Modelling of Combined Sewer Overflow for Future Climate Change and Urban Development in Trollhättan

A quantitative and water qualitative assessment for River Göta älv as a drinking water source

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:
River Göta älv in Trollhättan, the primary surface water recipient in the study area.
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ABSTRACT

Combined sewer overflows (CSOs) are an increasing challenge that the water management in cities faces, as climate change and urbanisation increase pressure on the system. The consequences of CSO events are the release of untreated wastewater into water bodies, leading to contamination and increased health risks. In this case study, hydraulic modelling is used to simulate CSO events in Trollhättan under future climate change and urban development scenarios with a focus on changes in the parameters volume, flow, and dilution. In addition, different rain events with varying duration and intensity are compared to find the most critical one for the sewer system. In the second part of this study, a quantitative microbial risk assessment (QMRA) was performed to evaluate the health risks for drinking water consumers downstream of Trollhättan for the pathogens *Campylobacter*, norovirus, *Cryptosporidium*. Two different drinking water treatment plants (DWTPs) were evaluated; one located in Gothenburg, and another arbitrary DWTP lacking UV-disinfection. The results from the hydraulic modelling show that climate change will significantly increase the amount of CSO, and the proportion of impervious areas has a great impact where implementation of green infrastructure is shown to have a reducing impact. Another finding is that intense and short-duration rainfall events are more critical than longer and less intense rainfall events. From the QMRA, the health risk due to CSOs from the sewer network in Trollhättan does not pose a risk to the drinking water consumers in Gothenburg. However, without UV-treatment, there is a risk for *Cryptosporidium* infection, which highlights the efficiency of the UV-treatment process and the importance of sufficient and efficient treatment barriers at DWTPs.

Key words: climate change, combined sewer overflow (CSO), hydraulic modelling, rainfall duration, rainfall intensity, quantitative microbial risk assessment (QMRA), urban development

Modellering av bräddningar vid framtida klimatförändringar och stadsutveckling i Trollhättan
En kvantitativ utvärdering och kvalitetsbedömning av Göta älv som dricksvattentäkt

Examensarbete inom masterprogrammet Infrastruktur och Miljöteknik

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SAMMANFATTNING

Klimatförändringar och stadsutveckling förväntas öka belastningen på avloppsystemet i framtiden, vilket kan öka utmaningar med bräddningar. Konsekvenser av bräddningar är att orenat avloppsvatten släpps ut vilket leder till att vattendrag kontamineras och medför ökade hälsorisker. I denna studie har hydraulisk modellering använts för att simulera bräddtillfällen i Trollhättan vid framtida klimatförändringar och stadsutveckling med fokus på parametrarna volym, flöde och utspädning. Regnhändelser med varierande varaktighet och intensitet jämfördes för att identifiera den mest kritiska typen för ledningssystemet. En kvantitativ mikrobiologisk riskbedömning (QMRA) utfördes för att bedöma hälsoriskerna av *Campylobacter*, norovirus och *Cryptosporidium* för dricksvattenkonsumenter nedströms Trollhättan. Två olika vattenverk utvärderades: ett vattenverk i Göteborg och ett godtyckligt vattenverk utan UV-desinfektion. Resultaten från hydraulisk modelleringen visar att klimatförändringar markant ökar volymen bräddvatten. Andelen hårdgjorda ytor har stor inverkan på volymen bräddvatten, där införandet av gröna lösningar har en minskande effekt. Kortvariga och intensiva regn är mer kritiska för bräddning än längre och mindre intensiva regnhändelser. Resultatet från QMRA visar ingen hälsorisk för dricksvattenkonsumenter i Göteborg till följd av bräddningar från ledningsnätet i Trollhättan. Utan UV-desinfektion finns det dock en risk, till följd av ökad nederbörd, för infektion av *Cryptosporidium* vilket belyser effektiviteten av UV som beredningsprocess och vikten av antalet barriärer i ett vattenverk.

Nyckelord: bräddning, hydraulisk modellering, klimatförändringar, kvantitativ mikrobiologisk riskbedömning (QMRA), regnintensitet, regnvaraktighet, stadsutveckling

Preface

This master's thesis was written as part of the Water Environment Technology (WET) division at Chalmers University of Technology. This project would not have been possible without some people we want to thank in particular.

Firstly, we would like to thank our supervisor Thomas Pettersson for his invaluable guidance, insightful feedback, and continuous support throughout the entire project. His expertise greatly contributed to the quality and direction of our work. We are also thankful to Frank Persson for serving as our examiner and for his constructive comments that helped improve the thesis.

We appreciate the support from Trollhättan Energi AB who has supported us with a model of the sewer system and other input data for our study. A particular thank you to Anna Kauffeldt whose cooperation and local knowledge were essential for understanding the practical and modelling aspects of our study.

A special thanks goes to DHI for providing access to the software through a student license, which enabled us to carry out key parts of the hydraulic modelling.

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Gothenburg, June 2025
Emma Hansson & Elin Karlsson

Abbreviations

The following abbreviations have been used throughout this thesis and are listed below in alphabetical order:

BGI	Blue-Green Infrastructure
CSO	Combined Sewer Overflow
DWTP	Drinking Water Treatment Plant
EPA	Environmental Protection Agency
GAC	Granular Activated Carbon
I&I	Infiltration and Inflow
QMRA	Quantitative Microbial Risk Assessment
RCP	Representative Concentration Pathway
SMHI	Swedish Meteorological and Hydrological Institute
SuDS	Sustainable Urban Drainage System
WWTP	Wastewater Treatment Plant

Contents

1 Introduction

Climate change is a global problem caused by human activities, mainly through the emission of greenhouse gases according to the Intergovernmental Panel on Climate Change (IPCC, 2023). Global warming leads to extreme weather and climate events, today and in the future. Rising temperatures lead to an acceleration of the water cycle as warmer temperatures increase the rate of evaporation and change precipitation patterns around the world (SMHI, 2024b). In Sweden, precipitation has increased over time and is expected to continue in the same manner, with more frequent and intense heavy rainfall. The potential consequences of heavy rains are flooding and high flows, which may cause problems for society.

Urban development with more inhabitants, change in use of land areas, and new regulations and requirements regarding water and wastewater management also bring challenges. A result of urbanisation in Sweden is that most of the population lives in cities, mainly in metropolitan areas (Boverket, 2014). This, in combination with more extreme weather results in larger demands on societal functions (United Nations, 2018). A potential consequence is that drinking water sources become contaminated with microorganisms due to combined sewer overflows (Swedish Food Agency, 2024a). This happens when the sewer system has reached its capacity and untreated wastewater is being discharged to the nearest water body. Another cause of overflow is that the wastewater treatment plant (WWTP) reaches its full capacity and releases partially treated water, which can further worsen the problem. Overflows have the potential to disrupt the freshwater ecosystem, affecting human health and recreation (Perry et al., 2024).

1.1 Background

Water is a human necessity that is crucial for development and for production of food and other essentials (United Nations, 2018). In 2015, Sweden and other countries of the United Nations agreed on 17 sustainable development goals in the 2030 Agenda (United Nations, 2018). The purpose is to achieve human rights within the three dimensions of sustainable development: economic, environmental, and social. Goal 6 Clean Water and Sanitation is stated to "Ensure availability and sustainable management of water and sanitation for all", which emphasises the importance of sustainable water management (United Nations, n.d.-a). Climate action, which is goal 13 and means "Take urgent action to combat climate change and its impacts", is related to climate change with focus on increasing capacity and knowledge and thereby minimises the risk of human tragedies (United Nations, n.d.-b).

The wastewater systems in many cities in Europe are old and usually consist of combined sewage systems (Perry et al., 2024). Combined sewage systems collect stormwater and wastewater in the same pipe (Swedish EPA, 2022). The other existing wastewater system is called a duplicate or separate sewage system, where the pipes that collect stormwater and wastewater are two separate pipes. A concern with the combined system is Combined Sewer Overflow (CSO), which is the discharge of untreated wastewater to the receiving water (Perry et al., 2024). That happens when the sewer system or wastewater treatment plant reaches its capacity and is designed to prevent damage to the system and basement flooding. CSO typically occurs when the system is overloaded, for example, in the case of heavy rainfall events. With more heavy rainfalls due to climate change and in combination with an aging water infrastructure in Sweden, this has resulted in more CSO the past year according to Svenskt Vatten (2024b). The consequences of these discharges are that pollutants, including pathogens, are spread into water bodies such as rivers and streams (Perry et al., 2024). This increases the risks to human health from waterborne diseases. In many parts of the world, including developed countries like Sweden, outbreaks linked to contaminated drinking water have highlighted the ongoing challenges of ensuring a safe and reliable drinking water supply (Swedish Food Agency, 2023; WHO, 2023).

The study area, Trollhättan municipality in Southern Sweden, faces several challenges with the water infrastructure. One of the challenges is that the city aims to increase the number of inhabitants in the coming years (Trollhättans Stad, 2022). With more people in the city, more wastewater is generated. As the city grows and becomes denser, more impervious surfaces will be in place and contribute to more stormwater runoff in urban areas (Trollhättans Stad, 2021). The combination of increased amount of wastewater and stormwater will lead to a higher load on the sewer system. Another challenge for the city is climate change. During the summer of 2024, it was reported in the news that a heavy rain caused several basement floods in Trollhättan (SVT Nyheter, 2024). Population growth and the effects of climate change could potentially lead to an overloaded system with more CSOs released to the River Göta älv.

1.2 Aim

The aim of this study is to evaluate how combined sewer overflows (CSO) are affected by future climate change, with a focus on heavy and extreme rainfall, population growth, increased impervious surfaces, and the implementation of green infrastructure until the year 2100, using Trollhättan municipality as a case study. The analysis includes quantification of CSO volumes, dilution of wastewater and peak flow during overflow events, providing insights about the performance of the sewer system under these events. In addition, a water quality assessment of the River Göta älv as a drinking water source downstream of Trollhättan is conducted. This assessment involves two different types of drinking water treatment plants (DWTPs); one similar to Alelyckan DWTP in Gothenburg and one arbitrary DWTP lacking UV-disinfection. The aim is to evaluate the health risk associated with pathogens, specifically *Cryptosporidium*, norovirus, *Campylobacter*, in relation to CSO events. Based on the analyses, measures to reduce the impact of CSO in terms of both quantity and water quality are proposed.

1.3 Research Questions

The research questions to be investigated are:

- How do different rainfall duration and intensity affect the volume of combined sewer overflow and dilution of wastewater?
- How will future climate change affect the volume of combined sewer overflow for single rain events?
- How does urban development affect the volume of combined sewer overflow for a single rain event?
- What are the future health risks for drinking water consumers relying on surface water sources affected by combined sewer overflow?

1.4 Limitations and Assumptions

The geographic area for modelling the volume of CSO is municipality of Trollhättan. The study is limited to climate change with a focus on heavy and extreme rainfall and does not consider other types of climate change, such as dry periods and temperature change. The catchment areas and the sewer system are analysed, excluding the wastewater treatment plant and its processes. Trollhättan is the only municipality taken into account as a contributor to the future impacts of River Göta älv. Other municipalities between Trollhättan and Gothenburg are not considered in this study. This applies for the water quality assessment for drinking water consumers downstream of Trollhättan and in Gothenburg dependent on water from River Göta älv. The water quality assessment is performed to only evaluate the risk of infection by pathogens (*Campylobacter*, norovirus, and *Cryptosporidium*) in River Göta älv. Quality parameters such as nutrients and organic matter are not included.

2 Literature Overview

To be able to understand and manage the challenges that Combined Sewer Overflows (CSOs) bring, an overview of the existing literature is required. Previous studies put the work in context and provide insight into methodology and research gaps. The overview addresses several topics, including precipitation and climate change, CSOs, hydraulic modelling, water quality, and measures to mitigate CSO impact. In addition, an inventory of existing legislation is made to understand the requirements for the management of storm- and wastewater.

2.1 Precipitation Concepts in Water Modelling

Precipitation is an important aspect in the design and management of sewer and drainage systems in urban areas. When modelling and designing the wastewater collection system for future scenarios, it is essential to take climate change effects into account. This can, for instance, be made by applying a climate factor (Olsson et al., 2017) or using the delta-change method (Olsson et al., 2009). Other factors related to precipitation and specific rain events are the duration and intensity of the rain, as well as its return period.

2.1.1 Precipitation and Climate Change

Precipitation is part of the hydrological cycle and includes both rain and snow that fall from the atmosphere (SMHI, 2023b). In Sweden, there is a geographical distribution and a seasonal difference in precipitation (SMHI, n.d.-b). More rain falls in southwestern Sweden compared to the east, and it rains most during the summer. According to SMHI (2024b), the precipitation in Sweden will increase in the future due to climate change. This predicted trend applies to the entire country and the entire year, leading to a higher frequency of heavy rain events.

According to SMHI (2023c), heavy rain is defined as a minimum precipitation of 1 millimeter (mm) in one minute or 50 mm in 60 minutes. These extreme rains can cause flooding and urban areas are particularly vulnerable because the water drainage system may not be sufficient to handle such large amounts of rainfall, leading to a rapid accumulation of water on streets and in basements. The intensity and frequency of heavy rains have increased over the past decades in Sweden (SMHI, 2024b). Several cities have been affected by these extreme weather events. For example, Malmö suffered from a heavy rainfall in August 2014, with reported rainfall exceeding 100 mm in the morning hours (SMHI, 2024a). This rain had great economic consequences due to damages on several properties. A more recent extreme weather event occurred in August 2023, when storm Hans brought heavy rain and flooding to various parts of the country, including western Sweden. According to SMHI (2023a), August 2023 was wetter than usual, with precipitation levels exceeding historical averages in many parts of the country. This highlights the impact of climate change and the need for municipalities to be better prepared for extreme weather.

2.1.2 Rainfall Intensity and Duration and Return Period

A rain event can be described in different ways. Rainfall intensity is typically defined as the amount of precipitation falling per unit of time and can be expressed as millimeters per hour (mm/h) (Svenskt Vatten, 2016). Another parameter describing a rain is the rainfall duration, which is the total time that a rainfall event occurs. These two parameters characterise the rain event and are crucial input when modelling rainfall-runoff scenarios and analysing the drainage system. They are also important parameters when evaluating different rain events.

A common concept when designing water infrastructure is to use the return period of rainfall (Svenskt Vatten, 2016). The return period of a rainfall is the estimated average time between rains of the same amount and duration in a given location. This is based on historical data from a long series of precipitation measurements. A 100-year rainfall event means that it has a 1% probability of occurring every year and is predicted to occur once in a period of 100-year. However, since rain events are random, they could occur more or less frequently due to natural variability.

2.1.3 Delta-Change Method

The delta change method is applied by calculating the changes (deltas) in precipitation between a reference period and future scenarios from climate models (Olsson et al., 2009). These changes are then used to adjust the observed rainfall data, allowing a more realistic representation of future climate conditions. The delta change method is presented by Nilsen et al. (2011) as a method for future prediction of precipitation for short- and long-term events. The authors describe this method as the most suitable for evaluating future precipitation even though major uncertainties and assumptions. In the article by Olsson et al. (2009), a Regional Climate Model (RCM) is used. A RCM is more detailed than global climate models by using a denser grid (SMHI, n.d.-a). This allows for a more accurate representation of local climate and climate change effects, making RCMs particularly valuable for local-scale applications such as water resource management.

2.1.4 Rain Data

There are three types of rain data that can be used when modelling and simulating rainfall and runoff events (Blomquist et al., 2016). These are block rain, CDS-rain (Chicago Design Storm) and historical measured rain. Block rain has the same intensity during the entire event, unlike CDS-rain, which is built from multiple block rains of varying durations. Block rains are typically used in Sweden to assess the capacity of the sewer system, and CDS-rain is used to dimension the system. Historical measured rains are typically used to calibrate the model.

2.1.5 Climate Factor

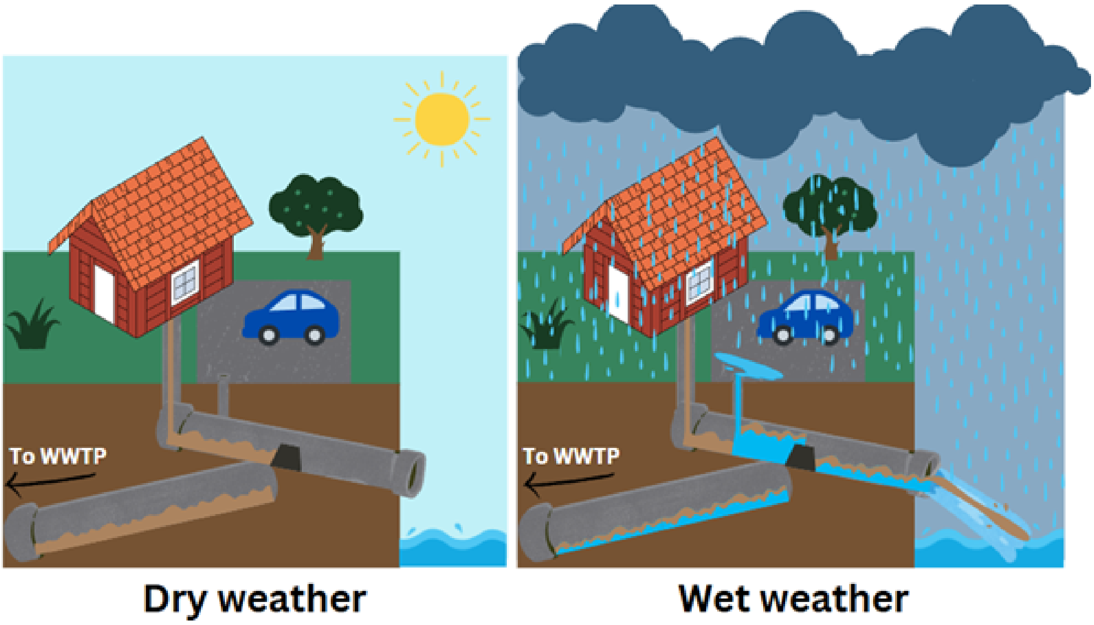
To take climate change into account when designing a wastewater collection system accounting for more intense rainfalls in the future, it is necessary to apply a climate factor to the precipitation. It is recommended by Svenskt Vatten (2016) that this factor is set to at least 1.25 for precipitation events less than one hour and 1.2 for rains with longer duration. An assumption to evaluate future climate conditions is with Representative Concentration Pathways (RCP) (SMHI, n.d.-c). These scenarios represent greenhouse gas emissions and their evolution over time. There are four different scenarios represented until the year 2100 with different years for peaks of emissions of carbon dioxide: RCP2.6, RCP4.5, RCP6 and RCP8.5. The number represent the difference between solar radiation and the energy emitted from the Earth. In a report by Olsson et al. (2017), calculations of future changes in extreme short-term precipitation are presented for different climate scenarios until 2100. The calculations were based on data for the entire country and the return periods (5, 10, 50, and 100 years) and the results, including the predefined assessment values, can be seen in Table 2.1.

