CHALMERS
UNIVERSITY OF TECHNOLOGY

Environmental risk assessment of stormwater run-off from central Gothenburg to Göta älv

Master's thesis in Industrial Ecology

JONATHAN BÖRJESSON
DAVID EKMAN ANKARBERG

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF ENVIRONMENTAL SYSTEMS ANALYSIS

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2026
www.chalmers.se

Master's thesis 2026

Environmental risk assessment of stormwater run-off from central Gothenburg to Göta älv

JONATHAN BÖRJESSON
DAVID EKMAN ANKARBERG

Department of Technology Management and Economics
Division of Environmental Systems Analysis
Chalmers University of Technology
Gothenburg, Sweden 2026

Environmental risk assessment of stormwater run-off from central Gothenburg to Göta älv
JONATHAN BÖRJESSON
DAVID EKMAN ANKARBERG

Supervisor: Rickard Arvidsson, Environmental Systems Analysis
Examiner: Rickard Arvidsson, Environmental Systems Analysis

Master's Thesis 2026
Department of Technology Management and Economics
Division of Environmental Systems Analysis
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Göta älv and Göteborg as seen from Älvsborgsbron (Picture taken by the authors, 2026)

Gothenburg, Sweden 2026

Environmental risk assessment of stormwater run-off from
central Gothenburg to Göta älv
JONATHAN BÖRJESSON
DAVID EKMAN ANKARBERG
Department of Technology Management and Economics
Chalmers University of Technology

Abstract

An environmental risk assessment of stormwater run-off from central Gothenburg was conducted for the Göta älv river catchment located between the estuary of the Säveån river and the Älvsborg bridge. The run-off from the catchment was modeled based on standard pollutant concentrations for each land-use type present within its geographical limits. Other sources, such as tributaries, wastewater treatment plants, and combined sewer overflow were modeled from measured concentrations. The environmental fate model was based on the GREAT-ER model. The assessed pollutants were selected on the basis of municipal prioritization and data availability. The pollutants were PFOS, tributyltin, trichloroethylene, benzene, benzo[a]pyrene, copper, zinc, chromium, arsenic, lead, cadmium, mercury, and nickel. No risk was observed for any individual substance in the risk assessment, with risk characterization ratios (RCR) below the risk threshold value of 1. However, the combined mixture toxicity RCR of the assessed substances showed that risk was present in the catchment. The metals zinc, copper, and nickel were found to be the key contributors to the mixture toxicity RCR. Bioretention cells were found to be an efficient measure in reducing the run-off pollutant load from central Gothenburg. However, it was shown that the reductions had a relatively low influence on the pollutant concentrations in the river catchment. The influence of the bioretention cells achieved a maximum RCR reduction of 5.8%. This suggested that such measures could be more efficient if implemented in catchment areas further upstream.

Keywords: Stormwater, run-off, pollution, bioretention cells, risk assessment, Göta älv, mixture toxicity.

Acknowledgements

We want to express our sincere gratitude to our examiner and supervisor Rickard Arvidsson for his knowledge, support, guidance, and wise words of advice. It has been a privilege to have him in our corner, always helping us find our way, thank you. We would also like to thank our supervisor from Göteborgs Stad - Kretslopp och vatten, Lina Ekholm, for her knowledge, encouragement, and help with problem solving. Finally, we want to thank Thomas and Cecilia Larm from StormTac stormwater solutions for providing us with some of the crucial data and knowledge that laid the foundation of our thesis.

Jonathan Börjesson, Gothenburg, June 2026
David Ekman Ankarberg, Gothenburg, June 2026

List of Acronyms

List of acronyms that have been used throughout this thesis listed in alphabetical order:

AF	Assessment Factor
CSO	Combines Sewer Overflow
EC50	Effective Concentration 50%
ECHA CHEM	European Chemicals Agency Chemical Database
ERA	Environmental Risk Assessment
GHG	Greenhouse Gas
GREAT-ER	Geo-referenced Regional Exposure Tool for European Rivers
HT	Heavy Traffic
LC50	Lethal Concentration 50%
LHT	Light Heavy Traffic
MEC	Measured Environmental Concentration
PAH	Polycyclic Aromatic Hydrocarbons
PEC	Predicted Environmental Concentration
PNEC	Predicted No Effect Concentration
RCP	Representative Concentration Pathways
RCR	Risk Characterization Ratio
SMHI	Sveriges Meteorologiska och Hydrologiska Institut
SÄ	Säveån-Älvsborgsbron
TSS	Total Suspended Solids
USEPA	United States Environmental Protection Agency
VISS	Vatteninformationssystem Sverige
WDF	Water Directive Framework
WWTP	Wastewater Treatment Plant

Nomenclature

Nomenclature of indices and parameters that have been used for calculations throughout this thesis.

Indices

i	Index for land-use types
j	Index for measured flows
m	Index for pollutants
n	Index for river segment

Parameters

A_i	Area per land-use type i
α	Assumed fraction of $Q_{run,i,pe}$ captured by bioretention cells
BCF_m	Bio concentration factor per pollutant m
β	Assumed pollutant removal efficiency of bioretention cell
$C_{base,i}$	Standard pollutant concentration for infiltrated water per land-use type i and pollutant m
$C_{end,n,m}$	Concentration at the end of the segment n per pollutant m
$C_{fish,j,m}$	Pollutant concentration (wet weight) in fish per measured flow j and pollutant m
$C_{j,m}$	Pollutant concentration per measured flow j and pollutant m
$C_{run,i,m}$	Standard pollutant concentration for run-off water per land-use type i and pollutant m
$C_{water,j,m}$	Pollutant concentration in water per measured flow j and pollutant m
E_i	Evapotranspiration intensity per land-use type i
$f_{d,m}$	Dissolved fraction of pollutant m
$f_{s,m}$	Sorbed fraction of pollutant m
$\Phi_{in,n,m}$	Total mass flow entering the segment n per pollutant m
$\Phi_{j,m}$	Pollutant mass flow per measured flow j and pollutant m
$\Phi_{out,n,m}$	Total mass flow at the end of the segment per pollutant m
$\Phi_{run,base,m}$	Total pollutant mass flow of run-off and baseflow per pollutant m
φ_i	Run-off coefficient per land-use type i
HRT_n	Hydraulic residence time of river segment n
k_2	Reaeration coefficient

$k_{deg,m}$	First-order degradation rate constant of pollutant m
$K_{inf,i}$	Infiltrated fraction of P per land-use type i
k_m	Total first-order elimination rate constant of pollutant m
$k_{sed,m}$	First-order sedimentation rate constant of pollutant m
$k_{vol,m}$	First-order volatilization rate constant of pollutant m
K_x	Fraction of K_{inf} reaching baseflow
L_n	Length of segment n
λ	Area of bioretention cell as share of catchment SÄ
P	Mean annual precipitation
P_{pe}	Precipitation of one precipitation event
PEC_m	Predicted environmental concentration per pollutant m
$PNEC_m$	Predicted no effect concentration per pollutant m
$Q_{base,i}$	Baseflow per land-use type i
Q_j	Flow per measured flow j
Q_n	River discharge (flow rate) in segment n
$Q_{run,i}$	Run-off flow per land-use type i
$Q_{run,i,pe}$	Run-off flow per land-use type i of one precipitation event pe
RE	Removal efficiency
RCR_m	Risk characterization ration per pollutant m
$t_{1/2,m}$	Degradation half-life of pollutant m
Θ_m	Water-film reference-substance parameter of pollutant m
U_n	Average flow velocity in segment n
Y_n	Average depth in segment n

Contents

List of Figures

List of Tables

1 Introduction

Göta älv is Sweden's most water-abundant river, covering 750 km through Norway and Sweden with a total catchment area of 50000 km^2, corresponding to 10% of Sweden's total surface area (Sveriges meteorologiska och hydrologiska institut (SMHI), n.d.a). The river provides habitats for 37 species of freshwater fish and many other aquatic organisms. It is also the single largest drinking water source in the country, serving 700000 people. Its estuary is located to the west of the city center of Gothenburg, flowing through the archipelago before reaching the Kattegat sea. To the east of the estuary, flowing through the middle of Gothenburg from the Säve river to the east to the Älvsborg bridge to the west, sits what this study denotes as catchment SÄ. The catchment area of catchment SÄ covers a large part of the city center, thus receiving much of its pollution (SMHI, 2022).

In larger cities such as Gothenburg, anthropogenic activities such as industries, agriculture, traffic, infrastructure, and spillages cause continuous emissions and buildup of environmentally harmful pollutants on surfaces throughout the city (Müller et al., 2020). During precipitation, some of these pollutants are suspended in the flowing water, eventually reaching the body of water connected to the catchment area onto which the precipitation occurs, specifically catchment SÄ of the Göta älv river in this study. This phenomenon is often referred to as stormwater run-off or stormwater discharged and has been identified as one of the main sources of pollution in urban environments (Gao et al., 2023).

The concentration of pollutants in stormwater discharge is positively correlated with precipitation volumes and intensity, which means that as precipitation increases, pollutant flows from stormwater run-off increase (Borris, 2016; Wijesiri et al., 2020; Yang et al., 2024). Given that precipitation is predicted to increase as a result of climate change, the question arises of whether these increased pollution flows pose a risk of harming aquatic organisms in catchment SÄ and what measures could be implemented to reduce it.

1.1 Aim and research questions

The aim of this study is to assess whether emissions of harmful substances to the Göta älv river resulting from untreated stormwater pose a risk of harming aquatic organisms in the river. The assessment will be made by conducting an environmental risk assessment using the framework of van Leeuwen and Vermeire (2007). If risk is determined to be present in the system, the study will provide suggestions for measures to reduce it. In addition, the study aims to conduct a qualitative assessment of the impact of future climate change scenarios on stormwater flows in Gothenburg. This can be formulated more precisely in the following research questions.

1. What are the flows of harmful substances from stormwater discharge to the Göta älv river?

2. What are the resulting mixed concentrations of these substances in the river?

3. Do these concentrations, individually or as a mixture, constitute a risk of harming species in the aquatic ecosystems of the river?

4. If risk is present, could measures be applied to sufficiently reduce it?

1.2 Limitations

The study was geographically limited to the section of the Göta älv river that flows through central Gothenburg, between the mouth of the Säve river to the east and the Göta älv estuary to the west, where the freshwater of the river meets the saltwater of the Rivö fjord in Kattegat. Limitations were also be made with respect to the number of substances included in the environmental risk assessment. The study made the selection based on the frequency of occurrence and severity of each substance's potential impact on aquatic organisms in the analyzed ecosystem.

2 Background

This chapter presents background information on future precipitation conditions, sewer systems, stormwater, and the chemicals present therein. Furthermore, it describes the Göta älv river and stormwater management in Gothenburg with a description of measures, currently implemented and planned, by Gothenburg's municipality.

2.1 Säve river-Älvsborg bridge (SÄ) catchment

Göta älv is Sweden's most water-abundant river (Göta älvs vattenvårdsförbund, 2015). Although the entire river system originates in Härjedalen and flows through Norway and the Klarälven river before reaching Lake Vänern (Sweden's largest lake), the stretch named Göta älv begins at the outlet of Lake Vänern, close to the city of Trollhättan. From there, the river flows 93 kilometers south towards Gothenburg. The river is vital for the Swedish west coast and serves as the primary source of drinking water for more than 700,000 people. In addition, it serves as a source of hydroelectric power and a major transport route for large volumes of goods. In addition, the river and its surrounding riparian meadows are of great ecological importance, hosting high levels of biodiversity. It also acts as a critical migration route for fish species that utilize its tributaries for spawning. Göta älv is rich in species diversity and hosts 37 of the 55 freshwater fish species present in Swedish waters (Park- och naturförvaltningen i Göteborg, 2015).

The final six kilometers of the Göta älv river from the confluence of the Säve river to the Älvsborg bridge, visualized in figure 2.1, is one of the river's catchments most heavily affected by pollutants (Miljöförvaltningen, 2025b). This area is characterized by intense anthropogenic pressure, dominated by port operations and dense urban infrastructure, which has led to artificial shorelines where buildings often extend all the way to the water's edge. It receives upstream flows from the river itself and three smaller rivers; Säveån, Kvillebäcken and Mölndalsån. The catchment is located downstream of the Gothenburg drinking water intake and is therefore classified as a less sensitive recipient (Miljöförvaltningen, 2021). This means that target values for pollutants are higher compared to other catchments further upstream. The catchment is also the recipient of cleaned waste and stormwater treated at the Ryaverket waste water treatment plant (WWTP). For migratory fish, this section serves primarily as a transportation corridor to spawning grounds further upstream (Miljöförvaltningen, 2025b).

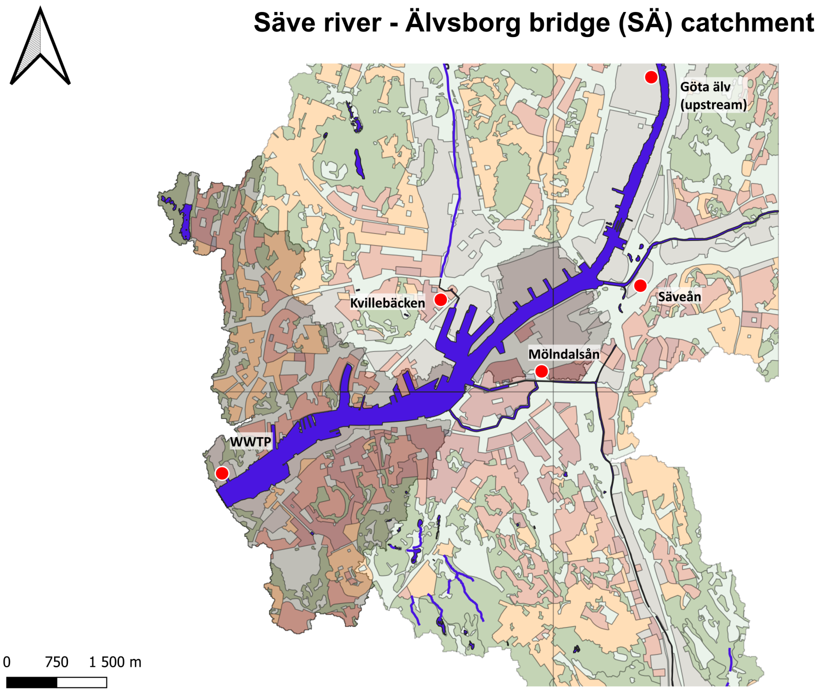

Figure 2.1: Map of catchment SÄ: Säveån river-Älvsborg bridge created på the authors in QGIS (2026) using data from SMHI (2022) and Lantmäteriet (n.d.a; n.d.b).

2.2 Future precipitation scenarios

When predicting future climate conditions, assumptions about future greenhouse gas (GHG) emissions must be considered. The intergovernmental panel on climate change (IPCC) has identified four different scenarios, each describing carbon emission pathways up to the year 2100, and from this calculated the resulting greenhouse effect (SMHI, n.d.b). These are called representative concentration pathways (RCP) and are used to inform different stakeholders about climate change and its effects with different concentrations of GHGs in the atmosphere. The RCP8.5 scenario presupposes no interventions and a continuation of greenhouse gas emissions until the end of the century, while the RCP4.5 scenario predicts a small rise until 2050 followed by a slow continuous decrease in emissions.

An increasing concentration of GHGs in the atmosphere will have an impact on weather conditions throughout the world, including precipitation. The west coast of Sweden is with its current climate the country's wettest region, mainly due to dominant westerly and southwesterly winds (SMHI, 2025). The annual mean precipitation is expected to increase approximately 25% for RCP8.5 and 12% for RCP4.5 (Länsstyrelsen i Västra Götalands län, 2011). The west coast of Sweden experiences the most days with extreme precipitation relative to the average of Sweden, which is defined as days with at least 20 mm of rain. The region experiences extreme precipitation 6-8 days a year, compared to other parts of Sweden that average 2-4 days a year. Days with extreme rainfall are predicted to double on the west coast in the RCP8.5 scenario, while the RCP4.5 scenario shows an increase close to doubling (SMHI, 2025). Historically, the 30-year mean annual precipitation in Gothenburg has already increased from 758 mm (1961-1990) to 912 mm (1991-2020) (SMHI, 2024).

