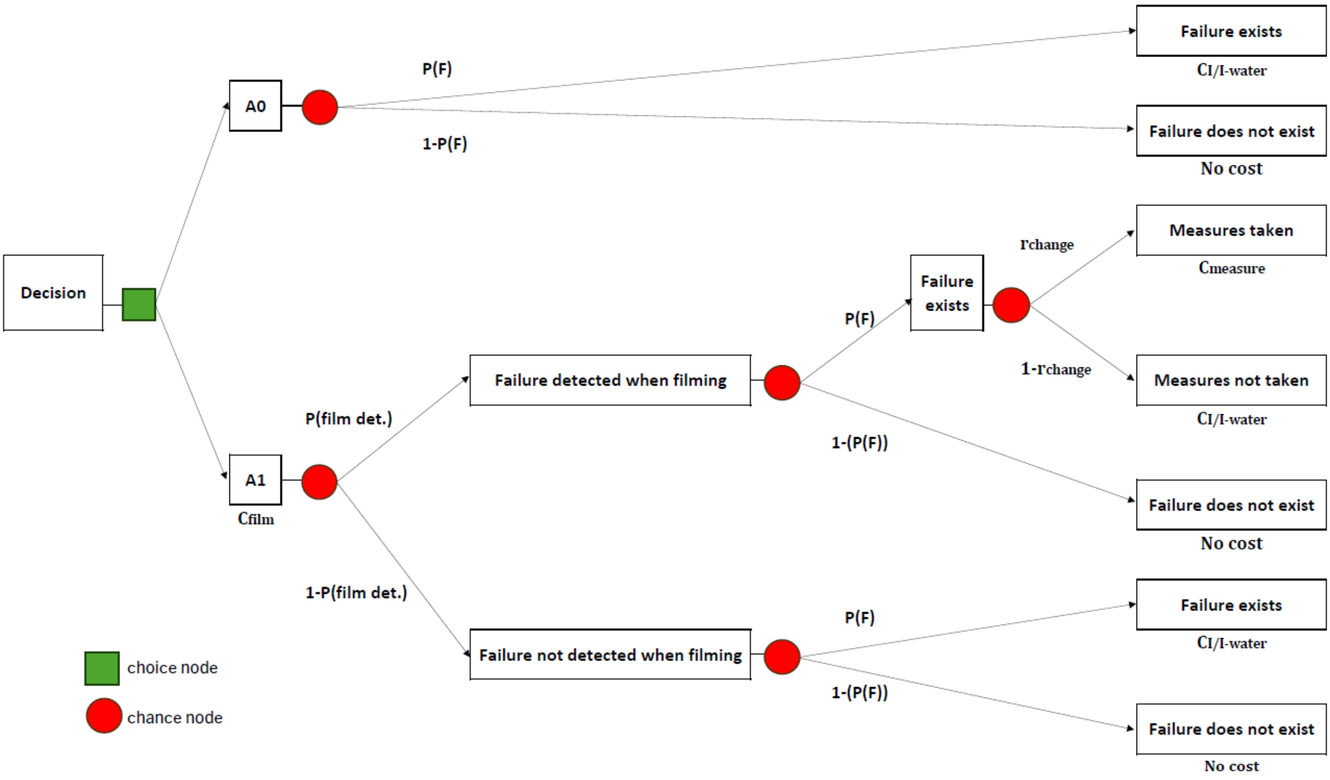

Figure 3.2: Decision-tree for prior analysis in I/I-water management.

3.4 Bayesian updating

To perform Bayesian updating and apply it in the preposterior analysis, the relevant probabilities are assessed and incorporated into Bayes' Theorem. Bayesian updating is used to refine probability estimates as additional information from the inspection methods is used, thereby improving the reliability of detection rates, see Figure 3.3. The probabilities assessed in Bayes' Theorem are related to the additional investigation methods, specifically, smoke testing and dye testing.

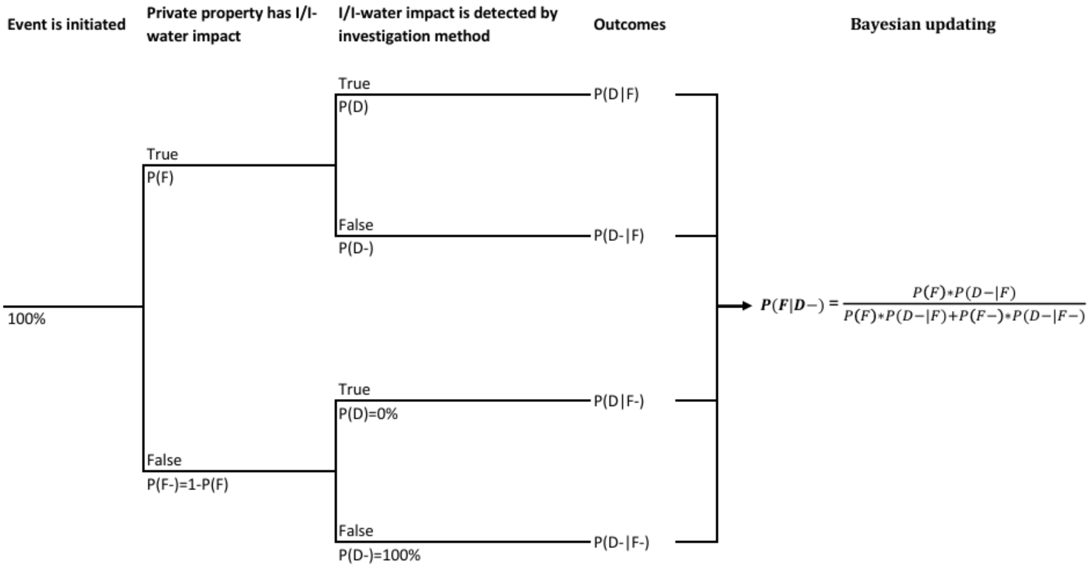

Figure 3.3: Event-tree for investigation methods and Bayesian updating concept.

In this context, failure refers to any kind of I/I-water impact, while detected and detection pertain to the accuracy of the smoke and dye testing in identifying failures, respectively. These probabilities are prior probabilities, meaning they are based on current knowledge. Note that it is assumed that false positive or false negative is not happening for both $P(D \mid F^{-})$ and $P(D^{-} \mid F^{-})$, as they are assumed to be 0% and 100%, respectively. The probabilities are defined as follows:

- $P(D)$: Probability of detection.
- $P(D^{-})$: Probability of no detection.
- $P(D \mid F)$: Probability that a failure is detected given that a failure exists.
- $P(D^{-} \mid F)$: Probability that a failure is not detected given that a failure exists.
- $P(D \mid F^{-})$: Probability that a failure is detected given that no failure exists.
- $P(D^{-} \mid F^{-})$: Probability that a failure is not detected given that no failure exists.

Based on these probabilities and the outcome of Bayes' Theorem, the probability that a failure has occurred given that it was not detected, $P(F \mid D^{-})$, is estimated (see Equation 3.8). This probability is subsequently used in the preposterior analysis.

$$P(F \mid D^{-}) = \frac{P(F) \cdot P(D^{-} \mid F)}{P(F) \cdot P(D^{-} \mid F) + (1 - P(F)) \cdot P(D^{-} \mid F^{-})} \tag{3.8}$$

3.5 Preposterior analysis

A preposterior analysis is performed to determine whether additional data collection efforts, such as smoke testing or dye testing, will significantly impact the decision-making process. This analysis helps assess whether gathering further information is economically justified before the actual investigation method is conducted. See Figure 3.4 for a schematic illustration of this analysis. As in the prior analysis, the A0 and A1 decision alternatives are evaluated, and costs are assigned to them accordingly. However, in the preposterior analysis, four contexts are considered instead of two, as the analysis accounts for the condition of either detection or no detection of failure.

The A0 cost given detection in the preposterior analysis is the cost of I/I-water per property since it is in fact detected, see Equation 3.9. Since we know that the failure is detected, no risk is associated to the costs in this step. Accordingly, the A1 cost given detection is calculated by summarizing the intervention cost of filming and the cost per property, see Equation 3.10. The outcome is dependent on the change rate of the property owners. Compared to the prior analysis calculations of A1, there is no remaining potential impact cost of I/I-water or probability of I/I-water detection (now 100%), since it is conditioned that the failure is found.

$$C^{\text{det.}}_{\text{prepost.},A_0} = C_{\text{I/I-water}} \tag{3.9}$$

$$C^{\text{det.}}_{\text{prepost.},A_1} = C_{\text{film}} + C_{\text{property}} \tag{3.10}$$

The expected costs related to no detection in the model are influenced by the Bayesian updated probability, $P(F \mid D^{-})$, which serves as an uncertainty parameter dependent

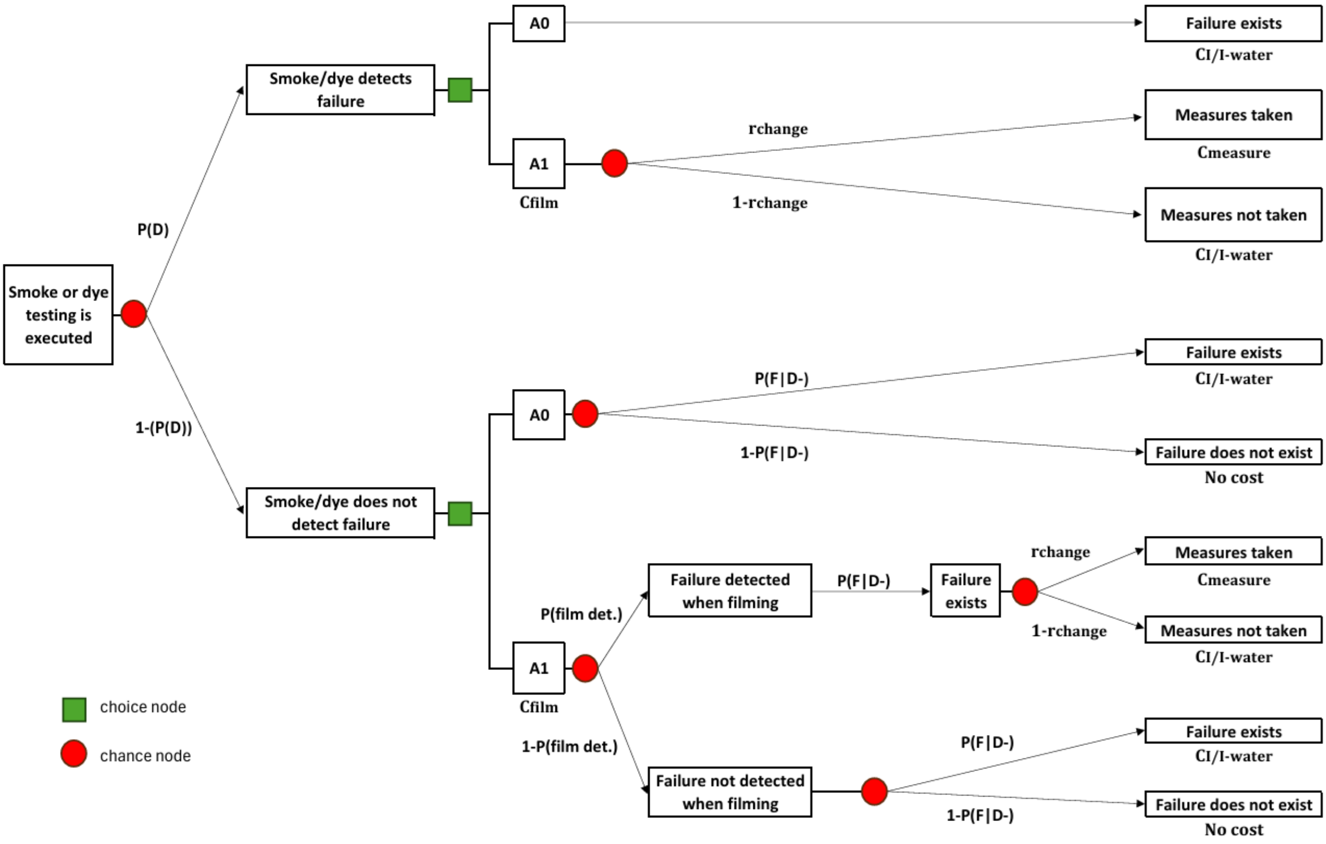

Figure 3.4: Decision-tree for preposterior analysis in I/I-water management.

on the accuracy of the detection methods. The A0 cost given no detection in the preposterior analysis is determined using this probability along with the cost of I/I-water per property, see Equation 3.11. The A1 cost given no detection is the sum of the intervention cost of filming, the accuracy of the intervention strategy, including filming and smoke or dye testing, expressed as a risk cost of still having I/I-water impact, and the cost incurred by property owners, see Equation 3.12. In addition to $P(F \mid D^-)$, the latter cost is also influenced by the probability of film detected I/I-water impact as in the prior analysis.

$$C^{\text{no det.}}_{\text{prepost.},A_0} = P(F \mid D^-) \cdot C_{\text{I/I-water}} \tag{3.11}$$

$$C^{\text{no det.}}_{\text{prepost.},A_1} = C_{\text{film}} + (1 - P(\text{film det.})) \cdot P(F \mid D^-) \cdot C_{\text{I/I-water}} + P(F \mid D^-) \cdot P(\text{film det.}) \cdot C_{\text{property}} \tag{3.12}$$

Given the different costs associated with A0 and A1 under both detection and no detection conditions, the decision alternative is chosen based on the scenario with the lowest cost, as in the prior analysis. Consequently, two decision alternatives are proposed. However, in the preposterior analysis, a weighted value is assigned, incorporating the two most cost-efficient alternatives for detection and no detection. This weighting considers the probabilities $P(D)$ and $P(D^-)$, see Equation 3.13 and Equation 3.14. This weighted value represents the total cost of additional investigation and is the key metric used when calculating and assessing the VoI.

$$P(D) = P(F) \cdot P(D \mid F) + P(F) \cdot P(D \mid F^{-}) \tag{3.13}$$

$$P(D^{-}) = 1 - P(D) \tag{3.14}$$

3.6 Value of information and decision-making

The VoI analysis evaluates the benefit of acquiring additional information by comparing the best possible decision before potential collection of new data (in the prior analysis), here called reference alternative, to the weighted expected value after the potential collection of new data (in the preposterior analysis). If the decision alternative stays the same (A0 or A1), the VoI is zero. If the decision alternative changes in the preposterior analysis (e.g., from A0 to A1), the VoI is quantified by how much higher the expected value becomes by comparing the weighted value of preposterior decision alternatives to the reference alternative cost in the prior analysis. The final result tells us whether the additional information adds a positive value and, if so, how much it improves decision-making.

To provide decision support, the quantified VoI value is compared to the cost of the investigation, specifically, the cost of smoke testing and dye testing, respectively. If the VoI value is greater than the cost of the chosen investigation method, then it is worth it to execute the investigation prior to potentially fixing the problem. If the VoI does not exceed the investigation method cost, the decision alternative stays the same as the reference alternative from the prior analysis. The decision result recommendation is based on whether the updated information changes the assessment enough to cross a predefined threshold of the investigation cost.

4 Method

This chapter describes the methodological approach, which is portrayed in Figure 4.1. To answer the research questions, a mixed-methods research design with both quantitative and qualitative elements was required. The qualitative component involved expert assessments through interviews and workshops, and the quantitative component included processing existing data. Also, the application of the model and the evaluation of the results included quantitative elements, where probabilistic analyses and Monte Carlo simulations were incorporated.

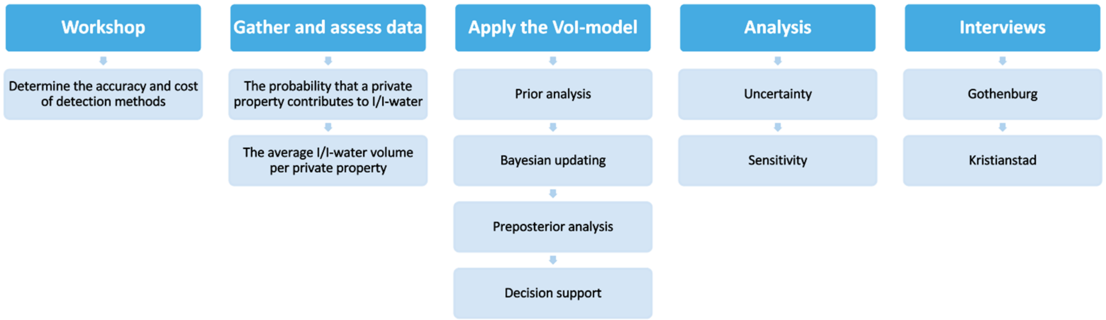

Figure 4.1: Method.

4.1 Workshop

To evaluate the precision and reliability of the three different detection methods; film inspection, smoke testing, and dye testing, a workshop was conducted with two experienced pipe inspectors. The workshop followed a structure inspired by the Sheffield Elicitation Framework (SHELF), a well-established method to systematically capture expert judgment under uncertainty (O'Hagan et al., 2006). SHELF was used to guide the elicitation of the minimum, most likely, and maximum probabilities for each method detecting at least one error. These three-point estimates were chosen to reflect uncertainty and enable more robust probabilistic modeling. The estimations were based on data from 37 projects covering 623 properties, mainly located in or around the Gothenburg region. In addition, the experts provided insight into different error types in terms of prevalence, sources, and optimal approaches.

4.2 Data assessment and assumptions

To be able to apply the VoI model in the Gothenburg area, calculations and estimations were performed based on data provided by KoV. An extraction of the FCF and GIS data sets can be seen in Figure 8.1 and Figure 8.2 in Appendix A. Based on this data, further evaluation was carried out as seen in Appendix B. Figure 8.3, Figure 8.4, Figure 8.5, and Figure 8.6 present all data assessed. When comparing the GIS data with the dataset from FCF, inconsistencies were found between the two sources. Several subareas classified as separate systems in the GIS data were not represented in the FCF dataset. As a result, the majority of the subareas with separate systems could not be included in the analysis due to missing key parameters such as the fast response component (FRC) and the slow response component (SRC). Only subareas where separate system classifications were present in both data sources, and where sufficient FCF information was available, were selected for further modeling.

Equation 4.1 and Equation 4.2 show the FRC and SRC estimations, respectively. These are the contributing areas of private properties, and were based on the assumption that the private and municipal network contribute proportionally to the I/I-water levels. This means that if, for instance, 70% of an subarea is private, 70% of the I/I-water would come from there. It is assumed that FRC directly correlates with the size of the impervious areas.

Table 4.1: List of variables used in the I/I-water contribution equations.