Table 2.1: Climate factors of increased rain intensity in % for different durations, time periods and emission scenarios (Olsson et al., 2017). Translated with permission.

Duration	2011-2040 (%)		2041-2070 (%)		2071-2100 (%)	
(hours)	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
1	9	11	14	20	21	36
2	9	11	15	20	22	38
3	9	11	17	20	21	40
6	7	12	17	21	19	41
12	9	10	15	20	18	38
Assessment	10	10	15	20	20	40

2.2 Combined Sewer Overflows (CSOs)

In a wastewater collection system consisting of a combined sewer system, there are differences in operation under different weather conditions (US EPA, 2024). Since wastewater and stormwater flows in the same pipe, the system can be hydraulically overloaded during rain events and is therefore designed and operated to have overflows of untreated wastewater throughout the system, which leads to discharge of pollutants see Figure 2.1. This is done to prevent basement flooding in buildings connected to the wastewater system. In combined sewer systems, excess flow can also lead to bypasses at WWTPs, leading to additional discharges of pollutants (Swedish EPA, 2022). In addition to stormwater and wastewater, inflow and infiltration (I&I) of groundwater or other non domestic sources, such as stormwater, also causes problem both in the pipeline network and at WWTPs (Clementson et al., 2020).



Dry weather

Wet weather

Figure 2.1: Combined sewer system in different weather conditions.

Statistics from Svenskt Vatten (2024a) show that during a five-year period (2019-2023), the CSOs in Sweden have increased in correlation with I&I and increased precipitation. With climate change and more heavy precipitation, this trend is expected to continue. In 2023, it was reported that more than 30 million cubic meters of untreated wastewater were discharged by overflows from the network and at WWTPs in Sweden. However, this amount is mainly stormwater that dilutes the wastewater. During the years 2012-2017, I&I water accounted for approximately 70% of the total volume of wastewater in Trollhättan (Clementson et al., 2020). This significant proportion highlights the challenges of excess water entering the sewer system. This in turn contributes to overflows and reduces the efficiency of treatment processes at the WWTP.

There are three methods that is used by municipalities to quantify the volume of CSOs from the sewer pipe network (Wennberg et al., 2017). These methods are 1) simplified calculations with estimates of precipitation and overflow volumes, 2) measurements of overflow volumes, and 3) calculations using hydraulic and hydrological models. Apart from the volume and number of overflows, the pollutant concentration in overflows is usually not reported by municipalities. In some cases, the dilution factor is estimated by calculating the fraction of wastewater in the CSO. The dilution factor differs between municipalities in Sweden. A report by Wennberg et al. (2017) provides data from three municipalities that calculate and report their fraction of wastewater. It is shown that it varies from 6% to 41% (during the time period 2012-2014) for the total overflows from the sewer network. The corresponding dilution factors range from 2.4 to 16.7.

Gooré Bi et al. (2015) showed that both the volume discharged and the peak flows will increase until 2050 with future climate change. The volume discharged in Québec, Canada, will increase up to 500% with an average value of 139% while the peak flow will increase up to 148% with 54% being average. Another study from Nie et al. (2009) has investigated increase in precipitation in Fredrikstad, Norway, where the increase in precipitation is not linear with the volume of CSO (until year 2071-2100). An increase in precipitation of 20% will lead to 36% increase of CSO, 30% lead to 54% CSO, and 50% lead to increase of CSO with 89%. Urbanisation, change in land use, and climate change are important factors for future predictions of CSO, shown from a case study in Helsingborg, Sweden (Semadeni-Davies et al., 2008). These factors in combination can potentially increase the CSO with 450% in the future (year 2081-2090).

2.3 Hydraulic Modelling

A model is a simplified representation of a real-world system that is made to better analyse and understand the system (Blomquist et al., 2016). Hydraulic modelling is an effective way to analyse water and wastewater systems. Modelling of water flows provides information about the system's capacity, need for action, and ability to withstand heavy rain and climate change. The applications of the model can be used for various purposes, for example, stormwater management and urban planning.

2.3.1 Hydraulic Modelling in SWMM

A hydraulic and hydrological model used in the field of water management is the Storm Water Management Model (SWMM), which is developed by the United States Environmental Protection Agency (EPA) (US EPA, 2025). The SWMM modelling software, which is a freeware, is used for single events or long-term rain series simulation that can be used to analyse both quantity and water quality. SWMM is used worldwide for planning, analyses, and design purposes related to stormwater runoff, wastewater, and drainage systems. The dynamic model can be applied in various ways, for example, to simulate rainfall and runoff in urban areas and to evaluate green infrastructure practices.

SWMM is the most commonly used software to evaluate SuDS (Sustainable Urban Drainage System) strategies according to the review article by Gutierrez et al. (2023). A study performed in Canada by Gooré Bi et al. (2015) has studied CSO for changing climate conditions for year 2013 compared to year 2050. The software used is SWMM for the existing system in the city, and much focus has been placed on the calibration of the model where the model proved to be useful for heavy rainfall. The study carried out by Versini et al. (2016) focused on the potential of green roofs to reduce CSO and flooding. They conducted their study in SWMM for both the evaluation of runoff and the potential of green roofs.

2.3.2 Hydraulic Modelling in MIKE+

Another modelling and simulation software for water infrastructure systems is MIKE+ powered by the Danish Hydraulic Institute DHI (DHI, n.d.-a). The software includes different models for different purposes and can be used for water distribution, stormwater and wastewater systems. One of the modules for wastewater is MIKE+ Collection Systems which is a module based on MIKE 1D for hydrodynamic pipe flow which is based on St Venant partial differential equations. Another principle for MIKE+ Collection Systems is the potential to use long-term statistics based on historical rain series, which generate results of, for example, CSOs. There are other modules for the evaluation of runoff, water quality, and water distribution, to mention a few.

A number of older programs of MIKE have been developed and are now available as modules in MIKE+ (DHI, n.d.-b). Therefore, older studies using other types of MIKE models have been identified in the literature. An example is Mike Urban which has been used for a specific area in Oslo, Norway, with data from the municipality of Oslo (Hernes et al., 2020). The purpose was to evaluate parameters in Mike Urban for green solutions, where the results showed a reliable model. Mike Urban and MIKE 11 have been used in Tokyo, Japan, to build a runoff model and a river flow model for evaluation of suspended solids (Ishikawa et al., 2018). The model and samples in the study matched well.

In MIKE+, there are several surface runoff models available (DHI, n.d.-a). The most commonly used method when describing surface runoff from impervious areas is the Time-Area method (Blomquist et al., 2016). The method is based on simple calculations and does not require much of data (DHI, n.d.-a). The parameters that are used in the model are imperviousness, time of concentration, Time-Area Curve, initial loss and reduction factor. The Time-Area model is defined as Model A in MIKE+.

2.4 Water Quality

According to the World Health Organization WHO (2023), microbial contamination from feces is the main risk to drinking water quality. Pathogens in the feces (bacteria, viruses, and parasites) pose a risk to drinking water safety (Kumar et al., 2021). These types of pathogens can cause waterborne diseases and infections that lead to gastrointestinal illnesses such as diarrhea.

2.4.1 Quantitative Microbial Risk Assessment (QMRA)

A tool to evaluate the risk of infection from pathogens is Quantitative Microbial Risk Assessment (QMRA) (DRICKS, 2021). The framework is used to assess health risks for drinking water consumers and to determine whether water treatment processes effectively remove or inactivate pathogens. The QMRA-tool can be used for different purposes, one of them is to model different risk events such as the discharge of untreated wastewater into raw water sources. It is not possible to analyse all of the pathogens that can be present in fecal-contaminated water, and therefore are reference pathogens needed (DRICKS, 2022). In the QMRA-tool, eight different reference pathogens can be chosen. It is recommended to choose at least one reference pathogen per group (bacteria, viruses, and parasites).

2.4.2 Microbial Contamination of Water Bodies

A study conducted in the Netherlands evaluated the impact of climate change on infection risks when bathing downstream of WWTP discharges and CSOs (Sterk et al., 2016). They modelled the change in pathogen concentrations of *Campylobacter*, *Cryptosporidium* and norovirus in surface water from untreated wastewater discharges. To assess the risk of infection during bathing, QMRA was used. They evaluated the overflow volume and pathogen concentration for future scenarios (2050 and 2085) and per season (during Winter, Spring, etc.). The key findings from the study are that CSO frequency, volume and duration will increase in the future, which will increase the concentration of *Cryptosporidium* and norovirus since they are persistent pathogens. Another risk assessment for water quality and bathing has been conducted in Copenhagen, Denmark, in the context of an Ironman competition (Andersen et al., 2013). In this area, overflow had not occurred from year 2007 until the time for the race 2010. Relevant pathogens were *Cryptosporidium*, *E. coli*, *Giardia*, *Campylobacter* and norovirus. From the QMRA-modelling results, it was observed that CSO has a crucial impact on the quality of the water and risk for human health.

2.4.3 Drinking Water Quality

Several significant waterborne disease outbreaks have occurred worldwide. One of the largest was the 1993 outbreak in Milwaukee, USA, where more than 400,000 people became ill due to *Cryptosporidium* contamination in the city's drinking water supply (Corso et al., 2003). The outbreak was linked to insufficient filtration at one of the city's water treatment plants and remains one of the most severe documented cases of waterborne illness in a developed country.

In Sweden, the pathogen that has caused most of the identified waterborne disease outbreaks in recent decades is norovirus (Swedish Food Agency, 2023). Other pathogens that have caused waterborne outbreaks in Sweden is *Campylobacter* (bacteria) and *Cryptosporidium* (parasite). *Cryptosporidium* is known to have caused serious consequences for the drinking water supply in two cities in Sweden (Östersund and Skellefteå). After these outbreaks, many waterworks have implemented UV-treatment as a solution because *Cryptosporidium* is resistant to chlorine (Folkhälsomyndigheten, 2016).

Urbanisation, snow melt, change in land use and population growth are important factors for CSO discharges that affect the drinking water quality (Jalliffier-Verne et al., 2015). The study performed in Canada with *E. coli* as an indicator of microbial contamination of the water showed that the number of CSOs is seasonal dependent, with the highest frequency during summer. The dilution and *E. coli* concentrations were lowest in the change in season from spring to summer based on historical data. For future conditions, they also concluded more extreme peak flows and a lower minimum flow (for short return periods). Low flows in rivers and streams were found to be the most critical for drinking water quality. They also highlight uncertainties with future predictions of *E. coli* concentrations and point out that it is not possible to predict, although this is an important topic. The effect of snow melt, river flow and precipitation can be evaluated but future concentration projections should be carefully evaluated.

Åström et al. (2009) simulated the microbial loads from wastewater sources to the River Göta älv. The authors evaluated both wet and dry weather conditions for the microbial load from WWTP, CSOs and emergency discharges. The study simulated fecal indicator organisms and pathogens load with Monte Carlo simulations and river sampling data. The main findings of the study were that wet weather increased the microbial load due to heavy rainfall and more CSOs discharges. The discharge from Trollhättan was the most significant source of microbial contamination because it is the largest city along the River Göta älv. A suggestion from the authors is to use the data to perform a QMRA to assess the risk for drinking water consumers. Åström et al. (2007) have performed a QMRA for drinking water consumers in Gothenburg 2004. The result showed that norovirus exceed the acceptable limit, while *Cryptosporidium* adjoint the value to be classified as a risk for drinking water consumers in case of CSO upstream of the raw water intake.

Along the River Göta älv river there are several measurement stations located (Göta älvs vattenvårdsförbund, 2020). At these stations, the water quality in the river is evaluated based on the parameters of conductivity, color, oxygen demand, turbidity, pH, and redox potential. At two of the stations is *E. coli* measured and one of them is located at the raw water intake for the City of Gothenburg. *E. coli* is the primary indicator to be used for fecal contamination since it have the optimal characteristics (Standridge, 2008). These characteristics include no reproducing in water, long lifetime, and easy to identify (Gerba, 2009; Standridge, 2008).

2.5 Legal Framework for Water Infrastructure

Effective management of water resources, wastewater and drinking water requires a legal framework. In Sweden and throughout the European Union, a number of laws, directives and regulations have been introduced to protect human health and the environment, ensure access to safe drinking water and control discharges from wastewater systems. However, some gaps remain regarding the regulation of microbial contaminants, such as pathogens.

2.5.1 EU Legislation on Water Management

The Water Framework Directive (Directive of the European Parliament and of the Council, 2000/60/EC), is a European Union legislative act aimed at protecting water bodies from pollution and ensuring sustainable water availability across member states. The purpose of this act is to create common guidelines and approaches for integrated water management within the European Union. It contains guidelines on how to characterise water sources and their status, as well as environmental impacts and monitoring requirements. For surface waters, ecological and chemical status parameters are evaluated while the status for groundwater is based on quantitative and chemical status.

The Urban Wastewater Treatment Directive (Directive of the Eurupean Parliament and of the Council, 2024/3019) introduces new requirements and recommendations aimed at reducing the environmental impact of wastewater discharges within the European Union. One key aspect of the directive is the inclusion of plans to reduce combined sewer overflows, specifically targeting urban areas with populations exceeding 10,000 pe. A recommendation within the directive is the implementation of blue-green infrastructure (BGI) as a sustainable strategy to mitigate and prevent overflow events. BGI solutions, such as green roofs, rain gardens, and permeable surfaces, are encouraged as effective tools to enhance stormwater management and improve urban resilience to heavy rainfall.

2.5.2 Environmental Legislation in Sweden

There are several laws that regulate the water infrastructure in Sweden. One of the most important is the Swedish Environmental Code (SFS, 1998:808), which came into force on 1 January, 1999. This code serves as the environmental protection legislation in Sweden and aims to promote sustainable development and ensure a healthy environment as well as protect human health. In chapter 9 of the legislation, environmentally hazardous activities are defined to include wastewater discharges. As a result, activities such as the operation of wastewater treatment systems require a permit or a notification according to the Swedish Environmental Assessment Ordinance (SFS, 2013:251). Furthermore, Chapter 26 of the Swedish Environmental Code (SFS, 1998:808) requires that operators of environmental hazardous activities, such as WWTPs, must submit an annual environmental report. Since 2017, the report must contain information about CSO events from the sewer network. This includes the locations of overflow points, the total number of overflows, and the total volume of wastewater discharged (Swedish EPA, 2024).

2.5.3 Municipal Water Responsibilities

The Public Water Service Act (SFS, 2006:412) aims to ensure that water supply and wastewater services are coordinated to protect public health and the environment. This law regulates the relationship between the municipality, the water utility, and the drinking water consumers, assigning responsibilities and legal rights to each stakeholder. The municipality is responsible for providing water and wastewater services, while the water and wastewater utility (Swedish: VA-huvudman) owns and manages the public facilities. In cases of basement flooding caused by the insufficient capacity of the system to handle a 10-year rainfall event, the water and wastewater utility is responsible for the damage (Boverket, 2024a). To address challenges related to heavy rainfall and to allow long-term planning of water services, each municipality is required to develop a Water Management Plan. The County Administrative Board is responsible for overseeing and inspecting these plans according to SFS, 2006:412.

2.5.4 Regulations for Wastewater Treatment Plants

To ensure the quality of wastewater discharges, the requirements NFS, 2016:6 from the Swedish Environmental Protection Agency (Swedish EPA) must be followed . These regulations include mandatory sampling of influent and effluent water in WWTP, where larger facilities should sample more frequently, as well as sampling of CSO. For influent water in WWTPs serving 2,000 population equivalents (pe) or more, sampling of organic pollutants and nutrients is required. For effluent water, the same parameters must be sampled from plants serving 200 pe or more. At larger WWTPs ($\geq$ 10,000 pe), sampling for ammonium and a range of metals is also required. Sampling of sewer overflow discharges is required at WWTP (Swedish EPA, 2023). This includes measurement of various metals, ammonium, nutrients and organic pollutants each time an overflow occurs. However, no limit values are currently specified for these parameters in CSO discharges in NFS, 2016:6.

2.5.5 Drinking Water Quality Regulation

To ensure good drinking water quality, detailed requirements for water treatment are described in LIVSFS, 2022:12, which come into force 1 January, 2023. These regulations specify quality parameters, procedures for monitoring and investigating water quality, and the obligations of water suppliers to inform consumers in the event of unsafe drinking water.

2.6 Measures to Reduce Overflows

There are several measures to reduce the volume and mitigate the effects of combined sewer overflows. An effective solution is the implementation of green infrastructure, such as rain gardens and green roofs, which help absorb rainwater. Other stormwater management practices include storing and delaying water through detention ponds and reservoirs. Infiltration basins and permeable surfaces are also viable alternatives, allowing water to soak into the ground. Lastly, transitioning to separated sewer systems and upgrading the existing sewer infrastructure can significantly reduce the risk of overflows.

2.6.1 Green Roofs and Rain Gardens

One way to delay stormwater and reduce peak flows is with green roofs (Svenskt Vatten, 2011). This is a construction where vegetation is placed on roofs and is most effective during frequent rains with limited precipitation. Green roofs are also useful for heavy rains, but mainly in the beginning of the rain and at the first flush. To ensure water treatment and sufficient delay capacity, regular maintenance is required (GSA, 2011). The study by Versini et al. (2016) shows that green roofs play an important role in reducing the risks of CSO and flooding by mitigating both peak flows and overflow volumes. However, the effect depends on how much of the available implementable roof surfaces is covered with vegetation. With 100% coverage, the discharge volume can be reduced by 30-60%. At a more realistic coverage of 25-50%, the consequences are expected to be partially reduced. An important note is that the results and use of green roofs are likely overestimated due to assumptions about optimal conditions.