There will be changes not only in the amount of precipitation, but also in the seasonal distribution (Länsstyrelsen i Västra Götalands län, 2011). The greatest increase will occur during the winter months with the RCP8.5 scenario indicating an increase of up to 40% by the end of the century. Summers are also likely to face a higher risk of drought, despite the overall increase in annual precipitation. This leads to a seasonal mismatch with wetter winters and drier summers, where pollutants are allowed to build up on hard surfaces and be quickly washed away by intense precipitation.

Intense rainfall refers to a large volume of precipitation during a short period of time, the exact definition being 50 mm in one hour or 1 mm in one minute (SMHI, 2025). Since intense rainfall events occur over a short time frame, it is also of interest to estimate how often they occur. A common example is 100-year rain, or 100-year storm as it is more commonly referred to, which is a term used to describe a certain extreme precipitation event with the probability of occurring once every 100 years. Intense rainfalls are expected to increase in intensity by approximately 10% by 2040, regardless of the RCP scenario. Looking further into the future, the intensity is expected to increase by 20-40% for the RCP4.5 and RCP8.5 respectively. Although there are no exact quantified changes in the frequency of extreme rainfall events, the increase in rainfall intensity indicates a higher likelihood of extreme precipitation (Länsstyrelsen i Västra Götalands län, 2011). Similarly, as precipitation increases, lighter precipitation is projected to decrease. The current stormwater infrastructure in Gothenburg is built to accommodate current precipitation and, therefore, might lack the increased capacity needed to manage future changes in precipitation characteristics. This insufficiency could lead to increased pollution if the infrastructure is not adapted.

2.3 Combined sewer overflow

Water management in cities can be handled in two different ways: combined sewer systems or separate sanitary sewer systems (United States Environmental Protection Agency [USEPA], 2025a). Separate systems are when wastewater and stormwater flow through separate pipes, while in the combined system they flow through the same pipe. A substantial share of the Gothenburg sewer system is in the form of combined sewer systems (Miljöförvaltningen, 2025a). Extreme rainfall puts increased pressure on a city's sewer system when large pulse volumes of water exceed the capacity of existing infrastructure (USEPA, 2025a). In combined sewer systems, this can cause overflow in basement floor drains, storm drains, or at the WWTP. To prevent this, untreated waste and stormwater is allowed to escape through combined sewer overflow systems (CSOs).

During extreme weather events, sewer systems might exceed their maximum capacity; such an event recently occurred when the storm Hans entered Gothenburg in August 2023 (SVT Nyheter, 2023). Between August 7th and 9th, the total rainfall exceeded 80 mm with a peak of 55 mm on the 8th of August alone. This event resulted in infrastructure disruptions, including closed roads and an overflow of the Göta river. As a safety measure to prevent untreated sewage water from contaminating the supply, the raw water intake was temporarily closed. This is a standard procedure during high water flows to ensure drinking water safety. The flow of water caused extensive overflows within the combined sewer system, marking the highest recorded flow levels in Gothenburg in a decade (Kretslopp och vattennämnden, 2024). Although there are no exact values of the wastewater volumes released during this event, throughout 2023, untreated wastewater released into Göta älv through overflow events accounted for 0.56 % of the total wastewater volume, corresponding to approximately 630,000 m^3.

2.4 Urban stormwater pollution

Run-off from urban areas is considered to be one of the primary sources of accumulated pollutants in the urban environment (Gao et al., 2023). It includes emissions from several sources but can collectively be described as anthropogenic emissions deposited on impermeable surfaces that are transported to a recipient through suspension in storm water. The issue has grown substantially in the post World War II era due to a rapid global urbanization, increasing both the amount of impermeable surfaces and pollutant emissions in urbanized areas.

2.4.1 Sources

Müller et al. (2020) defines the sources of urban run-off in three distinct categories; atmospheric deposition, drainage surfaces, and anthropogenic activities. Atmospheric deposition is substances suspended in the atmosphere that are deposited either through wet deposition from precipitation or dry deposition. The source is problematic in part due to its magnitude but also because of its broad origins. Drainage surfaces are particles that are offset from a variety of impermeable surfaces in the built environment such as roads, paved surfaces, roofs, facades, and other building surfaces, and other structural surfaces such as lamps and barriers. Anthropogenic activities is a collection of anthropogenic emissions originating from human activities, for example, emissions from combustion engines, vehicle wear, industry, construction, and road abrasion.

2.4.2 Pollutants

There are many different pollutants originating from run-off in urban environments that could cause harm to aquatic ecosystems; however, there are some that are more harmful and abundant than others regardless of location (Gao et al., 2023). Aryal et al. (2010) divide the most common pollutants into four categories; nutrients, heavy metals, polycyclic aromatic hydrocarbons (PAHs), and total suspended solids (TSS). Nutrients mainly include nitrogen and phosphorus originating in the leaching of chemical fertilizers from lawns and gardens and the emissions of untreated wastewater (Aryal et al., 2010). Heavy metals are harmful metals released mainly from the deterioration of vehicles, metal roofs, coatings, exhaust emissions, and leaching from vehicles. These include; copper (Cu), lead (Pb), cadmium (Cd), chromium (Cr), zinc (Zn), arsenic (As), and nickel (Ni). PAHs are a collection term used to describe a group of organic compounds formed through incomplete combustion of organic materials, commonly from fuel in combustion engines and industrial activity, or directly through oil spills (Honda & Suzuki, 2020). TSS is a measurement of the amount of particulate matter suspended in water (Montoya et al., 2024). There are many anthropogenic sources of TSS in the environment, including industrial activity, agriculture, shipping, and construction. However, natural processes such as changes in climate and weather patterns can also influence the TSS.

2.4.3 Status: catchment SÄ

As described in section 2.1, the catchment SÄ is classified as heavily modified (Miljöförvaltningen 2025b). The nutrient status is classified as within the target values with low nitrogen pollution (Länsstyrelsen, 2023a). Although phosphorus levels in the catchment exceed established target values, it is deemed to have little or no risk of hazardous eutrophication. However, Länsstyrelsen (2023a) has classified the chemical status as unsatisfactory, mainly because some ecotoxic substances exceed target values and are thus prioritized in the proposed mitigating efforts. These substances include polybrominated diphenyl ether (PBDE), mercury and its derivatives (Hg), the PFAS-compound perfluorooctanesulfonic acid and its derivatives (PFOS) and tributyltin derivatives (TBT). Several substances have been identified in concentrations close to exceeding hazardous or target values but are classified as unsure due to uncertainties or lack of measured data.

2.4.4 The first-flush effect

Most of the pollutants discharged during an intense precipitation event are flushed away in the early stages of precipitation, resulting in a pulse of highly polluted stormwater entering the recipient. This is known as the first-flush phenomenon and makes the first pulse of stormwater flows critical to the overall polluting effect of an intense precipitation event. The issue is made worse by the increasing duration and intensity of precipitation and dry-periods as a result of climate change (Directive of the European Parliament and of the Council 2024/3019; Gao et al., 2023). The extended dry-periods cause an increased accumulation of anthropogenic pollutants, after which a subsequent intense precipitation event flushes away the accumulated pollutants to a recipient.

2.4.5 Principles of stormwater run-off

Stormwater run-off is determined by rain intensity, the size of the catchment area, and the run-off coefficient (Svenskt Vatten, 2016). Urbanization changes the balance between these three factors. As seen in Svenskt Vatten (2016), converting a natural surface to a parking lot without water detention can result in a tenfold increase in run-off. This demonstrates the importance of considering run-off in the early stages of urban planning.

The run-off coefficient is not a static value and changes with seasonal conditions and soil saturation. During longer precipitation periods, there is the possibility that the pores of the soil on a given surface become fully saturated with water, leading to an increased run-off coefficient as the infiltration capacity of the soil is lost. The effect is most noticeable in the autumn when trees and vegetation go dormant and in the winter when frost makes the ground impermeable. Therefore, the choice of infrastructure plays an important role in stormwater management. Traditional underground pipes are limited to a fixed capacity, whereas open ditches can handle huge amounts of water during extreme weather events.

2.5 Water management guidelines

The water pollution resulting from human activity in urban environments in Sweden is regulated and enforced at several levels of the political hierarchy. The current regulations, the Water Directive Framework, was first signed into law by the European parliament in 2000 and was comprised of laws and directives that were mandatory for all member states of the European union (EU) to comply with (Directive of the European Parliament and of the Council 2000/60/EC (DEPC 2000/60/EC)). The framework has since been reworked, for example in in 2014. The directive mandates that all water-bodies within the territorial boundaries of the EU should be restored to and remain in what it defines as a "good status" (DEPC 2000/60/EC). This means that all forms of groundwater, surface water, inland water, and transition zones should be protected. Furthermore, it requires that the ecosystems surrounding these water-bodies be restored, pollution decreased, and monitoring of the sustainability of certain independent companies water usage.

Enforcement in member states is done differently depending on the governmental structure of the country in question. In Sweden, it is done in part by a direct application of the WDF but is also expanded on through the Swedish environmental code (SFS 1998:808). The environmental code regulating environmental status in water-bodies is translated into environmental quality standards (Sw. miljökvalitetsnormer) which regulate the presence of pollutants. The compliance monitoring of the environmental quality standards in Sweden is carried out by municipal organizations in each municipality who report their work and findings to their respective county administrative board (SFS 1998:808). The municipal organization monitoring and improving water quality, sewer systems, and stormwater pollution in the Gothenburg municipality is the environmental administration (Sw. Miljöförvaltningen) and the waste and water management administration (Sw. Kretslopp och vatten) (Göteborgs Stad, n.d.b; Göteborgs Stad, n.d.c).

2.5.1 Stormwater management in Gothenburg

The management of waste and stormwater in the city of Gothenburg consists of 2,476 km of underground pipes of which 871 km are stormwater pipes, 1,106 km sewage pipes and 499 km combined pipes (Göteborgs Stad, n.d.a). Stormwater pipes collect water from hard surfaces, such as roads or roofs, and guide it in many cases unprocessed to the river, while the sewage and combined pipes are directed to a 124 km long rock tunnel that directs the sewage water to Ryaverket WWTP. As described in section 2.5, the waste and water management and the environmental administrations are entrusted with the task of keeping the presence of substances harmful to humans and the environment within established target values to ensure the security of drinking water sources and aquatic ecosystems (Göteborgs Stad, n.d.b; Göteborgs Stad, n.d.c). The organizations measure and report the concentrations of several substances to their governing body, the regional court (Sw. Länsstyrelsen) (Länsstyrelsen, 2023a). However, following incidents of intense precipitation and thus large stormwater emissions, some particularly harmful substances are routinely measured (Miljöförvaltningen, 2020). Among them are those discussed in section 2.4.2, but also PFOS (or other perfluoroalkyl substances, PFAS), tributyltin, methyl tert-butyl ether, polychlorinated biphenyls, trichloroethylene, and benzene. Recently, microplastics and their effects have been proposed as an addition to the list.

Westergren et al. (2015) state that the most effective approach for stormwater management is multi-functionality. Since extreme rainfall events are rare, urban spaces should be used for more than water management. However, the soil properties of Gothenburg reduce the efficiency of certain mitigation options. This is due to the high clay content of the majority of the city's soil, with a limited capacity for water retention, making infiltration to groundwater less effective. Westergren et al. (2015) argue that infiltration should be the main priority both in terms of raingardens and drainage pipes in places where infiltration is efficient. In places where infiltration is not as efficient, modified raingardens with retention ponds and outlets could be implemented to prevent rapid flooding. In general, open green spaces are important in urban environments as they can manage average daily runoff while providing the additional capacity needed to store and transport water during extreme events.

The municipality of Gothenburg has developed a framework to manage the 100 year storm precipitation events (Göteborgs Stad, 2021). Its main purpose is to construct measures that transport water safely through the city, as existing sewer systems do not have the capacity to handle these volumes. To achieve this, several streets and surfaces have been identified in which large flows of stormwater accumulate during extreme precipitation events. These streets and surfaces are referred to as cloudburst arteries. When a street is determined to be a cloudburst artery, it must be modified to properly manage large stormwater flows. This may include lowering the street to remove water from houses or installing large culverts beneath the road (Göteborgs Stad, 2021). The cloudburst surfaces follow the same principle of being lower than the surrounding area and are often built with the ambition of achieving multi-functionality, meaning it could be built as a park or parking place. Such multi-functional mitigation strategies are closely aligned with bioretention cells.

2.5.2 Bioretention cells and retention ponds

Bioretention cells, also known as raingardens or bioinfiltration systems, have become more frequently used to manage stormwater during the 21st century (Davis et al., 2009). The concept is to design the system to mimic nature by letting the water infiltrate, transpire, or evaporate locally rather than being transported away in traditional pipes. The technical components of the bioretention cell consist of several layers. The first is a pooling area, essentially a plot of land that is lower than the surrounding area that can store water during storm events. Pre-treatment often consists of grass and vegetation to lower the flow velocity and erosion. Below the pooling area, there is a mulch layer that has an environment suitable for microorganisms that can degrade hydrocarbons and organic substances. The largest layer is a filter consisting of various types of sand, clay, and organic materials. This cell not only treats water but also reduces the total volume of untreated runoff reaching the recipient.

Since bioretention cells can be built and operated in different ways, predicting the exact removal of specific substances remains a challenge. For metal removal, an important factor is the addition of biochar to the filter which increases the pH value, thereby enhancing the adsorption of metals in the filter (Nazarpour et al., 2023). Metals already bound to particles are primarily removed by sedimentation and filtration in the cell. Nazarpour et al. (2023) shows that for metals such as copper, zinc, and lead, a well-constructed bioretention cell can achieve up to 90% removal efficiency from stormwater before reaching the recipient.

Retention ponds are lowered sections of land within the urban landscape that are empty or partially filled with water depending on the conditions of the specific area (Istenic et al., 2012). The remaining capacity is reserved for precipitation events where it can delay and partially clean stormwater. The volume of the pond is adapted to accommodate different volumes of precipitation. The pond cleans stormwater through a combination of sedimentation and filtration by letting the pond fill with stormwater and slowly letting it flow out, increasing the retention time of the water, thereby allowing metal particles to settle. A filter can be installed in the outlet pipe to allow cleaning of other pollutants such as dissolved metals or hydrocarbons. Retention ponds are most efficient if built where large stormwater flows occur and can easily be adapted to fit existing infrastructure. Common implementations are in the form of green areas or parks that can be great for biodiversity and provide visual and recreational addition to neighborhoods.

3 Method

This chapter presents the method used in the thesis, explaining how risk was assessed in catchment SÄ. The chapter begins with a short introduction to the concept of environmental risk assessment (ERA) followed by hazard identification, exposure assessment, effect assessment, and risk characterization. The chapter concludes with a quantitative assessment of the effect of the proposed mitigation option bioretention cells.

3.1 Environmental risk assessment

ERA is a broad term that can be divided into subcategories, such as human health, ecological, and applied industrial risk assessment, which all have their own respective subcategories (Mead & Williams, 1998). This report focuses on chemical risk assessment. The chemical risk assessment methodology can be divided into two main parts, risk assessment and risk management, both having four distinct steps (figure 3.1) (van Leeuwen & Vermeire, 2007). Risk management is often seen as a normative part, where the focus is on taking measures based on the assessment, while risk assessments are scientific, providing quantitative assessments of the risk. This study involves a quantitative risk assessment to determine if risk is present in the studied system. Thus, the following sections will outline and explain how the assessment was performed according to the steps in 3.1.