Variable	Description
FRC_p	FRC attributed to private properties
SRC_p	SRC attributed to private properties
FRC_{tot}	Total FRC for the entire subarea
SRC_{tot}	Total SRC for the entire subarea
$FRC_{p,sep}$	Adjusted FRC for private properties in separate systems
$SRC_{p,sep}$	Adjusted SRC for private properties in separate systems
IA_p	Impervious area of private properties
IA_{tot}	Total impervious area in the subarea
$Area_p$	Total area of private properties
$Area_{comb}$	Area serviced by combined sewer system
$Area_{sep}$	Area serviced by separate sewer system
$Area_{tot}$	Total area of the subarea
$No.\,prop._{SRC}$	Number of private properties contributing to SRC
$No.\,prop._{FRC}$	Number of private properties contributing to FRC
$P(FRC)$	Probability a property contributes to FRC
$P(SRC)$	Probability a property contributes to SRC
$P(F)$	Probability that a property contributes to either FRC, SRC, or both
$V_{property}$	I/I-water volume per property (m^3/yr)
$precip.$	Average annual precipitation
R	Runoff coefficient (scaling factor)
$No.\,of\;I/I\,prop.$	Number of properties contributing to I/I-water

$$FRC_p = \frac{\mathrm{IA}_p}{\mathrm{IA}_{tot}} \cdot FRC_{tot} \tag{4.1}$$

$$SRC_p = \frac{\mathrm{Area}_p}{\mathrm{Area}_{tot}} \cdot SRC_{tot} \tag{4.2}$$

For subareas that use both combined and separate systems, it is not considered reasonable to assume a proportional contribution due to the design and purpose of the system. For FRC, the area of the impervious surfaces that are connected to the combined system was therefore subtracted, as seen in Equation 4.3. This assumption presumed that 100% of the combined surfaces contribute to a FRC equal to their own area.

$$FRC_{p,sep} = FRC_p - IA_p \cdot \frac{Area_{comb}}{Area_{tot}} \tag{4.3}$$

For SRC, it is assumed that 35% of the total SRC origins from the separate system, as seen in Equation 4.4. This means that in a subarea where 60% of the system is separate, this part contributes to 15% of the SRC. This assumption was based on the fact that in combined systems, stormwater is intended to enter the pipes, resulting in a significantly higher contribution of I/I-water. As for SRC, drainage is typically connected to combined systems, which results in a significantly higher contribution of I/I-water. However, SRC is also largely influenced by infiltration due to damaged pipes, which can occur in both systems.

$$SRC_{p,sep} = SRC_p \cdot \frac{Area_{sep}}{Area_{tot}} \cdot 0.35 \tag{4.4}$$

When relating the FRC of private properties with the estimated hard surface area per property, the estimated number of properties that contribute to FRC was determined as seen in Equation 4.5. As for the number of properties that contribute to SRC, the calculation was similar, except that it was related to the total area of the property instead of the hard surface area (Equation 4.6). The estimated probability that a property contributes to FRC or SRC, respectively, was received when relating the result from Equation 4.5 and Equation 4.6 with the total number of properties for all subareas, respectively.

$$No.prop._{SRC} = \frac{SRC_{p,sep}}{Area/prop.} \tag{4.5}$$

$$No.prop._{FRC} = \frac{FRC_{p,sep}}{IA/prop.} \tag{4.6}$$

Since a property can have more than one issue simultaneously and therefore contribute to both FRC and SRC at the same time, the probability that a property contributes to either FRC, SRC, or both could be calculated with Equation 4.7. This became the "probability that a property contributes to I/I water" and was calculated for each subarea and used as $P(F)$ in the VoI model. A maximum value of 55% was determined, based on the statistics provided at the workshop.

$$P(FRC \cup SRC) = P(F) = 1 - (1 - P(FRC))(1 - P(SRC)) \tag{4.7}$$

The VoI analysis depends on the volume of I/I-water with which each property contributes in each subarea. The total I/I-water volume from each subarea was extracted from FCF. However, these numbers were only useful for the subareas that were 100% separate, since the distribution of I/I-water originating from the combined and separate systems, respectively, was unknown. Therefore, the I/I-water volume per property was calculated with Equation 4.8.

$$V_{prop} = \frac{(FRC_{p,sep} + SRC_{p,sep}) \cdot precip \cdot R}{No.\ of\ I/I\ prop.} \tag{4.8}$$

The results of the calculated volume for the 100% separate system were compared with the real data from FCF. A coefficient R, of 0.558 was introduced, acting as a scaling factor, to match the real data with the calculated data. The coefficient was applied to subareas with both combined and separate systems. The precipitation was calculated with over 45 years of precipitation data in Gothenburg.

4.3 Value of information analysis

To provide a recommendation for action, a VoI analysis, as described in chapter 3, was carried out. The VoI model used in this thesis accounts for uncertainty and probabilities to assess the VoI, specifically, either smoke testing or dye testing, by evaluating the trade-off between the cost of acquiring additional data and the potential benefits of reducing the risk of making an incorrect decision relative to an identified reference alternative. The VoI analysis was performed using Excel and @RISK.

As described in chapter 3, the decision alternatives included A0, A1, or further investigation using smoke or dye testing. The baseline for r_{change} was 75%. The SDR applied in the cost-benefit analysis (CBA) was 3.5%, and was the baseline in this analysis. The time horizon (T_{horizon}) for the volume costs related to the wastewater system, hence the $\sum(\text{NPV})$ was set to 60 years. This time horizon was based on the expected lifespan of the mitigation strategy.

4.4 Uncertainty and sensitivity analysis

To evaluate outcome variability and identify key drivers of risk, both uncertainty and sensitivity analyses were performed. This was achieved through a probabilistic approach using Monte Carlo simulations with 2000 iterations, applying the uncertainties in the input parameters of the model to the VoI calculation. Details regarding the specific uncertain input parameters included in these simulations, together with their assigned probability distributions and corresponding parameters, are provided in (Ohlin Saletti et al., 2025).

Based on the results of these simulations, the overall uncertainty in the VoI estimate was characterized by examining the distribution of the simulated VoI values. This provided a visualization of the range and likelihood of different possible VoI outcomes. Furthermore, Spearman rank correlation coefficients (SRCCs) were calculated to identify which specific input parameters contributed most significantly to the observed variation in the VoI results. The Spearman correlation was chosen because it can estimate correlation coefficients even when the relationships are non-linear and the data is not normally distributed.

In addition to the probabilistic analysis, a separate local sensitivity analysis was carried out by varying the r_{change} to 25%, 50%, 75%, and 100%; the social discount rate (SDR) to 1.5%, 3.5%, and 5%; and the social cost of carbon (SCC) to 1, 4, and 7 $SEK/kg \cdot CO_2 - eq$. Each parameter was individually varied while the others were kept constant at their baseline values: a r_{change} of 75%, an SDR of 3.5%, and an SCC of 4 $SEK/kg \cdot CO_2 - eq$, as previously defined. This approach allowed for evaluating how decision recommendations, VoI, and net benefits differ across subareas and assessing the robustness of the results to variations in specific key parameters.

4.5 Interviews

To gain a comprehensive understanding of how issues related to I/I-water are managed in practice, two qualitative interviews were conducted. One interview was held with a representative from the municipality of Gothenburg (KoV), and the other with a representative from the municipality of Kristianstad. Kristianstad was selected as a case due to its recognized success in implementing a strategic approach to I/I-water management. The primary aim of these interviews was to collect insights into overarching strategies and practical experiences, as well as to explore how the VoI model can be applied in a municipal context. The responses also served to support the interpretation of results obtained from the data assessment and the VoI analysis results. The interviews were conducted using an unstructured format, without a predefined interview guide.

5 Results

This chapter presents the results, based on expert illicitation, data analysis and application of the value of information (VoI) model. Key findings from the workshop is summarized, followed by outcomes from the data assessment and VoI analysis, including decision recommendations. The chapter also includes uncertainty and sensitivity analyses to evaluate the robustness of the VoI results and identify key influencing parameters. Finally, the main takeaways from the interviews are summarized.

5.1 Workshop

In the workshop, the accuracy probabilities of the detection methods for the P10, P50, and P90 percentiles were estimated, as seen in Table 5.1. Filming was identified as the most effective method, although it will not detect 100% of all issues. Realistically, this method is expected to identify 95% of problems, with a minimum detection rate of 80% and a maximum of 98%. An added benefit of this thorough inspection is the creation of a filmed record of the property's sewer line. Dye testing has a lower detection rate, estimated at 60% most likely, ranging from 30% to 65%. Dye testing can be less reliable during periods of heavy precipitation, where diluted or fast-moving water complicates tracing efforts. Furthermore, smoke testing is also dependent on specific conditions. It is most useful in areas without basements, where plastic pipes are prevalent, and where there are extensive paved surfaces. Dry weather typically improves the performance of smoke testing significantly, by allowing smoke to escape more visibly through cracks and faulty connections. In contrast, wet soil conditions after rainfall or snowmelt can trap smoke underground, leading to a higher risk of undetected faults. The effectiveness of smoke testing ranges from 20% (minimum) to 65% (maximum), with 50% being the most likely detection rate.

Table 5.1: Accuracy of detection methods, $P(D \mid F)$.

%	P10	P50	P90
Smoke	20	50	65
Dye	30	60	65
Film	80	95	98

Cost estimates for these methods were also provided. Filming typically costs around 6,000 SEK per property, with a range of 4,000 to 9,000 SEK. Smoke testing, which can cover approximately 50 properties per day, costs about 600 SEK per property for field work, ranging from 500 to 800 SEK. Simple dye testing, covering around 20 properties per day, averages 850 SEK per property, with a range of 700 to 1,200 SEK. In contrast, implementing an arbitrary rehabilitation measure in this context is significantly more expensive, typically costing 60,000 SEK per property, with costs ranging from 30,000 to 120,000 SEK. Out of 623 investigated properties in 37 different projects, 49% have exhibited at least one error. The 55% threshold value used when calculating $P(F)$ is based on these statistics, where 6 percentage points were added to acknowledge detection failures. The types of error and how prevalent they are can be seen in Figure 5.1, where direct incorrect connections (second alternative on the left), and different types of cross and in-leakages (alternatives three to eight) constitute the majority of failures. The pipe inspectors mainly operate in areas where there are reasons to believe that the error rate is high. This number is therefore assumed to be lower for Gothenburg in general, but it gives an indication of what the most problematic areas could look like.

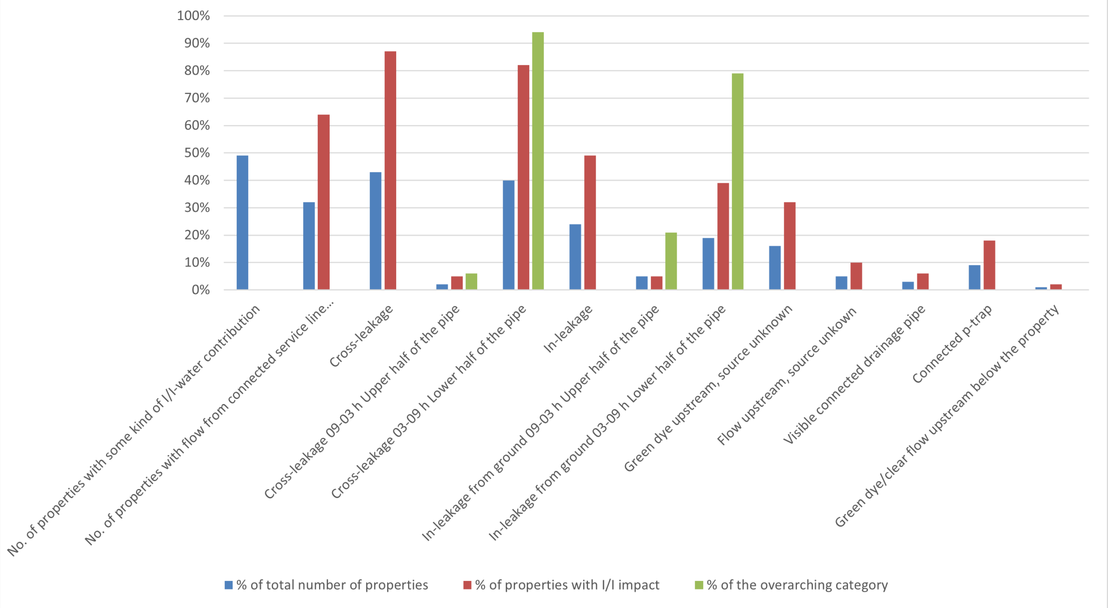

Figure 5.1: Error types and their occurrence (Personal communication, February 21st 2025, IRG).

5.2 Data assessment

The calculated I/I-water volume per property per year, V_{property}, varied significantly between subareas due to differences in property size. When normalized by property area, the volume ranged from 167 l/m^2/yr in area 1 to 2187 l/m^2/yr in area 44. Area 44 stands out as a clear outlier, and the second highest value being 865 l/m^2/yr (area 21). The overall mean I/I-water volume per square meter across all subareas was 490 l/m^2/yr. This is equal to around 0.016 ml/m^2/s, or around 1.3 l/m^2/day. Volumes and probabilities of I/I-water contributions for all subareas can be found in Appendix C.

As for the probability of I/I-water contribution, the number varied between 3$\%$ and the threshold value of 55$\%$. It should be noted that this value is expected to be low in subareas where a significant share of the system is combined. This is due to the fact that the probability applies for the whole area, but the I/I-water contribution is only for the separate system. Several subareas, including areas 2, 3, 10, 14, 21, 40, and 44, exhibit a share of properties contributing to the slow runoff component (SRC) that exceeds 55$\%$. Notably, areas 21 and 44 display particularly high shares of 98.6$\%$ and 247.1$\%$, respectively. In terms of the fast runoff component (FRC), one subarea (area 40) surpassed the 55$\%$ threshold, reaching a value of 55.73$\%$. In total, the estimated probability of a property contributing to either FRC or SRC, $P(F)$, was capped at a maximum of 55$\%$ in nine subareas. Following the implementation of this cap, the average $P(F)$ across all subareas was 30$\%$.

5.3 Value of information and decision recommendations

Table 5.2 presents the decision recommendations based on a social discount rate (SDR) of 3.5%, an social cost of carbon (SCC) of 4 $SEK/kg \cdot CO_2 - eq$, and a change rate of 75%. The results indicate that in 67% of cases, an intervention (A1) is recommended. Further investigation using smoke or dye testing is suggested in 20% of the subareas. The remaining 13% is split between A0 and dye-only testing. See Table 8.7 in Appendix D for the results per subarea.

Table 5.3 presents the mean VoI per property for additional smoke and/or dye testing under the same baseline parameters as mentioned above. Area 24 and 25 do not have any VoI from smoke testing but for dye testing. Figure 5.2 shows the mean net benefit of the investigation techniques per subarea, respectively, after subtracting the cost of smoke and dye testing from the VoI for each subarea. Note that the values in Table 5.3 do not account for the cost of conducting the investigations, why the ranking of subareas vary between the table and the above-mentioned figure. The highest net benefits for both smoke testing and dye testing are found in area 23 and area 22, while area 25 display the third highest net benefit for dye testing only.

Table 5.2: Decision alternative recommendations results.

Decision alternatives	Number of recommendations	Percentage
A0	4	9%
A1	30	67%
Smoke or dye	9	20%
Dye	2	11%

Table 5.3: Mean VoI per property for smoke and dye testing across different subareas sorted from highest to lowest for dye testing.

Subarea name	VoI per property for smoke testing	VoI per property for dye testing
Area 25	- kr	1,756 kr
Area 23	1,349 kr	1,674 kr
Area 24	- kr	1,431 kr
Area 22	1,142 kr	1,400 kr
Area 4	766 kr	947 kr
Area 17	763 kr	937 kr
Area 28	726 kr	897 kr
Area 13	537 kr	637 kr
Area 18	450 kr	541 kr
Area 7	402 kr	468 kr
Area 43	337 kr	380 kr

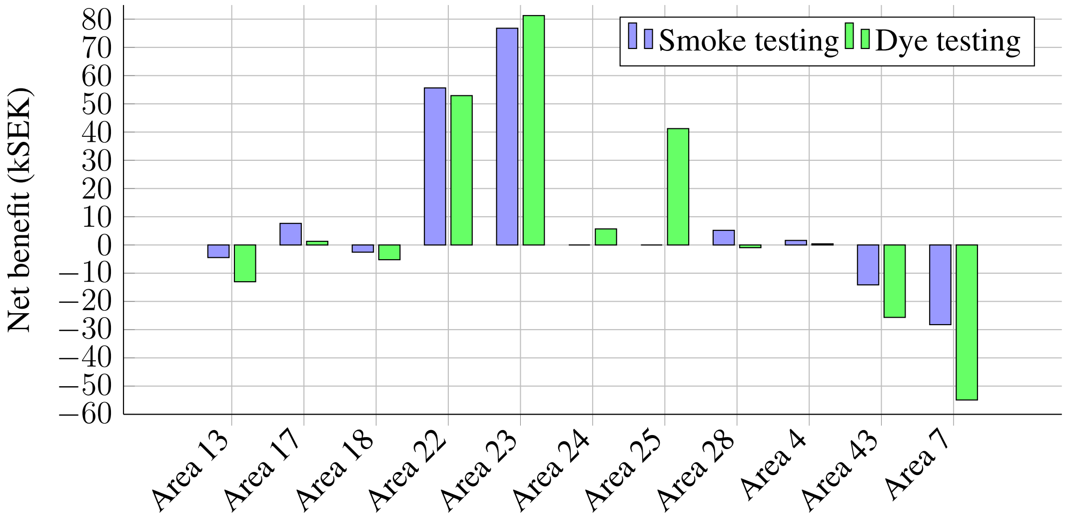

Figure 5.2: Mean net benefit (kSEK) per subarea for smoke and dye testing.

5.4 Uncertainty and sensitivity analysis

Table 5.4 present the variability in decision alternative recommendations when applying different SDRs, change rates and SCC values, respectively. Each parameter was individually varied while the others were kept constant at their baseline values, marked in red, as previously defined. Table 8.1-Table 8.6 in Appendix D show the sensitivity in the mean VoI and mean net benefit results when solely varying the change rates.

Table 5.4: Comparison of decision alternative recommendations across different values for SDR, change rate and SCC ($SEK/kg \cdot CO_2 - eq$).

Decision alternatives	**SDRs**			**Change rates**				**SCC values**		
	1.5%	**3.5%**	**5%**	**25%**	**50%**	**75%**	**100%**	**SCC 1**	**SCC 4**	**SCC 7**
A0	2	4	9	11	6	4	4	6	4	4
A1	41	30	25	21	26	30	34	29	30	31
Smoke or dye	2	9	11	11	13	9	6	8	9	7
Dye	0	2	0	2	0	2	1	2	2	3

Figure 5.3 illustrates probabilities related to the VoI from smoke and dye testing. Specifically, it shows for each subarea the probability that smoke testing yields a higher VoI than dye testing (blue bar), or vice versa (green bar), as well as the probability that at least one method yields a positive VoI (grey bar). The diagram is sorted from highest to lowest based on the latter.

Table 5.5 presents the probabilities of the recommended decision (A0, A1, smoke, or dye) being the best alternative for each subarea based on the VoI analysis. The table indicates that areas 22, 23, 24, and 25 all show over a 50% probability that "Smoke" or "Dye" is the best decision alternative, suggesting that further investigation is likely the optimal initial step in these subareas. Furthermore, approximately 20 subareas have a probability of 85% or higher that A1 is the best alternative under either the smoke or dye testing analysis scenario. Specifically, 14 subareas show a 100% probability that A1 is the best decision alternative.