Another vegetation-based measure is rain gardens that collect and delay urban stormwater (Erickson et al., 2013). Rain gardens can be established with or without infiltration and in different sizes in different locations in cities. They also have a positive effect on water quality and are beneficial for storage. A study conducted in Oslo evaluated the impact of green roofs and rain gardens on CSOs (Hernes et al., 2020). The result from the study showed that green roofs are the most optimal for smaller rain events, while rain gardens are better at reducing the volume of CSO and peak flows for larger events. However, the most optimal solution is to combine green roofs and rain gardens to achieve a reduction in peak flow and volume. Another study on the topic, conducted in Switzerland, investigated the potential of blue-green infrastructure (BGI) to reduce future combined sewer overflows (CSO) due to climate change (Cavadini et al., 2024). The results showed that bioretention cells (rain gardens) were the most effective measure in reducing both CSO volume and frequency of CSO events.

2.6.2 Stormwater Ponds and Delay Reservoirs

Stormwater ponds and delay reservoirs are important components of urban water management, designed to control and regulate stormwater runoff. Stormwater ponds, which can be either wet or dry, are designed to manage and control stormwater runoff to reduce flood risks (Erickson et al., 2013). The key difference between them is in the elevation of their inlets and outlets, which determines whether water is constantly present. Wet ponds are primarily constructed for long-term water storage, while dry pond are designed for short-term retention.

Another way to store and delay water is with open or closed reservoirs (Svenskt Vatten, 2011). Open reservoirs are commonly used as other public spaces in society, such as playgrounds. When rain occurs, the purpose of the area changes to being a storage for water. Closed reservoirs are placed underground and are mainly made of concrete or plastic. They are often used in places where the space above ground is limited, but storage is required. To ensure the functions of the reservoir, sedimentation should be avoided, and cleansing should be enabled. This can be done either in place or prevented by solutions upstream with sand trap and filtration.

2.6.3 Infiltration Basins and Permeable Areas

Erickson et al. (2013) explains that "An infiltration basin is a natural or constructed impoundment that captures, temporarily stores, and infiltrates a designed volume of stormwater within a targeted time period." (p. 45). The main purpose of infiltration basins is to manage water quantity while natural treatment processes occur. Other stormwater management solutions with similar characteristics are swales and trenches, which can be designed in various ways and placed between buildings, near roads or in parking lots (Svenskt Vatten, 2011). Swales requires large areas due to their small gradient and small depth, but are efficient for retention, runoff, and improving water quality through infiltration. Trenches are similar to swales, but require less space and have less capacity. These measures are for short-term storage (Erickson et al., 2013). Additionally, they can be connected to the sewer system using drainage pipes or high located wells, or can be directed to other low points (Svenskt Vatten, 2011).

Permeable areas can be used to reduce the amount of water that reaches water recipients (Svenskt Vatten, 2011). Examples of permeable areas include pervious pavements and permeable asphalt. Pervious pavements are designed to store water on-site by allowing it to infiltrate through materials such as macadam and/or grass between concrete blocks. These pavements can infiltrate up to 40% of the water, but since all water cannot be infiltrated, the gradient of the area is crucial to ensure proper flow and prevent stagnation. In the study by Cavadini et al. (2024) they found that combinations of rain gardens and porous pavement were the most cost-effective solutions. Permeable asphalt, another type of permeable surface, allows water to flow through a layer of macadam, where it is temporarily stored before being directed to drainage systems.

2.6.4 Separation of Combined Sewer Systems

A further solution to the problem of overflows is to separate the sewer network. A separated sewer system, where stormwater and wastewater are in separate pipes, has both advantages and disadvantages. An advantage is that it reduces the risk of the sewer system being overloaded during heavy rains, which can lead to flooding and overflows. Another advantage is that only wastewater is transported to the WWTP. This improves the purification efficiency and reduces the load on the WWTP. In WWTP, water is treated with mechanical, biological, and chemical processes with different levels of advanced treatment (Swedish EPA, 2022). These processes remove larger particles, as well as nutrients and organic matter. Stormwater on the other hand, is not treated at WWTPs in a separate system but can be made by some of the measures earlier described in this chapter. Stormwater is water that originates from precipitation events such as rain or snow. When it falls to the ground it can infiltrate or run off from surfaces such as roads, parking lots, and buildings. It often carries pollutants that accumulate on these surfaces and can contaminate water bodies and ecosystems (Boverket, 2024b). There are many different kinds of pollutants in stormwater and some examples are nutrients, metals, and microplastics.

In Sweden, 13% of the wastewater collection system is combined (Svenskt Vatten, 2016). Combined sewer systems were historically constructed to efficiently remove both stormwater and wastewater from urban areas to reduce the negative impacts of flooding and pollution (Swedish EPA, 2022). Cities are continuing to work on a shift towards a separated sewer system, where wastewater and stormwater are handled in separate pipes. This transition is driven by the need to improve water quality, reduce the risk of combined sewer overflows (CSOs), and improve overall system capacity. In Sweden, there has been a noticeable increasing trend in reinvestment in water and wastewater infrastructure during the period 2019-2023, with 2022 marking the highest level of reinvestment (Svenskt Vatten, 2024a). This trend highlights the need to modernise aging systems, improve capacity, and address challenges such as climate change and urbanisation.

The trend is also seen in the Swedish municipality of Trollhättan. Today, the wastewater infrastructure in Trollhättan consists mainly of separate systems, with one third (90 km) of the system still being combined (Trollhättans Stad, 2021). It is important to note that the proportion of the sewer network classified as a combined system can vary depending on the definition used. In some areas, both combined and stromwater pipes are present in the same area, which complicates the classification. Separation of combined systems began before the millennium due to the system being overloaded during heavy rainfalls. This work is still ongoing and supported by investments under the initiative know as "Vattenpaketet 2026" (English: Water Package 2026) (Trollhättan Energi, n.d.-a). The renewal rate is almost 5 km pipe per year, which will result in improved and more reliable water management, and this rate is planned to be increased (Trollhättan Energi, n.d.-b).

3 Materials and Methods

This study consists of two parts: a quantitative assessment and a water quality assessment. The quantitative assessment was performed by hydraulic modelling of the sewer system in Trollhättan. From this, the parameters volume, flow, and dilution could be evaluated. The water quality assessment was performed using a quantitative microbial risk assessment (QMRA). Evaluation of risk of infection for drinking water consumers downstream of Trollhättan for two different drinking water treatment plants (DWTPs) was carried out, more specifically one similar to Alelyckan in Gothenburg and an arbitrary DWTP similar to Alelyckan but without UV-treatment.

3.1 Case Study Description

Trollhättan is a municipality in western Sweden located southwest of Lake Vänern, see Figure 3.1. In 2023, the municipality had approximately 59,000 inhabitants (SCB, n.d.-a). The drinking water in the municipality comes from the River Göta älv and is provided by Trollhättan Energi AB to around 55,000 people in both Trollhättan and parts of the neighbouring municipality of Vänersborg (Trollhättan Energi, n.d.-c). The water is then released back to River Göta älv after treatment in the wastewater treatment plant (WWTP). Göta älv is a large river in Sweden that stretches from lake Vänern to the coast outside Gothenburg (Göta älvs vattenvårdsförbund, 2015). The river goes along several municipalities which are all dependent on the water quality and quantity to provide safe drinking water for their consumers.

Figure 3.1: Location of Trollhättan marked in red. Retrieved from Google (n.d.).

3.2 Quantitative Assessment of Water Discharges due to Climate Change and Urban Development

To enable simulations of current and future scenarios, input data to the hydraulic model was required. For future climate change and evaluation of different rain events, different single rain events were carried out from a 23-year-long rain series extrapolated to Trollhättan. Population growth, increase of impervious areas and implementation of green infrastructure were the selected scenarios to represent urban development. The collected data was applied in a pre-calibrated hydraulic model for each selected scenario and time period.

3.2.1 Model Description

The modelling software used in this study was MIKE+ powered by DHI (DHI, n.d.-a), and was used with a student license. The overflow model used in MIKE+ was provided by Trollhättan Energi AB. The model was a simplified and limited version of the main sewer system in the municipality of Trollhättan, where the WWTP were excluded as well as parts of the network (service pipes and other smaller pipes). The model was pre-calibrated and did not require additional input. The selected hydrological model was the Time-Area method (Model A).

The boundary condition for wastewater flow was connected to a catchment node in the model and was based on historical data on drinking water consumption. Another boundary condition was the positions of seven rainfall measurement stations in the hydraulic model. The same rainfall data set was placed at all measurement stations during the simulations in this study. The model also included a boundary condition for water quality by assigning a constant pollutant concentration of 1000 mg/m^3 of the domestic sewer flow. This concentration represents a wastewater system that contains only wastewater. To assess the fraction of wastewater within the system, this concentration was used where the value varied between 0 and 1000 mg/m^3 which corresponded to a fraction of wastewater between 0 and 100%.

3.2.2 Rain Data

In order to assess the impact of future climate change and urban development on the drainage system, rainfall data were needed. The study was carried out with a rain series from Trollhättan Energi AB, based on historically measured rain data from SMHI (the Swedish Meteorological and Hydrological Institute) from 1995 until 2018 in Vänersborg, a city located close to Trollhättan. The precipitation was measured every 15 minutes in millimeters, and to be applicable in Trollhättan, the data were extrapolated by weighting the data based on daily precipitation data from Trollhättan. The rain series was weighted and processed beforehand and was used to run the model prior to this study.

Since many years of rainfall data are presented in the original time series, see Figure 3.2, a selection of precipitation events with different intensity and duration was needed to be able to compare different rainfall events. According to SMHI (2025), events with more than 20 mm of rainfall in one day were classified as extreme rain, while events with precipitation between 10 mm and 20 mm were considered heavy rain. Rainfall duration was also taken into account. In this study, short-duration rain was defined as precipitation around one hour and long-duration rain was defined as an event lasting up to 12 h. These definitions were used to classify the rain events as short-term rain events in the context of applying the defined climate factors, see Table 2.1.

For the evaluation of the impact of urban development on CSO discharge, the rain event with the highest peak was selected for analyses. This rain event was classified as an extreme precipitation event when precipitation exceeding 20 mm in a day. The selected rain event occurred on 10 August, 2006, when almost 25 millimeters of precipitation fell in 15 minutes (intensity of 100 mm/h). During this single rain event, which lasted for one hour, fell in total 38 mm precipitation (mean intensity of 38 mm/h). Due to its high intensity and short duration, the event is classified as an Extreme & Short Rain Event (ES). The intensity and duration of this rain event is presented in Figure A.1 in Appendix A.

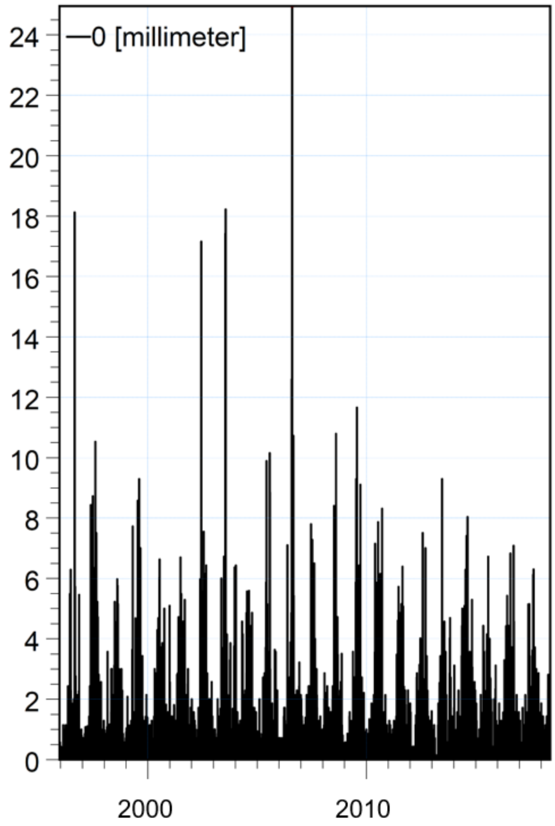


Figure 3.2: Precipitation time series in 1995–2018. Retrieved from Trollhättan Energi AB.

For the evaluation of the impact of climate change, three additional rain events were selected. Another extreme precipitation event was chosen: the Extreme & Long Rain Event (EL), defined by extreme precipitation of at least 20 mm during a day and duration less than 12 hours. The selected day for this event was June 26, 2006, when 25 mm of rain fell within 8 h (mean intensity of 3.1 mm/h). The rainfall intensity is presented in Figure A.2 in Appendix A.

A Heavy & Short Rain Event (HS) was selected based on the criteria of similar duration as ES and precipitation between 10 and 20 mm to be considered a heavy rainfall event. The selected event occurred on 26 July, 2009, where 16 mm fell in one hour and 15 minutes (mean intensity of 13 mm/h), and can be seen in Figure A.3 in Appendix A. During a Heavy & Long Rain Event (HL), 12 mm of precipitation fell over 7 hours on 19 August, 2006 (mean intensity of 1.7 mm/h), can be seen in Figure A.4 in Appendix A.

For each scenario, a simulation period of 24 h has been used. The selection of dates was limited to the summer months, as most rain falls during the summer (SMHI, n.d.-

b). Another criterion was to select single rain events before the year of 2011 since climate factors should be applied from that year. Another reason for selecting summer months was because of uncertainties as to whether the precipitation was snow or rain and if it had a direct impact on the system.

For scenarios with climate change, the original time series was multiplied with climate factors to evaluate future precipitation, see Table 2.1. These factors are presented in a study by (Olsson et al., 2017) and are applicable to heavy precipitation with short duration. These factors are presented for different RCP values, more precisely RCP4.5 and RCP8.5. Both scenarios indicate increased greenhouse gas emissions, where RCP8.5 represents a higher emission pathway. The numbers are also presented for different time periods 2011-2040, 2041-2070 and 2071-2100. Each combination of time period and RCP is evaluated with the Assessment value.

3.2.3 Scenario Selection

In the study, three time periods were selected: Base Case (2025), Distant Future (2070), and End of the Century (2100). This was made to enable a comparison between current system and future conditions. Different scenarios were selected to enable comparison between different aspects of future climate change and urban development. The selected scenarios are presented in Table 3.1. For these scenarios only the Extreme & Short Rain Event (ES) has been considered.

Two different climate change scenarios C1 (RCP4.5) and C2 (RCP8.5) were used to analyse future changes in precipitation using associated climate factors Table 2.1. Climate factors for Scenario C1 have also been used for the evaluation of parameters related to urban development for future scenarios, while climate factors for Scenario C2 have only been considered for the evaluation of the impact of climate change.

Table 3.1: Presentation of selected scenarios.

	C1: RCP4.5	C2: RCP8.5	P: Population	I: Impervious area	G: Green Infrastructure
Base Case	✓*	✓*			
Scenario C1	✓				
Scenario C2		✓			
Scenario P	✓		✓		
Scenario I	✓			✓	
Scenario G	✓				✓
Scenario P-I	✓		✓	✓	
Scenario P-G	✓		✓		✓

* Same value for C1 and C2
✓- included parameters

The impact of population growth is represented as Scenario P, increased impervious surfaces as Scenario I, and the implementation of green infrastructure as Scenario G. Scenarios have been performed with combinations of different aspects of urban development. Scenario P-I is a combination of population growth and an increase in proportion of impervious areas, and Scenario P-G is a combination of increased population and implementation of green infrastructure.

3.2.4 Population Growth

To assess how future population growth could affect the load on the sewer system and thus potentially lead to more overflows, population data from Trollhättan Energi AB was used. The data was provided by the municipal company and consisted of future population growth predictions within the municipality. It is assumed that the generated wastewater flow per person will remain constant in the future. Therefore, a linear relationship between population growth and wastewater flow in the system was used, where the population data were used to increase the generated wastewater flow in the system by the same percentage as the increase in population. These data can be seen in Table 3.2.

Table 3.2: Population projections for Trollhättan municipality (estimates from Trollhättan Energi AB).

Year	Population growth (population)	Difference (%)	Wastewater flow (l/s)
2025	59,300	-	128
2070	74,200	25	160
2100	86,200	45	185

3.2.5 Proportion of Impervious Areas

To model the effects of future urbanisation on CSO discharges, an increase in impervious areas of 10% by 2070 and 20% by 2100 was assumed for all catchments. This change is based on previous studies (Dong et al., 2017; Hamdi et al., 2011), where similar increases in impervious areas have been predicted for a European and a Chinese city. Salerno et al. (2018) reports that the increase in impervious surfaces in some European cities has been on average 0.3% per year, which also justifies the chosen urbanisation rate.

The evaluation of green infrastructure in the city of Trollhättan was modelled to investigate how effective these measures can be in reducing overflows and its consequences. To investigate the impact of implementation of green infrastructure, the imperviousness of all catchments was reduced by 10% and 20%. This represents the implementation of, for example, rain gardens, green roofs, or permeable pavements to increase infiltration and reduce runoff.

3.2.6 Volume Determination of Discharge

To determine the total volume of CSO discharge for each single rain event, the accumulated discharge volume was studied. For each CSO Weir (discharge point), the accumulated volume during the 24-hour period was evaluated. These volumes were then summarised in a spreadsheet table to determine the total CSO discharge volume for the entire CSO event. The volume determination of CSO discharge for the different scenarios was based on the Extreme & Short Rain Event (ES) to enable comparison between the different factors of urban development.