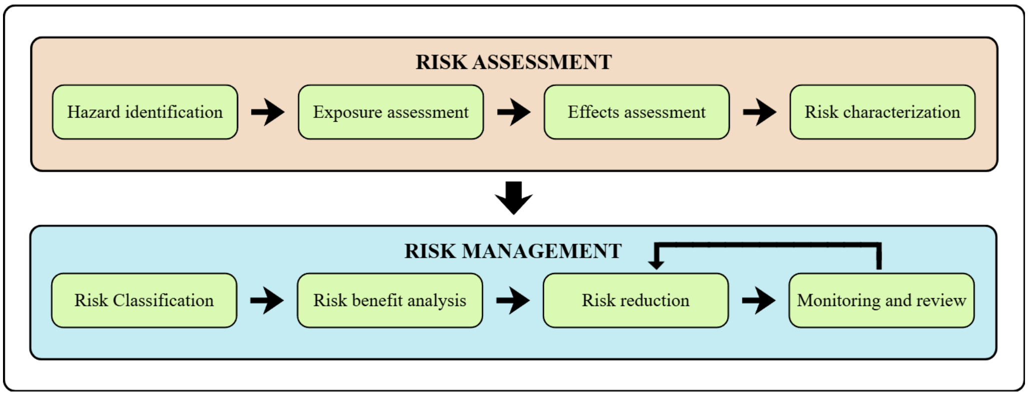

Figure 3.1: Illustration of the environmental risk assessment methodology developed by van Leeuwen and Vermeire (2007), created by the authors.

3.2 Hazard identification

Hazard identification involves identifying and describing the capacity of a substance to cause adverse effects in a given environmental compartment (van Leeuwen & Vermeire, 2007). It includes what type of harm a given substance could inflict on one or a larger group of organisms, for example, through toxic effects. It can be based on several different sources of data, such as toxicity studies, animal experiments, and accidental emissions of substances. Hazard identification may also include how a chemical behaves in an organism and interacts with organs, cells, or DNA. This study was performed with the Göta älv river as its target recipient; therefore, the selected pollutants were assessed based on their potential toxic effects on aquatic organisms in the river. Furthermore, the river was treated as a closed environmental compartment, which means that no consideration was taken of the possible amplification of pollutant concentrations along the food chain.

3.2.1 Selection of pollutants

The selection of pollutants was made based on three factors: the scientific literature on stormwater pollution outlined in chapter 2, the list of prioritized substances compiled by the Environmental Administration of the Gothenburg municipality (Miljöförvaltningen, 2020), and data availability. The main categories of pollutants found in stormwater run-off in urban environments are similar regardless of geographical location, often related to building materials and vehicle traffic (Müller et al., 2020). This includes heavy metals, nutrients, polycyclic aromatic hydrocarbons, and total suspended solids.

However, there are preconditions, such as industrial activities and previous pollutant emissions, that should be taken into account when assessing local stormwater pollution. The riverbanks of the Göta älv river at catchment SÄ consist of a mix of industrial and non-industrial structures, but have historically been the location of both industrial and shipping operations (Miljöförvaltningen, 2025b). Taking into account these local conditions, highly ecotoxic substances such as tributyltin (previously used in boat-hull paint) should be considered. The selected substances can be found in table 3.1 and are further described below.

Table 3.1: Selected substances and their respective acronyms.

Heavy metals	Acronym	Organic substances	Acronym
Copper	Cu	Perfluorooctanesulfonic acid	PFOS
Zinc	Zn	Tributyltin	TBT
Chromium	Cr	Benzene	BZ
Arsenic	As	Benzo[a]pyrene	BaP
Lead	Pb	Trichloroethylene	TcE
Cadmium	Cd		
Mercury	Hg		
Nickel	Ni		

Perfluoroalkyl substances (PFAS) were first developed in the 1930s and were used in a plethora of products and industries. Its use has decreased rapidly from the beginning of the 2000s due to rising environmental concerns (Ma et al., 2022). The key characteristic of PFAS is the strong carbon-fluoride bonds, which make them resistant to degradation, making them highly bioaccumulative and earning them the nickname, "forever chemical". Ma et al. (2022) describes that perfluorooctanesulfonic acid (PFOS) is one of the most commonly studied PFAS, mostly due to its toxic effects on living organisms, high persistence, and transportability. The toxicological effects of PFOS on aquatic organisms include cellular damage, reproductive, neuro, and genetic toxicity.

Du et al. (2013) describes tributyltin (TBT) as a synthetic organotin compound widely used in antifouling paints on boat hulls until it was globally phased out during the early 2000s due to its high toxicity. TBT has a half-life of up to 3 years in anaerobic conditions, which means that contaminated soil can continuously leach TBT even after its use has been limited (Du et al., 2013). Its high toxicity at concentrations as low as $1\frac{ng}{l}$ makes this especially relevant for harbors and shipyards such as Gothenburg (Du et al., 2013). The toxic effect of TBT on aquatic organisms includes endocrine disruption, immunotoxicity, and metabolic stress (Hoch, 2001).

Benzo[a]pyrene is a commonly used benchmark substance for the larger umbrella term polycyclic aromatic hydrocarbons, a collective term used to describe a group of organic compounds formed indirectly in the environment by incomplete combustion of organic materials, commonly from fuel in combustion engines and industrial activity, or directly through oil spills (Honda & Suzuki, 2020). Benzo[a]pyrene is a carcinogen with high environmental toxicity found in cigarette smoke and automobile exhaust. Honda and Suzuki (2020) determine the ecotoxicological effects of PAHs as developmental toxicity, oxidative stress, endocrine disruption genotoxicity, and immunotoxicity. Like heavy metals, although not as strong, many PAHs are bioaccumulating, furthering their ecotoxicological properties.

Heavy metals are harmful metals released mainly from the deterioration of vehicles, metal roofs, coatings, exhaust emissions, and leaching from vehicles. These include; copper, lead, cadmium, chromium, zinc, arsenic, and nickel. As described by Ali et al. (2019), exposure to heavy metals in aquatic ecosystems is known to cause severe neurotoxic effects on most fish species, with the most significant effects including growth deformities, inhibited reproductive capabilities, and acute toxic responses. Heavy metals possesses strong bioaccumulating properties which means that small flows can become problematic over time.

Trichloroethylene is a chlorinated aliphatic hydrocarbon and is a highly volatile and toxic compound (Canadian Council of Ministers of the Environment (CCME), 1999). Trichloroethylene was widely used throughout the world in the post world war 2 era in a multitude of applications (Houde et al., 2015). It has since been heavily restricted as a result of its carcinogenic properties but is still commonly used as a metal de-greaser, dry cleaning agent, and textile manufacturing. Emissions of trichloroethylene to the environment can occur through leaching from landfills, industrial discharges, and atmospheric deposition. The ecotoxicological effects of trichloroethylene on freshwater organisms include gill swelling, narcosis, growth deficiencies, and acute toxic responses (CCME, 1999).

Benzene is a cyclic hydrocarbon commonly used in the chemical and pharmaceutical industry as a synthetic intermediate and solvent and as an anti knocking agent in gasoline (Kuykendall, 2008). Benzene is emitted into the environment primarily through exhaust emissions from automobiles and industrial activities. The substance generally enters the environment through accidental spills or snow and rainwater but volatilizes quickly when suspended in surface water. The ecotoxicological effects of benzene are growth and reproductive deficiencies (Xu, 2020).

3.3 Exposure assessment

Exposure assessment investigates to what extent humans and environmental compartments are exposed (van Leeuwen & Vermeire, 2007). This step involves determining the source of the emissions, through which paths the substance travels, and how exposure occurs. The exposure assessment includes the frequency, magnitude, and duration of exposure and attempts to distinguish the exposed population or ecosystem. To quantify the exposure, measured data, models or a combination of both is used, and since uncertainties are high, the need for transparency and uncertainty analysis is especially important. The primary goal of an exposure assessment is to derive the predicted environmental concentration (PEC).

3.3.1 Release assessment

The modeling of stormwater flows was conducted through the creation of a mixing model based on a subdivision of stormwater pollution flows within the catchment area of SÄ. The stormwater flows used in the modeling were based on both measured data collected from the scientific literature and organizational data from the Gothenburg municipality and calculated flows. This section provides an in-depth description of how the modeling was performed. The pollution flows to catchment SÄ originating in stormwater pollution were subdivided into seven flows: (*i*) Upstream flows from the Göta älv river, its tributaries; (*ii*) Säveån, (*iii*) Mölndalsån, and (*iv*) Kvillebäcken, (*v*) Ryaverket WWTP, (*vi*) CSOs, and (*vii*) stormwater run-off, visualized in figure 3.2.

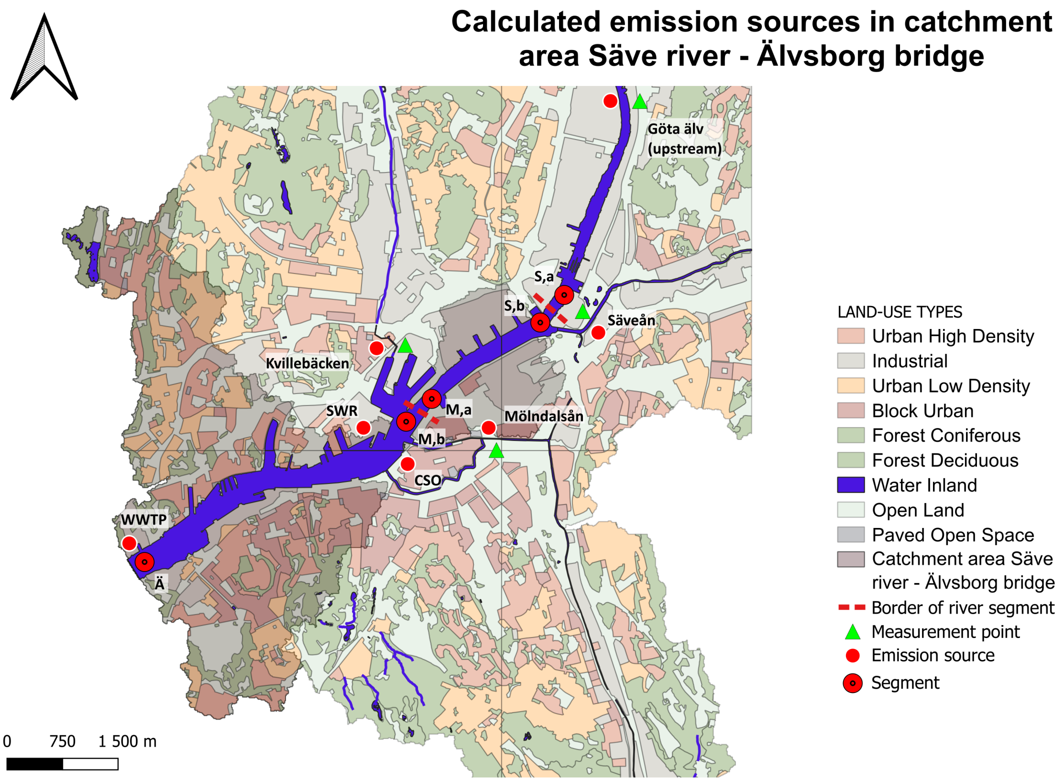

Figure 3.2: Map of emission sources, measurement points, borders of sedimentation areas, and land-use types for the catchment area SÄ created by the authors in QGIS (2026). Data gathered from SMHI (2022), Lantmäteriet (n.d.a; n.d.b), and Länsstyrelsen i Västra Götaland län (2018).

The upstream flows come from the Göta älv river and three smaller rivers; Säveån, Kvillebäcken, and Mölndalsån, all joining Göta älv in the catchment. Ryaverket WWTP located on the banks of the Göta älv river on the western border of the catchment causes continuous pollutant flows through the outlet of semi-treated storm and wastewater (Gryaab, 2025). CSOs have caused several pulse emissions through untreated stormwater released to the catchment during intense precipitation events (Miljöförvaltningen 2025a; J. Brunsten, personal communication, February 4, 2026). Emissions caused by stormwater discharge emitted at several discharge points located on the riverbanks adjacent to the catchment were also identified (Miljöförvaltningen, 2025b).

3.3.1.1 Stormwater run-off

Quantification of pollutant flows from stormwater run-off within the catchment area of catchment SÄ was performed by combining geo-spatial data rendering in QGIS with pollution data from the StormTac Database (2026). The study area was defined by the catchment area SÄ, defined by SMHI (2022). Land use and road network data was collected from Lantmäteriet (n.d.a; n.d.b). The datasets were compiled in the map visualized in figure 3.3.

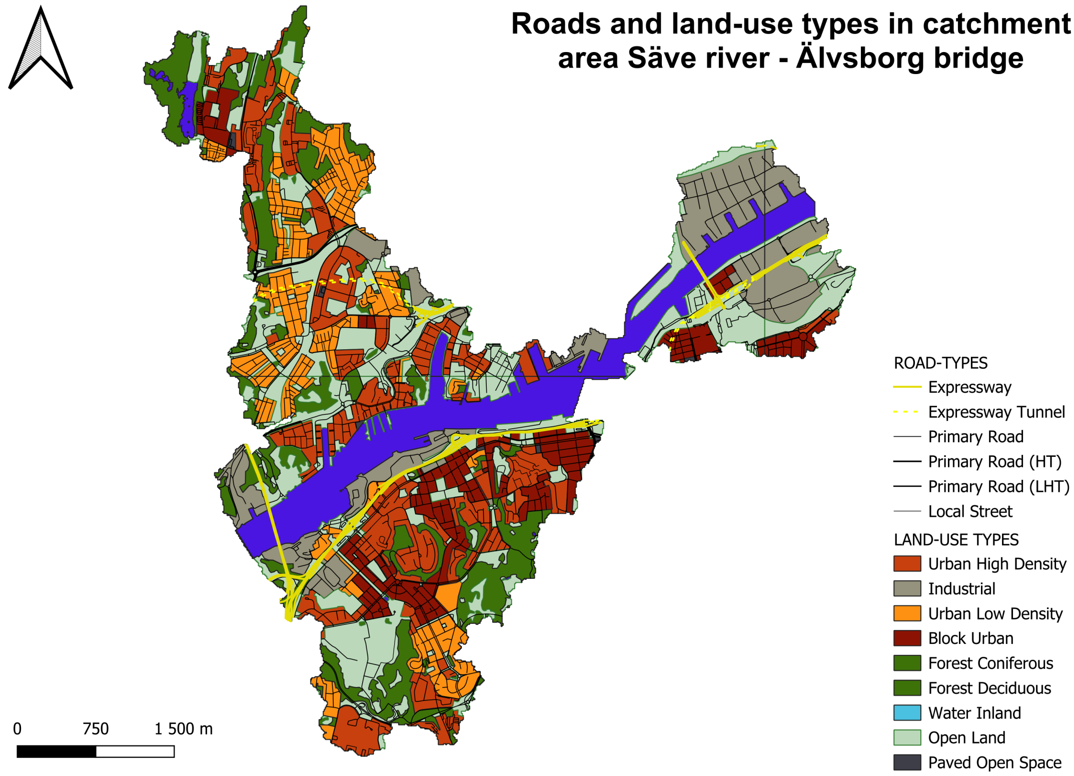

Figure 3.3: Map of roads and land-use types in catchment area SÄ, created by the authors in QGIS (2026). Data gathered from SMHI (2022) and Lantmäteriet (n.d.a; n.d.b).

The datasets containing geo-spatial data from Lantmäteriet (n.d.a; n.d.b) were adapted to fit the catchment area from SMHI (2022) to allow calculation of the total area per land-use type. Since the land use data were polygons, the area could be calculated directly in QGIS. The road network consisted of lines that made the layer unable to calculate properties other than length. Therefore, an approximation was made of the width of each road type, which could then be multiplied by the total length, resulting in an approximation of the area of each road type (table 3.2).