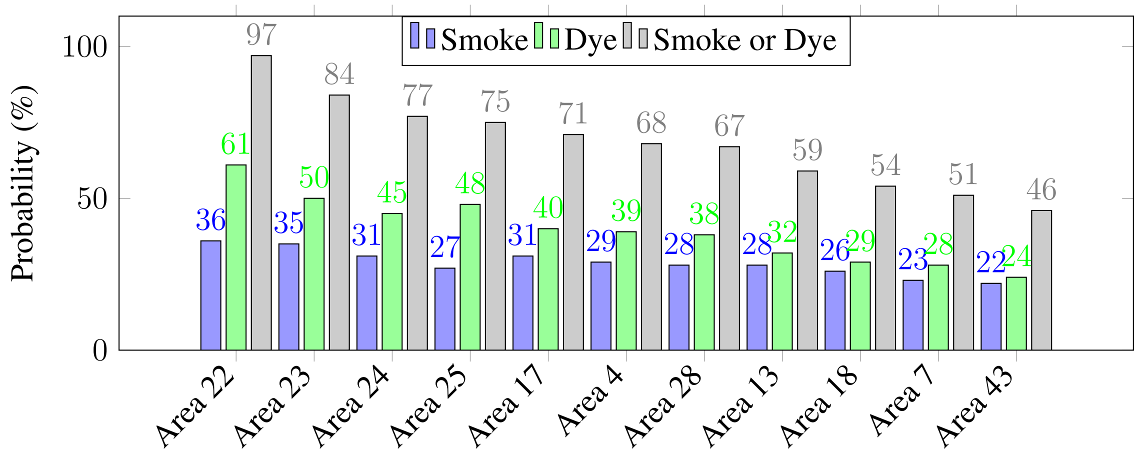

Figure 5.3: Probability that each investigation method yields higher VoI values.

Table 5.5: Probability that each recommended decision is the best alternative.

Subarea name	**VoI analysis for smoke testing**			**VoI analysis for dye testing**		
	A0	A1	Smoke	A0	A1	Dye
Area 1	0%	100%	0%	0%	100%	0%
Area 2	10%	87%	3%	11%	85%	4%
Area 3	14%	82%	5%	15%	81%	4%
Area 4	24%	39%	37%	25%	36%	40%
Area 5	22%	52%	26%	23%	48%	29%
Area 6	5%	84%	11%	6%	81%	13%
Area 7	44%	32%	23%	47%	30%	23%
Area 8	0%	100%	0%	0%	100%	0%
Area 9	3%	96%	2%	3%	95%	2%
Area 10	0%	100%	0%	0%	100%	0%
Area 11	0%	99%	1%	0%	99%	1%
Area 12	59%	28%	13%	61%	28%	11%
Area 13	41%	29%	31%	44%	27%	29%
Area 14	0%	100%	0%	0%	100%	0%
Area 15	39%	53%	8%	40%	51%	10%
Area 16	31%	62%	7%	31%	61%	8%
Area 17	31%	30%	39%	32%	28%	40%
Area 18	52%	23%	25%	54%	22%	24%
Area 19	0%	100%	0%	0%	100%	0%
Area 20	0%	100%	0%	0%	100%	0%
Area 21	0%	100%	0%	0%	100%	0%
Area 22	27%	5%	69%	33%	3%	64%
Area 23	9%	28%	63%	10%	26%	64%
Area 24	9%	39%	52%	10%	35%	55%
Area 25	0%	47%	53%	0%	40%	60%
Area 26	19%	47%	34%	21%	43%	36%
Area 27	6%	88%	7%	7%	86%	7%
Area 28	25%	39%	36%	26%	35%	38%
Area 29	86%	1%	13%	86%	1%	13%
Area 30	6%	86%	7%	7%	84%	9%
Area 31	3%	69%	28%	3%	62%	34%
Area 32	88%	1%	11%	88%	1%	11%
Area 33	0%	100%	0%	0%	100%	0%
Area 34	13%	56%	31%	14%	51%	35%
Area 35	10%	75%	15%	11%	70%	19%
Area 36	0%	100%	0%	0%	100%	0%
Area 37	0%	100%	0%	0%	100%	0%
Area 38	58%	16%	27%	60%	14%	26%
Area 39	0%	96%	4%	0%	92%	8%
Area 40	0%	100%	0%	0%	100%	0%
Area 41	0%	100%	0%	0%	100%	0%
Area 42	14%	81%	6%	15%	79%	6%
Area 43	49%	31%	20%	52%	29%	19%
Area 44	0%	100%	0%	0%	100%	0%
Area 45	0%	100%	0%	0%	100%	0%

5.4.1 Spearman rank correlation coefficients

The analysis of Spearman rank correlation coefficients (SRCCs) was performed for both smoke and dye testing across multiple subareas, with particular attention given to areas 22, 23, 24, and 25 due to their relatively high expected mean net benefit. The SRCC analysis was also conducted for the subarea displaying the lowest net benefit (area 7). The results for each of the subareas can be seen in Appendix C. The analysis shows that the VoI is highly sensitive to a limited number of key inputs, regardless of whether the net benefit is low or high. Five parameters consistently exert the strongest influence on the VoI from both smoke testing and dye testing:

- C_{film} (cost of film inspection per property): This parameter, modeled as a negative value, displayed a strong positive correlation with VoI (SRCCs up to 0.62). A positive correlation with a negative input implies that as the input value increases, the filming cost becomes cheaper, the VoI tends to increase.
- I_{FRC} (WWTP investment costs for fast response components): This parameter had high absolute SRCC values (up to 0.57), but the direction of the correlation varied by subarea. In areas 23, 24 and 25, the correlation was negative, suggesting that higher costs reduce the VoI. Conversely, in area 22, the correlation was positive, indicating that uncertainty around higher costs, tending to increase the VoI in this specific context.
- C_{measure} (cost of private rehabilitation measures): Also modeled as a negative input, this parameter mostly exhibited negative correlations with VoI (e.g., -0.39 in area 22), meaning that more expensive measures increase the VoI. This reflects the benefit of avoiding unnecessary high-cost interventions. Slight variations were noted, including a weak positive correlation in area 25 for dye testing.
- $P(D \mid F)$ (probability of detection given a fault): This parameter consistently showed a moderate positive correlation with VoI (typically 0.13–0.29), indicating that greater detection accuracy are generally associated with higher VoI outcomes.
- I_{SRC} (WWTP investment costs for slow response components): Though generally less influential than I_{FRC}, this parameter still showed correlations (up to 0.32), with direction depending on subarea and detection method. As with FRC, the societal cost of WWTP investments contributed notably to overall uncertainty.

5.4.2 Distribution histograms

As for the SRCCs, the distribution histograms of the estimated VoI from each further investigation scenario are presented in Appendix C for areas 22, 23, 24, and 25, as they had the highest net benefit (for dye testing). All subareas, for both smoke and dye testing, exhibit right-skewed distributions with a distinct peak at the zero mark on the x-axis. This indicates that zero (or a value near zero) is the most probable single outcome, while the long right tail reflects the potential for high positive VoI values. Across all subareas, the 90% intervals of the distributions range from 0 up to approximately 2,900-4,800 SEK, indicating substantial potential variability in outcomes.

5.5 Interviews

This section presents the key findings from interviews with representatives from the municipalities of Gothenburg and Kristianstad, outlining their strategies for managing

I/I-water and highlighting the specific challenges they face.

5.5.1 Municipality of Gothenburg

The representative from the municipality of Gothenburg held a position for approximately three years, focusing specifically on issues related to I/I-water from private properties. Their approach involved addressing reported I/I-water problems through follow-ups on separation projects, analysis of historical data from problematic properties, operational reports highlighting elevated flows at pump stations, and upstream investigations triggered by basement flooding incidents

To detect I/I-water on private properties, a range of methods were applied, including smoke testing, dye testing, and film inspections with length measurements. It was estimated that around one third of the total length of the sanitary sewer network is privately owned. This includes not only single-family homes, but also larger property owners managing extensive and often complex internal networks. A common issue identified was the lack of long-term renewal planning among private property owners, many of whom addressed problems only after complete failures occurred.

The representative emphasized the need for a holistic strategy, where municipal network improvements must be coordinated with private network interventions. Without such coordination, public investments risk being undermined by continued inflows from the private side. In areas where separation projects have been implemented, faulty connections were believed to be relatively common. Challenges often arise when new stormwater systems are added to existing networks, without verifying that private properties are properly connected. The municipal GIS database may show correct routing of the respective networks, yet on-site inspections often reveal mismatches. For instance, observations during rainfall events sometimes showed stormwater pipes completely dry while adjacent sewer lines experienced high flow levels, suggesting undetected faulty connections between the systems.

When expanding or separating sewer systems, successful outcomes depend on clear communication with property owners and detailed connection guidance. Without this, there is a risk of installing underutilized or entirely unused infrastructure. Additionally, many property owners lacked awareness regarding the nature of the I/I-water issue, the required corrective measures, and the associated costs. Formal demand letters were often insufficient in initiating measure implementation; instead, proactive engagement through meetings and personalized communication proved essential in avoiding legal conflict.

The representative pointed out that focusing exclusively on faulty connections overlooks a more significant issue: leakage from aging private sewer infrastructure. Measurement of the long-term effects of interventions was described as particularly challenging due to multiple factors and inconsistent data quality. Since the representative left this position, work on I/I-water mitigation related to private properties has largely stalled, highlighting the need for sustained institutional support and leadership in addressing these systemic issues.

5.5.2 Municipality of Kristianstad

The representative from the municipality of Kristianstad began his position in 2019, focusing on addressing I/I-water issues within the city. Since then, he has developed a systematic approach aimed at reducing I/I-water in wastewater systems. Initially, various strategies were tested, targeting either basement flooding or flow reduction in specific areas. Over time, it was concluded that the most effective method is a systematic, area-by-area approach, addressing all relevant factors within an entire district.

The process begins by selecting manageable areas and conducting extensive flow measurements over approximately two years to establish a baseline. This is followed by smoke and/or dye testing across both private and public networks to identify I/I-water sources. The representative emphasizes the necessity of addressing both municipal and private networks simultaneously to ensure that expected outcomes are achieved. Once issues are identified, they are documented through film inspections, and responsibility for necessary corrections is determined.

Municipal pipes are addressed first, through replacement, relining, or relocation. Property owners are then required to correct faults within six months, under the threat of water service disconnection if compliance is not achieved. According to the representative, the threat of service disconnection is essential for ensuring that corrective measures are implemented within a reasonable time frame. Political approval for this enforcement strategy was secured in advance to guarantee legitimacy and consistent application across all property owners. For this relatively strict approach to be effective, it is complemented by active communication and the provision of information and support. Formal notices initiate the process, followed by structured dialogue offering practical advice and procedural guidance to facilitate compliance.

The representative reports that this overall strategy has resulted in significant reductions in I/I-water, particularly in smaller communities where the effects are more readily observable. In some areas, the reductions have been so substantial that maintaining optimal operational conditions at the WWTP has presented new challenges. It is estimated that I/I-water has been reduced to only a few percent annually in certain projects. However, in larger systems, particularly at major WWTPs, the effects are harder to detect as variations are masked within the overall flow volumes. Economic benefits are more evident in areas where operational costs, such as continuous reliance on flushing trucks, have been eliminated. In gravity-based systems with lower operating costs, realizing these benefits takes longer. Notably, economic evaluations do not account for the reduction of bypass events, as these costs have not been formally quantified.

Regarding network characteristics, the representative has not observed a clear distinction in the prevalence of direct connection errors between areas originally constructed with separate sewer systems and those reconstructed from combined systems. Faulty connections are present across all types of developments. Newer developments (post the 1990s) generally exhibit a lower rate of faulty connections, around 10%, while older areas may reach up to 25%. Nevertheless, he emphasizes that faults can occur regardless of the age of a system or its construction history, indicating no straightforward correlation.

The representative highlights that Kristianstad is highly dependent on pumping stations due to the lack of elevation differences, whereas cities like Gothenburg can use gravitational-based systems to a larger extent. Furthermore, groundwater infiltration constitutes a particularly significant challenge in Kristianstad compared to cities like Gothenburg. Due to the region's low elevation and coastal proximity, many sewer pipes are located below the groundwater table, making them highly exposed to constant infiltration through damaged joints or pipes. He emphasizes that while rain-induced inflows lead to peak flows, and hence overflows, they can be addressed through targeted interventions. On the contrary, groundwater infiltration leads to persistent infiltration problems that require more extensive and ongoing mitigation efforts.

6 Discussion

The results presented in Table 5.2 suggest that the issue of infiltration and inflow (I/I) is widespread, since it would be economically beneficial for intervention in 67% of the subareas covered. This underlines the scale of the problem and highlights the potential for improved management through targeted interventions. More specifically, the model results suggest that alternative A1 was the best alternative in 100% of the simulations for 14 of the subareas, see Table 5.5. Hence, interventions should be prioritized there.

These findings point to the significant value that structured decision-support tools like value of information (VoI) analysis can offer for municipal infrastructure planning. They show how data-driven models can help identify where resources are likely to yield the greatest benefit. However, translating these model-based insights into real-world action is not straightforward. Since the wastewater system and all its infrastructure components are highly complex and context specific, realistically, more data should be gathered to gain a comprehensive understanding. Also, upon closer examination, several of these recommended subareas are associated with one or several challenges that stem from the limitations of the input data or from simplified assumptions within the model itself. Examples include potentially underestimated intervention costs in subareas with predominantly multi-family housing, highly uncertain or capped values for the probability of failure, variations in property size and complexity, or lack of sufficient calibration data in the FCF dataset.

This chapter discusses these issues in greater depth. It reflects on the value and limitations of smoke and dye testing, the influence of uncertainty and sensitivity in model outcomes, and the role of key parameters such as the property owner change rate. It also outlines the broader methodological and data-related constraints of the current model and considers the practical challenges of implementing VoI-based recommendations in a municipal context. Together, these discussions aim to provide a critical evaluation of the model's performance and offer guidance for how it can be strengthened and better applied in future I/I-water management efforts.

6.1 Value of smoke and dye testing

The use of smoke or dye testing would change the decision whether or not to make an intervention in 20% of the subareas. This indicate that it is useful in some subareas, but perhaps not to the degree that it should be implemented as default in the standard procedure. It could therefore be argued that using the VoI model would be a good complement, especially since the net benefits in some subareas are relatively high, as seen in Figure 5.2. This supports a shift towards a more VoI-driven approach, as it primarily signals that the current uncertainty surrounding the true state of I/I-water from the identified subareas is substantial.

However, Table 5.5 shows that even for the top subareas, such as areas 22 and 23, the probability of further investigation (smoke or dye testing) being the single best alternative is not absolute. For these subareas a roughly 30-35% risk that, even with high average VoI, the optimal path might still be intervention (A1) or no intervention (A0) once all uncertainties are considered probabilistically. This underscores that VoI shows strong potential rather than deterministic outcomes. When the model flags subareas as having high potential VoI, this signal should primarily initiate a more detailed, context-specific review, rather than directly concluding the need for immediate smoke and/or dye testing.

Additionally, while the top four subareas display relatively high net benefits, the corresponding distribution histograms reveal substantial uncertainty in achieving a positive VoI. Among them, area 22 stands out by showing a more consistent distribution spread across positive VoI outcomes. In other words, while area 22 has a slightly lower mean net benefit than area 23, it carries a lower risk of VoI being near or at zero. This highlights the importance of considering risks, not just mean outcomes, when making decisions about whether to pursue further investigations.

6.2 Sensitivity in value of information and decision recommendations

This section discusses how key input parameters influence the outcome of the VoI analysis and the resulting decision recommendations. Sensitivity analysis, including both global and local methods, was used to identify the most influential factors.

6.2.1 Detection accuracy and other key parameters

The observed variation in the Spearman rank correlation coefficients (SRCCs) across different parameters, testing methods, and subareas is expected and reflects the complexity of the system being modeled. Each parameter has a distinct weight and functional relationship within the model, leading to varying levels of influence on VoI variability.

The lack of a single, consistent common thread in correlations across all scenarios is a valuable finding. It suggests that the key uncertainties are context-dependent, and understanding these specific sensitivities is essential for effectively targeting efforts to reduce uncertainty. The results identify five parameters that consistently affect the robustness of the VoI. This emphasizes the importance of directing efforts such as data collection toward the parameters that most significantly influence the reliability of VoI estimates in each specific subarea and detection method. In contrast, other parameters consistently exhibit lower absolute SRCC (near zero), indicating that, within the scope and assumptions of this analysis, their uncertainty contributes minimally to the overall variability in the VoI outcome.

In general, the local sensitivity analysis (Table 5.4) shows that changes in all parameters affect the resulting decision recommendations, where the change rate has a notable impact, as further discussed in the next chapter. However, variations in the social cost of carbon (SCC) do not lead to as significant fluctuations in recommendations compared to the change rate and the SDR. This suggests that the SCC does not affect the resulting recommendations. Although, as the SDR increases from 1.5% to 5%, the model increasingly favors decision alternative A0, and conversely, decreases the recommendation for A1 with a higher SDR. This trend is expected, as a higher discount rate reduces the present value of future benefits. This is because the long-term costs of inaction or emission reductions are avoided.

6.2.2 Change rate

The local sensitivity analysis clearly demonstrates that it significantly affects both VoI, net benefits, and, more importantly, the prioritization of subareas for further investigation (see Table 8.1–Table 8.6 in Appendix D). The results show that subareas with the highest potential VoI or expected net benefit shift depending on the assumed level of compliance.

For instance, at a low change rate of 25%, areas such as 31 and 35 are ranked among the highest. However, as the change rate increases, their ranking tends to drop, and they may no longer appear among the top. Conversely, areas like 13 and 17, which are less prioritized at lower change rates, become highly ranked when the change rate reaches 100%. Areas 23 and 25 stand out for consistently maintaining high rankings across all scenarios, although their exact positions and preferred investigation methods may vary.

These findings highlight the strong influence of the assumed change rate on the prioritization of subareas for further investigation. The financial viability of targeted smoke and/or dye testing depends directly on the likelihood that corrective measures will be implemented after fault detection. Therefore, it is essential to account for this parameter carefully in both the modeling process and practical implementation in order to maximize theoretical net benefits and ensure sound decision-making.

The change rate also plays a key role in the selection of decision alternatives. As it increases, the model favors intervention (A1) more often, while the no-intervention alternative (A0) becomes less common. The recommendation for further investigation using smoke or dye testing follows a more complex pattern. This alternative is most frequently selected at a 50% change rate but becomes less common at higher rates. When the change rate is lower, the expected benefit of A1 decreases because fewer property owners are assumed to act on the findings. At the same time, uncertainty about the presence of I/I-water related failures persists. As a result, further investigation through smoke and/or dye testing becomes a more cost-effective way to reduce decision uncertainty, which increases the frequency of this alternative being recommended. At a 25% change rate, however, further investigation is rarely favored. In such cases, the model tends to favor A0, because the expected benefit of both A1 and further investigation is limited by the low probability of corrective measures being taken.

It is also important to consider whether treating the change rate as a fixed parameter in the VoI model is fully appropriate. Since it can be significantly influenced through active engagement and enforcement, it should perhaps be treated more dynamically. Insights from the interview with a representative from Kristianstad support this idea. There, the implementation of water service disconnection for non-compliance has proven effective in increasing adherence, resulting in a change rate approaching 100%. In contrast, Gothenburg currently lacks similar enforcement tools but could likely achieve higher compliance by introducing systematic follow-ups and binding requirements where necessary. Given this potential, it should be feasible to plan for and assume a change rate of 100%, provided that the appropriate measures are taken.

6.3 Model constraints

While the VoI model developed and applied in this study offers a structured approach to decision-making under uncertainty, it is subject to several limitations. These constraints relate both to the underlying assumptions of the model and to the practical challenges of applying it in a real-world context. This section outlines key methodological, input-related, and contextual limitations that influence the interpretation of results and the applicability of the recommendations of the model.