To calculate the volume of wastewater discharged during each rain event, a graphical method based on integration over time has been applied, see Equation (3.1). The CSO flow data and the fraction of untreated wastewater were obtained from the hydraulic modelling simulation. To simplify the calculations in this analysis, two-thirds (2/3) of the total CSO volume were considered. The simulation was conducted over a 24-hour period and each time step was 1 minute.

$$V_{\text{ww}} = \int Q_{\text{ww}}(t)dt \approx \sum_{i=1}^{n} Q_{\text{CSO}}(t_{\text{i}}) * f(t_{\text{i}}) * \Delta t \tag{3.1}$$

Where:

$V_{\text{ww}}(t_i)$ = The total volume of wastewater (m^3)
$Q_{\text{CSO}}(t_i)$ = The total CSO flow at time t_i (m^3/s)
$f(t_i)$ = The fraction of wastewater at time t_i (-)
Δt = Time step (60 sec)
n = The number of simulation steps

3.3 Water Quality Assessment of Pathogens

To assess the water quality, the Quantitative Microbial Risk Assessment tool (QMRA) has been used. This method is developed by DRICKS which is a collaboration in the field of drinking water between universities, municipalities, and water treatment plants (Chalmers, 2024). The pathogens analysed were norovirus, *Cryptosporidium* and *Campylobacter* to cover the three different types of pathogens (virus, parasite, and bacteria).

3.3.1 Selection of Drinking Water Treatment Plants

Two different drinking water treatment plants has been studied. A representation of a DWTP similar to Alelyckan in Gothenburg has been used for evaluation of annual health risk for their drinking water consumers. The drinking water treatment steps are conventional treatment, activated carbon filtration, UV-disinfection, and chlorination (Göteborgs Stad, n.d.-b). No specific data on $\log_{10}$-reduction or specifications on the different types of treatment steps are available, therefore was the default values in the QMRA-tool used. There is no default treatment step for activated carbon and therefore has an Additional Treatment Barrier been used. Granular activated carbon (GAC) was assumed and the $\log_{10}$-reduction of pathogens was found from Medema et al. (2006) and was set with a Triangular distribution as (0.9, 1.4, 2.9) for *Campylobacter*, (0.2, 0.4, 0.7) for norovirus and (0.7, 0.9, 1.1) for *Cryptosporidium*. GAC is not considered as a microbial barrier according to Swedish Food Agency (2024b) while the other treatment steps are considered as microbial barriers. GAC was still considered in the QMRA-tool. For chlorination was Free Chlorine assumed to be used with a Dosing Concentration (Cdose) of 0.25 mg/L. This assumption is supported by Göteborgs Stad (n.d.-a) who argue for a low dose in the drinking water in Gothenburg.

An arbitrary drinking water treatment plant has also been studied to represent a smaller

DWTP with fewer treatment processes than the one representing Alelyckan DWTP in Gothenburg. The difference between them is that the arbitrary DWTP does not have UV-disinfection. The parameters for conventional treatment, GAC and chlorination are set to the same values as for the representation of Alelyckan DWTP.

3.3.2 Assumptions of Pathogen Concentrations

In the QMRA-tool, pathogen concentrations are required. The two different types of water used in the tool were Untreated Sewage and Raw Water. The pathogen concentrations in wastewater was based on modelled values at Trollhättans WWTP from Tyréns (2018) and was used as a Point Estimate for Untreated Sewage. The Point Estimate for Raw Water represent the surface water quality in the River Göta älv, and are from Abrahamsson et al. (2009). The values for each pathogen and type of water are presented in Table 3.3.

Table 3.3: Pathogen concentration used in QMRA.

	Campylobacter (bacteria/L)	norovirus (viruses/L)	*Cryptosporidium* (oocysts/L)
Wastewater [a]	70,000	100,000	1,000
Raw water [b]	1	1	0.4

[a] Modelled values from Tyréns (2018).

[b] Standard values from Abrahamsson et al. (2009).

3.3.3 Peak Flow Approach

The dilution factor within the system for each scenario was needed to enable the Source Water Characterisation in the QMRA-tool. To calculate the dilution factor in Equation (3.2), two different flows were needed. The flows for each time step during the day for a rain event from each CSO Weir were summarised in a table in a spreadsheet to obtain the total CSO discharge from the system. The flow was then plotted over time for visualisation. The highest peak represents the factor Q_{CSO}, and the time step when this specific flow occurred was found in the graph. To find $Q_{\text{ww,peak}}$ was the fraction of wastewater in each CSO Weir at the same time step needed. This was found from the pollutant concentration in the hydraulic model. The wastewater flow in each CSO Weir was calculated by multiplying the fraction of wastewater with the CSO discharge. These flows were then summarised in a spreadsheet table to obtain the wastewater flow rate $Q_{\text{ww,peak}}$ within the system.

$$D_{\text{system,peak}} = \frac{Q_{\text{CSO}}}{Q_{\text{ww,peak}}} \tag{3.2}$$

Where:

$D_{\text{system,peak}}$ = Dilution factor for peak flow within the system (-)

Q_{CSO} = CSO discharge at peak flow (m^3/s)

$Q_{\text{ww,peak}}$ = Untreated wastewater at peak flow within the system (m^3/s)

The dilution factor in the river was calculated with Equation (3.3). Calculation of the dilution in the River Göta älv was based on two flows, Q_{CSO} and Q_{river}. The flow in the river was set to 565 m^3/s and is the mean value of the flow in River Göta älv (Göta älvs vattenvårdsförbund, 2015).

$$D_{\text{river,peak}} = \frac{Q_{\text{river}} + Q_{\text{CSO}}}{Q_{\text{CSO}}} \tag{3.3}$$

Where:

$D_{\text{river,peak}}$ = Dilution factor in the river at peak flow (-)
Q_{CSO} = CSO discharge at peak flow (m^3/s)
Q_{river} = River flow, 565 m^3/s (Göta älvs vattenvårdsförbund, 2015)

The total dilution was calculated with Equation (3.4). This was made to enable comparison between rain events.

$$D_{\text{total,peak}} = D_{\text{system,peak}} * D_{\text{river,peak}} \tag{3.4}$$

Where:

$D_{\text{total,peak}}$ = Total dilution factor at peak flow (-)
$D_{\text{system,peak}}$ = Dilution factor within the system at peak flow Equation (3.2) (-)
$D_{\text{river,peak}}$ = Dilution factor in the river at peak flow Equation (3.3) (-)

3.3.4 Pathogen Concentration Approach

Another way to characterise the source water in the QMRA-tool was to calculate the pathogen concentration. To estimate the concentration of pathogens in the River Göta älv after discharge of CSO from the system in Trollhättan, a mass balance was used. Complete mixing was assumed and the concentration in the river was calculated using Equation (3.5). The wastewater flow rate $Q_{\text{ww,pathogen}}$ was calculated by dividing the total volume of wastewater discharged by the total duration of the CSO event. The duration of the CSO event was determined using the flow curve presented in Figure B.1-B.4 in Appendix B. This was made to get an average flow rate during the event.

$$C_{\text{river}} = C_{\text{pathogen}} * \frac{Q_{\text{ww,pathogen}}}{Q_{\text{river}}} \tag{3.5}$$

Where:

C_{river} = Pathogen concentration in the river (number/L)
C_{pathogen} = Pathogen concentration in wastewater (number/L) (From Table 3.3)
$Q_{\text{ww,pathogen}}$ = wastewater discharge flow (m^3/s)
Q_{river} = River flow, 565 m^3/s (Göta älvs vattenvårdsförbund, 2015)

Estimation of pathogen concentration at a downstream intake point C_{intake} for a 24-hour period was based on Equation (3.6). This approach was made to account for the contaminated plume and the baseline concentration of the raw water. These pathogen concentrations were then used as raw water concentrations for the Source Water Characterisation in the QMRA-tool.

$$C_{\text{intake}} = \frac{C_{\text{river}} * t_{\text{CSO,event}}}{t_{\text{day}}} + C_{\text{raw}} \tag{3.6}$$

Where:

C_{intake} = Average pathogen concentration at the intake point (number/L)
C_{river} = Pathogen concentration in the river during the CSO event (number/L)
$t_{\text{CSO,event}}$ = Duration of the CSO event (hours)
t_{day} = Total duration of the day (24 hours)
C_{raw} = Raw water pathogen concentration (number/L)

3.3.5 Annual Health Risk Assessment

To calculate the annual health risk, Equation (3.7) was used. The daily risk of infection P_{inf} for the various pathogens was derived from the output of the QMRA model. The calculated annual probability P_{annual}, was compared with 10^{-4}, which is the tolerated annual health risk defined by the US EPA and means that 1 person out of 10,000 is tolerated to be infected per year (DRICKS, 2020).

$$P_{\text{annual}} = 1 - \left[(1 - P_{\text{inf,normal}})^{t_{\text{normal}}} * (1 - P_{\text{inf,ES}})^{t_{\text{ES}}} * (1 - P_{\text{inf,HS}})^{t_{\text{HS}}}\right] \tag{3.7}$$

Where:

P_{annual} = Annual probability of infection (-)
$P_{\text{inf,normal}}$ = Daily probability of infection during normal days (-)
t_{normal} = Number of normal days (days)
$P_{\text{inf,ES}}$ = Daily probability of infection during CSO events caused by extreme precipitation (-)
t_{CSO} = Number of days with CSO events due to extreme precipitation (days)
$P_{\text{inf,HS}}$ = Daily probability of infection during CSO events caused by heavy precipitation (-)
t_{HS} = Number of days with CSO events due to heavy precipitation (days)

The number of days with extreme (t_{ES}) respectively heavy (t_{HS}) precipitation for the different years (2025, 2070 and 2100) was taken from SMHI's Climate Change Scenario Tool (SMHI, 2025). In the tool, the data was filtered by selecting the Geographical Area of Västra Götaland County and the Climate Indicator to days with Extreme, respectively, Heavy precipitation, where extreme precipitation is defined as days with more than 20 mm of precipitation, and heavy precipitation is days with precipitation between 10 and 20 mm. Thereafter, the Emission Scenario RCP4.5 was selected, the Season was set to Year and the data were filtered for the different Time Periods (2011-2040, 2041-2070 and 2071-2100). The number of days with normal, extreme, respectively, heavy precipitation for the chosen years is presented in Table 3.4. The sum of normal, extreme, and heavy precipitation is 365 days.

Table 3.4: Number of days with normal conditions and with extreme and heavy precipitation.

Year	Normal conditions t_{normal} (Days)	Extreme precipitation t_{ES} (Days)	Heavy precipitation t_{HS} (Days)
2025	334.9	4.9	25.2
2070	333.5	5.3	26.2
2100	332.2	5.7	27.1

4 Results and Discussion

The results from the hydraulic modelling of the sewer system in Trollhättan are presented and analysed in this chapter. The different rain events are compared in terms of their impact on flow and generated CSO volumes, dilution, and pathogen concentration. Moreover, the influence of urban development factors on CSO volumes is evaluated based on the defined scenarios and their effect on CSO discharge volumes. The increased health risk for drinking water consumers downstream of CSO discharge are also assessed. Finally, uncertainties related to the hydraulic model are discussed along with recommended strategies to reduce the occurrence of CSO and its health impact.

4.1 Comparison between Different Single Rain Events

In this study, four different types of rain events have been evaluated based on volume discharge, dilution, pathogen concentration, and peak flow. This was done to show the effects of differences in intensity and duration between different rainfall events. In addition, the fraction of wastewater in relation to the CSO discharge has been visualised to further understand the relationship between flow or volume and dilution.

4.1.1 Discharge Volume

Short-duration rainfall events result in the largest volumes of CSO, see Figure 4.1. It can also be seen in the figure that the intensity impacts the volume, where a high intensity contributes to a larger volume of CSO discharge. The conclusion from the graph is therefore that an extreme rain event is more critical than a heavy rain and that a short rain is more critical than a long rain in terms of total CSO discharge.

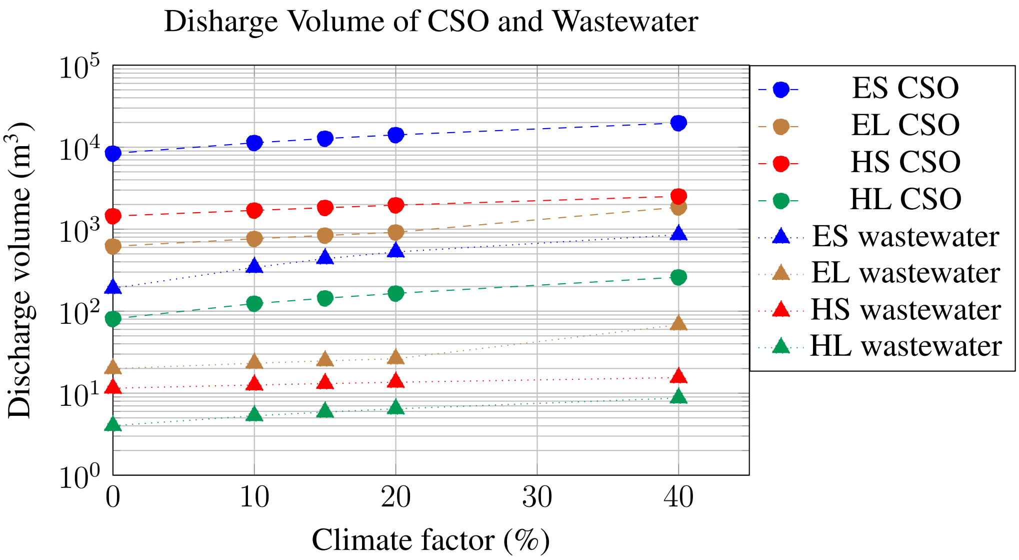


Figure 4.1: Volume of CSO and wastewater being discharge for different rain events with different climate factors. The rain events are ES (Extreme & Short Rain Event), EL (Extreme & Long Rain Event), HS (Heavy & Short Rain Event) and HL (Heavy & Long Rain Event). Detailed values of discharged volume is available in Table C.1 in Appendix C.

In Figure 4.1, the total discharge of wastewater during the CSO event is also included. It can be observed that the ES rain event results in the highest volume of wastewater discharge, followed by the EL event. This does not follow the same order as the total CSO discharge volume curves. In terms of wastewater discharge, the two extreme rain events are more critical than the heavy rain events. With respect to duration in this case, shorter duration rainfall events appear to have a more critical impact than longer events.

4.1.2 Dilution and Peak Flow

The two short rain events, ES and HS, are the least diluted at peak flow, as can be seen in Figure 4.2. The factor that varies the most between rain events is the dilution factor in the river. That is due to the variation in the CSO flow and that the river flow is kept constant, see Equation (3.3).

Another finding from the study is the dynamics of the dilution, where a high CSO flow results in greater dilution factor within the sewer system due to the high fraction of stormwater. This in turn leads to a lower dilution factor in the river as the CSO discharge increases while the river flow is assumed to be constant. However, this assumption is a simplification of reality, and only the mean value of the river flow is used. If a lower river flow is used in Equation (3.3), the result would be a lower dilution factor and is therefore more critical. This agrees with the findings from (Jalliffier-Verne et al., 2015), which conclude that low river flows are more critical for the water quality.

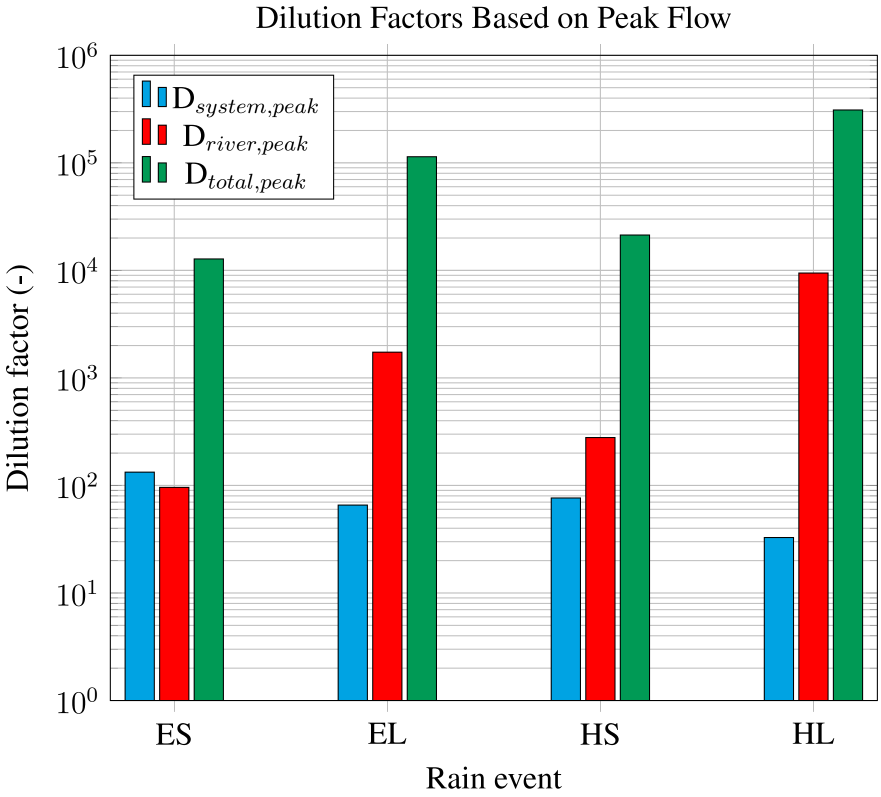


Figure 4.2: Dilution factors (within system, in the river and total) for different rain events based on peak flow with climate factor 20%. Detailed values on the different dilution factors is found in Table D.1 in Appendix D.

The peak flows for each rain event are presented in Table 4.1 where it can be seen that the Extreme & Short Rain Event is shown to have the highest flow of all. There could also be seen a significant difference between the short and long events with differences in flow of around 10-100 times.

Table 4.1: Peak flow for different single rain events with climate factor 20%.

	Peak flow (m^3/s)
Extreme & Short Rain Event (ES)	5.95
Extreme & Long Rain Event (EL)	0.326
Heavy & Short Rain Event (HS)	2.04
Heavy & Long Rain Event (HL)	0.0598

The peak flows for the different rain events, with a climate factor of 20%, are shown in Figure B.1-B.4 in Appendix B. Short rain events have a significant peak in flow over a short period of time, which indicates a rapid and high overflow response. The long rain events show multiple peaks, with the overflow event occurring more spread throughout the day. This difference may be due to the fact that the response in the system varies depending on rain intensity and duration, with an immediate response to an intense short rain and a delayed response to longer rain events.

4.1.3 Discharge and Wastewater Fraction

In Figure 4.3 the relationship between the fraction of wastewater and CSO discharge for peak flow is shown. For the two different short rain events, ES and HS, it is observed that an increase in CSO discharge results in a smaller fraction of wastewater. Another observation is that this relationship does not follow a linear decrease. This could be due to the varying intensities of the rain events.