The expressways were modeled with two driving lanes in each direction, each 3.5 meters wide and a shoulder width of two meters. Following the standards of Trafikverket (2024), a total width of 20 meters was used for area calculations. This category consisted primarily of the E45 expressway and has the highest traffic intensity with an annual average daily traffic exceeding 45000 vehicles (Trafikverket, 2025). The primary roads in Gothenburg vary in design, but according to Göteborgs Stad (2017), the majority have two lanes in each direction with a width of 3.5 meters per lane. As these roads typically lack shoulders in the urban environment, a total width of 15 meters was used for the calculations. The traffic flow for this category has an annual average daily traffic of more than 6000 vehicles. Local streets are also highly variable, and their designs often depend on speed limits. To account for this variability, the total width of roads was chosen to be a one lane street with parking on one side, resulting in a total width of 10 meters (Göteborgs Stad, 2017). These streets are estimated to have an average annual daily traffic of about 3500 vehicles. The data used for calculation on road-dimensions is shown in appendix A2.

Table 3.2: Area (A) per land-use type (i) in catchment SÄ, created by the authors in QGIS (2026). Data gathered from SMHI (2022), Lantmäteriet (n.d.a).

Land-Use Type	A_i **[ha]**	**Road Type**	A_i **[ha]**
Urban High Density	287.24	Expressway	51.87
Industrial	205.32	Expressway Tunnel	13.48
Urban Low Density	183.25	Primary Road	295.53
Block Urban	144.76	Primary Road HT	8.07
Forest Coniferous	237.41	Primary Road LHT	2.34
Forest Deciduous	0.80	Local street	7.88
Water Inland	225.70		
Open Land	402.27		
Paved Open Space	3.32		

The stormwater precipitation run-off flows were calculated by multiplying the annual mean precipitation in the Gothenburg region and the run-off coefficients and areas of each land-use type within catchment SÄ, as shown in equation 3.1. The run-off coefficients represent the fraction of precipitation that reaches the river as surface run-off and were assumed to be constant throughout the year. These coefficients were provided by Larm (2000) and take into consideration the losses of water from infiltration and evaporation. The values can be found in table 3.3.

Table 3.3: Run-off coefficients (φ_i) assigned to land-use categories based on Larm (2000, Table 7.2).

Land-Use Category	φ_i [-]
Asphalt surface (no traffic)	0.85
Road	0.85
Downtown	0.70
Industrial	0.60
Residential (multi-family)	0.45
Residential (single houses)	0.25
Forest	0.10
Grass	0.18

$$Q_{run,i} = 10 \cdot P \cdot \varphi_i \cdot A_i \tag{3.1}$$

Where:
$Q_{run,i}$: annual run-off flow per land-use type i $[\frac{m^3}{year}]$
A_i : surface area per land-use type i $[ha]$
P : mean annual precipitation $[\frac{mm}{year}]$
φ_i : run-off coefficient per land-use type i [-]

According to Larm (2005), the traditional urban drainage systems are primarily a transport system for excess water to prevent flooding. Consequently, no significant treatment occurs for fine particles and the only barrier in a standard system is a pot with a sand trap. A sand trap is located at the base of a manhole and is designed to capture large materials such as gravel. The removal efficiency for heavy metals and hazardous substances in these sand traps is between 0-10%. This indicates that water is transported almost untreated to the Göta älv river and that the removal efficiency could be set at the mean value of 5% and was calculated using equation 3.2.

$$C_{run,i,m} = (1 - RE) \cdot C_{run,i,m} \tag{3.2}$$

Where:
RE : removal efficiency of 5% [-]
$C_{run,i,m}$: standard pollutant concentration for stormwater per land-use type i and pollutant m $[\frac{\mu g}{l}]$

Also taken into consideration was the baseflow of water (Larm, 2000). Baseflow is defined as the flow of water that occurs in both dry and wet weather and is derived from drainage and natural groundwater. Essentially, the precipitation on a given surface that does not evaporate nor is carried away as run-off. Instead, it infiltrates the surface on which it precipitates, of which a fraction eventually reaches a recipient, such as rivers or lakes. The calculation of the baseflow was made using the framework developed by Arwidsson (2011) and was expressed using equation 3.3.

$$Q_{base,i} = 10 \cdot P \cdot K_x \cdot K_{inf,i} \cdot A_i \tag{3.3}$$

Where:
$Q_{base,i}$: annual baseflow per land-use type i $[\frac{m^3}{year}]$
P : mean annual precipitation $[\frac{mm}{year}]$
$K_{inf,i}$: infiltrated fraction of yearly precipitation per land-use type i [-]
K_x : fraction of K_{inf} reaching baseflow [-]
A_i : surface area per land-use type i $[m^2]$

The infiltrated fraction of the yearly precipitation, $K_{inf,i}$ in equation 3.3, is based on the evapotranspiration intensity of the specific climate and surface on which precipitation occurs. The amount of precipitated water that evaporates and was calculated using equation 3.4.

$$K_{inf,i} = \frac{P - (P \cdot \varphi_i) - E_i}{P} \tag{3.4}$$

Where:
P : mean annual precipitation $[\frac{mm}{year}]$
φ_i : run-off coefficient per land-use type i [-]
E_i : evapotranspiration intensity per land-use type i $[\frac{m^3}{year}]$
$\varphi_i \leq 0.9$: $E_i = 1000 \cdot (0.50 - 0.55\varphi)$ $[\frac{mm}{year}]$
$\varphi_i > 0.9$: $E_i = 0$ $[\frac{mm}{year}]$
φ_{forest} : $E_{forest} = 445$ $[\frac{mm}{year}]$

Based on Larm (2000), the total annual mass flow from stormwater run-off was calculated using equation 3.5, combining the annual storm and baseflows with their corresponding pollutant concentrations gathered from the StormTac Database (2026), shown in appendix A6 and A7. The data consisted of estimates of standard pollutant concentrations, which can be defined as typical pollution concentrations for a specific land-use type and region.

$$\Phi_{run,base,m} = \sum Q_{run,i} \cdot C_{run,i,m} + \sum Q_{base,i} \cdot C_{base,i,m} \tag{3.5}$$

Where:
$\Phi_{run,base,m}$: total pollutant mass flow of run-off and baseflow per pollutant m $[\frac{\mu g}{year}]$
$Q_{run,i}$: annual run-off flow per land-use type i $[\frac{m^3}{year}]$
$C_{run,i,m}$: standard pollutant concentration for run-off water per land-use type i and pollutant m $[\frac{\mu g}{l}]$
$Q_{base,i}$: annual baseflow per land-use type i $[\frac{m^3}{year}]$
$C_{base,i,m}$: standard pollutant concentration for infiltrated water per land-use type i and pollutant m $[\frac{\mu g}{year}]$

3.3.1.2 Other inflows

Flows from CSOs, Ryaverket WWTP, and the rivers Säveån, Mölndalsån and Kvillebäcken (3.2) were calculated using data on measured concentration (MEC) values (Länsstyrelsen, 2023b-e; Gryaab, 2025; J. Brunsten, personal communication, February 4, 2026) and mean annual discharge rates (Miljöförvaltningen, 2025c-d; Exploateringsförvaltningen, 2025; Gryaab, 2025; J. Brunsten, personal communication, February 4, 2026). The basic calculation principle shown in equation 3.6 was implemented directly for flows with MEC values taken from their respective discharge points to catchment SÄ, see appendix A1.

$$\Phi_{j,m} = Q_j \cdot C_{j,m} \tag{3.6}$$

Where:
$\Phi_{j,m}$: total annual pollutant mass flow per measured flow j and pollutant m $[\frac{\mu g}{year}]$
Q_j : annual flow per measured flow j $[\frac{m^3}{year}]$
$C_{j,m}$: pollutant concentration per measured flow j and pollutant m $[\frac{\mu g}{l}]$

Unlike Säveån, Mölndalsån, Kvillebäcken, CSOs, and Ryaverket WWTP, the MEC values for the upstream flow from Göta älv could not be found at its discharge point in catchment SÄ. Therefore, data gathered near the intake point for drinking water in Alelyckan, located $4.8km$ north of catchment SÄ was used (Miljöförvaltningen, 2025b; Länsstyrelsen, 2023e) (3.2). Due to the relationship between aquatic retention time and environmental fate processes such as sedimentation and degradation, it was assumed that the transportation of pollutants from Alelyckan to catchment SÄ imposed a reduction in concentration. Therefore, it was determined that its flow should be treated as part of the fate modeling to fully account for potential losses.

Measured concentrations expressed as $\frac{\mu g}{l}$ could be found for all flows and pollutants except Hg, whose concentration is most often given as $\frac{\mu g}{kg} ww$ $(ww = wet, weight)$ in the tissue or organs of fish. These had to be converted to $\frac{\mu g}{l}$ using Bio Concentration Factors (BCF), a factor that describes the relationship between the accumulated concentration in fish and the surrounding water. The BCF for mercury in freshwater environments used in the study was 5.81 (Baeyens et al., 2003). The relationship can be expressed according to equation 3.7.

$$C_{water,j,m} = \frac{C_{fish,j,m}}{BCF_j} \tag{3.7}$$

Where:

BCF_m : bio concentration factor per pollutant m $[\frac{l}{kg}]$

$C_{fish,j,m}$: pollutant concentration (wet weight) in fish per measured flow j and pollutant m $[\frac{\mu g}{kg}]$

$C_{water,j,m}$: pollutant concentration in water per measured flow j and pollutant m $[\frac{\mu g}{l}]$

3.3.2 Fate modeling

The geo-referenced regional exposure assessment tool for European rivers (GREAT-ER) is a software designed to predict the concentrations of chemicals in surface waters (Koormann, 2011). The model uses mathematical models integrated with GIS to compute the predicted environmental concentration values. The river is represented as segments and nodes where the segments are physical stretches where the chemical fate processes biodegradation, volatilization, and sedimentation, are assumed to occur. The nodes represent physical locations where disruptions or changes, such as a discharge point or the confluence of two rivers, affect the flow of pollutants. This division was made in order to calculate the mass balances of the substances as they flow downstream. The conceptual model used for the calculations on catchment SÄ is shown in figure 3.4.

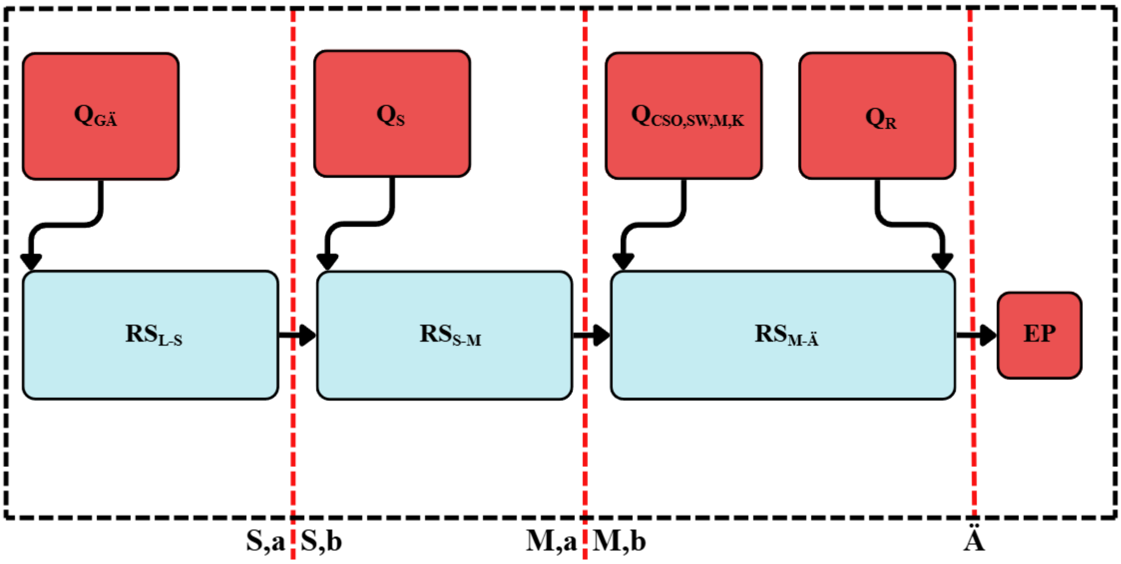

Figure 3.4: Model visualizing the conceptual partitioning of segments, emission-sources and points of interest used for calculations in the fate-modeling, created by the authors. Q = inflow, RS = river segment, EP = endpoint. S,a-Ä = points of interest in the river where concentrations are calculated.

The discharge points were calculated as point sources, as depicted in figure 3.2, although the discharge of stormwater and CSO occurs from several points along the river banks of catchment SÄ. Data limitations on discharge volumes from specific discharge points inhibited reliable modeling; therefore, the study used a simplified approach where the total volumes of stormwater and CSO discharge were treated as point sources. Assuming constant first order removal rates along the catchment, the sources were modeled as being located in the middle of catchment SÄ as a way of approximating accurate removal throughout the catchment.

In this study, the documentation and model descriptions of the GREAT-ER model were used as inspiration to perform the fate modeling of pollutants in catchment SÄ. Specifically, the principles of first order elimination rates were adopted. Even though the original software was not used due to compatibility issues with new operating systems, its logic for mass flow and first order elimination provided the base for the fate modeling. The unchanged expression used for calculations of the chemical removal rate constant, defined in GREAT-ER is shown in equation 3.8.

$$k_m = k_{deg,m} + f_{s,m} \cdot k_{sed,m} + f_{d,m} \cdot k_{vol,m} \tag{3.8}$$

Where:

k_m : total first-order elimination rate constant of pollutant m $[h^{-1}]$
$k_{deg,m}$: first-order degradation rate constant of pollutant m $[h^{-1}]$
$f_{s,m}$: sorbed fraction of pollutant m [-]
$k_{sed,m}$: first-order sedimentation rate constant of pollutant m $[h^{-1}]$
$f_{d,m}$: dissolved fraction of pollutant m [-]
$k_{vol,m}$: first-order volatilization rate constant of pollutant m $[h^{-1}]$

According to Göransson et al. (2013), the sedimentation rate in the Göta älv river is negligible under normal conditions. The reason is primarily its high turbulence, which provides strong vertical mixing, thus preventing particles from settling. Another preventing factor is the high clay content of the total suspended solids of the river, which are lighter and smaller than other particles and therefore remain suspended throughout the catchment. Based on this, it was assumed that sedimentation was negligible as a removal process, giving k_{sed} the value 0 for all substances assessed in the study.

The first order degradation rate constants were derived from degradation half-life values for each substance in freshwater river aquatic environments gathered from the PubChem chemical database (National Center for Biotechnology Information (NCBI), 2026). However, most of the substances assessed in the study were found to degrade very slowly or not degrade at all when suspended in freshwater. Thus, the substances relevant for degradation were PFOS, tributyltin, and benzo[a]pyrene. The constants were calculated using the standard formulation of first order degradation found in the GREAT-ER manual as can be seen in equation 3.9 (Koormann, 2011).

$$k_{deg,m} = \frac{\ln(2)}{t_{1/2,m}} \tag{3.9}$$

Where:

$k_{deg,m}$: first-order degradation rate constant of pollutant m $[h^{-1}]$.
$t_{1/2,m}$: degradation half-life of pollutant m $[h]$.

According to Thomas (1990, as cited in USEPA, 2025b), a substance's Henry's law constant is used as the determining factor for whether the substance is volatile from the surface of a river. Substances with a Henry's law constant below the threshold value of $H < 10^{-7}\text{atm} \cdot \text{m}^3/\text{mol}$ are classified as essentially nonvolatile. Substances with a value below this threshold evaporate slower than water and therefore no volatilization is assumed in rivers or lakes ($k_{vol} = 0$). In this study, substances with a Henry's law constant near the 10^{-7} threshold were also set to $k_{vol} = 0$. This is justified by the short river section of only 7 km and the high water flow velocity. The hydraulic residence time within this section is thus too short for any meaningful volatilization to occur even for substances slightly above the threshold.