6.3.1 Lack of benefits

An important limitation of this model is that the analysis does not account for potential benefits related to the reduction of bypassing events and basement flooding. Although the reduction of I/I-water would likely decrease the risk of overloading the separate wastewater system, and thereby reduce the occurrence of untreated bypasses and basement flooding, quantifying the exact economic value of these avoided consequences is challenging.

Basement flooding can cause significant damage to private properties, leading to high repair costs, insurance claims, and social disruption for residents. Similarly, bypassing untreated wastewater into the environment can result in ecological damage and health risks. However, the monetary valuation of these events is complex and site-specific, depending on factors such as local rainfall patterns, system design, property vulnerability, and enforcement practices.

Due to the lack of reliable data linking I/I-water reduction directly to the prevention of bypassing or basement flooding in Gothenburg's separate sewer system, these benefits were not included in the VoI analysis. As a result, the net benefit calculations presented are conservative. In reality, the full societal value of I/I-water management efforts is likely higher than what is captured by the model.

6.3.2 Detection methods

The presented results indicate that dye testing outperforms smoke testing, and provides a higher VoI overall.

While this variability is accounted for in the model through the use of uncertainty intervals for detection probabilities, these represent an annual average perspective. In practice, when planning and implementing specific investigations, considering prevailing weather conditions at the time of testing can improve detection success. Thus, the VoI results provide valuable guidance at a strategic level, but tactical decisions on further investigations must adapt to real-time environmental factors.

6.3.3 Intervention cost

In the model, a uniform intervention cost interval is assumed across all subareas. This interval was initially established based on interventions for single-family houses; however, several subareas included in the analysis are predominantly composed of multi-family buildings. As a result, the general cost interval applied in the model is likely underestimated, since the typically higher intervention costs associated with multi-family buildings were not fully incorporated.

The cost of addressing I/I-water problems can vary substantially depending on a range of factors. If the property owner is able to undertake parts of the work independently, such as excavation, the overall costs can be significantly reduced. In contrast, where the participation of contractors is necessary, costs tend to increase. Further determinants of intervention cost include the feasibility of implementing local on-site stormwater management solutions, the accessibility to the service pipe, the property type and land use designation within the area. Additionally, site-specific conditions, such as variations in local soil characteristics may significantly influence excavation complexity and, consequently, total project costs. In central urban areas, for example, property-level interventions may be significantly more costly due to the need to shut down traffic, manage older or combined sewer systems, or navigate spatial constraints. As a result, costs in dense inner-city areas are likely underestimated, while those further away from the city center may be overstated.

While a general uncertainty range was incorporated into the model to account for expected variability, a more detailed assessment of the local conditions of each subarea could allow for the development of tailored cost intervals. This would enable for more precise and robust cost estimates for estimating the net benefit, particularly since the SRCC results highlights that uncertainty surrounding high rehabilitation costs is a key driver of VoI. Introducing area-specific distributions for the intervention cost, such as adjusting the P10 and P50 inputs based on site-specific implementation constraints would likely enhance the realism of the model and its value as a decision-support tool.

6.3.4 Variability in failure impact

An important limitation of the current analysis is the assumption that all detected failures contribute equally to I/I-water volumes. In reality, the impact of individual failures can vary significantly. For example, a single property with a severe defect, such as a direct stormwater connection, a failed foundation drain, or major pipe damage, may contribute a disproportionately large I/I-water volume. Conversely, a large number of properties with minor defects can collectively have a comparable or even greater cumulative effect.

This variability is not accounted for in the current VoI model, which applies an average estimated volume per property. As a result, the model may overestimate or underestimate the true economic benefit of detecting and addressing specific failure types. Identifying high-volume failures is particularly critical, as mitigating these could yield significantly greater system-wide benefits than average-based assumptions suggest. Additionally, the parameters $P(F)$ and V_{property} were not treated stochastically in the model. Instead, they were set as fixed inputs for each subarea, based on data assessment and assumptions, and represent a *best estimate*. While variability across subareas affects the mean VoI and net benefit outcomes, the uncertainty within each subarea estimate was not explicitly modeled. This explains their absence from the SRCC plots and limits direct evaluation of how parameter uncertainty influences VoI results.

Ideally, a more detailed assessment of failure types and their respective I/I-water contributions would be incorporated into the analysis. Such refinement could distinguish between high- and low-risk properties, enabling more cost-effective prioritization of further investigations and interventions. Integrating uncertainty intervals into the model would also help quantify the effect of parameter uncertainty on results. However, acquiring the detailed field data required for this level of analysis was beyond the scope and data availability of the current study.

6.3.5 Variability in property size and characteristics

It should be mentioned that property configurations vary widely, which can significantly affect both the time and cost required to perform I/I-water investigations. For example, a single property may include several residential buildings that share a service line, or multiple separate properties may be connected to a common private sewer. In other cases, two buildings on the same property may each have individual connections. Some properties contain multiple buildings with a mix of shared and individual service lines, which requires customized investigation method strategies. These configurations are especially common in older or denser urban areas, where ownership boundaries and infrastructure have evolved over time.

This influences practical implementation in several ways. Investigating properties with shared or complex service pipes may involve greater coordination efforts, longer inspection times, and challenges in determining the exact source and responsibility for a detected issue. To account for variability, the model includes a general cost interval for investigations. However, this interval could be further refined for each subarea, where factors such as building density, connection type, and infrastructure complexity could be taken into account. Integrating property-level data into future analyses could therefore enhance both the economic accuracy and practical applicability of the model outputs.

For example, the majority of the subareas analyzed have a significantly larger property area than average: Area 1 and area 8 have an average property size of around 70,000 m^2 and 16,000 m^2, respectively. The four subareas with A0 are also the four smallest. While the current model relates costs to property size, it could be argued that service pipe length might offer a more accurate basis for assessment. However, this would require detailed pipe length data, which was beyond the scope and data availability of the current study.

6.4 Input-data constraints

The values for the fast and slow runoff components (FRC and SRC) used in this study were derived from FCF, which uses values that origin from a MIKE+ simulation model. These parameters are initially calibrated using flow measurements taken at selected locations in the sewer network. The calibration process involves adjusting several model parameters, including catchment area, to ensure that the simulated flow curves match the observed ones. However, the model is not calibrated for each individual subarea. Due to the limited number of flow measurements available, the calibrated values are instead applied across broader upstream catchment areas, with assumptions of uniformity within those subareas.

This approach introduces a degree of uncertainty in the FRC and SRC values attributed to individual subareas. While this uncertainty may be acceptable when evaluating larger, aggregated areas, it can affect the reliability of the VoI analysis at finer scales. In smaller subareas, or when comparing individual investigation zones, the underlying data assumptions may not reflect the true hydraulic conditions.

Additionally, the analysis is limited by the availability of data from FCF. Data coverage is incomplete, particularly for many subareas with separate sewer systems. As a result, large parts of the city are not included in the model-based evaluation. This limits the comprehensiveness of the analysis and may lead to the exclusion of potentially high-priority subareas from further consideration.

Improving the precision of input data, whether through expanded flow monitoring, higher resolution modeling, or more area-specific parameter calibration, would improve the robustness and accuracy of future analyzes. In particular, more localized calibration could enable more nuanced prioritization of interventions, better reflecting the true variation in system performance and I/I-water contributions across the city.

6.5 Methodological constraints

In addition to limitations related to data and model inputs, several methodological assumptions have influenced the structure and outcomes of the analysis. These assumptions were necessary to enable practical application of the VoI model but introduce simplifications that may affect the precision and generalisability of the results. This section highlights the most important methodological constraints and their implications for the interpretation of the findings.

6.5.1 FRC and SRC

One limitation in the calculation of FRC is that it is derived exclusively from impervious surfaces, where the area classified as combined impervious has been subtracted without applying a runoff coefficient. This simplification could lead to under- or overestimation of FRC in certain subareas, as contributions from partially impervious or misclassified surfaces may not be fully accounted for. Additionally, combined impervious surfaces may include local stormwater management solutions, which prevent all runoff from reaching the sewer network.

Furthermore, it was assumed that 35% of the SRC originates from the separate system in subareas where both combined and separate sewer systems are present. This simplification was needed to be able to analyse subareas where both system types are in place. However, it constitutes a rough assumption that introduces a significant uncertainty into the analysis. In reality, the proportion of SRC that origins from the separate system likely varies substantially between different subareas. Some subareas may have much higher infiltration from the separate system, particularly where the private sewer network is old, while others may be dominated by inflows from older combined infrastructure.

Because the SRC values are directly used to estimate the probability of a property contributing to I/I-water, and to determine the corresponding economic impact per property, the precision of these assumptions is critical to the accuracy of the overall VoI analysis. Ideally, separate and more detailed assumptions should have been made for each subarea, based on local conditions and a finer assessment of the sewer system composition. However, due to limitations in the available data and the scope of this study, it was not feasible to conduct such a detailed evaluation for all subareas. As a result, the current analysis relies on a general estimate that, while practical, introduces a level of uncertainty that should be considered when interpreting the results.

6.5.2 Threshold of failure rate

The proportion of properties assumed to contribute to I/I-water was estimated based on calculated volumes and average volume contribution per property. In subareas where the calculated failure rate exceeded 55% of all properties, the value was capped at this number. This was applied on nine of the subareas, where all of them had a large SRC value. This could be related to prevalence of basements, and/or high groundwater levels in combination with old pipes. This would allow for an unlimited water source to enter the system. This adjustment was made to avoid unrealistic interpretations of the data, as failure rates above this threshold were considered not very likely based on reference values and empirical experience communicated in the workshop.

This cap implies the assumption that in subareas with very high I/I-water volumes, the elevated contribution stems not from an unusually high number of failing properties, but rather from a smaller number of properties each contributing disproportionately large volumes. This assumption reflects known variability in individual failure magnitudes, where a single improperly connected foundation drain or direct stormwater connection can generate significantly higher inflow than typical cases.

While this approach increases the plausibility of the estimates, it introduces a methodological limitation. The imposed threshold is not based on site-specific data, but rather on expert judgements and reference values. Consequently, the capped failure rate may underestimate the true number of failing properties in some subareas, or conversely, overestimate the volume contributed per property. The decision represents a trade-off between mathematical consistency and empirical credibility.

6.6 Practical implementations

A recurring theme in both interviews was that effective management of I/I-water requires interventions not only on private properties but also within the municipal network. Excluding either the private or municipal side will likely just shift the location of the issue to the other side. The VoI model, as applied in this study, focuses on decision support related to the private sewer network. However, for the decision recommendations of the model to translate into meaningful system-wide improvements, its use should be incorporated within a broader strategy that includes assessments and potential interventions on the municipal side.

In Gothenburg, several factors must be addressed before the VoI model can be used effectively. One key limitation is the availability and consistency of data and flow measurement. As mentioned in earlier chapters, many subareas lack sufficient information, which affects the precision of the calculated failure probabilities and the estimated volumes of I/I-water from private properties. In addition, several subareas that are classified as separate in the GIS database are not represented at all in FCF, which means that they could not be included in the analysis.

Another challenge is the fact that the system in Gothenburg consists of both combined and separate networks. To address the coexistence of these systems, assumptions and simplifications were needed in the calculations, which increases the uncertainty in flow analysis. The presence of combined systems also introduces a prioritization challenge, as efforts to address I/I-water in the separate system may be less urgent, particularly in subareas where the network can technically handle the excess volume without resulting in basement flooding or overflows. Given the substantial proportion of the network that still consists of combined sewers, economic and operational priorities may arguably be better directed toward those parts of the system where the consequences of I/I-water are more immediate and severe.

Interviews with municipal staff also indicate that the work related to I/I-water on private properties has not been continuous. The discontinuation of targeted initiatives due to changes in staffing or shifting priorities has limited the ability of the municipality to sustain a long-term strategy. Furthermore, the municipality currently lacks formal mechanisms to ensure that property owners take corrective measures when faults are identified. While the responsibility for private sewer networks lies with the property owner, there are few practical means of enforcing compliance. The absence of consequences for inaction lowers the expected change rate, which in turn reduces the estimated benefit of interventions in the VoI analysis. For the VoI model to be implemented successfully in Gothenburg, these issues must be addressed. This includes improving the quality and resolution of input data, and establish clear processes for follow-up and enforcement.

In contrast, Kristianstad provides an example of a municipality where the conditions and the applied I/I-water approach better align with the requirements of the model. The entire sewer system in Kristianstad is fully separated. This means that the simplifications and assumptions that were implemented to account for the combined system are not necessary, which increases the reliability of the results. Furthermore, Kristianstad applies a structured, area-by-area intervention strategy that matches the logic of the VoI approach. Investigations are based on long-term flow measurements, and the system is inspected and addressed in a coordinated manner. Another factor that enables the implementation of this strategy is the use of formal enforcement tools. Property owners are required to implement corrective measures within a specified time frame, and the municipality disconnects water services in cases of non-compliance. This results in a high change rate, which supports the economic justification for further investigations and interventions.

In addition, the widespread use of pumping stations in Kristianstad increases the operational cost of I/I-water. This makes the consequences of I/I-water more directly observable and provides a strong incentive for the municipality to act. The ability to detect and quantify changes in flow also supports the validation of model results and helps evaluate the effectiveness of implemented measures. Together, these conditions make it possible to apply the VoI model in Kristianstad with minimal adaptation. The model can serve as a complementary tool for prioritizing between areas, evaluating the marginal value of additional investigations, and supporting resource allocation in a systematic manner.

7 Conclusion

This Master´s thesis has explored the use of VoI as a decision-support tool for managing I/I-water in wastewater systems. Specifically targeting private properties within the separate sewer network in Gothenburg, the findings confirm that the issue of I/I-water is both widespread and significant, as an intervention is recommended in 67% of the subareas. Further investigations (smoke and/or dye testing) are suggested to be the most cost-effective strategy in 20% of the subareas, notably in areas 22 and 23. Among the subareas evaluated, area 25 stood out for the highest potential VoI.

Uncertainty proved to be a central factor influencing the outcomes. Sensitivity analyses revealed that key input parameters such as the costs of measures, film inspection, and WWTP investments, as well as detection accuracy and especially the change rate (i.e., property owner compliance), significantly affect the VoI results. The critical role of the change rate highlights the need for active enforcement and clear communication to ensure effective implementation. Its use also exposed limitations related to assumptions and data availability. Variability in intervention costs, generalized I/I-water failure impacts, and property-specific characteristics point to the need for more localized data input, perhaps through a qualitative assessments, and context-specific modeling.

However, despite these uncertainties and limitations, the VoI model provides a structured framework and is generalizable and applicable to other municipalities, such as Kristianstad, where relevant homogeneous data are available. Importantly, this thesis reinforces that effective wastewater infrastructure planning must account for both economic and risk considerations. VoI analysis supports risk-based decisions by identifying where additional data meaningfully reduce uncertainty and where they do not.

In conclusion, the VoI model is a powerful prioritization tool. Rather than prescribing fixed actions and recommendations, it helps municipalities determine where further investigations and context-specific data collection is economically justified before potentially proceeding with interventions. To reach its full potential, the model requires continuous refinement with updated data and strategic integration into municipal planning. With these efforts, VoI-based approaches can improve infrastructure resilience in wastewater management in Gothenburg and other municipalities by making more informed, targeted, and cost-effective I/I-water mitigation decisions.

8 Future Research

To enhance the usefulness and accuracy of the VoI framework, several promising directions for future research could be explored. Firstly, the current analysis predominantly focuses on cost savings derived from reduced treatment and pumping. Future studies should significantly broaden the scope of evaluation criteria to encompass a wider range of benefits. These could include quantifying avoided basement flooding incidents, reducing sewer overflows, improving environmental quality, and enhancing public acceptance of I/I-water management strategies. Simultaneously, this thesis primarily explored a single intervention alternative (A1); future research should incorporate a wider array of mitigation options. To comprehensively evaluate and compare these alternatives against the expanded set of criteria, multi-criteria analysis (MCA) could be employed. This approach would allow for decisions based on a set of objectives beyond purely economic considerations, integrating factors like social equity or environmental impact.

Beyond expanding the evaluation framework, integrating more dynamic data sources is crucial. Linking the model to real-time flow and rainfall data would enable more responsive decision-making to current conditions. Furthermore, machine learning techniques could enhance predictions of failure probability and detection rates by identifying complex patterns within large datasets, thereby making the model inherently more adaptive and precise. Another important refinement would be to reflect the varying severity of I/I-water failures. The current model treats all I/I-water failures equally, yet some faults, such as major cross-connections or direct stormwater connections, lead to substantially larger inflows. Future research could better differentiate these impacts, allowing for prioritization of high-impact failures to improve cost-effectiveness and enable more targeted data gathering.

Finally, the VoI approach could be extended beyond private networks. Applying this method to municipal networks and other critical components of the wastewater system, such as pumping stations, stormwater infrastructure, or combined sewer overflows, would support broader, system-level decisions. This comprehensive application would empower municipalities to evaluate where investigations and interventions yield the most value across the entire system, rather than being confined solely to the private side. Together, these advancements can make the VoI framework an even more robust and versatile tool for sustainable wastewater management.