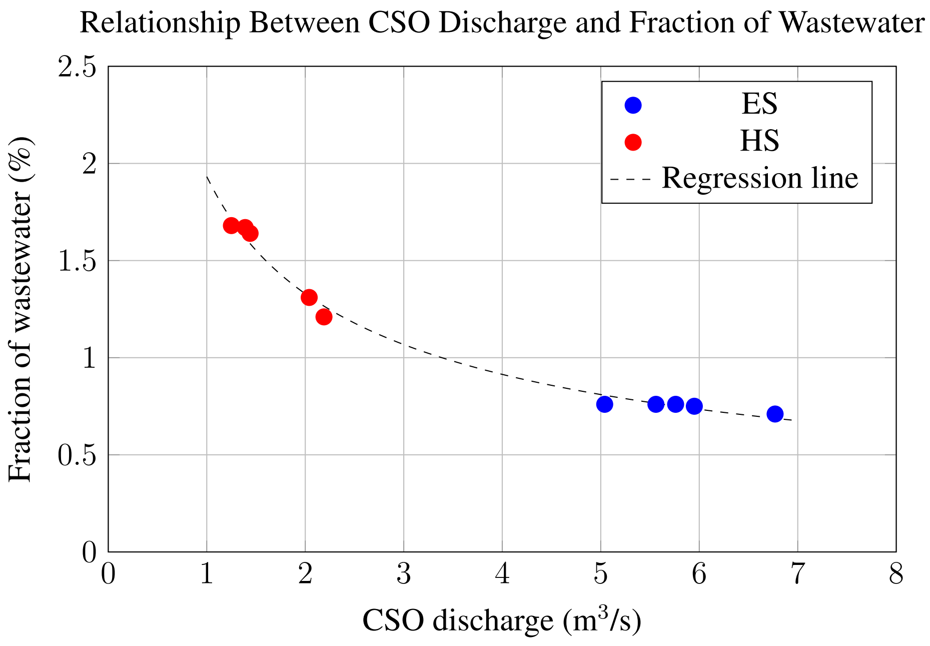


Figure 4.3: CSO discharge at peak flow and its fraction of wastewater for different rain events.

Furthermore, in Figure 4.3, a higher flow results in a higher dilution within the system, which reduces the pathogen concentration in the discharge. However, the relationship should be interpreted with caution. This is further supported by Figure 4.4, where no clear trend between the fraction of wastewater and CSO discharge volume can be seen. Therefore, the relationship in Figure 4.3 can be questioned. This is because the relationship within each rain event differs from the overall trend.

In Figure 4.4 below, the fraction of wastewater in the CSO discharge volume is presented for each rain event. It can be seen that no common trend is shown between the different rain events. However, for the ES event, there is a relationship where an increase in CSO discharge volume is associated with a higher amount of wastewater. Overall, the fraction of wastewater in the overflow is approximately 3%, with the exception of the HS rain event, where the fraction is below 1%. For comparison, reported values from Wennberg et al. (2017) show that the wastewater fraction in overflow from the wastewater network was approximately 10% annually during the period 2012-2014. This difference shows that the wastewater fraction in overflow can vary greatly between individual single rain events and the yearly average. Single events may have lower wastewater fractions due to factors like rainfall intensity and dilution, while annual values reflect a mix of many events leading to a higher average.

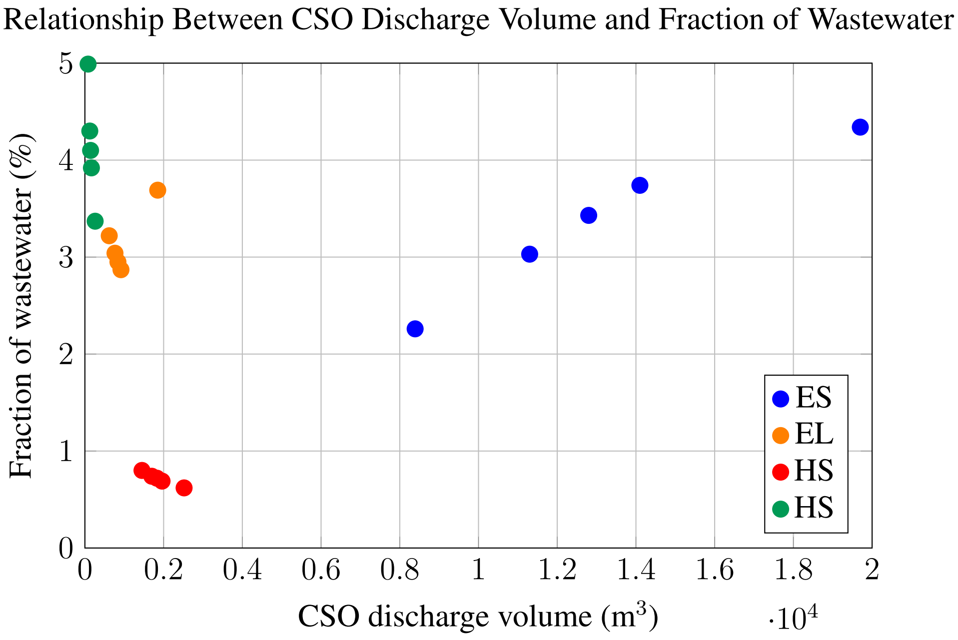


Figure 4.4: CSO discharge volume and its fraction for different rain events.

4.1.4 Pathogen Concentration from CSO

The pathogen concentration in the river C_{river} due of CSO events are presented in Table 4.2. The rain events with extreme precipitation account for the largest addition of pathogens to the raw water. When comparing duration, short-duration events (ES and HS) account for more pathogens than the long-duration rain events (EL and HL). Overall, it can be seen that *Cryptosporidium* is the pathogen that adds the least amount of pathogen per litre.

Table 4.2: Pathogen concentration from CSO events in River Göta älv.

	Climate factor %	*Campylobacter* (bacteria/L)	norovirus (viruses/L)	*Cryptosporidium* (oocysts/L)
ES	10	0.491	0.701	0.007
	15	0.627	0.895	0.009
	20	0.758	1.082	0.011
	40	1.228	1.755	0.018
EL	10	0.033	0.048	0.000
	15	0.036	0.051	0.001
	20	0.038	0.054	0.001
	40	0.098	0.140	0.001
HS	10	0.018	0.026	0.000
	15	0.019	0.027	0.000
	20	0.019	0.028	0.000
	40	0.022	0.032	0.000
HL	10	0.008	0.011	0.000
	15	0.008	0.012	0.000
	20	0.009	0.013	0.000
	40	0.013	0.018	0.000

4.2 Hydraulic Modelling

The modelled volumes of CSO under different scenarios are presented and discussed in this section. The results are compared with previous studies to identify similarities, differences, and possible causes of variations. The discussion also includes uncertainties in the assumptions. Figure 4.5 below shows the combined sewer overflow volumes for each scenario.

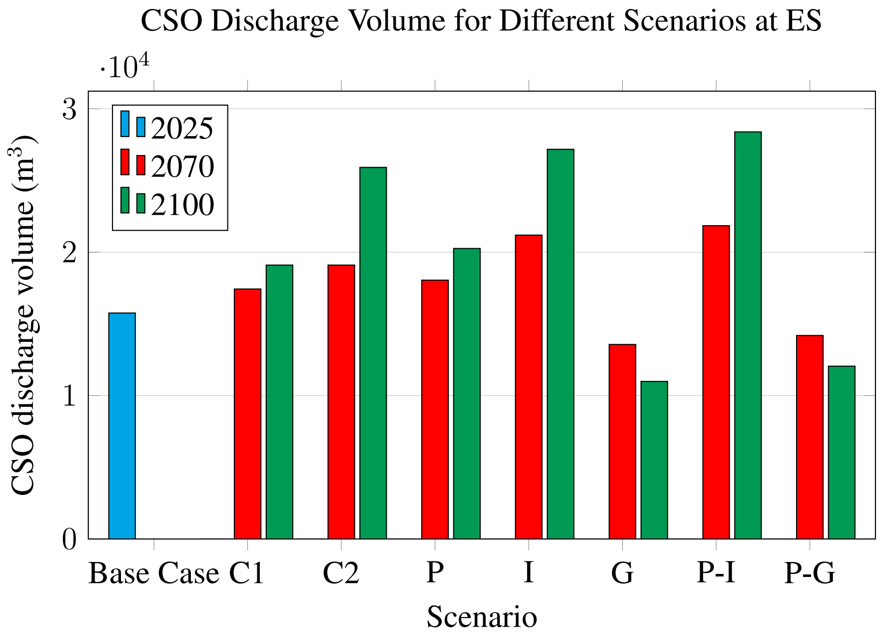


Figure 4.5: Volume CSO discharge for different scenarios at year 2025, 2070 and 2100 at rain event ES. Detailed values is found in Table E.1 in Appendix E.

4.2.1 Impact of Climate Change

The modelling results from rain event ES show an increase in CSO volumes from 2025 to 2100 for both climate scenarios C1 and C2, see Figure 4.5. The results also show, as can be expected, that the overflow volumes are higher in climate scenario C2 than in scenario C1. Scenario C2 (RCP8.5) represents a high-emission pathway with stronger climate change effects, and is therefore more critical for the capacity of the sewer system. For example, the overflow volume in scenario C2 is greater than C1 by approximately 6,810 m^3 in 2100 (36%). This highlights that climate change will have a strong effect on the system and that the extreme emission scenario has a significant impact on the CSO discharged volume.

Since the two climate change scenarios (C1 and C2) are modelled based on climate factors, the relationship between these and the change in CSO volume is also interesting to evaluate, see Figure 4.6. The figure shows a linear trend between changes in CSO volume and the climate factor for each rain event (ES and HS). This indicates that the overflow volume increases proportionally as the climate factor increases, but the increase differ between the rain events. Specifically, an increase of the climate factor by one percent increases the CSO volume discharge by approximate 2.8% for ES and 1.8% for HS. This shows that precipitation has a strong impact on the CSO discharge volume since the extremer event increases by one percentage point more than the heavy rain event.

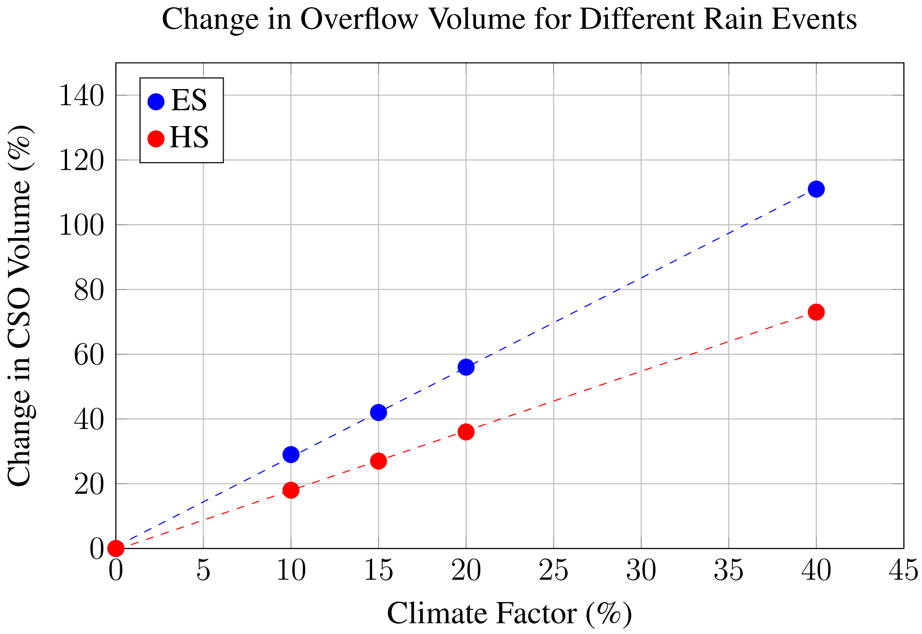


Figure 4.6: Increase of CSO volume in percentage for different rain events (ES and HS) with different climate factors.

An increase in precipitation with a climate factor of 20% results in an 56% increase in CSO discharge volume for ES and 36% for HS. In comparison, a study conducted in Norway reported that, for a single rain event, a 20% increase in precipitation led to an increase in the CSO discharge volume by 41% (Nie et al., 2009). However, this comparison should be carefully evaluated since various parameters such as sewer system design, precipitation event, and other local conditions differ between studies. These differences make the results not directly comparable, but both illustrate that the trend is that increased precipitation leads to a larger increase in CSO volumes. Therefore, it is important to plan for these additional flows due to climate change in the future.

An uncertainty with this approach is that it is not possible to determine if the future will follow Scenario C1 (RCP 4.5), Scenario C2 (RCP 8.5), or another path. Therefore, the use of C1, as the choice in the other scenarios, is a simplified assumption that aims to provide an estimate of possible climate impacts, without assuming worst-case scenario.

4.2.2 Impact of Population Growth

The effects of population growth in the future result in increased volume of CSO discharged into River Göta älv, see Figure 4.5. Compared to the Base Case (2025), the CSO volume increases with 15% in the Distant Future (2070) (with 25% population growth) and with 29% in the End of the Century (2100) (with 45% population growth). In Table 4.3 are Scenario P and Scenario C1 presented to enable evaluation of how population growth itself affects the CSO volume. This is because Scenario P is affected by the climate change scenario C1 and population growth. The effects of population growth are shown to be marginal in comparison to Scenario C1 where only 3.4% and 5.7% of the CSO discharge volume is from population growth year 2070 and 2100 respectively. It can also be seen that the influencing factors of population growth for the future time periods are similar (0.14 and 0.13) which shows for each percentage of population growth, the corresponding CSO volume increases with roughly 0.14%. This shows that the relationship between population growth and increased CSO volume is almost linear. As seen in Table 4.3, the amount of wastewater does not significantly affect the total discharge volumes. Therefore, the primary factor influencing the CSO volumes is the amount of stormwater entering the system, which highlights the importance of focusing on the reduction of stormwater.

Table 4.3: Effects of population growth.

	Base Case 2025	Distant Future 2070	End of Century 2100
Population growth (%)	0	25	45
Scenario P (m^3)	15,800	18,100	20,300
Scenario C1 (m^3)	15,800	17,400	19,100
Difference P-C1 (m^3)	0	617	1,160
Volume due to pop. growth (%)	0	3.4	5.7
Influencing factor (-)	0	0.14	0.13

In the model, the wastewater flow is assumed to increase linearly with population growth over time. However, this assumption can be questioned based on current societal trends. According to SCB (n.d.-b), the water consumption in Sweden has decreased compared to the 1990s, despite an increase in population during this period. The reason for this decrease is the use of more efficient household appliances. Therefore, the assumption of a linear increase in wastewater flow with population growth may be overestimated.

Another uncertainty is the prediction of population growth. This is because many factors are involved in the assumption such as urbanisation, birth rates, migration, and other political decisions, which may influence the number of inhabitants. However, population growth is often correlated with increased infiltration and inflow (I&I) in the sewer system. As new areas are built and the sewer network is expanded, the total length of the pipe infrastructure increases, which in turn increases the risk of leaks, faulty connections, and groundwater intrusion. This may not be fully captured by using the drinking water consumption.

4.2.3 Impact of Impervious Areas and Green Infrastructure

The results show that an increased proportion of impervious areas increases the volume of CSO being discharged, see Figure 4.5. When evaluating the volume from the single parameter scenarios, impervious areas is found to be the most critical parameter for overflow. The influencing factors for Distant Future (2070) and End of the Century (2100) differ from each other, with Distant Future having a slightly more impact than End of the Century (1.8, respectively 1.5), see Table 4.4. When comparing the influencing factor with those from Scenario P (Table 4.3, i.e. 0.14, 0.13), a significant difference of about 10 times can be seen. This shows that impervious areas have great impact on the results. This can be explained by the fact that more impervious areas lead to more runoff, which in turn leads to more stormwater that must be managed in the system.

Table 4.4: Effects of increased proportion of impervious areas.

	2025	2070	2100
Increased imperviousness (%)	0	10	20
Scenario I (m^3)	15,800	21,200	27,200
Scenario C1 (m^3)	15,800	17,400	19,100
Difference I-C1 (m^3)	0	3,760	8,070
Volume due to increased imperviousness (%)	0	18	30
Influencing factor (-)	0	1.8	1.5

The assumption of 10 and 20 percent increase in impervious surfaces of all catchments (based on literature from Dong et al. (2017) and Hamdi et al. (2011)) should be considered as a rough estimate and simplification in this case study. This is due to local variations in land use between different catchment areas. For example, it may not be realistic to increase the imperviousness of the city center by 20%, as it is already densely built. However, the municipality may also grow in the outer parts, which is not considered in this study. Another uncertainty is the planning context, where there are strategies for stormwater mitigation in the municipality (Trollhättans Stad, 2021). The goal of the strategy is to create resilient urban environments that can withstand climate change by implementing sustainable drainage systems (SuDS) and the separation of the sewer system. Therefore, the municipality no longer builds combined sewer systems. As a result, future increases in impervious surfaces will not directly lead to additional loading on the wastewater network. However, it will potentially lead to an increase in infiltration and inflow (I&I), since it is not possible to build completely compact networks, and incorrect connections will still occur.

Implementation of green infrastructure reduces CSO discharge volumes because it manages stormwater at its source and thus prevents system overload, see Figure 4.5. This is valid for both Distant Future (2070) and the End of the Century (2100). The influencing factors in Table 4.5 are negative, which indicates a volume reduction compared to not implement green infrastructure. The factors are similar (-2.2 and -2.1), indicating an almost linear relationship between decreased imperviousness and reduction in CSO discharge volume. Other studies argue that the implementation of green infrastructure has a positive impact on CSO volume. Green roofs in combination with rain gardens are shown by Hernes et al. (2020) to have a strong positive impact. The solutions by themselves are also contributing to reduction of CSO volume (Cavadini et al., 2024; Versini et al., 2016). The results, with support from the literature, showed that reducing the impervious areas is an effective measure to reduce the volumes of CSO and are therefore recommended to implement.