Therefore, trichloroethylene and benzene were identified as the only two substances relevant for further calculations regarding volatilization. United states geological survey (USGS) (1998) derived the volatilization constant k_{vol} using the reaeration coefficient of the river k_2, shown in equation 3.10 and 3.11. k_2 reflects the hydraulic characteristics of the Göta älv river, specifically the depth and velocity. The reaeration rate was weighted with a substance specific value, using the liquid-film coefficient ratios Θ. This accounts for the molecular differences between oxygen and benzene or trichloroethylene. Data of river properties can be seen in appendix A4 and A5.

$$k_{vol,m} = \frac{k_2 \cdot \Theta_m}{24} \tag{3.10}$$

$$k_2 = 3.93 \cdot U_n^{0.5} \cdot Y_n^{-1.5} \tag{3.11}$$

Where:
$k_{vol,m}$: first-order volatilization rate constant of pollutant m $[h^{-1}]$
k_2 : reaeration coefficient $[day^{-1}]$
U_n : average flow velocity in segment n $[\frac{m}{s}]$
Y_n : average depth in segment n $[m]$
Θ_m : water-film reference-substance parameter of pollutant m [-]

The elimination rate constants used in equation 3.8 were adapted from the GREAT-ER model to calculate the mass flows at the end of the three river segments visualized in figure 3.2 (Koormann, 2011). The calculations were performed stepwise at the beginning, Φ_{out}, and the end, Φ_{in}, of each segment to account for the degradation and volatilization of pollutants from upstream sources.

$$\Phi_{out,n,m} = \Phi_{in,n,m} \cdot e^{-k_m \cdot HRT_n} \tag{3.12}$$

Where:
$\Phi_{out,n,m}$: mass flow at the end of the segment n per pollutant m $[\frac{kg}{s}]$
$\Phi_{in,n,m}$: total mass flow entering the segment n per pollutant m $[\frac{kg}{s}]$
k_m : first-order elimination rate constant per pollutant m $[h^{-1}]$
HRT_n : hydraulic residence time of river segment n $[h]$

Hydraulic residence time (HRT) is the time during which the substance remains suspended in the water of a river segment while transported downstream (Koormann, 2011). Its purpose in equation 3.12 is to determine how much of the potential degradation and volatilization will take place in a certain river segment, thereby determining how much of the substance remains in the river at a given point in the catchment. The HRT was calculated using equation 3.13 with data of river properties seen in appendix A5.

$$HRT_n = \frac{L_n}{U_n \cdot 3600} \tag{3.13}$$

Where:
HRT_n : hydraulic residence time of segment n $[h]$
U_n : average flow velocity of segment n $[\frac{m}{s}]$
L_n : length of segment n $[m]$

To calculate the concentration of a substance at the downstream endpoint of the river, equation 3.14 was used. This approach is based on mass conservation, where there is a constant flow of water, river discharge Q, and a total mass flow of substances, Φ. The equation relies on the assumption that there is a rapid complete mixing of the substances and equal mass flows over time that are added to a specific patch of water as it moves through the river.

$$C_{end,n,m} = \frac{\Phi_{out_{n,m}}}{Q_n} \tag{3.14}$$

Where:

$C_{end,n,m}$: concentration at the end of the segment n per pollutant m $[\frac{\mu g}{l}]$
$\Phi_{out,n,m}$: total mass flow at the end of the segment n per pollutant m $[\frac{\mu g}{s}]$
Q_n : river discharge (flow rate) in segment n $[\frac{m^3}{s}]$

3.4 Effect assessment

The effect assessment assesses the connection between the level of exposure and the severity of adverse effects (van Leeuwen & Vermeire, 2007). Risk assessment of chemicals involves analyzing toxicity data in multiple species to acquire values for the predicted no effect concentration (PNEC). This step also distinguishes the nature of an effect (for example, reversible or irreversible), relevance, and quality of data. The effect assessment relies on ecotoxicological information to determine whether observed or predicted exposures are likely to cause harm. PNEC is the most reliable ecotoxicological effect assessment value used in risk assessment of chemicals and is also the most comprehensive and data intensive (van Leeuwen & Vermeire, 2007). They are most commonly derived from LC50 (lethal concentration 50%) or EC50 (effective concentration 50%) and can be either chronic (long-term and low-dose exposure) or acute (short-term and high-dose exposure). An assessment factor (AF) is often applied to the LC50 or EC50 values to correct for inadequacies in the toxicity data compared to the specific substance and ecosystem properties assessed in a risk assessment of chemicals. AF can vary in magnitude but is most often within the 5-1000 interval depending on the comprehensiveness and uncertainty of the available toxicity data. Factors to consider are temporal (acute or chronic), number of trophic levels assessed, and substance properties (bioaccumulating or persistent).

PNEC values for the substances used in the study were gathered in part from the established literature, but mainly through the European Chemicals Agency Chemicals Database (https://chem.echa.europa.eu). van Leeuwen and Vermeire (2007) present three key criteria that must be met if the derived PNEC values are to be taken at face value and used reliably in a risk assessment of chemicals: (*i*) the species used in deriving chronic toxicity values (LC50 or EC50) must be representative of the species present in the analyzed ecosystem, (*ii*) the lowest observed chronic toxicity threshold is to be used as the chronic toxicity threshold for the ecosystem, and (*iii*) it is the species and species-level properties that are the most sensitive recipient in the ecosystem.

3.5 Risk characterization

The risk characterization ratio (RCR) combines previously-derived PEC and PNEC values to assess the likelihood of adverse effects, i.e., risk (van Leeuwen & Vermeire, 2007). This is typically done by using the relationship described in equation 3.15.

If the resulting value of this equation exceeds or closely approaches 1, there is risk present in the system, and sufficient action should be taken to counteract it. Should the value be in the ranges of $0.3 - 0.7$ or lower, there is no immediate risk. However, if an increase in the PEC value of a substance is to be expected, measures might be needed to prevent the RCR from closer approaching 1. The PEC ($C_{end,n,m}$) and PNEC values derived in the previous sections were compared for each substance and river segment.

$$RCR_m = \frac{PEC_m}{PNEC_m} \tag{3.15}$$

Where:
RCR_m : risk characterization ration per pollutant m [-]
PEC_m : predicted environmental concentration per pollutant m [$\frac{\mu g}{l}$]
$PNEC_m$: predicted no effect concentration per pollutant m [$\frac{\mu g}{l}$]

3.5.1 Mixture toxicity

Organisms in aquatic ecosystems are rarely exposed to one single toxic substance. Therefore, the study assessed the combined effects of all substances included in the study using the concept of concentration addition described in van Leeuwen and Vermeire (2007). Concentration addition has been shown to be a conservative but accurate method in most circumstances, independent of differences in the toxic modes of action of the substances (Backhaus et al., 2025). The method is applied by calculating the sum of the individual RCR values to assess the total risk of harm inflicted by the mixture of analyzed substances, as shown in equation 3.16.

$$RCR_{mix} = \sum_m \frac{PEC_m}{PNEC_m} \tag{3.16}$$

Where:
RCR_{mix} : mixture toxicity risk characterization ration [-]
PEC_m : predicted environmental concentration per pollutant m [$\frac{\mu g}{l}$]
$PNEC_m$: predicted no effect concentration per pollutant m [$\frac{\mu g}{l}$]

3.6 Bioretention cells

Bioretention cells in the form of stormwater retention ponds and retention channels have been shown to be an efficient measure of reducing the concentration of pollutants in stormwater and were therefore chosen for modeling of mitigation efforts in this study (Istenic et al., 2012; Westergren et al., 2015). The considered land-use types were selected based on their total area and the size of their run-off coefficient to optimize the impact of the implemented bioretention cells. The selected land-use types were urban high density, industrial, urban low density, paved open space, expressway, primary road, primary road high traffic, primary road light heavy traffic, and local street. This study assumed that up to 100% of the annual run-off flows could be captured by bioretention cells if they are constructed in strategic locations where large flows accumulate.

Precipitation occurs irregularly in isolated events throughout any given year (SMHI, 2025). The efficiency of a bioretention cell depends on the precipitation intensities that its retention capacity, or volume, can accommodate (Istenic et al., 2012). The future changes in precipitation characteristics described in chapter 2, with more precipitation events with intense flows and fewer events with slow flows, make retention capacity an important parameter to consider. Rain intensities are defined as a certain volume of precipitation (mm) occurring within a certain time-frame (SMHI, 2025). This study performed calculations based on a precipitation event defined as a 1-year rain ($10\frac{mm}{h_{1/2}}$, where $h_{1/2}$ is one half hour). The retention capacity of a 1-year rain can not retain the total stormwater flow of the more intense 5-year or 10-year rains of ($20\frac{mm}{h_{1/2}}$) and ($30\frac{mm}{h_{1/2}}$). However, due to their low frequency of occurrence, the total overflow of these events would only represent a fraction of the total yearly flow, $< 0.1\%$, and was therefore assumed to be negligible in terms of their impact on the annual pollution load.

The retention capacity of a bioretention cell can be adjusted by altering its height or area. The study assumed a constant retention height of 1m. Therefore, only the bioretention cell area was considered for the adjustment of retention capacity. However, the area can pose challenges with respect to integration with existing infrastructure in densely developed land-use types. Therefore, in the calculations described in equation 3.17, the area of bioretention cells per hectare was considered in relation to the varying reduction of the run-off pollution load. This study assumed a strategic placement of the bioretention cells where the majority of the run-off flow could be collected. Therefore, the coverage of $Q_{run,i,pe}$, represented by α, was assumed to be 0-100% while the pollutant reduction capacity of a bioretention cell, represented by β, was set at 90, 60, and 40% (Nazarpour et al., 2023; Hossain et al., 2005; Birch et al., 2007). α and β, when applied to the run-off flow as shown in equation 3.17, is thereby directly proportionate to the reduction of the run-off pollution load. Assuming a negligible overflow resulting from more intense 5-year or 10-year rains, the reduction of the pollution load from the calculated 1-year rain could be assumed to approximate the reduction of the annual run-off pollution load.

$$\lambda = \frac{\sum_i 10 \cdot P_{pe} \cdot \varphi_i \cdot A_i \cdot \alpha \cdot \beta}{\sum_i A_i} = \frac{\sum_i Q_{run,i,pe} \cdot \alpha \cdot \beta}{\sum_i A_i} \tag{3.17}$$

Where:

λ : area of bioretention cells as share of catchment SÄ [-]
$Q_{run,i,pe}$: run-off flow per land-use type i of one precipitation event pe $[\frac{m^3}{h_{1/2}}]$
P_{pe} : precipitation of one precipitation event pe $[\frac{mm}{h_{1/2}}]$
φ_i : run-off coefficient per land-use type i [-]
A_i : surface area per land-use type i $[m^2]$
α : assumed fraction of $Q_{run,i,pe}$ captured by bioretention cells [-]
β : assumed pollutant removal efficiency of bioretention cells [-]

4 Results

The current chapter begins by presenting and explaining the results of the exposure assessment, starting with the calculated annual pollution load of each input source and the resulting PEC values. Furthermore, it shows the PNEC values derived in the effect assessment before moving on to present the individual and mixed RCR values. Finally, it concludes by showing the calculations made on the implementation of bioretention cells and their potential for decreasing risk.

4.1 Exposure assessment

The exposure assessment showed that the pollution load of the stormwater run-off and baseflow from catchment SÄ was relatively low for each substance compared to other contributing sources. As seen in tables 4.1 and 4.2, the distribution of the pollution load between roads and other surfaces varies for both run-off and baseflow depending on the substance. It can also be observed that the run-off pollution loads were higher than the baseflow pollution loads for all substances, with varying orders of magnitude from 10 to 1000.

Table 4.1: Run-off - annual pollutant load $[\frac{kg}{year}]$.

Pollutant	**Total (land-use)**	**Total (road)**	**Total**
PFOS	0.076	0.038	0.114
TBT	0.29	0.0047	0.29
Benzene	0.42	11.76	12.19
Benzo[a]pyrene	0.36	0.53	0.89
Cu	134.16	126.69	260.85
Zn	640.67	647.60	1288.27
Cr	40.70	68.70	109.50
As	14.82	11.46	26.29
Pb	75.46	57.23	132.68
Cd	4.07	1.47	5.54
Hg	0.21	0.29	0.50
Ni	42.51	38.89	81.40

Table 4.2: Baseflow - annual pollutant load [$\frac{kg}{year}$].

Pollutant	Total (land-use)	Total (road)	Total
PFOS	0.00030	0.000028	0.00032
TBT	0.0036	0.00033	0.0039
Benzene	0.0044	0.00042	0.0049
Benzo[a]pyrene	0.019	0.0012	0.021
Cu	19.82	3.60	23.42
Zn	80.38	15.23	95.60
Cr	3.28	0.50	3.78
As	0.68	0.064	0.74
Pb	3.75	0.83	4.58
Cd	0.14	0.0094	0.15
Hg	0.027	0.0089	0.036
Ni	8.24	1.50	9.74

The pollution loads of the sources calculated from the measured concentrations can be seen in table 4.3. A correlation between annual water discharge (appendix A3) and annual pollutant load, ϕ, is indicated as the loads are higher for all substances for sources with high discharge. For example, the sources with the highest annual water discharge, Göta älv (upstream) and Säveån, each have pollution loads that are 10-1000 times larger compared to the other sources.

Table 4.3: Annual pollutant load for each input source (MEC) [$\frac{kg}{year}$].

Pollutant	RV	CSO	KB	GÄ (US)	SÅ	MÅ
PFOS	0.00	0.00	0.083	3.47	0.98	0.17
TBT	0.00	0.00	0.0020	0.32	0.025	0.0030
Trichloroethylene	0.00	0.00	1.89	1603.61	31.54	13.69
Benzene	0.00	0.00	1.14	171.051	63.072	68.43
Benzo[a]pyrene	0.00	0.00	0.0040	1.069	4.73	0.37
Cu	979.21	79.96	30.65	5612.62	1009.15	205.30
Zn	1301.14	120.73	110.69	8873.28	2144.45	554.99
Cr	48.29	3.76	2.37	2672.68	214.45	19.85
As	0.00	0.00	3.31	1282.88	176.60	21.21
Pb	20.12	3.92	2.19	416.94	56.77	14.65
Cd	2.68	0.16	0.095	32.072	5.68	1.57
Hg	2.68	0.094	0.00	3.54	0.00	0.17
Ni	362.17	5.17	16.59	2314.54	498.27	42.018

Note: RV=Ryaverket, CSO=Combined sewer overflow, KB=Kvillebäcken, GÄ (US)=Göta älv upstream, SÅ=Säveån, MÅ=Mölndalsån.

4.1.1 Fate modeling

The PEC values for each river segment derived by applying the GREAT-ER model to the annual pollution loads are shown in figure 4.1 reported in $\frac{\mu g}{l}$. Concentrations increase further downstream for most substances, such that $PEC_{S,a} < PEC_{S,b} < PEC_{M,a} < PEC_{M,b} < PEC_{\text{Ä}}$. However, the concentration of trichloroethylene showed the opposite trend with its highest value in segment S, a. Furthermore, TBT, benzene, Benzo[a]pyrene, Cr, and As achieved their highest concentrations in segment M, b.