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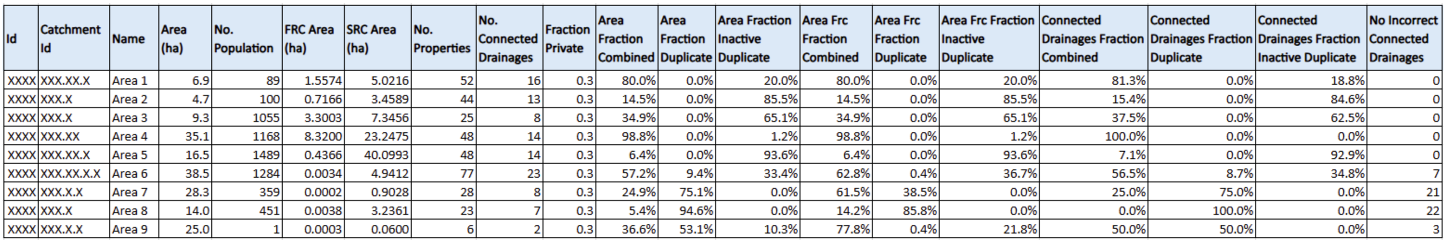
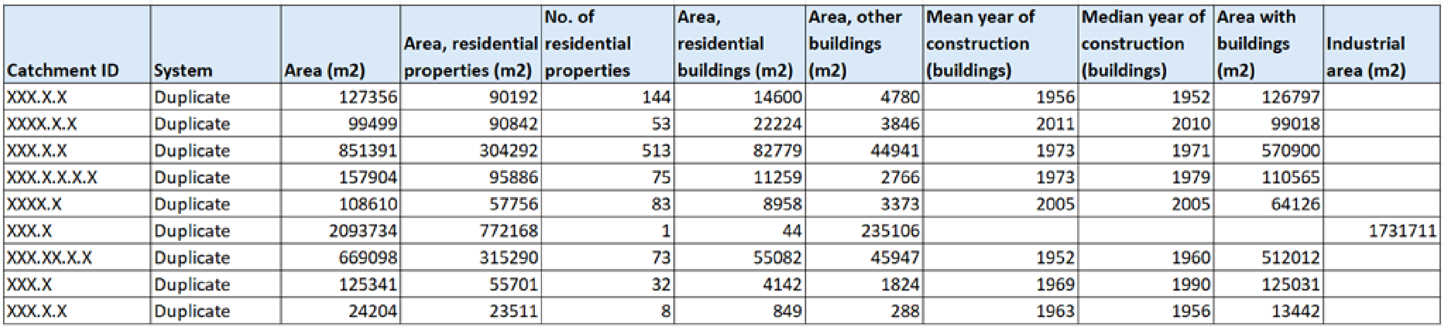
Appendix A



Id	Catchment Id	Name	Area (ha)	No. Population	FRC Area (ha)	SRC Area (ha)	No. Properties	No. Connected Drainages	Fraction Private	Area Fraction Combined	Area Fraction Duplicate	Area Fraction Inactive Duplicate	Area Frc Fraction Combined	Area Frc Fraction Duplicate	Area Frc Fraction Inactive Duplicate	Connected Drainages Fraction Combined	Connected Drainages Fraction Duplicate	Connected Drainages Fraction Inactive Duplicate	No Incorrect Connected Drainages
XXXX	XXX.XX.X	Area 1	6.9	89	1.5574	5.0216	52	16	0.3	80.0%	0.0%	20.0%	80.0%	0.0%	20.0%	81.3%	0.0%	18.8%	0
XXXX	XXX.X	Area 2	4.7	100	0.7166	3.4589	44	13	0.3	14.5%	0.0%	85.5%	14.5%	0.0%	85.5%	15.4%	0.0%	84.6%	0
XXXX	XXX.X	Area 3	9.3	1055	3.3003	7.3456	25	8	0.3	34.9%	0.0%	65.1%	34.9%	0.0%	65.1%	37.5%	0.0%	62.5%	0
XXXX	XXX.XX	Area 4	35.1	1168	8.3200	23.2475	48	14	0.3	98.8%	0.0%	1.2%	98.8%	0.0%	1.2%	100.0%	0.0%	0.0%	0
XXXX	XXX.XX.X	Area 5	16.5	1489	0.4366	40.0993	48	14	0.3	6.4%	0.0%	93.6%	6.4%	0.0%	93.6%	7.1%	0.0%	92.9%	0
XXXX	XXX.XX.X.X	Area 6	38.5	1284	0.0034	4.9412	77	23	0.3	57.2%	9.4%	33.4%	62.8%	0.4%	36.7%	56.5%	8.7%	34.8%	7
XXXX	XXX.X.X	Area 7	28.3	359	0.0002	0.9028	28	8	0.3	24.9%	75.1%	0.0%	61.5%	38.5%	0.0%	25.0%	75.0%	0.0%	21
XXXX	XXX.X	Area 8	14.0	451	0.0038	3.2361	23	7	0.3	5.4%	94.6%	0.0%	14.2%	85.8%	0.0%	0.0%	100.0%	0.0%	22
XXXX	XXX.X.X	Area 9	25.0	1	0.0003	0.0600	6	2	0.3	36.6%	53.1%	10.3%	77.8%	0.4%	21.8%	50.0%	50.0%	0.0%	3

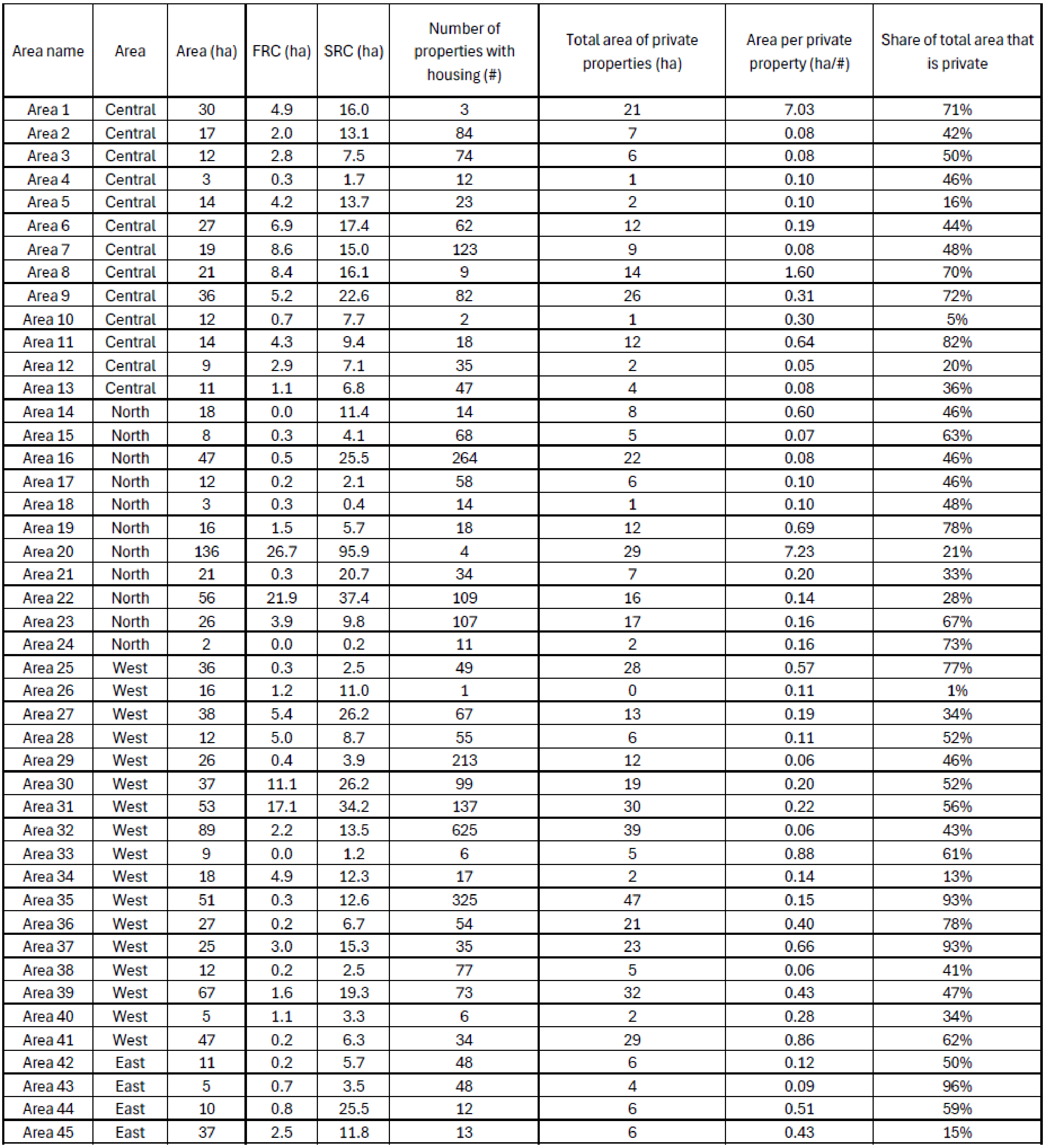
Figure 8.1: Extraction of raw data from future city flow.



Catchment ID	System	Area (m2)	Area, residential properties (m2)	No. of residential properties	Area, residential buildings (m2)	Area, other buildings (m2)	Mean year of construction (buildings)	Median year of construction (buildings)	Area with buildings (m2)	Industrial area (m2)
XXX.X.X	Duplicate	127356	90192	144	14600	4780	1956	1952	126797	
XXXX.X.X	Duplicate	99499	90842	53	22224	3846	2011	2010	99018	
XXX.X.X	Duplicate	851391	304292	513	82779	44941	1973	1971	570900	
XXX.X.X.X.X	Duplicate	157904	95886	75	11259	2766	1973	1979	110565	
XXXX.X	Duplicate	108610	57756	83	8958	3373	2005	2005	64126	
XXX.X	Duplicate	2093734	772168	1	44	235106				1731711
XXX.XX.X.X	Duplicate	669098	315290	73	55082	45947	1952	1960	512012	
XXX.X	Duplicate	125341	55701	32	4142	1824	1969	1990	125031	
XXX.X.X	Duplicate	24204	23511	8	849	288	1963	1956	13442	

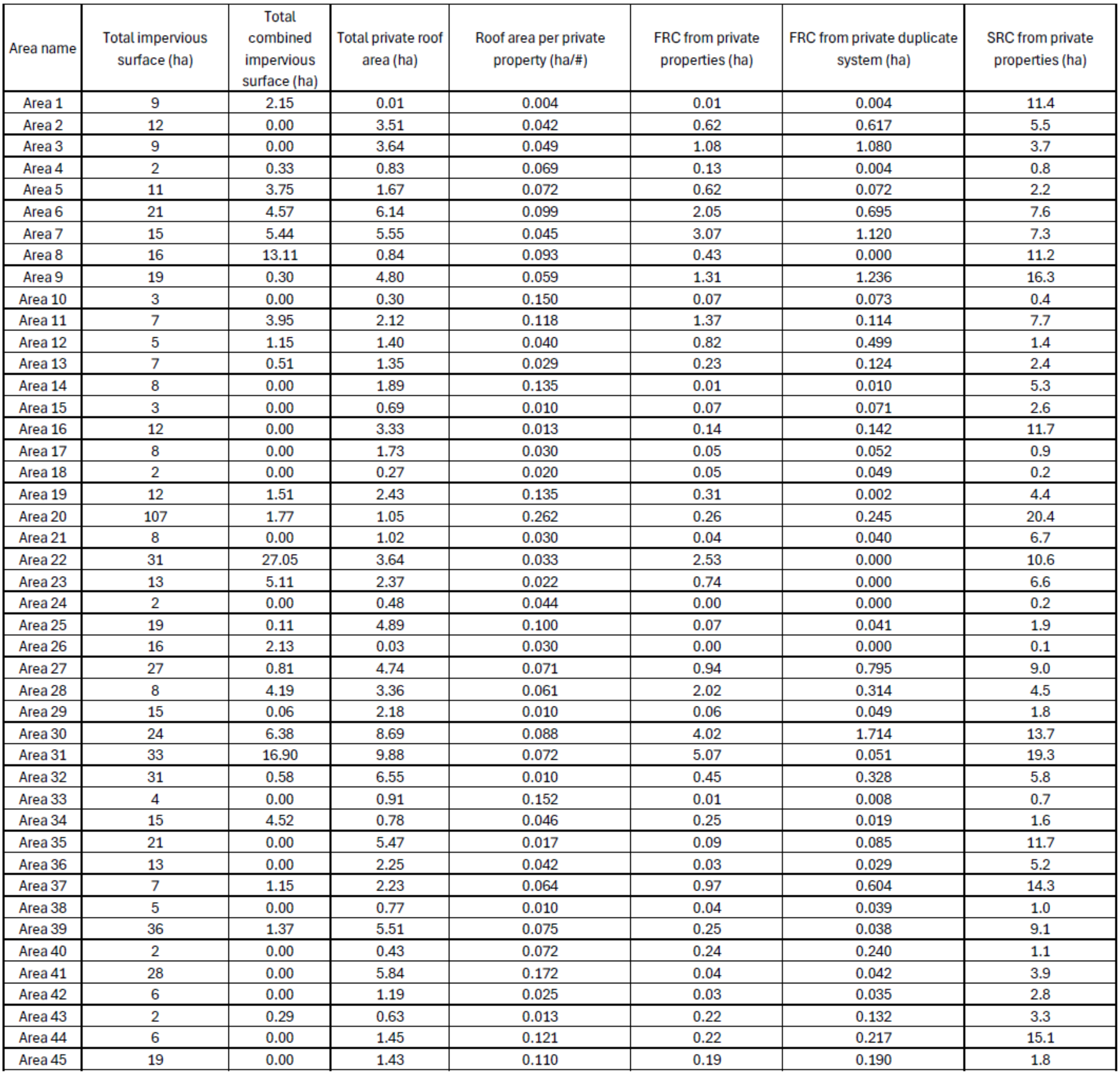
Figure 8.2: Extraction of raw data from GIS.

Appendix B



Area name	Area	Area (ha)	FRC (ha)	SRC (ha)	Number of properties with housing (#)	Total area of private properties (ha)	Area per private property (ha/#)	Share of total area that is private
Area 1	Central	30	4.9	16.0	3	21	7.03	71%
Area 2	Central	17	2.0	13.1	84	7	0.08	42%
Area 3	Central	12	2.8	7.5	74	6	0.08	50%
Area 4	Central	3	0.3	1.7	12	1	0.10	46%
Area 5	Central	14	4.2	13.7	23	2	0.10	16%
Area 6	Central	27	6.9	17.4	62	12	0.19	44%
Area 7	Central	19	8.6	15.0	123	9	0.08	48%
Area 8	Central	21	8.4	16.1	9	14	1.60	70%
Area 9	Central	36	5.2	22.6	82	26	0.31	72%
Area 10	Central	12	0.7	7.7	2	1	0.30	5%
Area 11	Central	14	4.3	9.4	18	12	0.64	82%
Area 12	Central	9	2.9	7.1	35	2	0.05	20%
Area 13	Central	11	1.1	6.8	47	4	0.08	36%
Area 14	North	18	0.0	11.4	14	8	0.60	46%
Area 15	North	8	0.3	4.1	68	5	0.07	63%
Area 16	North	47	0.5	25.5	264	22	0.08	46%
Area 17	North	12	0.2	2.1	58	6	0.10	46%
Area 18	North	3	0.3	0.4	14	1	0.10	48%
Area 19	North	16	1.5	5.7	18	12	0.69	78%
Area 20	North	136	26.7	95.9	4	29	7.23	21%
Area 21	North	21	0.3	20.7	34	7	0.20	33%
Area 22	North	56	21.9	37.4	109	16	0.14	28%
Area 23	North	26	3.9	9.8	107	17	0.16	67%
Area 24	North	2	0.0	0.2	11	2	0.16	73%
Area 25	West	36	0.3	2.5	49	28	0.57	77%
Area 26	West	16	1.2	11.0	1	0	0.11	1%
Area 27	West	38	5.4	26.2	67	13	0.19	34%
Area 28	West	12	5.0	8.7	55	6	0.11	52%
Area 29	West	26	0.4	3.9	213	12	0.06	46%
Area 30	West	37	11.1	26.2	99	19	0.20	52%
Area 31	West	53	17.1	34.2	137	30	0.22	56%
Area 32	West	89	2.2	13.5	625	39	0.06	43%
Area 33	West	9	0.0	1.2	6	5	0.88	61%
Area 34	West	18	4.9	12.3	17	2	0.14	13%
Area 35	West	51	0.3	12.6	325	47	0.15	93%
Area 36	West	27	0.2	6.7	54	21	0.40	78%
Area 37	West	25	3.0	15.3	35	23	0.66	93%
Area 38	West	12	0.2	2.5	77	5	0.06	41%
Area 39	West	67	1.6	19.3	73	32	0.43	47%
Area 40	West	5	1.1	3.3	6	2	0.28	34%
Area 41	West	47	0.2	6.3	34	29	0.86	62%
Area 42	East	11	0.2	5.7	48	6	0.12	50%
Area 43	East	5	0.7	3.5	48	4	0.09	96%
Area 44	East	10	0.8	25.5	12	6	0.51	59%
Area 45	East	37	2.5	11.8	13	6	0.43	15%

Figure 8.3: Data.



Area name	Total impervious surface (ha)	Total combined impervious surface (ha)	Total private roof area (ha)	Roof area per private property (ha/#)	FRC from private properties (ha)	FRC from private duplicate system (ha)	SRC from private properties (ha)
Area 1	9	2.15	0.01	0.004	0.01	0.004	11.4
Area 2	12	0.00	3.51	0.042	0.62	0.617	5.5
Area 3	9	0.00	3.64	0.049	1.08	1.080	3.7
Area 4	2	0.33	0.83	0.069	0.13	0.004	0.8
Area 5	11	3.75	1.67	0.072	0.62	0.072	2.2
Area 6	21	4.57	6.14	0.099	2.05	0.695	7.6
Area 7	15	5.44	5.55	0.045	3.07	1.120	7.3
Area 8	16	13.11	0.84	0.093	0.43	0.000	11.2
Area 9	19	0.30	4.80	0.059	1.31	1.236	16.3
Area 10	3	0.00	0.30	0.150	0.07	0.073	0.4
Area 11	7	3.95	2.12	0.118	1.37	0.114	7.7
Area 12	5	1.15	1.40	0.040	0.82	0.499	1.4
Area 13	7	0.51	1.35	0.029	0.23	0.124	2.4
Area 14	8	0.00	1.89	0.135	0.01	0.010	5.3
Area 15	3	0.00	0.69	0.010	0.07	0.071	2.6
Area 16	12	0.00	3.33	0.013	0.14	0.142	11.7
Area 17	8	0.00	1.73	0.030	0.05	0.052	0.9
Area 18	2	0.00	0.27	0.020	0.05	0.049	0.2
Area 19	12	1.51	2.43	0.135	0.31	0.002	4.4
Area 20	107	1.77	1.05	0.262	0.26	0.245	20.4
Area 21	8	0.00	1.02	0.030	0.04	0.040	6.7
Area 22	31	27.05	3.64	0.033	2.53	0.000	10.6
Area 23	13	5.11	2.37	0.022	0.74	0.000	6.6
Area 24	2	0.00	0.48	0.044	0.00	0.000	0.2
Area 25	19	0.11	4.89	0.100	0.07	0.041	1.9
Area 26	16	2.13	0.03	0.030	0.00	0.000	0.1
Area 27	27	0.81	4.74	0.071	0.94	0.795	9.0
Area 28	8	4.19	3.36	0.061	2.02	0.314	4.5
Area 29	15	0.06	2.18	0.010	0.06	0.049	1.8
Area 30	24	6.38	8.69	0.088	4.02	1.714	13.7
Area 31	33	16.90	9.88	0.072	5.07	0.051	19.3
Area 32	31	0.58	6.55	0.010	0.45	0.328	5.8
Area 33	4	0.00	0.91	0.152	0.01	0.008	0.7
Area 34	15	4.52	0.78	0.046	0.25	0.019	1.6
Area 35	21	0.00	5.47	0.017	0.09	0.085	11.7
Area 36	13	0.00	2.25	0.042	0.03	0.029	5.2
Area 37	7	1.15	2.23	0.064	0.97	0.604	14.3
Area 38	5	0.00	0.77	0.010	0.04	0.039	1.0
Area 39	36	1.37	5.51	0.075	0.25	0.038	9.1
Area 40	2	0.00	0.43	0.072	0.24	0.240	1.1
Area 41	28	0.00	5.84	0.172	0.04	0.042	3.9
Area 42	6	0.00	1.19	0.025	0.03	0.035	2.8
Area 43	2	0.29	0.63	0.013	0.22	0.132	3.3
Area 44	6	0.00	1.45	0.121	0.22	0.217	15.1
Area 45	19	0.00	1.43	0.110	0.19	0.190	1.8

Figure 8.4: Data.