Table 4.5: Effects of implementation of green infrastructure in terms of decreased proportion of impervious areas.

	2025	2070	2100
Decreased imperviousness (%)	0	10	20
Scenario G (m^3)	15,800	13,600	11,000
Scenario C1 (m^3)	15,800	17,400	19,100
Difference G-C1 (m^3)		-3,870	-8,120
Volume due to decreased imperviousness (%)	0	-22	-43
Influencing factor (-)	0	-2.2	-2.1

4.2.4 Impact of Combinations of Urban Development

As seen in Figure 4.5, combinations of population growth with increased imperviousness and green infrastructure are also included to evaluate the interaction between population growth and urban planning strategies. The results show that the combination of population growth and increased imperviousness (P-I) among the different scenarios causes the largest volumes of CSO being discharge into the River Göta älv. In contrast, the scenario with population growth and green infrastructure (P-G) reduces the volume of the CSO compared to the Base Case. However, the differences are small compared to the single factor scenarios (P and G) due to the low impact of population growth.

The combination scenarios are considered the most likely outcomes for the future, but some uncertainties remain regarding future urban development. This will depend on how new developments are designed and to what extent green solutions are implemented. In reality, a mix of these may be more realistic, with some areas implementing stormwater mitigation measures, while others will be densified with more impervious areas.

4.2.5 Uncertainties Regarding Hydraulic Modelling

The hydraulic model used in this study was a simplified version of the sewer system and did not include the entire collection system. For example, the wastewater treatment plant was not included in the model, which excludes CSO occurring at or after the WWTP. This leads to an underestimate of the pathogen load to the River Göta älv as the total volume and flow from the municipality is not taken into account.

Another limitation of the model is the assumption that the sewer system remains unchanged throughout the analysis period. The simulations do not account for ongoing or future sewer separation projects, which in reality are expected to reduce the frequency and volume of combined sewer overflows.

The selected hydraulic model was time-area (Model A), which is a simplified method. Processes such as evapotranspiration and temperature effects were not included since the RDI (Rainfall Dependent Infiltration) module (Model B in MIKE+) was not used. Excluding RDI means, for example, that variations in groundwater infiltration caused by rainfall intensity are not included. This can in turn lead to an underestimation of combined sewer overflow volumes.

However, the results shown from the hydraulic modelling are representative for this study, where the impact of climate change and different urban development factors is compared. The focus of this study was to see the overall trends between these scenarios. The model is based on many assumptions, which means that a higher level of detail in some parts (e.g. RDI and sewer system) does not improve the overall quality of the work.

4.3 Quantitative Microbial Risk Assessment - QMRA

Drinking water treatment plants differ in $\log_{10}$-reduction of pathogens depending on what kind of treatment processes being involved. In this study, two different cases have being evaluated; one for drinking water consumers in Gothenburg with a representation of a DWTP similar to Alelyckan and one for drinking water consumers downstream of Trollhättan represented by an arbitrary DWTP. The DWTPs are similar to each other with the same input data, with the difference that the arbitrary DWTP does not include UV-disinfection as a treatment process. The annual risk of infection P_{annual} has been calculated using Equation (3.7) based on Scenario C1.

4.3.1 Annual Risk of Infection in Gothenburg: Peak Flow Approach

The selected pathogens *Campylobacter*, norovirus and *Cryptosporidium* does not pose a risk for drinking water consumers in Gothenburg at any of the scenarios inculded in this study. This can be seen in Figure 4.7 where the bars for annual risk of infection are below the accepted value of 10^{-4} where 1 out of 10,000 persons become sick per year. Even though all pathogens are below the limit value is *Cryptosporidium* the one closest to the limit with a risk of annual infection of roughly 10^{-6}.

Important to take into account when drawing the conclusion of no risk for drinking water consumers in Gothenburg is that only the sewer system in Trollhättan is considered, which excludes CSO from and after the WWTP which probably would underestimate the result. The water quality in the River Göta älv is also dependent on sewer systems and WWTPs along River Göta älv such as Lilla Edet, Ale, and Kungälv. It is also notable that other sources of pathogens are not considered when evaluating the risk of annual infection, like farming and agricultural. *Cryptosporidium* mainly occurs from animals and humans, and *Campylobacter* come from different sources; water, food, animals like cattle and birds (WHO, 2022). Norovirus comes from sick human beings and from contaminated food (Swedish Food Agency, 2024c). Fecal matter from animals and humans is a common source of pathogens (Göta älvs vattenvårdsförbund, 2015).

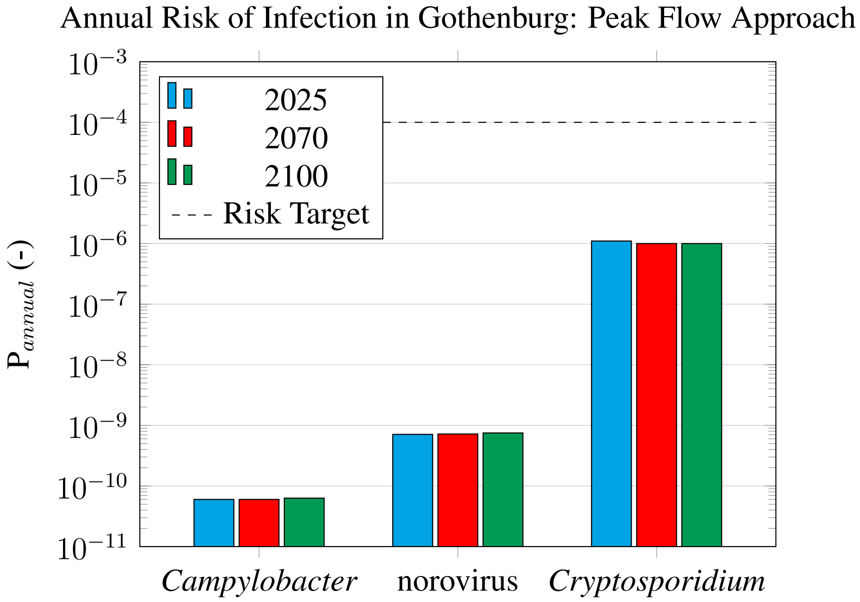


Figure 4.7: Annual risk of infection for Scenario C1 for different types pathogens in Gothenburg. Detailed values of daily and annual risk of infection is found in Table F.1 in Appendix F.

The processes in the drinking water treatment plant in this study have high $\log_{10}$-reduction for each pathogen, see Table 4.6. The DWTP consists of three microbial barriers; conventional treatment, UV-treatment and chlorination (GAC is not a microbial barrier according to Swedish Food Agency (2024a)). The results shows that the DWTP in Gothenburg is sufficient to handle CSO from the sewer system in Trollhättan. Important to note is also that the input data of pathogen removal efficiency are set to predefined values in the QMRA-tool when available, which might under or over estimate the efficiency of the DWTP.

Table 4.6: Log_{10} reduction for treatment processes in Gothenburg. Note: predefined values in the QMRA-tool have mainly been used for the treatment processes except for GAC.

	Conventional Treatment $\log_{10}$ red.	GAC $\log_{10}$ red.	UV $\log_{10}$ red.	Chlorination $\log_{10}$ red.
Campylobacter	2.1	1.7	5.3	3.4
norovirus	3.0	0.43	4.2	4.0
Cryptosporidium	3.2	0.90	3.0	0

4.3.2 Annual Risk of Infection for an Arbitrary DWTP: Peak Flow Approach

Evaluation of a drinking water treatment plant similar to Alelyckan but without UV-treatment was made to enable comparison between two DWTPs with different setup of microbial barriers. The arbitrary DWTP has conventional treatment and chlorination as microbial barriers, and also has GAC as a treatment process. UV-treatment was excluded since it was the treatment process with the overall largest $\log_{10}$-reduction, see

Table 4.6. The exclusion of UV-treatment is the only difference between the arbitrary DWTP and the one representing Alelyckan DWTP, and the input data for the treatment processes remained the same.

In Figure 4.8, it can be seen that the risk for all pathogens has increased compared to including UV-disinfection (as in Chapter 4.3.1). Although the risk for all pathogens has increased, it is only *Cryptosporidium* that pose a risk for water safety since it exceeds the accepted value of 10^{-4}, thus more than 1 out of 10,000 persons become sick each year. This highlights the importance of UV as a treatment step in DWTPs and the importance of efficient and sufficient microbial barriers. Two of the most well-known outbreaks in Sweden in the 2000s are the outbreaks of *Cryptosporidium* in Östersund and Skellefteå (Swedish Food Agency, 2025). In Östersund, they added UV as a treatment step after the outbreak (Östersunds kommun, 2025). The same actions were taken in Skellefteå (Folkhälsomyndigheten, 2016).

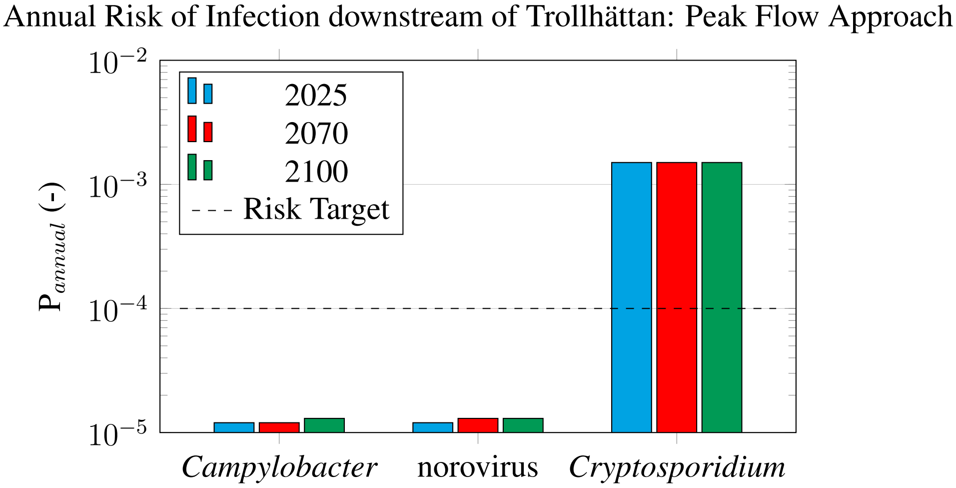


Figure 4.8: Annual risk of infection for Scenario C1 for different types pathogens at an arbitrary drinking water treatment plant. Detailed values of daily and annual risk of infection is found in Table G.1 in Appendix G.

4.3.3 Pathogen Concentration at Raw Water Intake: Pathogen Concentration Approach

For the calculation of the annual risk of infection based on the pathogen concentration method, the average pathogen concentration under 24 hours at the intake point for flow 565 m^3/s in Table 4.7 was used. These values were calculated with Equation (3.6) which take pathogens in the raw water and pathogens from the CSO event into consideration. It can be seen that the pathogen concentration slightly increases with time from 2025 to 2100 for the Extreme & Short Rain Event (ES). However, the pathogen concentration at the Heavy & Short Rain Event (HS) remains the same during all three different time periods. Another conclusion is that pathogen concentrations are higher for the extreme rain event compared to the heavy rain event. This highlights that extreme rain events are more critical for the water quality at the raw water intake.

The flow in the river has been shown to be a sensitive parameter when evaluating the pathogen concentration. The low flow (i.e. 18 m^3/s) in Table 4.7 is symbolised by the average annual flow in Säveån (Göta älvs vattenvårdsförbund, 2018) which is a river located in the western part of Sweden and the high flow (i.e. 1030 m^3/s) represents the maximum flow in River Göta älv (Göta älvs vattenvårdsförbund, 2015). It can be seen that a raw water source with low flow has a significant impact on the pathogen load except for *Cryptosporidium*, while a higher river flow has slightly lower pathogen load compared to the values where the flow was 565 m^3/s which is the average flow in River Göta älv (Göta älvs vattenvårdsförbund, 2015). From this it can be concluded that low flows are more critical than high flows for raw water quality. This is supported by Jalliffier-Verne et al. (2015) who also argue for low flow being more critical (worst-case) than high flow for water quality.

Table 4.7: Pathogen concentration at raw water intake for Scenario C1 for different flows in the water source (for Extreme & Short Rain Event (ES) and Heavy & Short Rain Event (HS)).

				2025	2070	2100
ES	565 m^3/s [a]	*Campylobacter*	(bacteria/L)	1.49	1.63	1.76
		norovirus	(viruses/L)	1.70	1.90	2.08
		Cryptosporidium	(oocysts/L)	0.407	0.409	0.411
HS	565 m^3/s [a]	*Campylobacter*	(bacteria/L)	1.02	1.02	1.02
		norovirus	(viruses/L)	1.03	1.03	1.03
		Cryptosporidium	(oocysts/L)	0.400	0.400	0.400
ES	18 m^3/s [b]	*Campylobacter*	(bacteria/L)	16.4	20.7	24.8
		norovirus	(viruses/L)	23.0	29.1	35.0
		Cryptosporidium	(oocysts/L)	0.620	0.681	0.740
ES	1030 m^3/s [c]	*Campylobacter*	(bacteria/L)	1.27	1.34	1.42
		norovirus	(viruses/L)	1.39	1.49	1.59
		Cryptosporidium	(oocysts/L)	0.404	0.405	0.406

[a] Mean flow in River Göta älv (Göta älvs vattenvårdsförbund, 2015).
[b] Annual average flow in Säveån (Göta älvs vattenvårdsförbund, 2018).
[c] Maximum flow in River Göta älv (Göta älvs vattenvårdsförbund, 2015).

4.3.4 Annual Risk of Infection in Gothenburg: Pathogen Concentration Approach

The same drinking water treatment plant as in Chapter 4.3.1, with the same treatment steps and log$_{10}$-reduction are evaluated with the pathogen concentration approach. The average flow in River Göta älv of 565 m^3/s was used and it can be seen in Figure 4.9 that no annual risk of infection occurs since the values for all time periods are below the accepted value of 10^{-4}. Compared with the peak flow based analysis (see Figure 4.2), the risks are slightly lower when evaluating the annual risk of infection based on the pathogen concentration appraoch. The trends remain the same, with *Cryptosporidium* posing the highest risk among the studied pathogens (although it does not exceed the health risk target), followed by norovirus and *Campylobacter*. Important to note is that only two-thirds of the volume from the sewer system was evaluated when calculating the annual risk of infection. This simplification impacts the results of the annual risk of infection which are now underestimated.

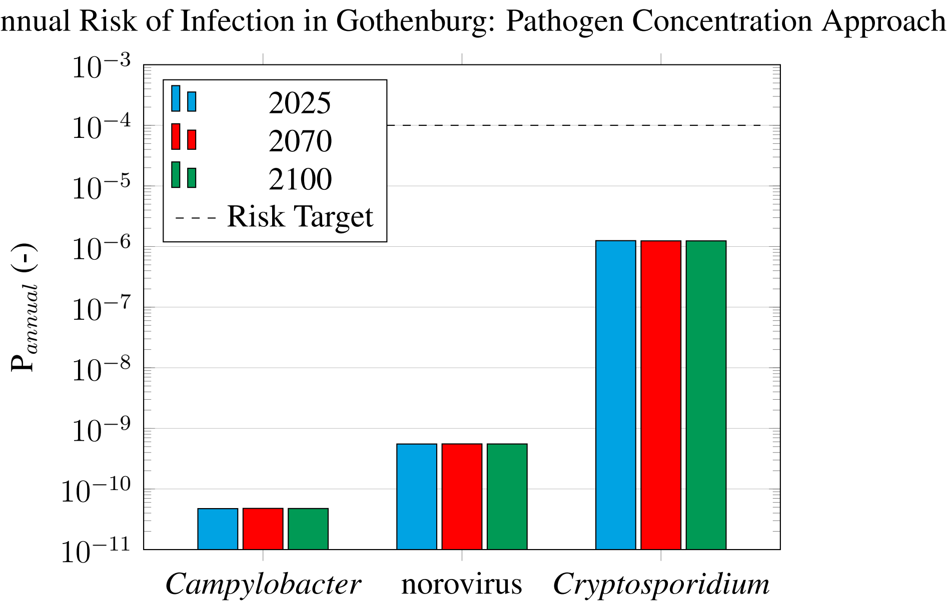


Figure 4.9: Annual risk of infection for Scenario C1 for different types pathogens in Gothenburg. Detailed values of daily and annual risk of infection is found in Table H.1 in Appendix H.

4.3.5 Annual Risk of Infection for a Arbitrary DWTP: Pathogen Concentration Approach

It can be seen in Figure 4.10 that *Cryptosporidium* pose a risk for drinking water consumers relying on water from the arbitrary DWTP since the risk is higher than the accepted value of 1 out of 10,000 persons become sick each year. Almost 10 out of 10,000 are expected to be exposed to a risk. Compared to the risk in the peak flow approach for the arbitrary DWTP (Figure 4.8), the same trend can be observed, with *Cryptosporidium* posing the highest health risk, followed by norovirus and *Campylobacter*, but the values are slightly lower in this case.

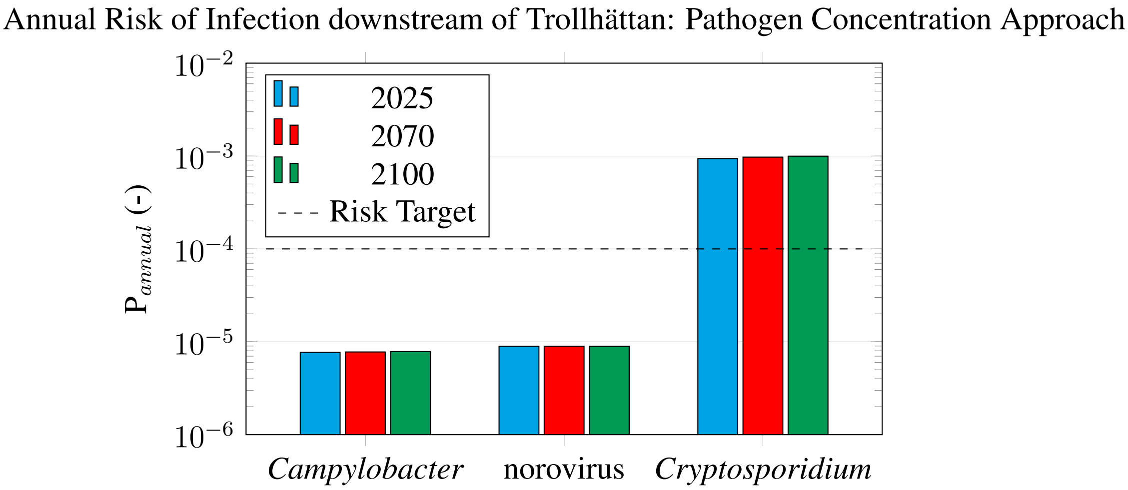


Figure 4.10: Annual risk of infection for Scenario C1 for different types of pathogens at an arbitrary drinking water treatment plant. Detailed values of daily and annual risk of infection is found in Table I.1 in Appendix I.