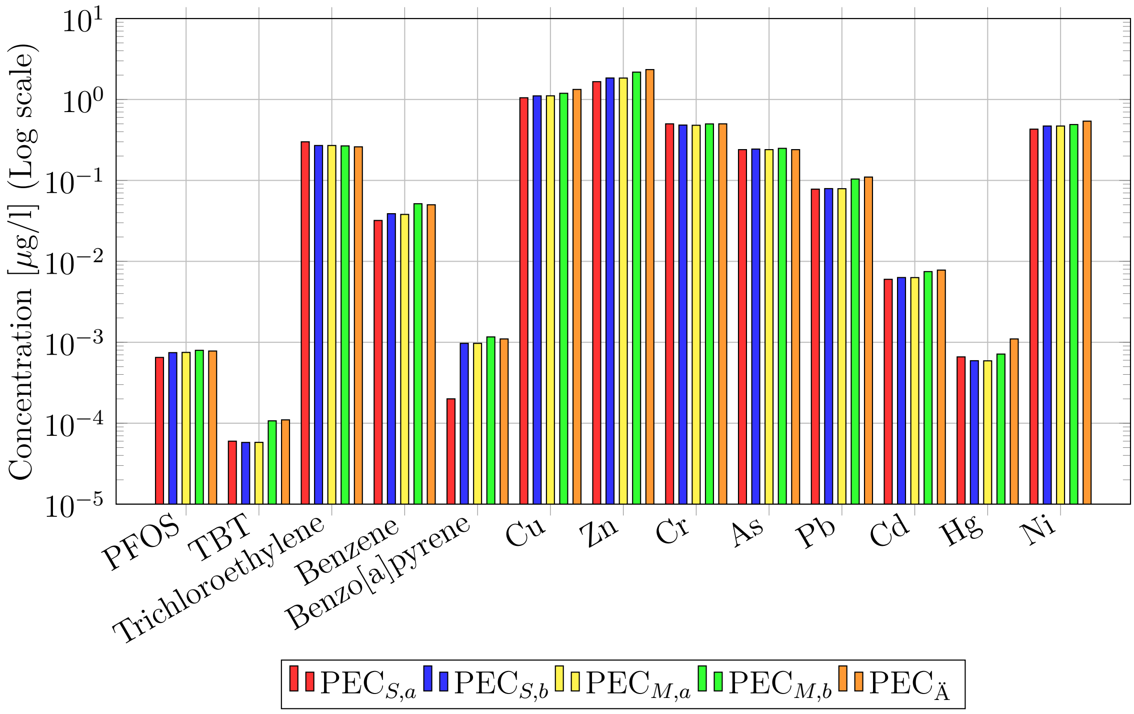

Figure 4.1: Modeled predicted environmental concentrations (PEC) for all substances individually across the five river segments. Note the logarithmic y axis, which allows for comparison of both high- and low-concentration pollutants.

4.2 Effect assessment

Predicted no effect concentrations (PNEC) derived according to the method presented in chapter 3 are shown in table 4.4. The substances differ greatly in their chronic toxicity in aquatic ecosystems, with chronic PNEC values varying in order of magnitude by up to 1000.

Table 4.4: CAS numbers and PNEC values for the selected substances.

Substance	**CAS**	**PNEC** $[\frac{\mu g}{l}]$	**Source**
PFOS	1763-23-1	1.2	(Li et al., 2021)
TBT	1461-22-9	0.008	(Environment Canada, 2009)
Benzene	71-43-2	80	(ECHA, 2026)
Benzo[a]pyrene	50-32-8	0.049	(Zheng & Ni, 2024)
Trichloroethylene	79-01-6	57.6	(ECHA, 2026)
Cu	7440-50-8	6.3	(ECHA, 2026)
Zn	7440-66-6	7.8	(ECHA, 2026)
Cr	7440-47-3	6.5	(ECHA, 2026)
As	7440-38-2	5.6	(ECHA, 2026)
Pb	7439-92-1	3.3	(ECHA, 2026)
Cd	7440-43-9	0.19	(ECHA, 2026)
Hg	7439-97-6	0.057	(ECHA, 2026)
Ni	7440-02-0	2.74	(ECHA, 2026)

4.3 Risk characterization

The RCR represents the ratio between the PEC and PNEC values. As shown in figure 4.2, zinc, copper, and nickel were the three substances with RCR values closest to one, although no values exceeded this threshold. It can be seen that most of the values followed a trend similar to the PEC values presented in figure 4.1, where $RCR_{S,a} < RCR_{S,b} < RCR_{M,a} < RCR_{M,b} < RCR_{\text{Ä}}$. Similarities were also observed in the exceptions where TBT, benzene, benzo[a]pyrene, Cr, and As achieved their highest RCR values in segment M, b and trichloroethylene in segment S, a. Two of the substances, PFOS and benzene, consistently had a low RCR value, suggesting a low risk.

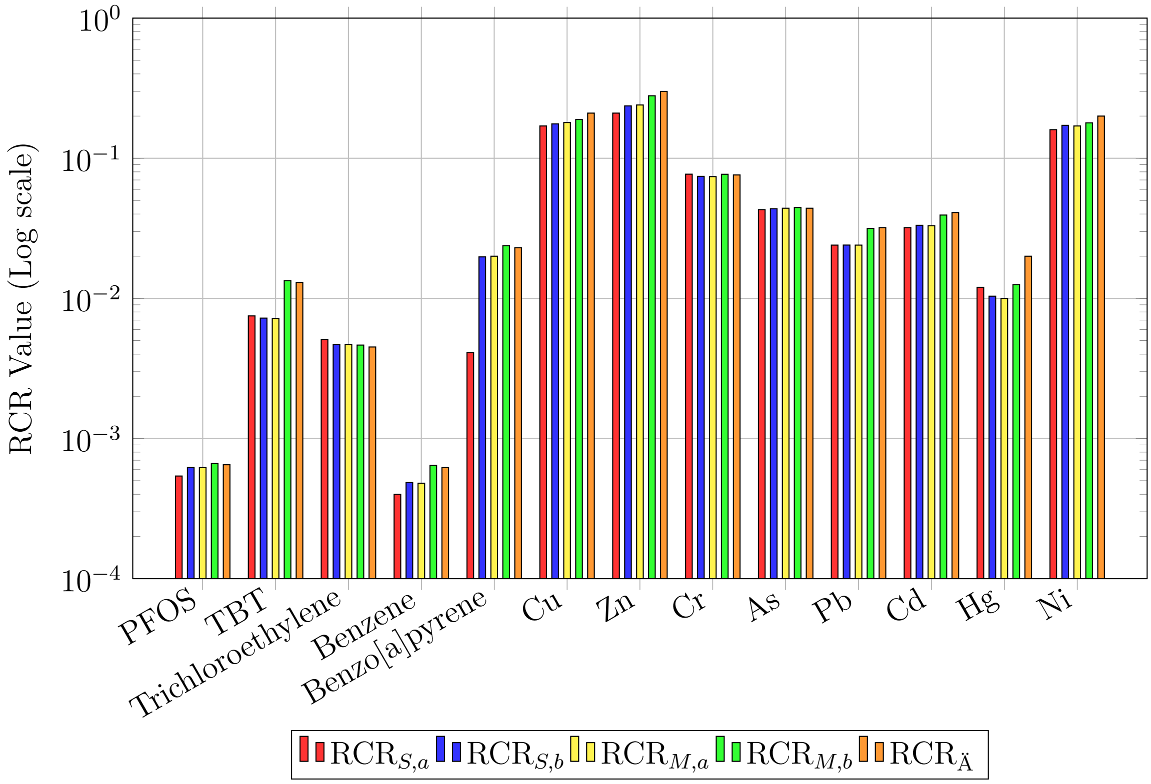

Figure 4.2: Risk characterization ratios for all substances individually across the five river segments. Note the logarithmic y axis, which allows for comparison of both high- and low-risk pollutants.

4.3.1 Mixture toxicity

The RCR values for mixture toxicity were found to be below the risk threshold value of 1 for all segments of the river, as shown in table 4.5 and figure 4.3. However, it was shown to increase downstream, closely approaching 1 in segment Ä, located at the outlet of Ryaverket WWTP. From segment S, a to segment Ä, the mixture toxicity RCR value increased by 29.7%.

Table 4.5: Mixture toxicity RCR values based on modeled concentrations at each segment.

Segment	$\mathbf{RCR_{S,a,mix}}$	$\mathbf{RCR_{S,b,mix}}$	$\mathbf{RCR_{M,a,mix}}$	$\mathbf{RCR_{M,b,mix}}$	$\mathbf{RCR_{Ä,mix}}$
$\mathbf{RCR_{mix}}$	0.74	0.80	0.80	0.90	0.96

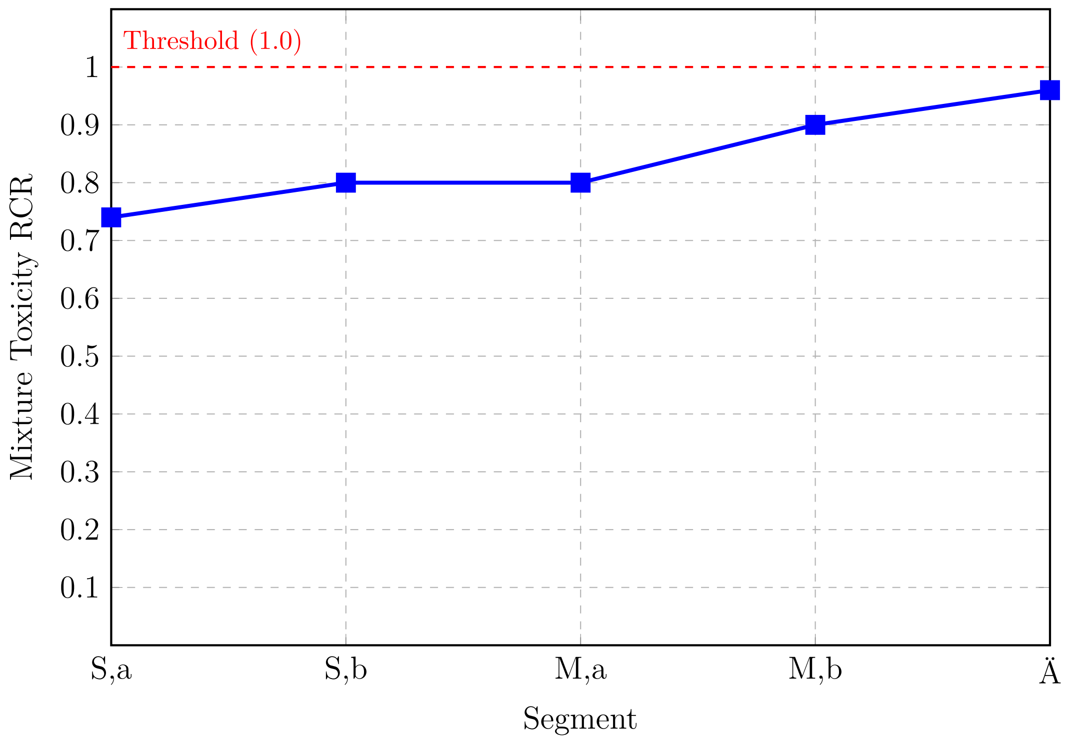

Figure 4.3: Mixture toxicity values for each river segment.

4.4 Bioretention cells

Figure 4.4 illustrates the total reduction in the pollutant load from stormwater run-off in catchment SÄ as a function of land converted to bioretention cells. The results are presented in three scenarios covering different internal removal efficiencies of the bioretention cell: 0.4, 0.6 and 0.9. A nearly linear correlation can be observed between converted land and the reduction of pollutants. To achieve a 40% reduction, the scenario with $\beta = 0.9$ requires 0.38% of land to be converted, while $\beta = 0.6$ and $\beta = 0.4$ require 0.57 and 0.86%, respectively. This shows that the reduction of the stormwater run-off pollution loads using bioretention cells is notably dependent on its removal efficiency. However, substantial reductions can still be achieved with lower efficiencies. Although, the lower efficiencies require a larger land-conversion.

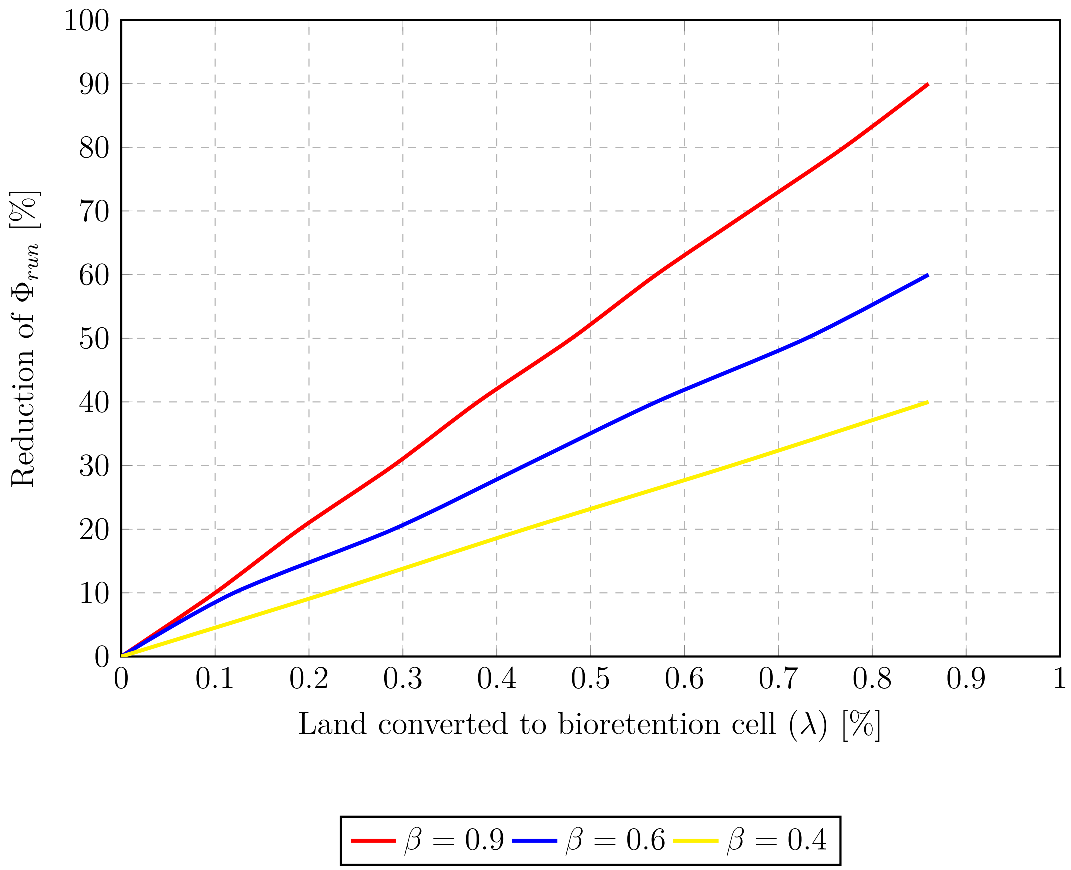

Figure 4.4: Reduction of run-off pollutant load (Φ_{run}) as a function of impermeable land converted to bioretention cells in catchment SÄ (λ) for different bioretention cell removal efficiencies (β).

As illustrated in figure 4.5, the reduction in the mixture toxicity RCR value in river segment Ä follows a nearly linear relationship to the surface area of catchment SÄ converted to bioretention cells. The figure illustrates that the reduction potential is dependent on the reduction capacity (β) of the bioretention cells, where a low β value demands a greater land conversion compared to a high value. Although, it can also be seen that the impact on $RCR_{Ä,mix}$ from reductions in Φ_{ro} is small even with the highest removal efficiency. The theoretical maximum reduction of Φ_{ro} of

90% corresponds to a reduction of $RCR_{\text{Ä},mix}$ of only 5.8%.