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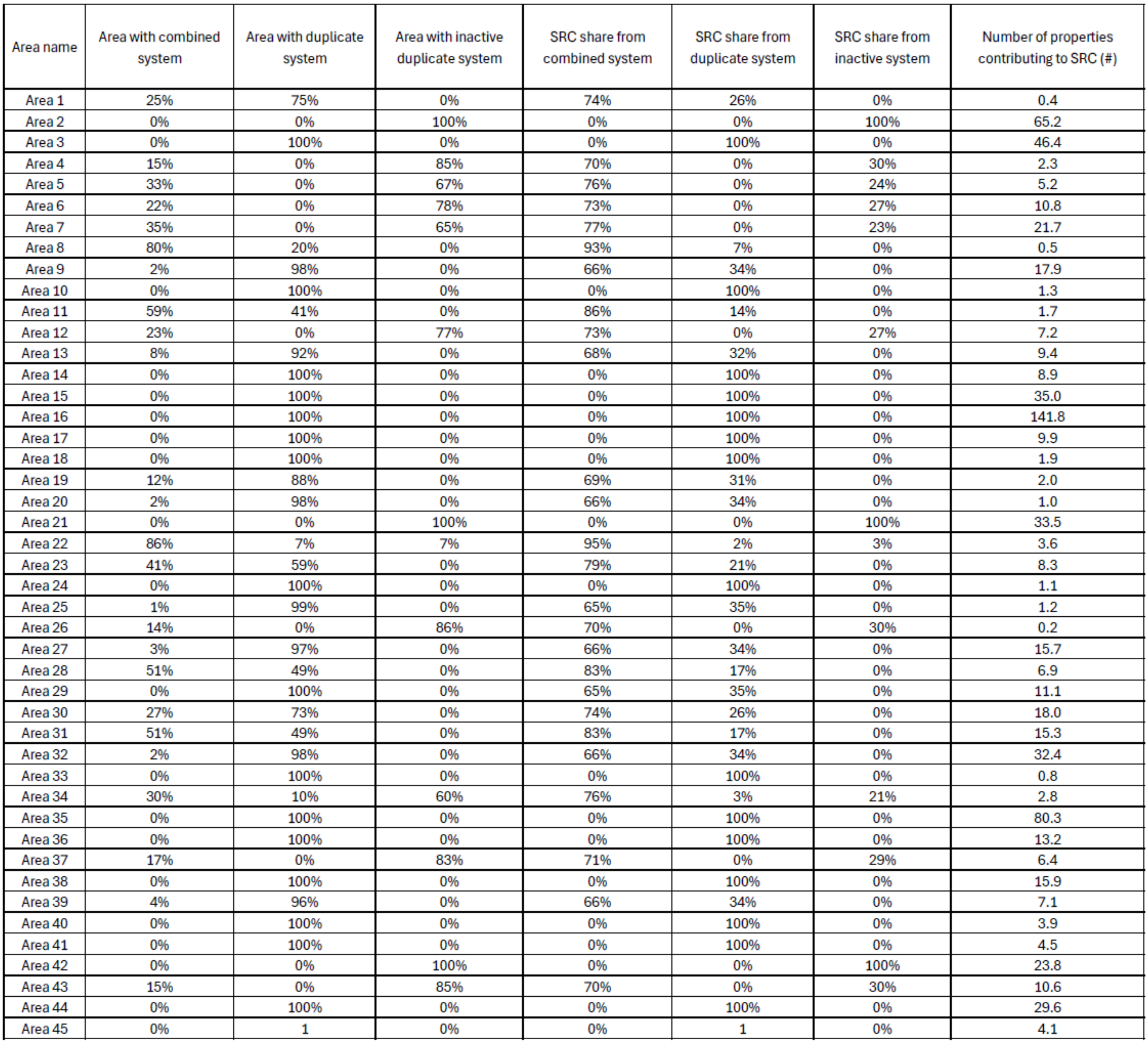

Area name	Area with combined system	Area with duplicate system	Area with inactive duplicate system	SRC share from combined system	SRC share from duplicate system	SRC share from inactive system	Number of properties contributing to SRC (#)
Area 1	25%	75%	0%	74%	26%	0%	0.4
Area 2	0%	0%	100%	0%	0%	100%	65.2
Area 3	0%	100%	0%	0%	100%	0%	46.4
Area 4	15%	0%	85%	70%	0%	30%	2.3
Area 5	33%	0%	67%	76%	0%	24%	5.2
Area 6	22%	0%	78%	73%	0%	27%	10.8
Area 7	35%	0%	65%	77%	0%	23%	21.7
Area 8	80%	20%	0%	93%	7%	0%	0.5
Area 9	2%	98%	0%	66%	34%	0%	17.9
Area 10	0%	100%	0%	0%	100%	0%	1.3
Area 11	59%	41%	0%	86%	14%	0%	1.7
Area 12	23%	0%	77%	73%	0%	27%	7.2
Area 13	8%	92%	0%	68%	32%	0%	9.4
Area 14	0%	100%	0%	0%	100%	0%	8.9
Area 15	0%	100%	0%	0%	100%	0%	35.0
Area 16	0%	100%	0%	0%	100%	0%	141.8
Area 17	0%	100%	0%	0%	100%	0%	9.9
Area 18	0%	100%	0%	0%	100%	0%	1.9
Area 19	12%	88%	0%	69%	31%	0%	2.0
Area 20	2%	98%	0%	66%	34%	0%	1.0
Area 21	0%	0%	100%	0%	0%	100%	33.5
Area 22	86%	7%	7%	95%	2%	3%	3.6
Area 23	41%	59%	0%	79%	21%	0%	8.3
Area 24	0%	100%	0%	0%	100%	0%	1.1
Area 25	1%	99%	0%	65%	35%	0%	1.2
Area 26	14%	0%	86%	70%	0%	30%	0.2
Area 27	3%	97%	0%	66%	34%	0%	15.7
Area 28	51%	49%	0%	83%	17%	0%	6.9
Area 29	0%	100%	0%	65%	35%	0%	11.1
Area 30	27%	73%	0%	74%	26%	0%	18.0
Area 31	51%	49%	0%	83%	17%	0%	15.3
Area 32	2%	98%	0%	66%	34%	0%	32.4
Area 33	0%	100%	0%	0%	100%	0%	0.8
Area 34	30%	10%	60%	76%	3%	21%	2.8
Area 35	0%	100%	0%	0%	100%	0%	80.3
Area 36	0%	100%	0%	0%	100%	0%	13.2
Area 37	17%	0%	83%	71%	0%	29%	6.4
Area 38	0%	100%	0%	0%	100%	0%	15.9
Area 39	4%	96%	0%	66%	34%	0%	7.1
Area 40	0%	100%	0%	0%	100%	0%	3.9
Area 41	0%	100%	0%	0%	100%	0%	4.5
Area 42	0%	0%	100%	0%	0%	100%	23.8
Area 43	15%	0%	85%	70%	0%	30%	10.6
Area 44	0%	100%	0%	0%	100%	0%	29.6
Area 45	0%	1	0%	0%	1	0%	4.1

Figure 8.5: Data.

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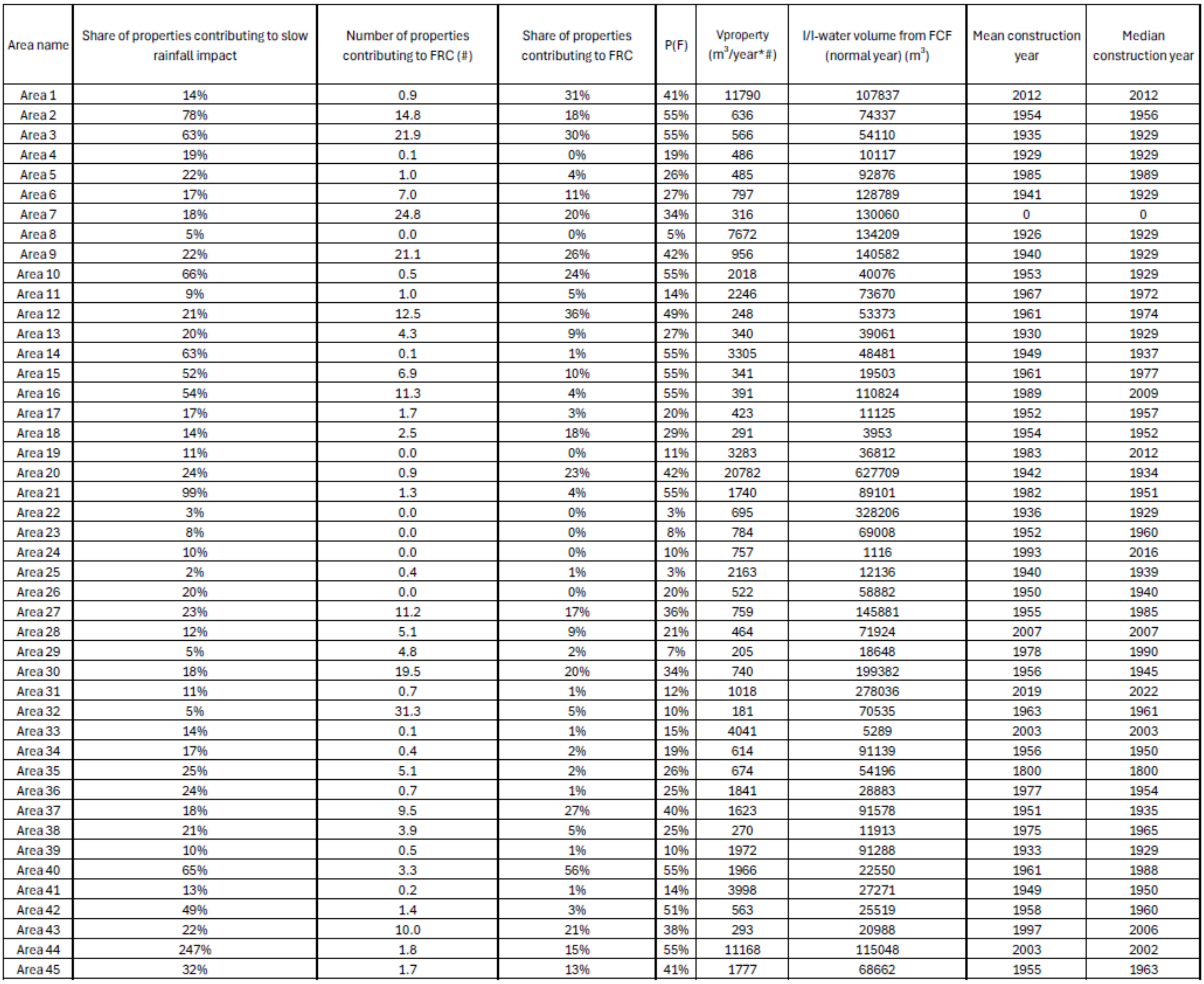

Area name	Share of properties contributing to slow rainfall impact	Number of properties contributing to FRC (#)	Share of properties contributing to FRC	P(F)	Vproperty (m^3/year*#)	I/I-water volume from FCF (normal year) (m^3)	Mean construction year	Median construction year
Area 1	14%	0.9	31%	41%	11790	107837	2012	2012
Area 2	78%	14.8	18%	55%	636	74337	1954	1956
Area 3	63%	21.9	30%	55%	566	54110	1935	1929
Area 4	19%	0.1	0%	19%	486	10117	1929	1929
Area 5	22%	1.0	4%	26%	485	92876	1985	1989
Area 6	17%	7.0	11%	27%	797	128789	1941	1929
Area 7	18%	24.8	20%	34%	316	130060	0	0
Area 8	5%	0.0	0%	5%	7672	134209	1926	1929
Area 9	22%	21.1	26%	42%	956	140582	1940	1929
Area 10	66%	0.5	24%	55%	2018	40076	1953	1929
Area 11	9%	1.0	5%	14%	2246	73670	1967	1972
Area 12	21%	12.5	36%	49%	248	53373	1961	1974
Area 13	20%	4.3	9%	27%	340	39061	1930	1929
Area 14	63%	0.1	1%	55%	3305	48481	1949	1937
Area 15	52%	6.9	10%	55%	341	19503	1961	1977
Area 16	54%	11.3	4%	55%	391	110824	1989	2009
Area 17	17%	1.7	3%	20%	423	11125	1952	1957
Area 18	14%	2.5	18%	29%	291	3953	1954	1952
Area 19	11%	0.0	0%	11%	3283	36812	1983	2012
Area 20	24%	0.9	23%	42%	20782	627709	1942	1934
Area 21	99%	1.3	4%	55%	1740	89101	1982	1951
Area 22	3%	0.0	0%	3%	695	328206	1936	1929
Area 23	8%	0.0	0%	8%	784	69008	1952	1960
Area 24	10%	0.0	0%	10%	757	1116	1993	2016
Area 25	2%	0.4	1%	3%	2163	12136	1940	1939
Area 26	20%	0.0	0%	20%	522	58882	1950	1940
Area 27	23%	11.2	17%	36%	759	145881	1955	1985
Area 28	12%	5.1	9%	21%	464	71924	2007	2007
Area 29	5%	4.8	2%	7%	205	18648	1978	1990
Area 30	18%	19.5	20%	34%	740	199382	1956	1945
Area 31	11%	0.7	1%	12%	1018	278036	2019	2022
Area 32	5%	31.3	5%	10%	181	70535	1963	1961
Area 33	14%	0.1	1%	15%	4041	5289	2003	2003
Area 34	17%	0.4	2%	19%	614	91139	1956	1950
Area 35	25%	5.1	2%	26%	674	54196	1800	1800
Area 36	24%	0.7	1%	25%	1841	28883	1977	1954
Area 37	18%	9.5	27%	40%	1623	91578	1951	1935
Area 38	21%	3.9	5%	25%	270	11913	1975	1965
Area 39	10%	0.5	1%	10%	1972	91288	1933	1929
Area 40	65%	3.3	56%	55%	1966	22550	1961	1988
Area 41	13%	0.2	1%	14%	3998	27271	1949	1950
Area 42	49%	1.4	3%	51%	563	25519	1958	1960
Area 43	22%	10.0	21%	38%	293	20988	1997	2006
Area 44	247%	1.8	15%	55%	11168	115048	2003	2002
Area 45	32%	1.7	13%	41%	1777	68662	1955	1963

Figure 8.6: Data.

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Appendix C

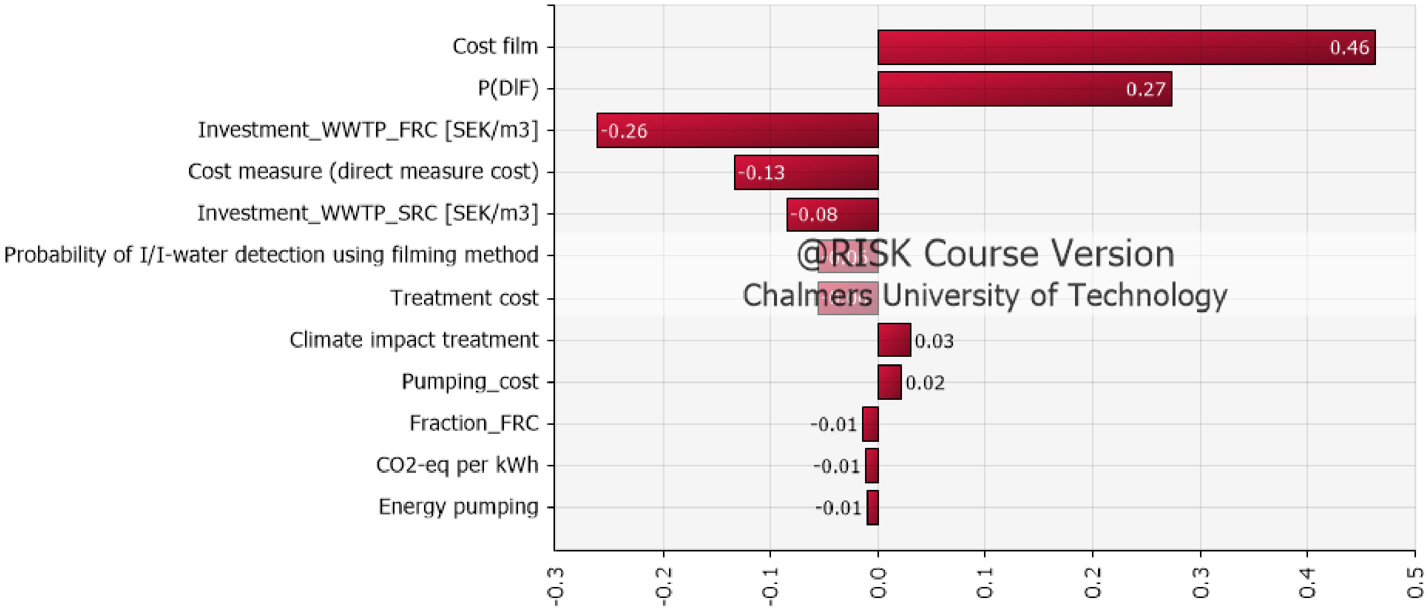

Figure 8.7: Spearman rank correlation coefficients for the value of information from smoke testing for area 23.

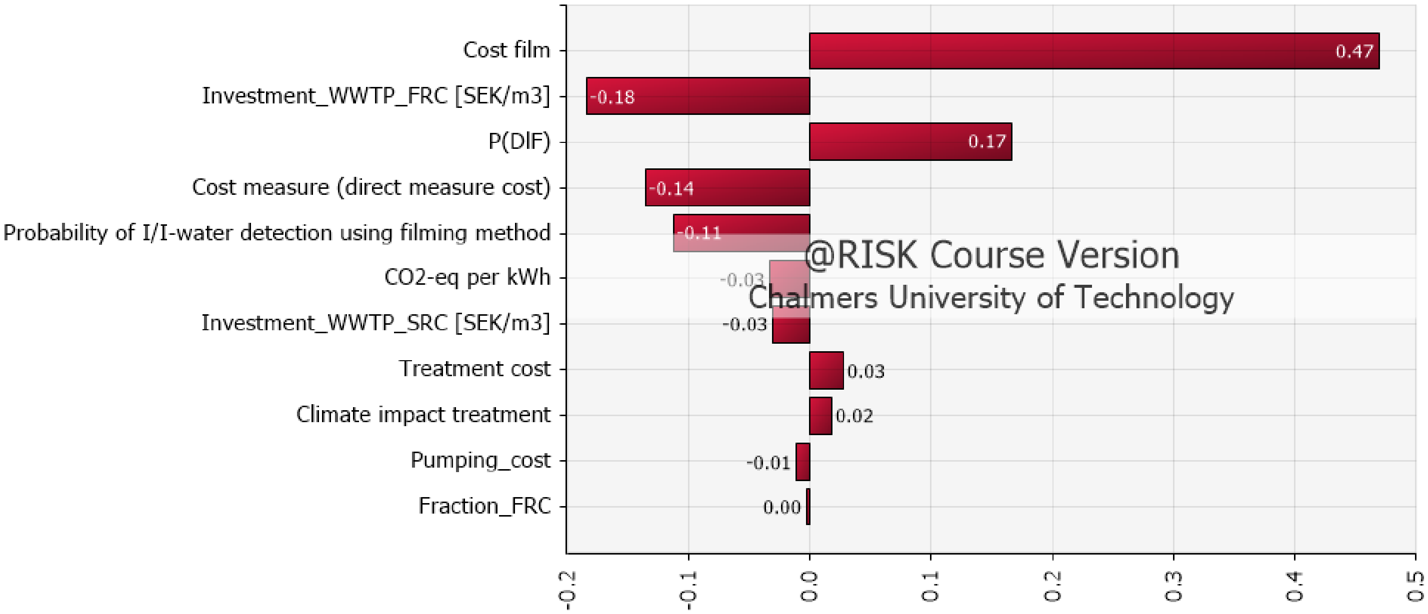

Figure 8.8: Spearman rank correlation coefficients for the value of information from dye testing for area 23.