4.3.6 Reflection of Approaches: Peak Flow vs Pathogen Concentration

The peak flow method shows slightly higher pathogen concentrations than the pathogen concentration method, see Figure 4.11. That is because the peak flow approach is based on a short-term perspective and a worst-case scenario. In contrast, the pathogen concentration approach produces lower estimated concentrations, as it distributes the total daily discharge evenly over a 24-hour period. It is interesting that the *Cryptosporidium* concentrations are lower in the peak flow method compared to the mass balance method. This is due to the fact that the CSO discharge during peak flow contained *Cryptosporidium* levels lower than the concentration in the raw water. To improve the accuracy of the peak flow method, it would be recommended to include the *Cryptosporidium* concentration in the raw water.

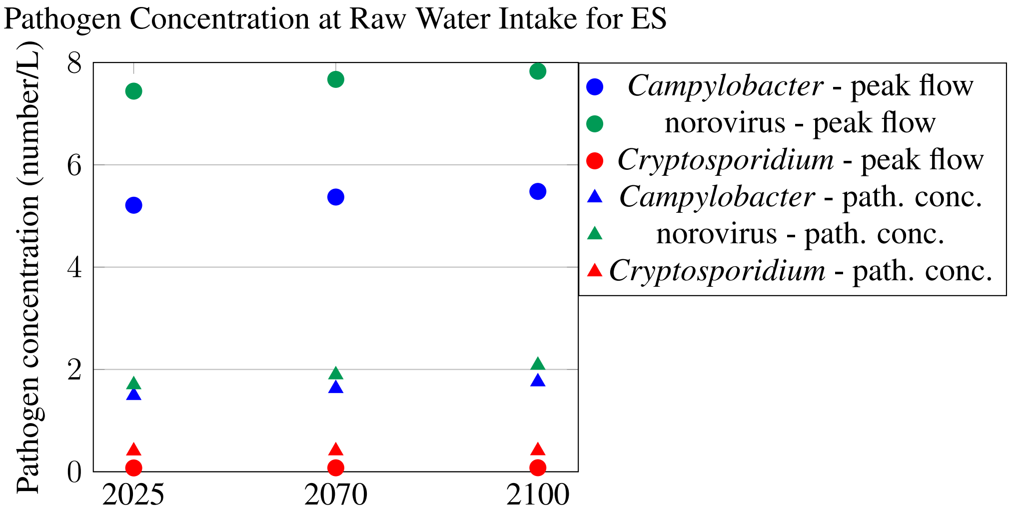


Figure 4.11: Volume of CSO and wastewater being discharge for different rain events with different climate factors.

The method using peak flow to evaluate dilution factors is based on a momentary event, i.e., the peak flow during a rain event and the wastewater flow at that moment. The other method, using pathogen concentration, is based on the volume of wastewater being discharged during the whole event. This volume was recalculated to an average flow of wastewater discharge during each rain event. Both methods are simplifications, where only the heaviest flow during the rain events for calculations of annual risk of infections are considered in the peak flow method. In the pathogen concentration method, an average value of wastewater flow during the rain event is calculated based on a graphical determination of the duration of the CSO event. Another simplification is that only two-third of the system is evaluated. The time perspective, both for the CSO event and the spread of contamination in the river, is considered when using the pathogen concentration method, which is not included in the peak flow method.

4.3.7 Uncertainties Regarding QMRA

For all pathogens except *Cryptosporidium*, the risk is projected to increase in the future compared to Base Case 2025 when using the peak flow approach. The reason why *Cryptosporidium* poses the highest risk today (2025) is due to a higher concentration in the raw water compared to the diluted untreated wastewater. There is a wide range of *Cryptosporidium* concentrations in untreated wastewater reported in other studies. A literature review from Nasser (2016) validates the argument of a large spread of concentrations, 0-60,000 oocysts per litre worldwide. A study from Robertson et al. (2006) in Norway shows concentrations of untreated sewage of 100-28,000 oocysts per litre with median values of 200-4,000 oocysts per litre. In Sweden has Ottoson et al. (2006) found concentrations of *Cryptosporidium* up to about 160 oocysts per litre. This highlights the uncertainty of selecting a specific value, as the concentrations differ in several orders of magnitude. The value of 1,000 oocysts per litre used in this study was a modelled value from Tyréns (2018) and the order of magnitude is consistent with other studies, which approves the selected pathogen concentration of *Cryptosporidium*.

The pathogen concentration is therefore an uncertain parameter in QMRA, as it can vary due to several reasons such as season and population health. The concentration of norovirus in untreated wastewater was reported with a minimum value of about 195 viruses per litre and a maximum value of about 4,470 viruses per litre (Ottoson et al., 2006). However, in this study, the concentration was set to 10^5 viruses per litre, according to modelled values from Trollhättan which ranged from almost 1,000 to around 10^6 (Tyréns, 2018). For *Campylobacter* the concentration was set to 70,000 per litre according to modelled values (Tyréns, 2018). However, the modelled concentration varied between 4,000 and 100,000, which is a wide range, but the selected concentration was considered the most appropriate given the time of year, so it reflected a typical seasonal trend for the summer period.

The selected concentrations for the raw water were set to a specific standrad value for each pathogen. For *Campylobacter*, this value vas set to 1 bacteria/L, norovirus to 1 viruses/L and *Cryptosporidium* to 0.4 oocysts/L (Abrahamsson et al., 2009). This study relies on one specific value for each pathogen, which implies uncertainties for this study. Since the ranges are broad for pathogen concentrations in untreated wastewater, it can be assumed that there are also broad variations in the raw water quality. Therefore, it would be more realistic to assign the raw water with values of probability distribution. One possible way to gain more detailed data is by sampling in the raw water source. However, this is time consuming and may not be a cost-effective solution.

Another uncertainty in the results is that the raw water intake at Alelyckan in Gothenburg is closed for approximately 100 days per year (Göta älvs vattenvårdsförbund, 2015). The main reason for these closures is the suspected or confirmed microbiological impact, often associated with heavy rainfall and CSO events upstream. This means during a significant part of the year, no raw water is taken in for drinking water production from the River Göta älv (instead a reserve raw water source is used), which affects the ability to fully assess the actual impact of CSOs events from Trollhättan on the drinking water supply. The QMRA in this study has been conducted for 365 days, which means that the model assumes that the raw water intake is open every day. The implications of this assumption are that the risk is overestimated and should be carefully evaluated.

4.4 Suggested Improvements

In this study, the most efficient solution to improve water management is to implement green infrastructure in the city. This will lead to smaller volumes of stormwater generated during rain events and then less CSO being discharged from the wastewater sewer system in the municipality to the recipient, which in this case is the River Göta älv. The implementation of green infrastructure is an effective way to reduce the amount of impervious surfaces and thereby reduce the CSO volumes.

Another proposed solution is to continue with the separation of the combined sewer system. From this study, it is seen that most of the water discharged is stormwater, with only a few percentages being wastewater. Stormwater from impervious areas has a strong impact on the volume of CSO discharged. By separating stormwater from wastewater, the amount of wastewater discharged will be reduced, limiting the pathogen loads in water bodies, in this case from Trollhättan municipality into River Göta älv. However, separation of the sewer system also brings challenges. A challenge can be the discharge of polluted stormwater with micropollutants into the recipient without treatment. This can lead to increased pollution from surface runoff including, for example, microplastics, heavy metals, and organic pollutants. This can lead to a shift from pathogen-related health risks to health risks associated with micropollutants, but it can be managed by implementation of green infrastructure and measures described in Chapter 2.6. Another challenge for the separated system is the I&I that increases the total hydraulic load on the wastewater system. This highlights the importance of working with regular pipe network maintenance and long-term planning to have a well-functioning system.

To reduce the annual risk of infection, the microbial barriers in the drinking water treatment plants are crucial. In this study, UV-disinfection is shown to be an important barrier to ensure safe drinking water. The suggested improvement is for DWTPs to review that there are sufficient microbial barriers even in case of emergencies, but also to ensure that all processes are robust and efficient.

There are limited regulations regarding pathogen loads from combined sewer overflows into water bodies. Many guidelines focus on controlling nutrient levels and chemical pollutants, but pathogens such as bacteria, viruses, and parasites are often less regulated or monitored. This regulatory gap should be reconsidered to better protect public health and the environment from harmful pathogens.

5 Conclusion and Further Research

The key findings related to combined sewer overflows under varying rainfall events and urbanisation scenarios are summerised. The associated health risk posed by the pathogen load from CSO events is assessed. Finally, knowledge gaps are identified and directions for further research are suggested to improve CSO prediction and mitigation methods in the context of changing climate and urban conditions.

5.1 Conclusion

In this study, the sewer system in the municipality of Trollhättan has been studied. Four different rain events have been evaluated based on volume, dilution, pathogen concentration, and peak flow, where rain events with short duration (around one hour) are more critical than rain events with longer duration (up to 10h). High intensity rain events are shown to be most critical, where the largest volumes of wastewater (containing pathogens) are discharged and are the least diluted.

Increased precipitation in the future due to climate change leads to increased volume of CSO being discharged. Scenario C2 (RCP8.5) becomes more critical than Scenario C1 (RCP4.5). For short duration rain events are the relationship between climate factor and increased CSO discharged volume linear within each rain event, but larger than than 1:1. For urban development factors, population growth (Scenario P) does not show any significant impact on the CSO discharge volume, while the proportion of impervious area has a great impact. Increased proportion of impervious area (Scenario I) shows larger volumes of overflow, while implementation of green infrastructure (Scenario G – evaluated as decreased proportion of impervious areas) reduces the overflow volume. Therefore, the proportion of impervious areas is shown to be the most critical parameter of urban development in this study, while climate change is the overall most critical factor for CSO discharge volume.

The quantitative microbial risk assessment was carried out for *Campylobacter*, norovirus and *Cryptosporidium*. Two different DWTP types have been studied: a DWTP in Gothenburg (represented by a DWTP similar to Alelyckan) and an arbitrary DWTP (similar to Alelyckan DWTP but without UV-disinfection). Two different approaches have been studied (peak flow and pathogen concentration), which showed similar results. For the DWTP in Gothenburg, no annual risk of infection was identified, but for the arbitrary DWTP, the annual risk of infection exceeding the tolerated risk level of 1 out of 10,000 persons per year being infected with *Cryptosporidium*. Since only UV-treatment differs between the two DWTPs, it highlights the importance of UV-disinfection. However, other processes are not evaluated, which could potentially lead to exceeding the accepted risk of annual infection.It is notable that no details about $\log_{10}$-reduction for the processes in the DWTPs were identified, therefore standard values were used. Only the sewer system in the municipality of Trollhättan was considered, where CSO from the wastewater treatment plant, but also other factors that affect the water quality in River Göta älv, such as farming and agriculture runoff are excluded from the calculation of annual risk of infection. This highlights that these results reflect the impact from the sewer system on drinking water consumers downstream Trollhättan municipality, but the risk of infection in reality are also depending on CSO from other cities, including WWTPs and other diffuse sources.

5.2 Suggestions for Future Research

Future research on this topic should aim to reduce some of the uncertainties stated in this report and increase the level of detail in each aspect studied. A suggestion is to analyse a wider range of rainfall events and different time periods to obtain a more comprehensive understanding of CSO behavior. To be able to recommend certain green measures, it would be suggested to use the existing LID (Low Impact Development) module in MIKE+ to have more realistic assessment. Model the separation of the collection system could also be made in future research.

Further, it is suggested to include the WWTP and its processes in the modelling part. It would also be interesting to include the quality and quantity of the effluent wastewater from the WWTP to ensure the full impact of a rain event. The concentration of pathogens in untreated wastewater and in raw water could be improved by sampling. Another suggestion is to also model the transport time, dispersion, and diffusion of the pollution plumes in the River Göta älv, which could be made in a three-dimensional (3D) modelling software.

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Appendix A

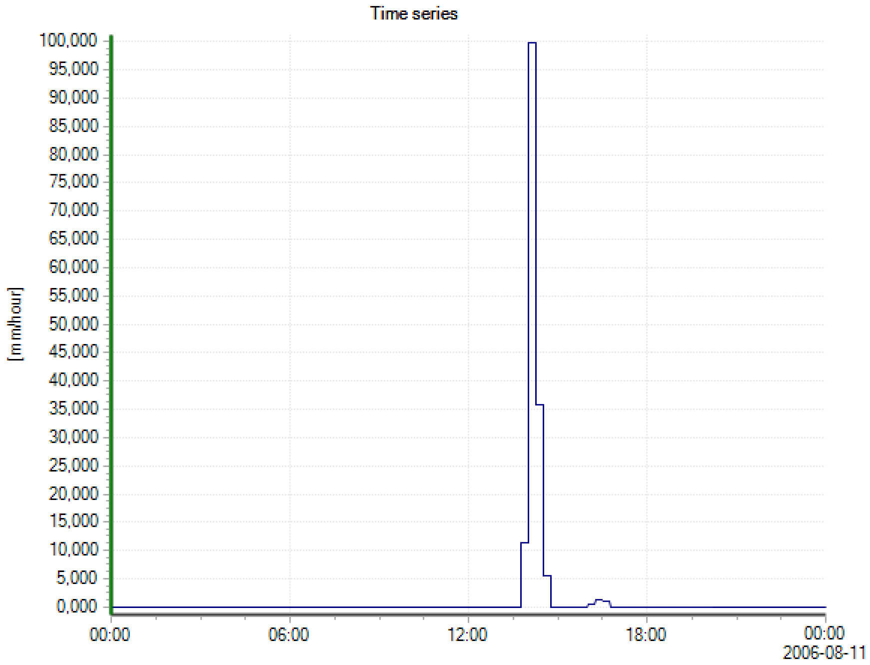

Figure A.1: Precipitation Extreme & Short Rain Event (ES) on 10 August 2006. Total rain volume during rain event was 38 mm.

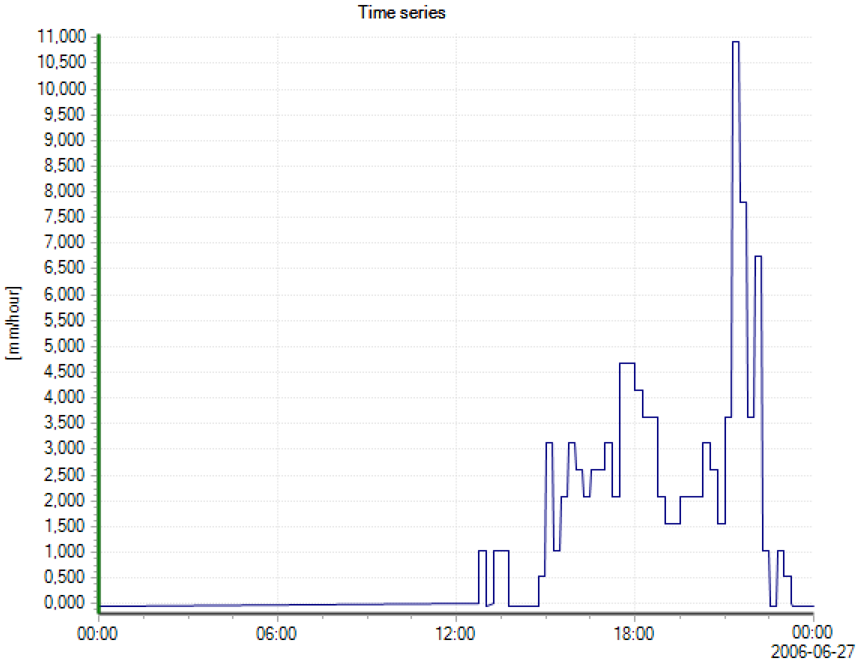

Figure A.2: Precipitation Extreme & Long Rain Event (EL) on 26 June 2006. Total rain volume during rain event was 25 mm.

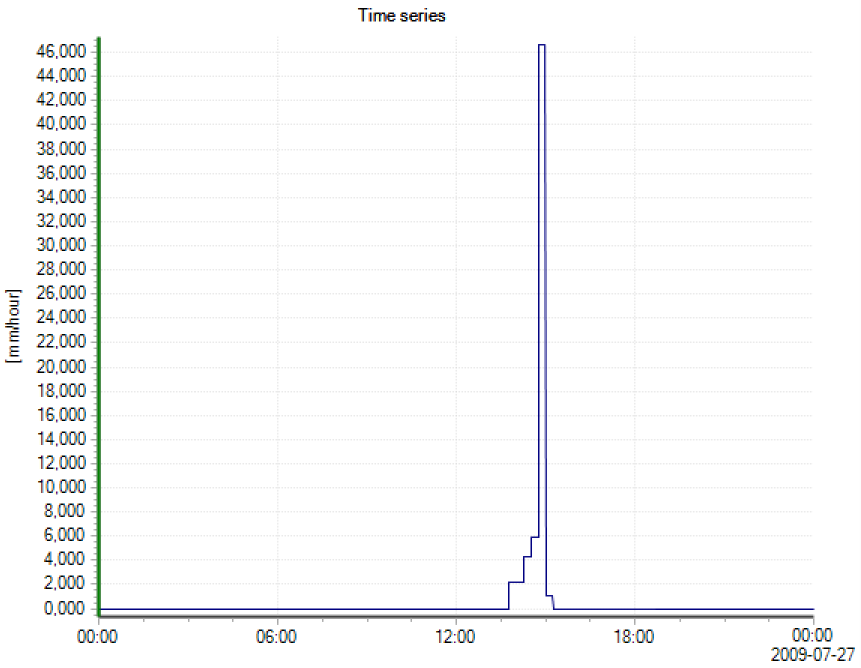

Figure A.3: Precipitation Heavy & Short Rain Event (HS) on 26 July 2009. Total rain volume during rain event was 16 mm.