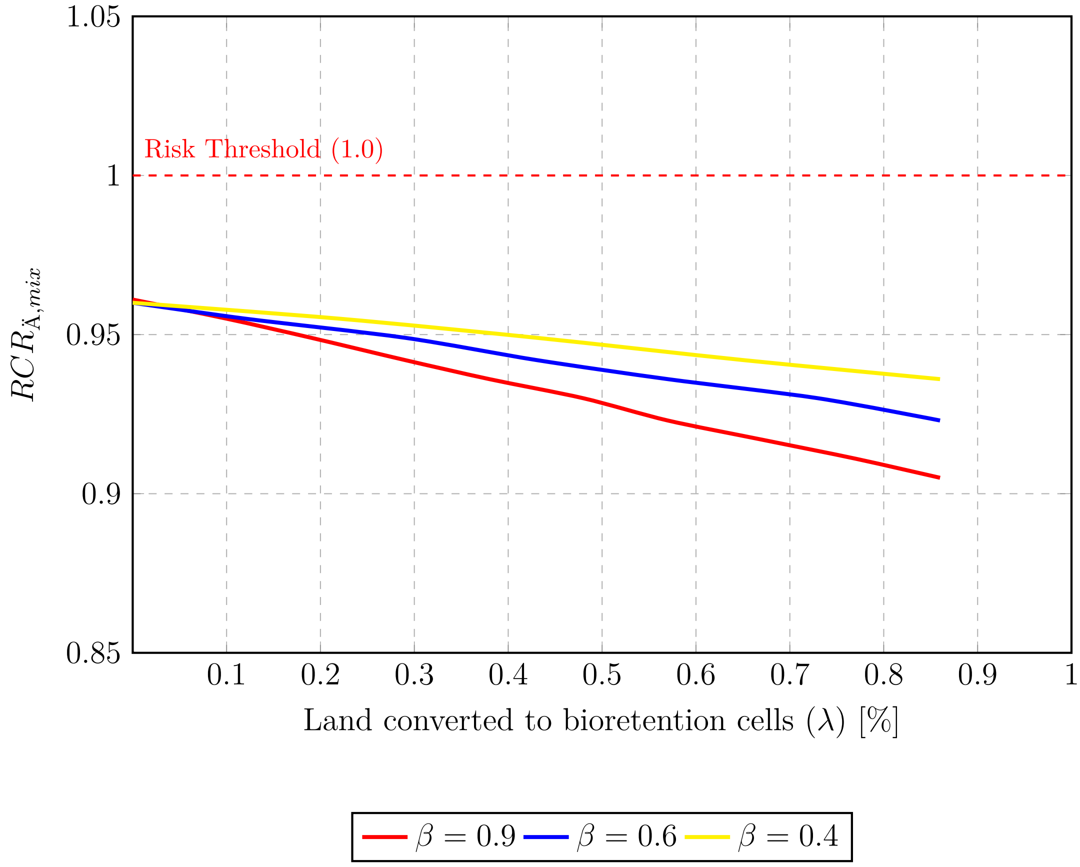

Figure 4.5: Mixture toxicity RCR value in river segment Ä as a function of impermeable land converted to bioretention cell in catchment SÄ (λ) for different bioretention cell removal efficiencies (β). Observe the 0.85 lower limit of the y-axis.

5 Discussion

This chapter discusses the method and results presented in the previous chapters. It evaluates insights, considers flaws and uncertainties, and suggests how further research could build on the study to gain additional insights that the study could not provide.

5.1 Interpretation of results

The mixture toxicity RCR, as seen in figure 4.3, is close to 1 for all the assessed river segments, particularly in segment Ä. The results suggest that risk can be said to be present in the system in the segment. This means that mitigation efforts should be implemented to reduce risk. The contribution of the stormwater discharge from central Gothenburg to both PEC and RCR values in catchment SÄ is small relative to the total values. This suggests that mitigation efforts to lower the RCR would be more effective if they were implemented in the catchment areas of the sources that provide large pollution loads, such as Göta älv (upstream) and Säveån.

Metals were found to be the main contributor to the mixture toxicity RCR, accounting for 96% of the total value, with Cu, Zn, and Ni alone contributing 69%. The high contribution suggests that targeted mitigation efforts towards metals would be an efficient method to decrease the aquatic risk in the catchment. Mitigation efforts such as bioretention cells have been shown to be particularly efficient in reducing the concentration of metals in stormwater and could therefore be an approachable option. The concentration could also be reduced by preventing anthropogenic emissions. However, the abundance of Cu, Zn, and Ni in both use and existing infrastructure in urban environments could make reductions difficult (Ali et al., 2019).

5.2 Selection of pollutants

The study assessed only a fraction of the harmful substances that can be found in stormwater and freshwater sources in Gothenburg and Sweden at large. Länssyrelsen (2023e) presents measured concentrations of more than 80 substances that, in theory, could have been included in the study. However, insufficient measured data limited the number of assessed substances to those where measured concentrations were available for all input sources, thereby making such a large assessment unattainable. Including a larger number of substances would have yielded more accurate results and likely a higher mixture toxicity RCR value. In addition, the exclusion of other substances might inflate the relative impact of the substances that were assessed.

Examples of excluded substances include polychlorinated biphenyls and brominated diphenyl ether. Polychlorinated biphenyls and brominated diphenyl ether are extremely hydrophobic, and bind to fatty tissue and river sediments (Nyberg et al., 2018). Therefore, measurements of environmental concentrations of these substances are often given as concentrations in the biota of the river and are rarely measured in the water itself. These can be converted into concentrations in water using bio concentration factors, as was preformed for mercury. However, biota concentration measurements were not available for most of the tributaries included in the study. Therefore, the substances were excluded to avoid inaccurate estimations of their respective pollution loads. Including these substances in the ERA would likely have resulted in a higher mixture RCR. Another relevant source of freshwater pollution that could have been included in the study is pharmaceutical residues. Using a similar modeling approach based on the GREAT-ER model, Furberg (2014) demonstrates that while there is no risk for individual substances, the mixture toxicity approaches the threshold value of 1 for pharmaceuticals in the Göta älv river.

5.3 Future precipitation scenarios

SMHI (2025) predicts an increase in precipitation volume and intensity of 25% and 100%, respectively. Others have shown that more frequent and extreme precipitation events are positively correlated with pollutant concentration in urban stormwater and total stormwater pollution load (Borris, 2016; Wijesiri et al., 2020; Yang et al., 2024). However, estimates of how much the concentration and load will increase are difficult to make when expressing it relative to the mean annual load. Such estimations would have been reliant on assumptions and were therefore not preformed. This study found that calculations on future climate conditions and their impact on stormwater pollution transport are difficult to perform on large temporal and geographical scales. Climate change affects more than precipitation, for example groundwater levels and the duration of dry periods, and varies depending on geographical location. This makes it difficult to find studies whose insights can be directly applicable to the Göta älv case. A field study conducted in Göta älv indicated that there is a possible correlation between precipitation and pollution transport (Frogner-Kockum et al., 2016). Increased metal concentrations have been linked to an increase in both run-off and groundwater levels. Based on future RCP scenarios, it is projected that increased precipitation leads to higher groundwater levels, which in turn may cause a higher pollution load within the region.

5.4 The influence of the first-flush effect

Rising temperatures are projected to alter seasonal characteristics, with longer periods of drought interrupted by shorter and more intense precipitation events (SMHI, 2025). These variations will lead to more first flush events, causing pollution loads to fluctuate across the year with higher peak flows and concentrations. The higher peak flows may introduce concentrations in catchment SÄ that approach acute toxicity thresholds, which were not assessed in this study. However, the literature on future first-flush events and their effects on acute toxicity is somewhat inconclusive. For example, a field study conducted in Denmark by Sharma et al. (2016) suggested that future events can lead to increased peak concentrations and pollutant loads. However, the study found that while concentrations were higher, acute toxicity was only slightly affected due to the low increase in dissolved metals relative to particle bound metals. More research thus seems to be needed to understand the first-flush effect before it can be included in environmental risk assessment.

5.5 Software access

Throughout this study, several different modeling software were evaluated to simulate pollutant transport and hydraulic flows. However, direct access to the software could not be obtained. Therefore, the study relied heavily on publications and instructional reports published by developers of the considered software. The primary source of data and inspiration for modeling the pollutant flows to catchment SÄ was the StormTac database and reports published by the company, while the inspiration drawn from the GREAT-ER model was used to build the environmental fate model. The restricted access to the tools and instructions on how they should be applied might have caused missteps or gaps in calculations made in chapter 3. Although such software and their models always include inaccuracies in their representations of real conditions, direct access to the software might have rendered more accurate results.

5.6 Bioretention cells

As described in section 2.5.1, conventional infiltration-based bioretention cells are largely ineffective in Gothenburg due to the high clay content in the soil. However, bioretention cells could be efficient if done in the form of stormwater retention ponds. As described in section 2.5.1, retention ponds utilize retention and evaporation rather than relying on infiltration, thus counteracting the issues given by the high clay content. As demonstrated in figure 4.4, the area needed to integrate bioretention cells is quite large, which could become problematic in parts of the city where space is a prime resource. To address this issue, bioretention cells could be viewed as multifunctional urban spaces. By integrating stormwater management with public spaces built for recreational activities such as football or discgolf, the area becomes useful in multiple ways. However, a long term challenge that has to be taken into account is the long term accumulation of pollutants within the filters as described in section 2.5.2. Over time, the soil from which the bioretention cell has been constructed can be classified as hazardous and require special waste handling. Future planning may need to add information and planning strategies for safe disposal to ensure that pollutants do not become liabilities in the future.

5.7 Factors of uncertainty

This study builds on data from many different sources. The study gathered data primarily from the StormTac database and Water Information Systems Sweden (VISS) provided by the administrative board of the Västra Götaland county (StormTac Database, 2026; Länsstyrelsen, 2023b-d). The measured concentrations for Göta älv upstream, Säveån, Mölndalsån, and Kvillebäcken found in VISS are presented in management cycles that span 2-3 years of measured data. The most recent cycle, 2023-2026, had not yet been published during the making of this study. Thus, measured concentrations from the previous cycle, 2021-2023, had to be used. More recent concentrations would likely have produced a more accurate assessment of the current conditions in catchment SÄ.

Standard pollutant concentrations gathered from the StormTac database for all land-use types, with the exception of roads, were adapted to fit Swedish regional conditions, not the specific conditions of Gothenburg. Although pollutant concentration might not vary considerably between Swedish cities, some differences likely exist. Such differences were not corrected for when modeling stormwater flows and might have affected the results. Furthermore, the classification used for land-use types gathered from Lantmäteriet (n.d.a; n.d.b) differed slightly from the classification used in the StormTac Database (2026). Therefore, the study translated their respective classifications when assigning standard pollutant concentrations to a land-use area of catchment SÄ. Some land-use types might have been assigned pollutant concentrations that are not entirely representative of real conditions, resulting in slight changes in pollution loads.

Difficulties arose during the collection of PNEC values, specifically the inconsistency in the available data. ECHA CHEM was originally intended to be the only source of PNEC values considering the organization's prominence. However, chronic PNEC values for fresh water sources were not available in ECHA CHEM for some substances. In such cases, values found in various scientific publications were used. Although the publications used similar methods for deriving their PNEC values, some differences might have affected the results of the study. Furthermore, the assumptions made regarding mixture toxicity in section 3.5.1 were based on the concept of concentration addition as described by van Leeuwen and Vermeire (2007). Although the concept is established in the field of ERA, it is likely that the resulting mixture RCR differs slightly compared to real-world conditions.

6 Conclusion

The study showed that risk is effectively present in catchment SÄ of the Göta älv river in terms of chronic harm to aquatic organisms. Although no single substance alone reached RCR values close to the risk threshold, the combined effects of multiple substances closely approached the risk threshold in river segment Ä to which the metals Cu, Zn, and Ni were found to be the largest contributors. Furthermore, it showed that bioretention cells with combined stormwater infiltration and retention could be an efficient measure to capture polluting substances and decrease risk in the catchment. However, the study showed that the contribution of stormwater run-off from the catchment area of catchment SÄ was small compared to the total annual pollution load and RCR in the catchment. Therefore, measures such as bioretention cells need to be implemented further upstream in other urban catchment areas.

Future research could include a larger number of substances using measured concentrations from the unreleased 2023-2026 management cycle to achieve more accurate RCR and mixture RCR values. Given the low contribution of stormwater run-off from catchment SÄ relative to the total pollution load. Calculations similar to those made in section 3.3.1.1 could be made for the catchments connected to the main contributors to the pollution load, namely Göta älv (upstream) and Säveån, to provide additional precision in identifying the sources of pollution. Such an assessment could also provide valuable insight as to where mitigation efforts, such as bioretention cells, are most effectively implemented. Studies could also assess where and how bioretention cells could be implemented most efficiently in central Gothenburg. Lastly, future research could attempt to assess the impact of future precipitation characteristics and the first flush effect on stormwater run-off in Gothenburg.

Bibliography

Ali, H., Khan, E., Ilahi, I. (2019). Environmental Chemistry and Ecotoxicology of HazardousHeavy Metals: Environmental Persistence, Toxicity,and Bioaccumulation. *Journal of Chemistry, 2019*(1). https://doi.org/10.1155/2019/6730305

Arwidsson, M. (2011). *Modelling the importance of baseflow in the runoff and transport of pollution in stormwater ditches and stormwater pipes.* [Master thesis, University of Manchester]. StormTac. https://stormtac.com/admin/Uploads/Dissertation%202011_Modelling%20Baseflow%20in%20StormTac.pdf

Aryal, R., Vigneswaran, S., Kandasamy, J., Naidu, R. (2010). Urban stormwater quality and treatment. *Korean Journal of Chemical Engineering, 27*(5), 1343-1359. 10.1007/s11814-010-0387-0

Backhaus, T., Scholze, M., Brack, W., Martin, O., Slunge, D., Ågerstrand, M., Kortenkamp, A., Escher, B. (2025). Include a mixture allocation factor to improve EU chemical risk management. *Science, 390(6774)*, 678–680. https://doi.org/10.1126/science.aeb6374

Baeyens, W., Leermakers, M., Papina, T., Saprykin, A., Brion, N., Noyen, J., De Gieter, M., Elskens, M., Goeyens, M. (2003). Bioconcentration and Biomagnification of Mercury and Methylmercury in North Sea and Scheldt Estuary Fish. *Archives of Environmental Contamination and Toxicology, 45*(4), 498-508. https://doi.org/10.1007/s00244-003-2136-4

Birch, G. F., Matthai, C., Fazeli, M. S. (2007). Efficiency of a retention/detention basin to remove contaminants from urban stormwater. *Urban Water Journal, 3*, 69-77. https://doi.org/10.1080/15730620600855894

Borris, M. (2016). *Future trends in urban stormwater quality: effects of changes in climate, catchment characteristics and processes and socio-economic factors.* [Doctoral thesis, Luleå University of Technology]. DiVA. https://ltu.diva-portal.org/smash/record.jsf?pid=diva2%3A999269&dswid=-5944

Canadian Council of Ministers of the Environment [CCME]. (1999). *Canadian water quality guidelines for the protection of aquatic life: Chlorinated ethenes—1,1,2-Trichloroethene (trichloroethylene).* https://ccme.ca/en/res/chlorinated-ethenes-112-trichloroethene-en-canadian-water-quality-guidelines-for-the-protection-of-aquatic-life.pdf

Davis, A. P., Hunt, W. F., Traver, R. G., Clar, M. (2009). Bioretention technology: Overview of current practice and future needs. *Journal of Environmental Engineering, 135*(3), 109–117. https://doi.org/10.1061/(ASCE)0733-9372(2009)135:3(109)

Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy [DEPC 2000/60/EC]. Official Journal of the European Union, L 327, 1-93. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02000L0060-20141120

Directive (EU) 2024/3019 of the European Parliament and of the Council of 27 November 2024 concerning urban wastewater treatment [DEPC 2024/3019]. Official Journal of the European Union, L 3019, 1-62. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02024L3019-20241212

Du, J., Chadalavada, S., Chen, Z., Naidu, R. (2013). Environmental remediation techniques of tributyltin contamination in soil and water: A review. *Chemical Engineering Journal, 235*(2014), 141-150. http://dx.doi.org/10.1016/j.cej.2013.09.044

Environment Canada. (2009). Follow-up to the 1993 ecological risk assessment of organotin substances on Canada's Domestic Substances List. *Government of Canada.* https://www.canada.ca/content/dam/eccc/migration/main/lcpe-cepa/documents/substances/org/final/followup_organotin-eng.pdf

European Chemicals Agency [ECHA]. (2026). *ECHA Chemicals Database.*https://chem.echa.europa.eu/

Exploateringsförvaltningen. (2025). *Vattenverksamhet Backaplan, Kvillebäcken. Samrådsunderlag till kombinerat undersöknings- och avgränsningssamråd enligt 6 kap. 24 § andra stycket miljöbalken* (R2025:10). Göteborgs Stad. https://www5.goteborg.se/prod/fastighetskontoret/etjanst/planobygg.nsf/vyFiler/Backaplan%20-%20detaljplan%203%3A%20Bost%C3%A4der%2C%20lokaler%20m.m.%20vid%20Backav%C3%A4gen%20och%20Norra%20Deltav%C3%A4gen-Vattenverksamhet%20-%20samr%C3%A5d-Samr%C3%A5dsunderlag%20f%C3%B6r%20vattenverksamhet%20vid%20Backaplan/$File/Samr%C3%A5dsunderlag%20vattenverksamhet%20Backaplan%20251007.pdf?