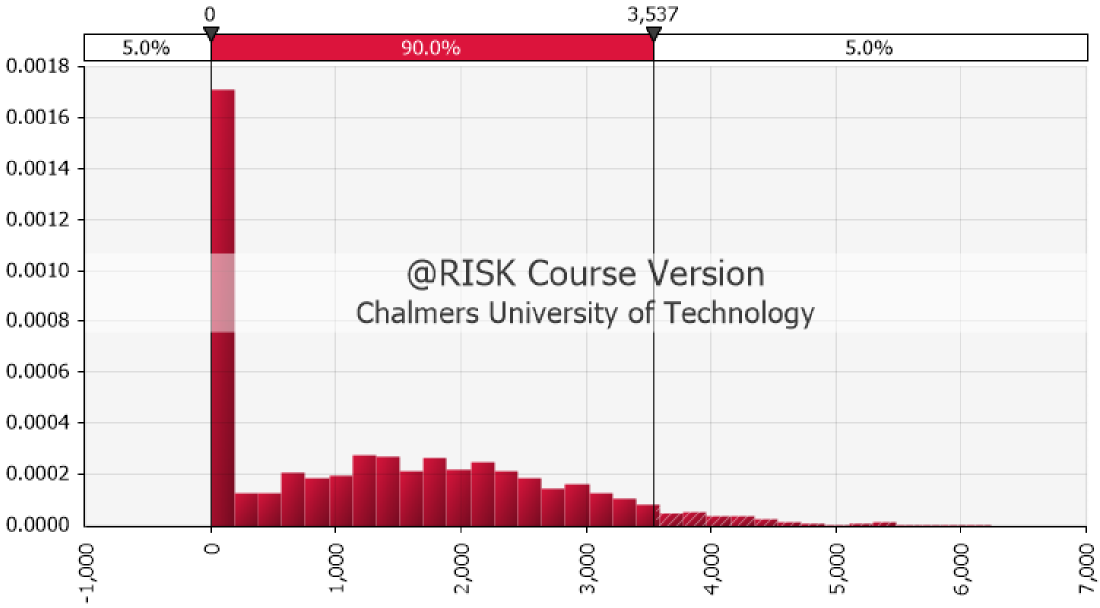

Figure 8.9: Distribution histogram for the value of information from smoke testing for area 23.

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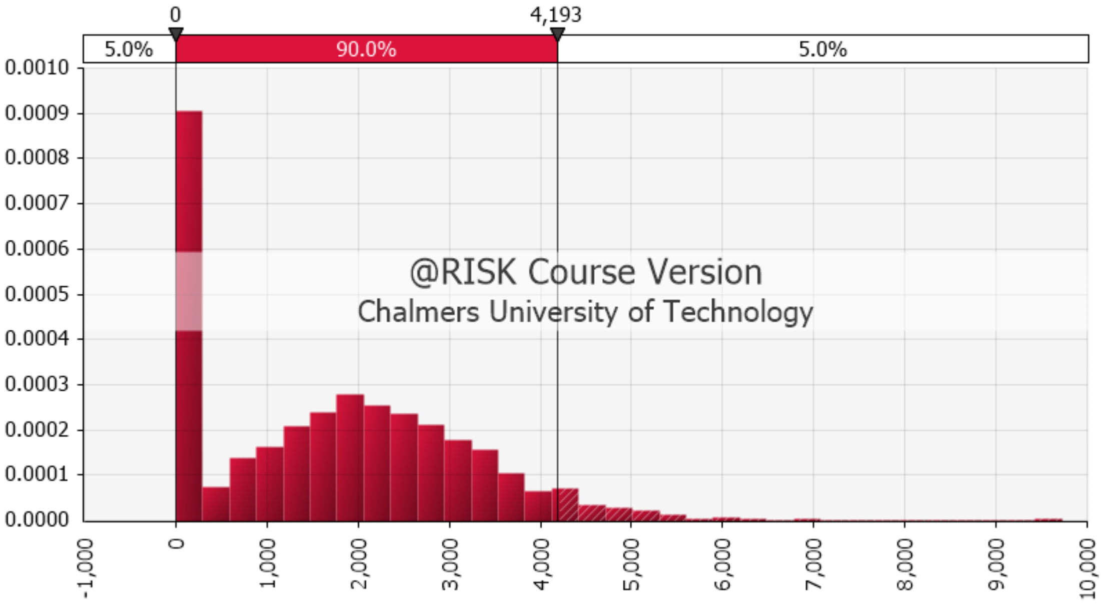

Figure 8.10: Distribution histogram for the value of information from dye testing for area 23.

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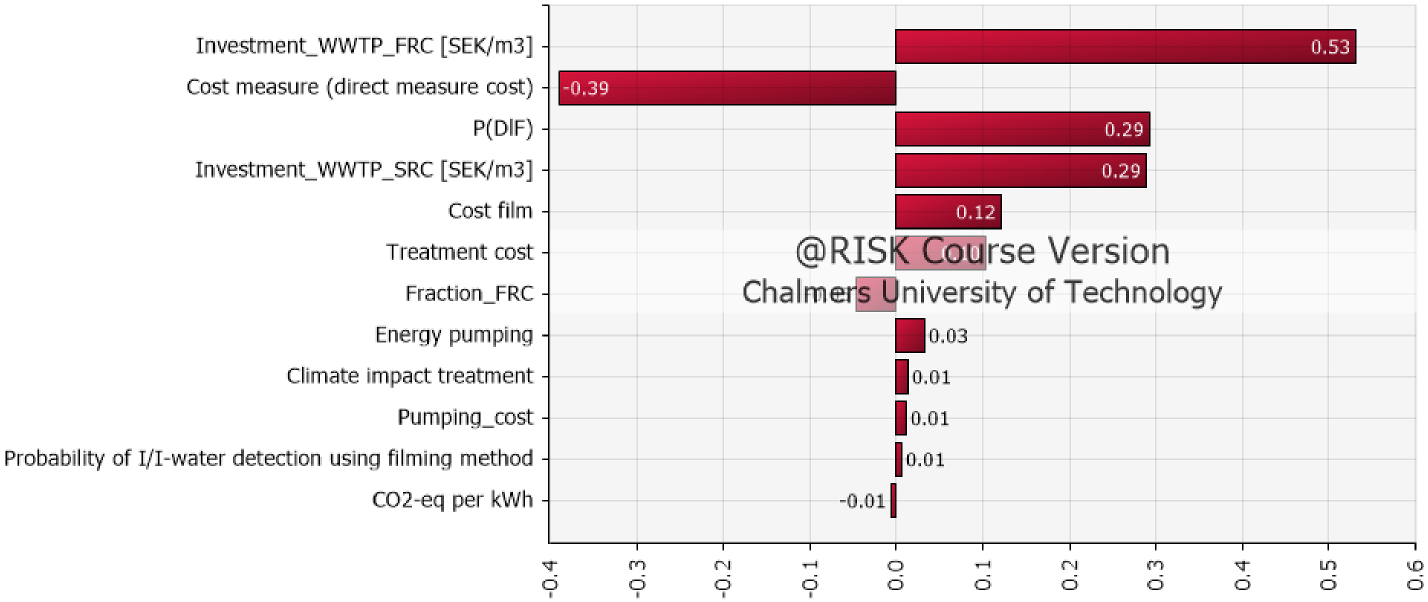

Figure 8.11: Spearman rank correlation coefficients for the value of information from smoke testing for area 22.

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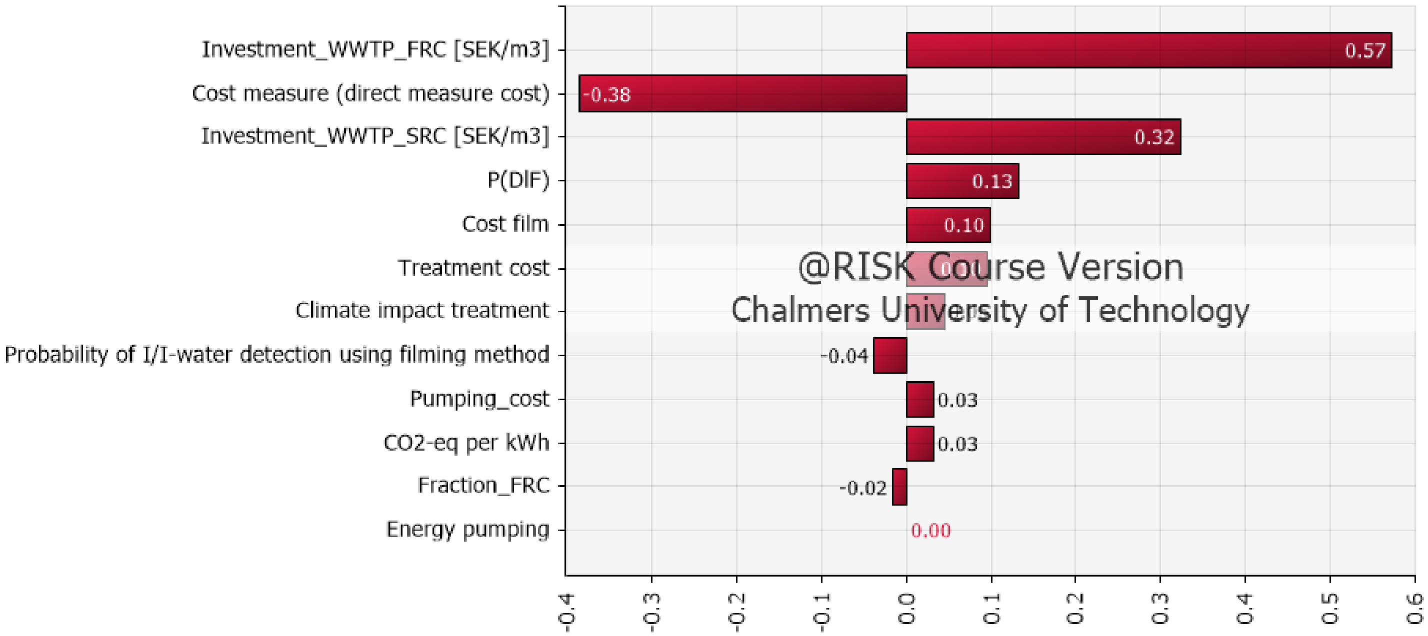

Figure 8.12: Spearman rank correlation coefficients for the value of information from dye testing for area 22.

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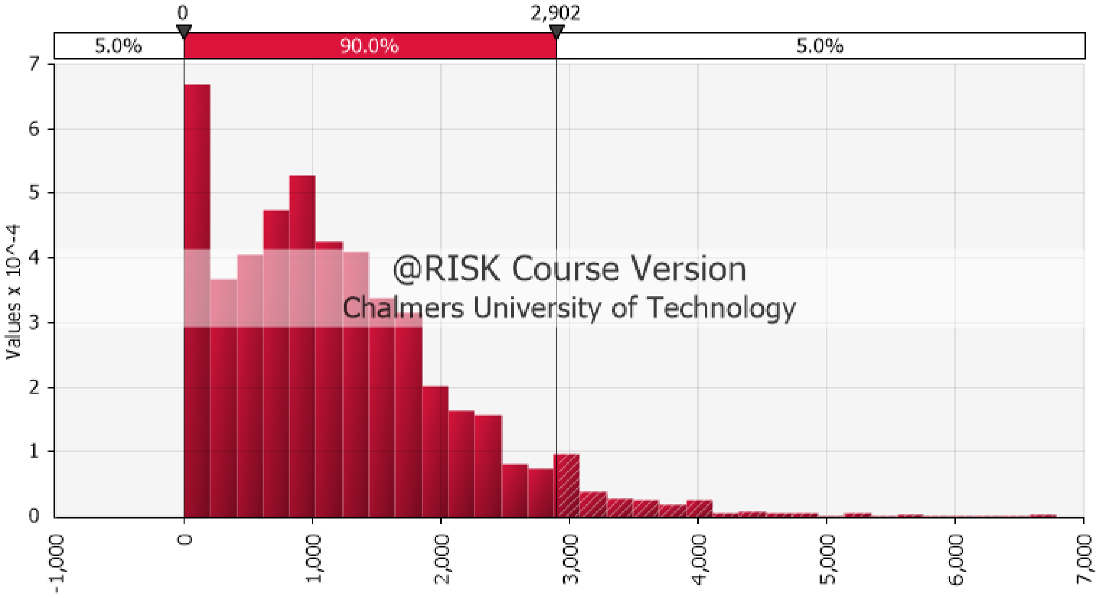

Figure 8.13: Distribution histogram for the value of information from smoke testing for area 22.

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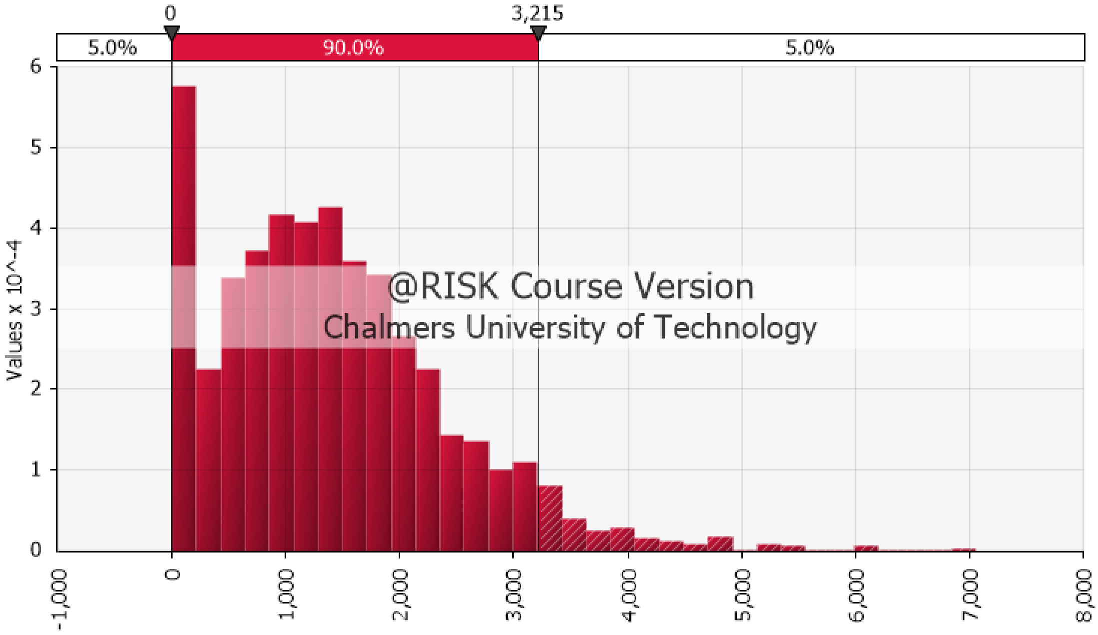

Figure 8.14: Distribution histogram for the value of information from dye testing for area 22.

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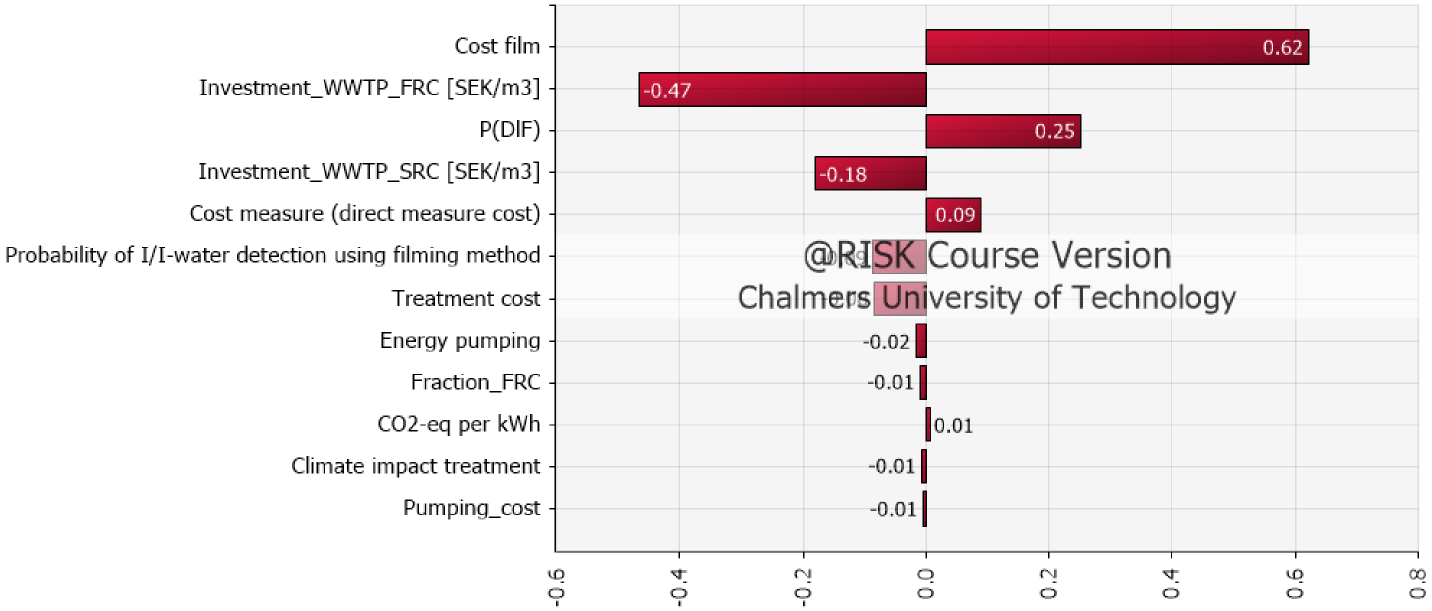

Figure 8.15: Spearman rank correlation coefficients for the value of information from dye testing for area 25.

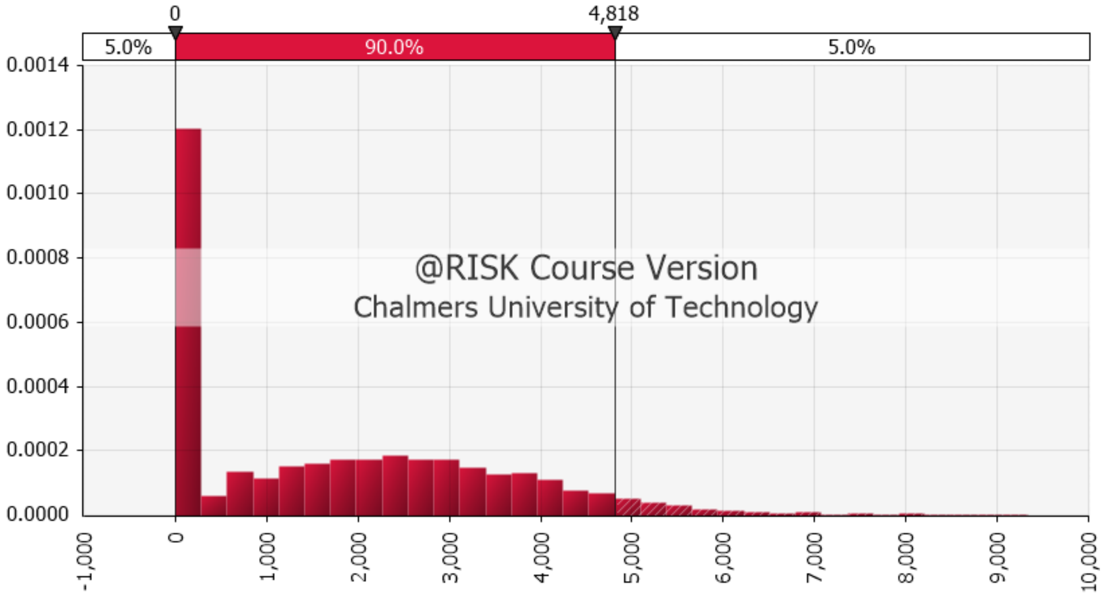

Figure 8.16: Distribution histogram for the value of information from dye testing for area 25.