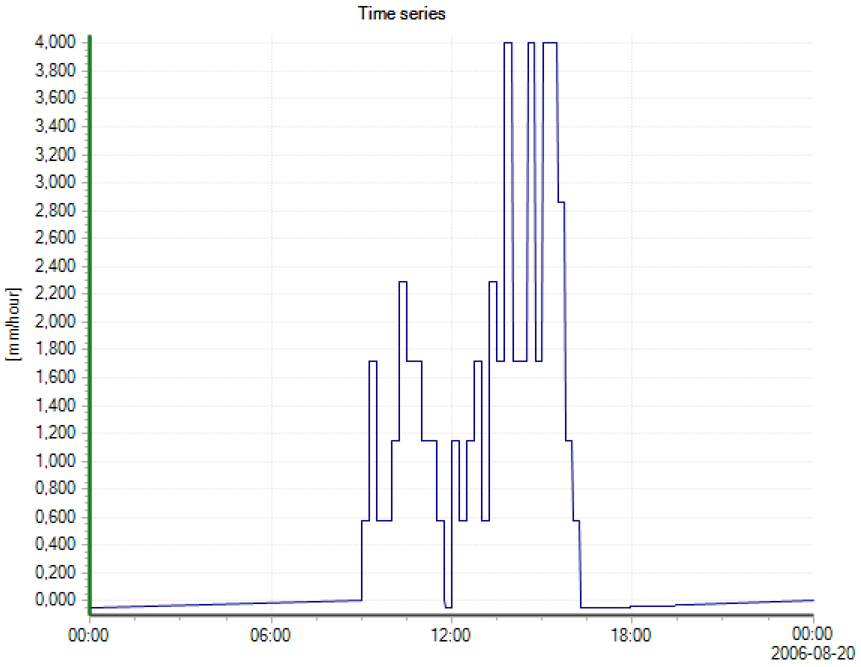

Figure A.4: Precipitation Heavy & Long Rain Event (HL) on 19 August 2006. Total rain volume during rain event was 12 mm.

Appendix B

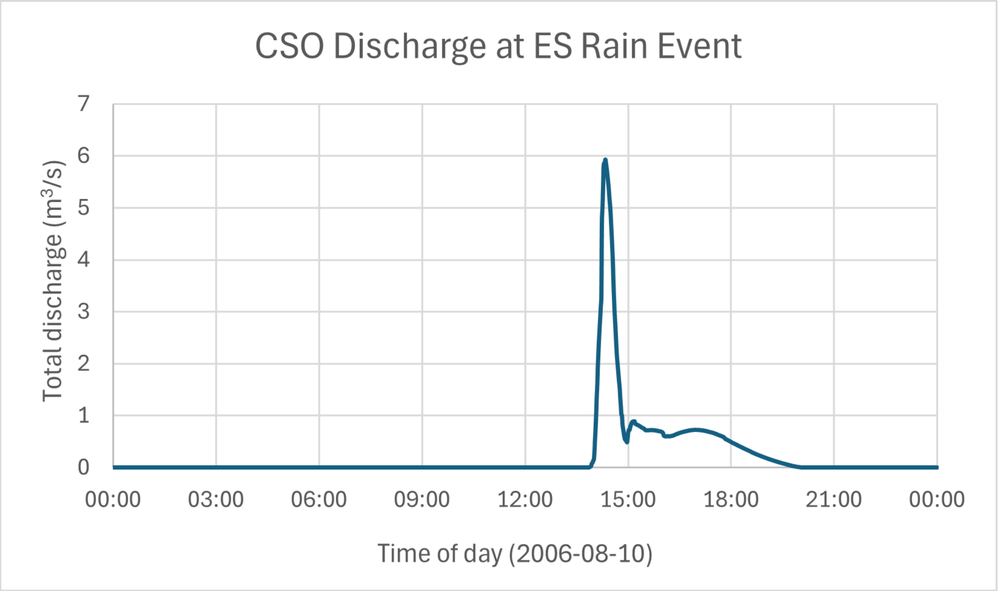

Figure B.1: Total CSO discharge flow during 2006-08-10. Peak flow occur at 14:20.

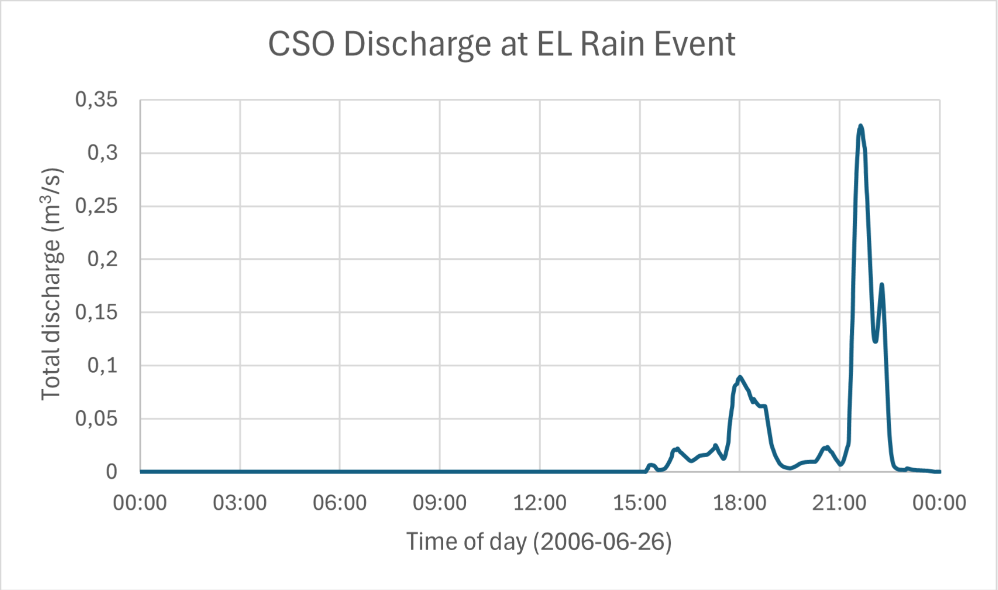

Figure B.2: Total CSO discharge flow during 2006-06-26. Peak flow occur at 21:37.

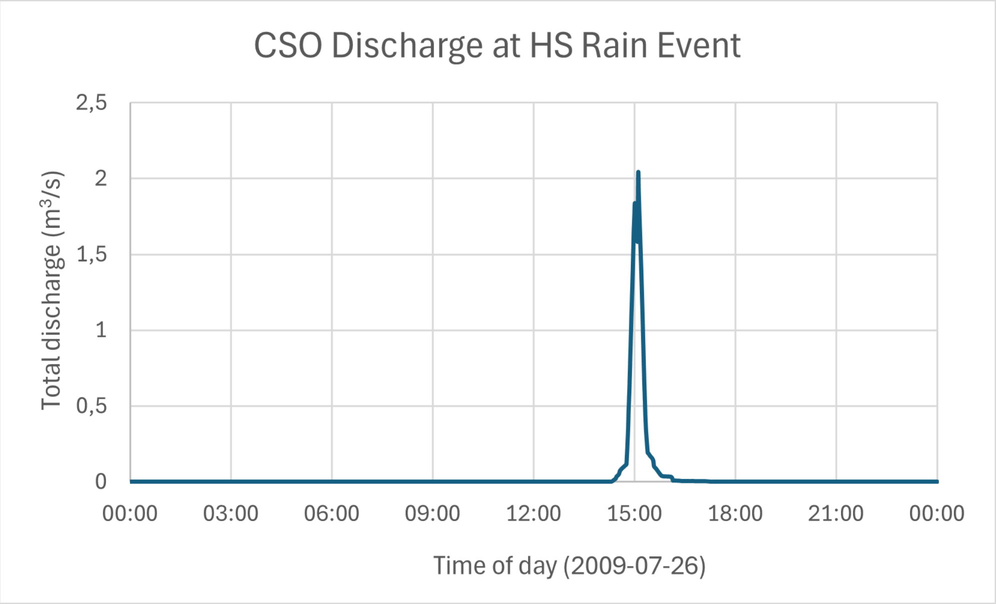

Figure B.3: Total CSO discharge flow during 2009-07-26. Peak flow occur at 15:06.

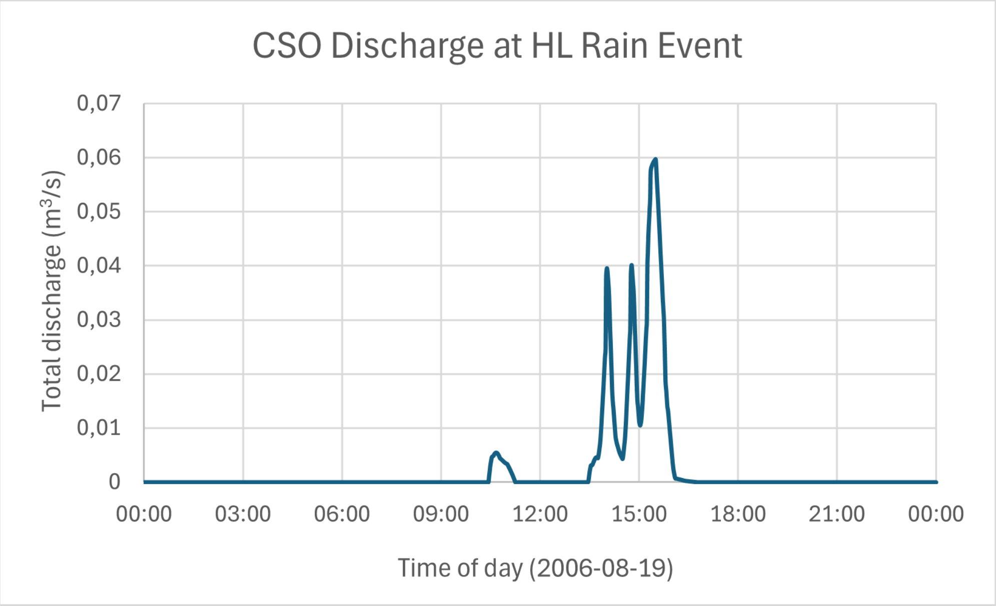

Figure B.4: Total CSO discharge flow during 2006-08-19. Peak flow occur at 15:30.

Appendix C

Table C.1: Discharge volume of CSO and wastewater discharge for different rain events and climate factors.

	Volume CSO (m^3)					Volume wastewater (m^3)				
Climate change scenario	-	C1/C2	C1	C1/C2	C2	-	C1/C2	C1	C1/C2	C2
Year	-	2025	2070	2100/2070	2100	-	2025	2070	2100/2070	2100
Climate factor (%)	0	10	15	20	40	0	10	15	20	40
Extreme & Short Rain Event (ES)	8,390	11,300	12,800	14,100	19,700	190	342	437	528	856
Extreme & Long Rain Event (EL)	618	764	839	916	1,850	19.9	23.2	24.8	26.3	68.3
Heavy & Short Rain Event (HS)	1,450	1,700	1,830	1,960	2,520	11.5	12.6	13.1	13.6	15.5
Heavy & Long Rain Event (HL)	80.6	124	144	165	260	4.02	5.31	5.89	6.45	8.74

Appendix D

Table D.1: Dilution factors for different rain event with climate factor 20%.

	D_{system} (-)	D_{river} (-)	D_{total} (-)
Extreme & Short Rain Event (ES)	133	96.0	12,800
Extreme & Long Rain Event (EL)	65.7	1,740	114,000
Heavy & Short Rain Event (HS)	76.5	279	21,300
Heavy & Long Rain Event (HL)	32.8	9,450	310,000

Appendix E

Table E.1: Discharge volume of CSO for different scenarios at Extreme & Short Rain Event (ES). Corresponding climate change scenario in parenthesis after each presented scenario.

	Volume CSO (m^3)		
	2025	2070	2100
Base Case (C1/C2)	15,800	-	-
Scenario C1 (C1)	-	17,400	19,100
Scenario C2 (C2)	-	19,100	25,900
Scenario P (C1)	-	18,100	20,300
Scenario I (C1)	-	21,200	27,200
Scenario G (C1)	-	13,600	11,000
Scenario P-I (C1)	-	21,800	28,400
Scenario P-G (C1)	-	14,200	12,100

Appendix F

Table F.1: Risk of infection in Gothenburg: peak flow approach.

		P_{inf} (ES)			P_{inf} (HS)			P_{annual}		
		2025	2070	2100	2025	2070	2100	2025	2070	2100
Campylobacter	Raw water	1.4E-13*	1.4E-13*	1.4E-13*	1.4E-13*	1.4E-13*	1.4E-13*	-	-	-
	Base Case	6.5E-13	-	-	4.0E-13	-	-	6.0E-11	-	-
	Scenario C1	-	7.2E-13	7.8E-13	-	3.7E-13	4.5E-13	-	6.0E-11	6.3E-11
norovirus	Raw water	1.5E-12*	1.5E-12*	1.5E-12*	-	-	-	-	-	-
	Base Case	1.1E-11	-	-	6.1E-12	-	-	7.1E-10	-	-
	Scenario C1	-	1.2E-11	1.1 E-11	-	6.1E-12	7.0E-12	-	7.2E-10	7.5E-10
Cryptosporidium	Raw water	3.1E-09*	3.1E-09*	3.1E-09*	-	-	-	-	-	-
	Base Case	9.1E-10	-	-	3.5E-10	-	-	1.1E-06	-	-
	Scenario C1	-	6.9E-10	6.8E-10	-	3.0E-10	2.9E-10	-	1.0E-06	1.0E-06

* Calculated with standard values, assumed to be constant over time for each pathogen.

Appendix G

Table G.1: Risk of infection downstream of Trollhättan: peak flow approach.

		P_{inf} (ES)			P_{inf} (HS)			P_{annual}		
		2025	2070	2100	2025	2070	2100	2025	2070	2100
Campylobacter	Raw water	2.8E-08*	2.8E-08*	2.8E-08*	2.8E-08*	2.8E-08*	2.8E-08*	-	-	-
	Base Case	1.4E-07	-	-	7.9E-08	-	-	1.2E-05	-	-
	Scenario C1	-	1.3E-07	1.4E-07	-	8.0E-08	9.0E-08	-	1.2E-05	1.3E-05
norovirus	Raw water	2.6E-08*	2.6E-08*	2.6E-08*	2.6E-08*	2.6E-08*	2.6E-08*	-	-	-
	Base Case	1.9E-07	-	-	1.0E-07	-	-	1.2E-05	-	-
	Scenario C1	-	2.0E-07	2.0E-07	-	1.1E-07	1.2E-07	-	1.3E-05	1.3E-05
Cryptosporidium	Raw water	4.5E-06*	4.5E-06*	4.5E-06*	4.5E-06*	4.5E-06*	4.5E-06*	-	-	-
	Base Case	6.7E-07	-	-	3.2E-07	-	-	1.5E-03	-	-
	Scenario C1	-	8.3E-07	6.6E-07	-	4.0E-07	3.8E-07	-	1.5E-03	1.5E-03

* Calculated with standard values, assumed to be constant over time for each pathogen.

Appendix H

Table H.1: Risk of infection in Gothenburg: pathogen concentration approach.

		P_{inf} (ES)			P_{inf} (HS)			P_{annual}		
		2025	2070	2100	2025	2070	2100	2025	2070	2100
Campylobacter	Raw water	1.3E-13*	1.3E-13*	1.3E-13*	1.3E-13*	1.3E-13*	1.3E-13*	-	-	-
	Base Case	1.8E-13	-	-				4.74E-11	-	-
	Scenario C1	-	2.0E-13	2.0E-13	-	1.3E-13	1.2E-13	-	4.78E-11	4.76E-11
norovirus	Raw water	1.5E-12*	1.5E-12*	1.5E-12*	1.5E-12*	1.5E-12*	1.5E-12*	1.5E-12*	-	-
	Base Case	2.5E-12	-	-	1.5E-12	-	-	5.52E-10	-	-
	Scenario C1	-	2.7E-12	3.0E-12	-	1.5E-12	1.4E-12	-	5.54E-10	5.53E-10
Cryptosporidium	Raw water	3.4E-09*	3.4E-09*	3.4E-09*	3.4E-09*	3.4E-09*	3.4E-09*	-	-	-
	Base Case	3.3E-09	-	-	3.9E-09	-	-	1.25E-06	-	-
	Scenario C1	-	4.6E-09	3.8E-09	-	3.1E-09	3.4E-09	-	1.24E-06	1.24E-06

* Calculated with standard values, assumed to be constant over time for each pathogen.

Appendix I

Table I.1: Risk of infection downstream of Trollhättan: pathogen concentration approach.

		P_{inf} (ES)			P_{inf} (HS)			P_{annual}		
		2025	2070	2100	2025	2070	2100	2025	2070	2100
Campylobacter	Raw water	2.1E-08*	2.1E-08*	2.1E-08*	2.1E-08*	2.1E-08*	2.1E-08*	-	-	-
	Base Case	3.1E-08	-	-	2.0E-08	-	-	7.7E-06	-	-
	Scenario C1	-	3.5E-08	3.7E-08	-	2.2E-08	2.4E-08	-	7.8E-06	7.8E-06
norovirus	Raw water	2.4E-08*	2.4E-08*	2.4E-08*	2.4E-08*	2.4E-08*	2.4E-08*	-	-	-
	Base Case	4.4E-08	-	-	2.7E-08	-	-	8.9E-06	-	-
	Scenario C1	-	4.9E-08	4.9E-08	-	2.6E-08	2.5E-08	-	8.9E-06	8.9E-06
Cryptosporidium	Raw water	2.6E-06*	2.6E-06*	2.6E-06*	2.6E-06*	2.6E-06*	2.6E-06*	-	-	-
	Base Case	2.2E-06	-	-	2.3E-06	-	-	9.4E-04	-	-
	Scenario C1	-	4.2E-06	3.4E-06	-	3.2E-06	4.2E-06	-	9.7E-04	1.0E-03

* Calculated with standard values, assumed to be constant over time for each pathogen.

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