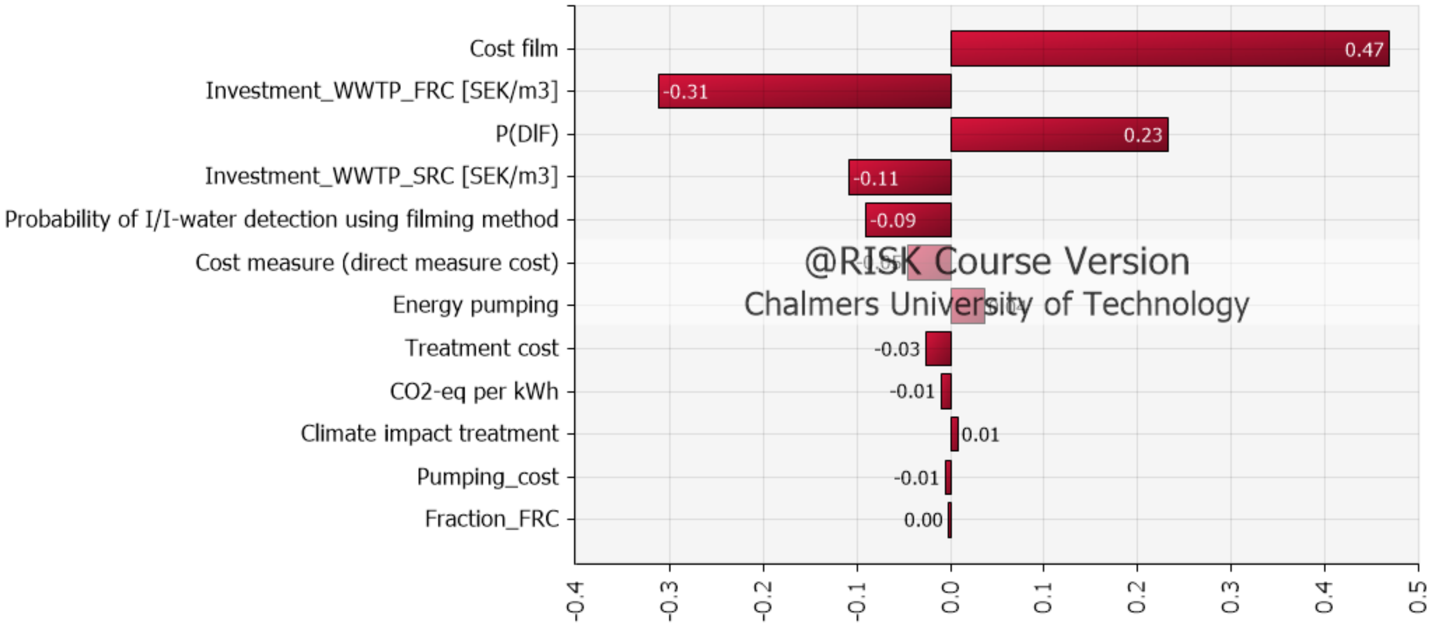

Figure 8.17: Spearman rank correlation coefficients for the value of information from dye testing for area 24.

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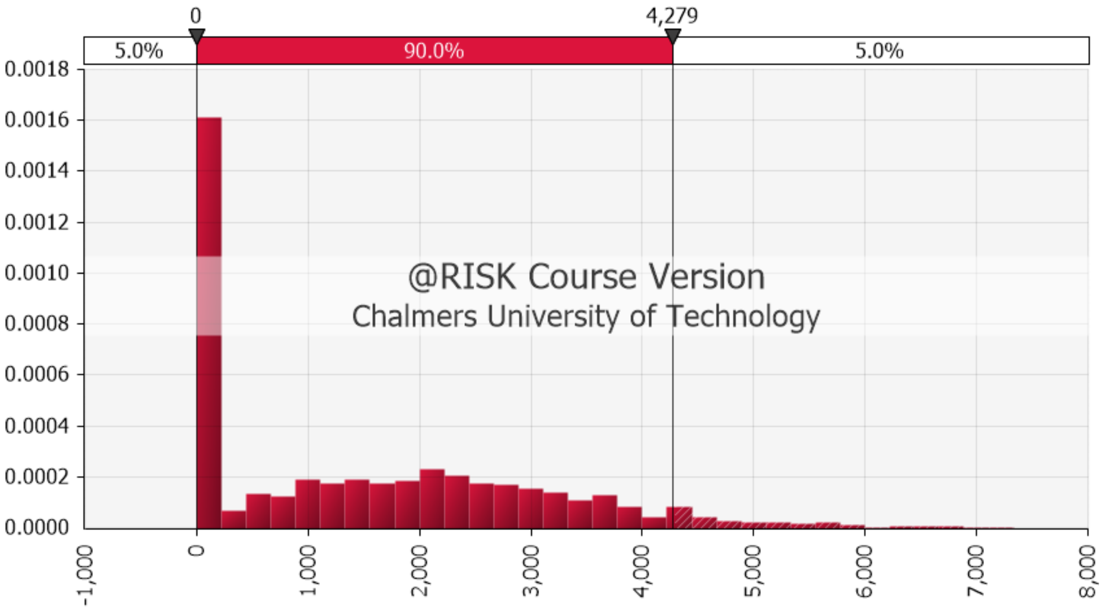

Figure 8.18: Distribution histogram for the value of information from dye testing for area 24.

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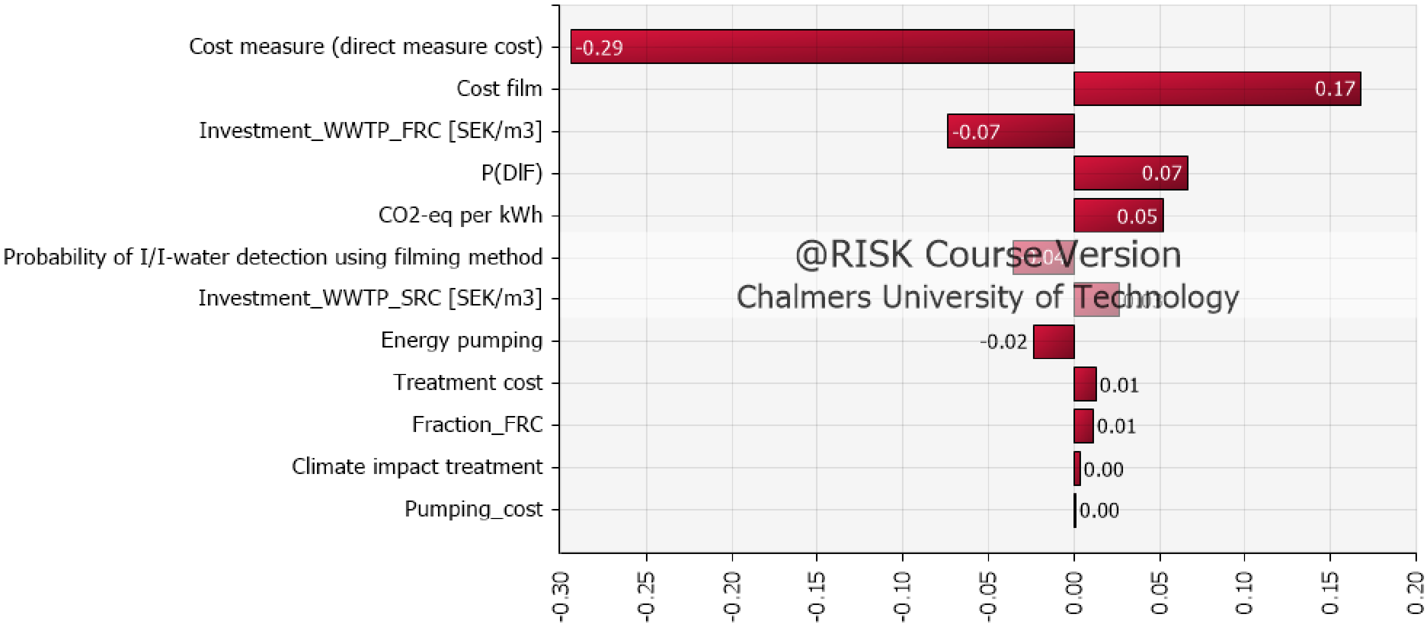

Figure 8.19: Spearman rank correlation coefficients for the value of information from smoke testing for area 7.

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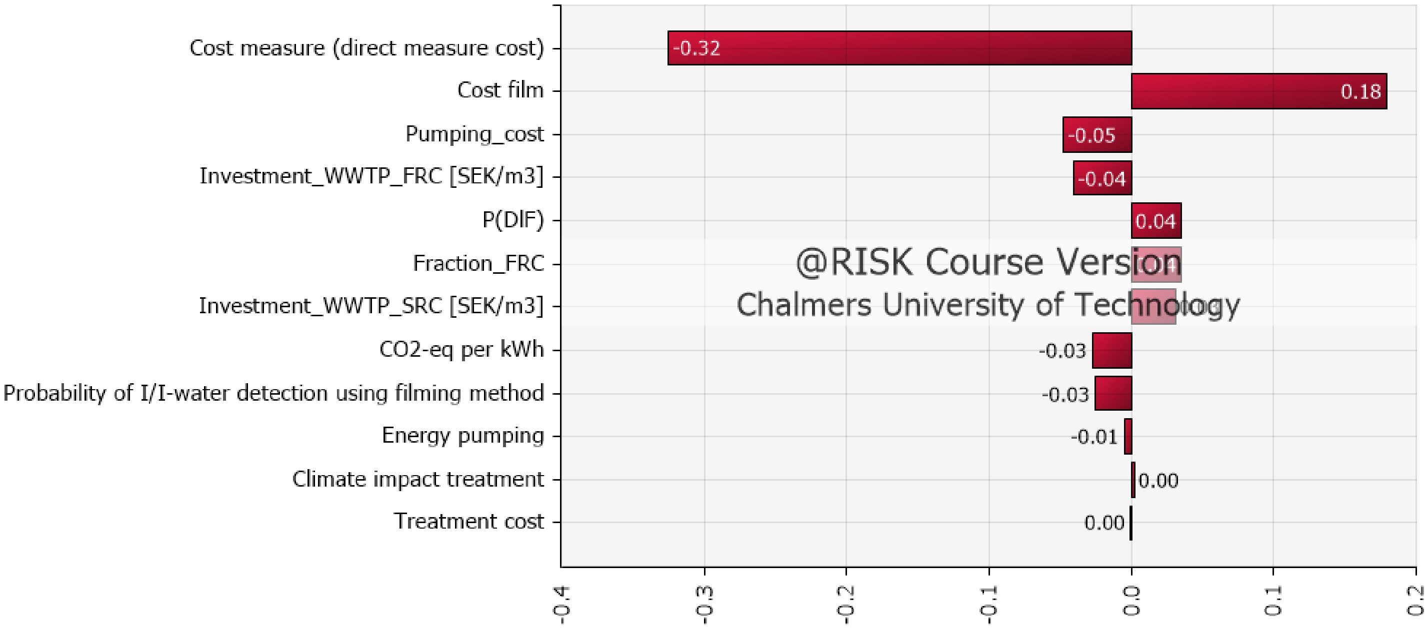

Figure 8.20: Spearman rank correlation coefficients for the value of information from dye testing for area 7.

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Appendix D

Table 8.1: VoI per property for smoke and dye testing (SCC 4; change rate 25%; SDR 3.5%; sorted from highest to lowest by dye testing VoI)

Subarea name	VoI per property for smoke testing	VoI per property for dye testing
Area 25	1,553 kr	1,875 kr
Area 31	1,417 kr	1,752 kr
Area 39	- kr	1,628 kr
Area 24	1,094 kr	1,333 kr
Area 34	993 kr	1,230 kr
Area 23	983 kr	1,193 kr
Area 35	891 kr	1,145 kr
Area 6	- kr	1,115 kr
Area 26	833 kr	1,031 kr
Area 4	756 kr	932 kr
Area 5	743 kr	924 kr
Area 28	713 kr	881 kr
Area 16	265 kr	341 kr
Area 17	608 kr	- kr

Table 8.2: Net benefit per subarea for smoke and dye testing (SCC 4; change rate 25%; SDR 3.5%; sorted from highest to lowest by dye testing net benefit)

Subarea name	Net benefit per area for smoke testing	Net benefit per area for dye testing
Area 31	107,654 kr	114,721 kr
Area 35	84,421 kr	74,813 kr
Area 39	- kr	52,080 kr
Area 25	45,167 kr	47,049 kr
Area 23	37,665 kr	29,759 kr
Area 6	- kr	12,427 kr
Area 34	6,152 kr	5,359 kr
Area 24	5,089 kr	4,603 kr
Area 4	1,496 kr	214 kr
Area 5	2,563 kr	207 kr
Area 26	202 kr	116 kr
Area 17	-1,343 kr	- kr
Area 28	4,512 kr	-1,872 kr
Area 16	-96,738 kr	-151,407 kr

Table 8.3: VoI per property for smoke and dye testing sorted from highest to lowest by dye testing (SCC 4; change rate 50%; SDR 3.5%)

Subarea name	VoI per property for smoke testing	VoI per property for dye testing
Area 25	1,745 kr	2,248 kr
Area 23	1,406 kr	1,755 kr
Area 24	1,332 kr	1,701 kr
Area 34	916 kr	1,217 kr
Area 4	866 kr	1,125 kr
Area 26	855 kr	1,121 kr
Area 28	819 kr	1,063 kr
Area 17	805 kr	1,033 kr
Area 22	829 kr	996 kr
Area 5	684 kr	899 kr
Area 13	559 kr	726 kr
Area 7	423 kr	561 kr
Area 15	191 kr	244 kr

Table 8.4: Net benefit per subarea for smoke and dye testing sorted from highest to lowest by dye testing (SCC 4; change rate 50%; SDR 3.5%)

Subarea name	Net benefit per area for smoke testing	Net benefit per area for dye testing
Area 23	82,827 kr	90,031 kr
Area 25	54,563 kr	65,382 kr
Area 22	21,583 kr	8,960 kr
Area 24	7,709 kr	8,663 kr
Area 28	10,335 kr	8,173 kr
Area 17	10,078 kr	6,878 kr
Area 34	4,841 kr	5,147 kr
Area 4	2,811 kr	2,530 kr
Area 26	223 kr	207 kr
Area 5	1,219 kr	-339 kr
Area 13	-3,382 kr	-8,821 kr
Area 7	-25,641 kr	-43,400 kr
Area 15	-29,958 kr	-45,588 kr

Table 8.5: VoI per property for smoke and dye testing sorted from highest to lowest by dye testing (SCC 4; change rate 100%; SDR 3.5%)

Area name	VoI per property for smoke testing	VoI per property for dye testing
Area 22	1,338 kr	1,613 kr
Area 23	- kr	1,507 kr
Area 17	611 kr	805 kr
Area 13	413 kr	544 kr
Area 18	368 kr	468 kr
Area 7	301 kr	391 kr
Area 43	247 kr	311 kr

Table 8.6: Net benefit per subarea for smoke and dye testing sorted from highest to lowest by dye testing (SCC 4; Change Rate 100%; SDR 3.5%)

Subarea name	Net benefit per area for smoke testing	Net benefit per area for dye testing
Area 22	76,946 kr	76,202 kr
Area 23	- kr	63,429 kr
Area 18	-3,693 kr	-6,248 kr
Area 17	-1,170 kr	-6,340 kr
Area 13	-10,293 kr	-17,407 kr
Area 43	-18,439 kr	-28,933 kr
Area 7	-40,659 kr	-64,314 kr

Table 8.7: Decision recommendations results for all subareas (SDR=3.5%, SCC=4, change rate=75%).

Subarea name	Smoke VoI analysis	Dye VoI analysis
Area 1	A1	A1
Area 2	A1	A1
Area 3	A1	A1
Area 4	Smoke	Dye
Area 5	A1	A1
Area 6	A1	A1
Area 7	Smoke	Dye
Area 8	A1	A1
Area 9	A1	A1
Area 10	A1	A1
Area 11	A1	A1
Area 12	A0	A0
Area 13	Smoke	Dye
Area 14	A1	A1
Area 15	A1	A1
Area 16	A1	A1
Area 17	Smoke	Dye
Area 18	Smoke	Dye
Area 19	A1	A1
Area 20	A1	A1
Area 21	A1	A1
Area 22	Smoke	Dye
Area 23	Smoke	Dye
Area 24	A1	Dye
Area 25	A1	Dye
Area 26	A1	A1
Area 27	A1	A1
Area 28	Smoke	Dye
Area 29	A0	A0
Area 30	A1	A1
Area 31	A1	A1
Area 32	A0	A0
Area 33	A1	A1
Area 34	A1	A1
Area 35	A1	A1
Area 36	A1	A1
Area 37	A1	A1
Area 38	A0	A0
Area 39	A1	A1
Area 40	A1	A1
Area 41	A1	A1
Area 42	A1	A1
Area 43	Smoke	Dye
Area 44	A1	A1
Area 45	A1	A1

Table 8.8: Probabilities of positive data retrieval for the value of information from smoke testing, dye testing, and from either smoke testing or dye testing.

Subarea name	Smoke better	Dye better	Any data (Smoke or Dye)
Area 1	0%	0%	0%
Area 2	4%	6%	10%
Area 3	6%	7%	13%
Area 4	29%	39%	68%
Area 5	22%	30%	52%
Area 6	10%	14%	24%
Area 7	23%	28%	51%
Area 8	0%	0%	0%
Area 9	2%	3%	5%
Area 10	0%	0%	0%
Area 11	1%	1%	2%
Area 12	15%	17%	32%
Area 13	28%	32%	59%
Area 14	0%	0%	0%
Area 15	11%	14%	25%
Area 16	9%	13%	22%
Area 17	31%	40%	71%
Area 18	26%	29%	54%
Area 19	0%	0%	0%
Area 20	0%	0%	0%
Area 21	0%	0%	0%
Area 22	36%	61%	97%
Area 23	35%	50%	84%
Area 24	31%	45%	77%
Area 25	27%	48%	75%
Area 26	27%	35%	62%
Area 27	6%	9%	15%
Area 28	28%	38%	67%
Area 29	22%	25%	47%
Area 30	7%	11%	18%
Area 31	19%	32%	51%
Area 32	18%	21%	38%
Area 33	0%	0%	0%
Area 34	23%	33%	56%
Area 35	14%	21%	35%
Area 36	0%	0%	1%
Area 37	0%	0%	1%
Area 38	26%	30%	56%
Area 39	4%	8%	12%
Area 40	0%	0%	0%
Area 41	0%	0%	0%
Area 42	7%	8%	15%
Area 43	22%	24%	46%
Area 44	0%	0%	0%
Area 45	0%	0%	0%

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