Frogner-Kockum, P., Göransson, G., o Haeger-Eugensson, M. (2016).*Climate impact on contaminant dispersion in the river basin of Göta Älv, Sweden* (SGI Publication 29). Swedish Geotechnical Institute (SGI). https://www.diva-portal.org/smash/get/diva2:1300108/FULLTEXT01.pdf

Furberg, A. (2014). *Environmental risk assessment of pharmaceutical exposure to fish in the Swedish Göta Älv river* [Master's thesis, Chalmers University of Technology]. Chalmers Publication Library.

Gao, Z., Zhang, Q., Li, J., Wang, Y., Dzakpasu, M., Wang, X. C. (2023). First flush stormwater pollution in urban catchments: A review of its characterization and quantification towards optimization of control measures. *Journal of Environmental Management, 340.* https://doi.org/10.1016/j.jenvman.2023.117976

Gryaab. (2025). *Miljörapport: Gryaab, Ryaverket 2024.* (2025:2). https://www.gryaab.se/wp-content/uploads/2025/04/Miljorapport-2024-Ryaverket-inklusive-bilagor.pdf

Göransson, G., Larson, M., Bendz, D. (2013). Variation in turbidity with precipitation and flow in a regulated river system-river Göta Älv, SW Sweden. *Hydrology and Earth System Sciences, 17*(7), 2529-2542. https://doi.org/10.5194/hess-17-2529-2013

Göteborgs Stad. (2017). *Teknisk Handbok.* (2017:1). https://tekniskhandbok.goteborg.se/Arkiv/2017-1/__site/__planering__utformning__gataochv%C3%A4g__typsektion.html

Göteborgs Stad. (2021). *Strukturplan för hantering av översvämningsrisker: Metodbeskrivning.* Kretslopp och vatten. https://www.vattenigoteborg.se/Downpour/DownpourReports

Göteborgs Stad. (n.d.a). Avloppsstatistik. Kretslopp och vatten. Retrieved January 29, 2026, from https://goteborg.se/wps/portal/start/kommun-och-politik/kommunens-organisation/forvaltningar-och-namnder/kretslopp-och-vatten/kretslopp-och-vattens-verksamhet/avloppsstatistik

Göteborgs Stad. (n.d.b). Miljöförvaltningen. Retrieved February 16, 2026, from https://goteborg.se/wps/portal/start/kommun-och-politik/kommunens-organisation/forvaltningar-och-namnder/miljoforvaltningen

Göteborgs Stad. (n.d.c). Kretslopp och Vatten. Retrieved February 16, 2026, from https://goteborg.se/wps/portal/start/kommun-och-politik/kommunens-organisation/forvaltningar-och-namnder/kretslopp-och-vatten

Göta älvs vattenvårdsförbund. (2015). *Fakta om Göta älv: En beskrivning av Göta älv och dess avrinningsområde nedströms Vänern 2015. Göta älvs vattenvårdsförbund.* https://www.gotaalvvvf.org/download/18.2f0ad835166c596881356a83/1540998119692/fakta_om_gota_alv_webb.pdf

Hoch, M. (2001). Organotin compounds in the environment — an overview. *Applied Geochemistry, 16*(7-8), 719-743. https://doi.org/10.1016/S0883-2927(00)00067-6

Honda, M., & Suzuki, N. (2020). Toxicities of Polycyclic Aromatic Hydrocarbons for Aquatic Animals. *International Journal of Environmental Research and Public Health, 17*(4). https://doi.org/10.3390/ijerph17041363

Hossain, M. A., Alam, M., Yonge, D. R., Dutta, P. (2005). Efficiency and Flow Regime of a Highway Stormwater Detention Pond in Washington, USA. *Water, Air, and Soil Pollution, 164*, 79–89. https://doi.org/10.1007/s11270-005-2250-1

Houde, M., Douville, M., Gagnon, P., Sproull, J., J, Cloutier. (2015). Exposure of Daphnia magna to trichloroethylene (TCE) and vinyl chloride (VC): Evaluation of gene transcription, cellular activity, and life-history parameters. *Ecotoxicology and Environmental Safety, 116*, 10-18. https://doi.org/10.1016/j.ecoenv.2015.02.031

Istenic, D., Arias, C. A., Vollertsen, J., Nielsen, A. H., Wium-Andersen, T., Hvidved-Jacobsen, T., Brix, H. (2012). Improved urban stormwater treatment and pollutantremoval pathways in amended wet detention ponds. *Journal of Environmental Science and Health, 47*, 1466–1477. 10.1080/10934529.2012.673306

Koormann, F. (2011). GREAT-ER Desktop Version 3.0 Model Description. Intevation GmbH.

Kretslopp och vattennämnden. (2024). *Årsrapport 2023: Kretslopp och vattennämnden.* Göteborgs Stad. https://goteborg.se/wps/wcm/connect/191394cb-4815-4c52-b09d-8b87c07ed933/Arsrapport+Kretslopp+och+vatten+2023.pdf?MOD=AJPERES

Kuykendall, J. R. (2008). Benzene. In Jørgensen, S. E (Eds.), *Encyclopedia of Ecology* (Vol 1 A-C) (pp. 326-332). Elsevier B.V.

Lantmäteriet. (n.d.a). Fastighetskartan: Markdata (Property map Land data) [Dataset]. Sveriges lantbruksuniversitet, Geodata Extraction Tool (GET). Retrieved 2026-02-20 from https://maps.slu.se/get/

Lantmäteriet. (n.d.b). Fastighetskartan: Kommunikation (Property map Transport networks) [Dataset]. Sveriges lantbruksuniversitet, Geodata Extraction Tool (GET). Retrieved 2026-02-20 from https://maps.slu.se/get/

Larm, T. (2005). *Karaktärisering av dagvatten: föroreningshalter och belastningar* (Rapport 2005-05). Svenskt Vatten (VA-Forsk). https://vav.griffel.net/filer/VA-Forsk_2005-05.pdf

Larm, T. (2000). *Utformning och dimensionering av dagvattenreningsanläggningar* (VA-FORSK Rapport 2000-10). Stockholm: VAV AB. https://www.stormtac.com/admin/Uploads/Dimension.pdf

Li, Q., Wang, P., Hu, B., Wang, C., Li, D. (2021). Perfluorooctanoic Acid (PFOA) and Perfluorooctanesulfonic Acid (PFOS) in Surface Water of China: National Exposure Distributions and Probabilistic Risk Assessment. *Archives of Environmental Contamination and Toxicology, 81*, 470–481. https://doi.org/10.1007/s00244-021-00837-z

Länsstyrelsen. (2023a). *Göta älv - Säveåns inflöde till mynningen vid Älvsborgsbron.* Vatteninformationssystem Sverige (VISS). Retrieved February 2, 2026, from https://viss.lansstyrelsen.se/Waters.aspx?waterMSCD=WA68736339#pagemodule85

Länsstyrelsen. (2023b). *Mölndalsån - Ullevi till Liseberg / Delsjöbäckens inflöde.* Vatteninformationssystem Sverige (VISS). Retrieved March 9, 2026, from https://viss.lansstyrelsen.se/Waters.aspx?waterMSCD=WA17398396

Länsstyrelsen. (2023c). *Säveån - Olskroken till Brodalen.* Vatteninformationssystem Sverige (VISS). Retrieved March 9, 2026, from https://viss.lansstyrelsen.se/Waters.aspx?waterMSCD=WA19625233

Länsstyrelsen. (2023d). *Kvillebäcken.* Vatteninformationssystem Sverige (VISS). Retrieved March 9, 2026, from https://viss.lansstyrelsen.se/Waters.aspx?waterMSCD=WA95875860

Länsstyrelsen. (2023e). *Göta älv - förgreningen med Nordre älv till Säveåns mynning.* Vatteninformationssystem Sverige (VISS). Retrieved March 9, 2026, from https://viss.lansstyrelsen.se/Waters.aspx?waterMSCD=WA33908756

Länsstyrelsen i Västra Götalands län. (2011). *Klimatanalys för västra götalands län (Rapport baserad på SMHI:s klimatunderlag).* https://www.lansstyrelsen.se/download/18.8cd5a1b19362fb4fc2771/1732533972404/Klimatanalys%20f%C3%B6r%20V%C3%A4stra%20G%C3%B6talands%20l%C3%A4n.pdf

Länsstyrelsen i Västra Götaland län. (2018). *Mätkampanj 2017 - Miljögifter i ytvattenförekomster.* (2018:44). https://viss.lansstyrelsen.se/ReferenceLibrary/54425/Slutversion%20rapport.pdf

Ma, T., Ye, C., Wang, T., Li, X., Luo, Y. (2022). Toxicity of per- and polyfluoroalkyl substances to aquatic invertebrates, planktons, and microorganisms. *International Journal of Environmental Research and Public Health, 19*(24), 16729. https://doi.org/10.3390/ijerph192416729

Mead, C. D., & Williams, W. P. (1998). *Environmental risk assessment: Approaches, Experiences and Information Sources.* European environment agency. https://www.eea.europa.eu/en/analysis/publications/gh-07-97-595-en-c2

Miljöförvaltningen. (2020). *Riktlinjer och riktvärden för utsläpp av förorenat vatten till dagvattennät och recipient.* (R2020:13). Göteborgs Stad. https://goteborg.se/wps/wcm/connect/a227da55-ea58-4410-a00f-ba75014080e4/N800_R_2020_13_Riktlinjer+och+riktv%C3%A4rden+f%C3%B6r+utsl%C3%A4pp+av+f%C3%B6rorenat+vatten.pdf?MOD=AJPERES

Miljöförvaltningen. (2021). *Reningskrav för dagvatten* (R2021:03:11). Göteborgs Stad. https://goteborg.se/wps/wcm/myconnect/2997f065-9532-4a05-9812-c0336237292e/Reningskrav+dagvatten+2021-03-11.pdf?MOD=AJPERES

Miljöförvaltningen. (2025a). *Lokala åtgärdsprogram Göteborg - Bakgrund och metodik* (R2025:1). Göteborgs Stad. https://goteborg.se/wps/wcm/connect/72c9f7b7-c8ac-4fe6-af3a-faf2f3ea1b8a/R800_2025_01+Lokala+%C3%A5tg%C3%A4rdsprogram+G%C3%B6teborg.+Bakgrund+och+metodik.pdf?MOD=AJPERES

Miljöförvaltningen. (2025b). *Lokalt åtgärdsprogram för Göta älvs huvudfåra: Avrinningsområdet inom Göteborgs Stad* (R2025:02). Göteborgs Stad. https://goteborg.se/wps/wcm/connect/0aa5310b-417a-44ef-98c0-9dc75b851e65/R800_2025_02+Lokalt+%C3%A5tg%C3%A4rdsprogram+f%C3%B6r+G%C3%B6ta+%C3%A4lvs+huvudf%C3%A5ra.pdf?MOD=AJPERES

Miljöförvaltningen. (2025c). *Lokalt åtgärdsprogram för Säveån - Avrinningsområdet inom Göteborgs Stad* (R2025:04). Göteborgs Stad. https://www4.goteborg.se/prod/Intraservice/Namndhandlingar/SamrumPortal.nsf/93ec9160f537fa30c12572aa004b6c1a/2be2bd03d608007ac1258c120026e69b/$FILE/Handling%2013%20Bilaga%204%20MKN%2020250121.pdf

Miljöförvaltningen. (2025d). *Lokalt åtgärdsprogram för Mölndalsån - Avrinningsområdet inom Göteborgs Stad* (R2025:03). Göteborgs Stad. https://goteborg.se/wps/wcm/connect/c8d9cd55-9184-4c76-ab64-5f15d6445ff8/R800_2025_03+Lokalt+%C3%A5tg%C3%A4rdsprogram+f%C3%B6r+M%C3%B6lndals%C3%A5n.pdf?MOD=AJPERES

Montoya, X. C., Thompson, W. A., Smith, C. M., Wilson, J. M., Vijayan, M. M. (2024). Exposure to Total Suspended Solids (TSS) Impacts Gill Structure and Function in Adult Zebrafish. *Bulletin of Environmental Contamination and Toxicology, 113*(14). https://doi.org/10.1007/s00128-024-03922-w

Müller, A., Österlund, H., Marsalek, J., Viklander, M. (2020). The pollution conveyed by urban runoff: A review of sources. *Science of the Total Environment, 709*. https://doi.org/10.1016/j.scitotenv.2019.136125

Nazarpour, S., Gnecco, I., Palla, A. (2023). Evaluating the effectiveness of bioretention cells for urban stormwater management: A systematic review. *Water, 15*(5). https://doi.org/10.3390/w15050913

Nyberg, E., Faxneld, S., Danielsson, S., Bignert, A. (2018). *The National Swedish Contaminant Monitoring Programme for Freshwater Biota, 2018*. (Report nr: 3:2018). Swedish Museum of Natural History. https://viss.lansstyrelsen.se/ReferenceLibrary/54338/PBDE%20och%20Hg.pdf

National Center for Biotechnology Information [NCBI]. (2026). *PubChem*. https://pubchem.ncbi.nlm.nih.gov/

Park- och naturförvaltningen i Göteborg (2015). *Sötvattenslevande fiskar i Göteborgs kommun* (Rapport 2015:01). Göteborgs Stad. https://goteborg.se/wps/wcm/connect/492021f8-76d6-4977-bc34-49e1155586f0/S%C3%B6tvattenslevande+fiskar+i+G%C3%B6teborg.pdf?MOD=AJPERES

SFS 1998:808. *Miljöbalken* [The Swedish environmental code]. Ministry of Climate and Enterprise. https://www.riksdagen.se/sv/dokument-och-lagar/dokument/svensk-forfattningssamling/miljobalk-1998808_sfs-1998-808/

Sharma, A. K., Vezzaro, L., Birch, H., Arnbjerg-Nielsen, K., Mikkelsen, P. S. (2016). Effect of climate change on stormwater runoff characteristics and treatment efficiencies of stormwater retention ponds: A case study from Denmark using TSS and Cu as indicator pollutants. *SpringerPlus, 5*(1). https://doi.org/10.1186/s40064-016-3103-7

Sjöfartsverket. (2024). *Lotsområde Göteborg - Nautisk information.* https://www.sjofartsverket.se/sv/tjanster/lotsning/lotsomrade-goteborg/nautisk-information/

StormTac Database. (2026). Stormwater, baseflow, surface water and wastewater database, v.2026-01-08. StormTac Corporation. https://www.stormtac.com/

Svenskt Vatten. (2016). *Avledning av dag-, drän- och spillvatten. Funktionskrav, hydraulisk dimensionering och utformning av allmänna avloppssystem. Del I – Policy och funktionskrav för samhällens avvattning* (Publikation P110 – Del I). https://vattenbokhandeln.svensktvatten.se/wp-content/uploads/2025/08/P110_del1_web_low_0220.pdf

Sveriges meteorologiska och hydrologiska institut [SMHI]. (2025). *Klimatunderlag för klimat- och sårbarhetsanalyser.* https://www.smhi.se/publikationer-fran-smhi/sok-publikationer/2025-02-10-klimatunderlag-for-klimat--och-sarbarhetsanalyser

Sveriges meteorologiska och hydrologiska institut [SMHI]. (n.d.a). *Sveriges största vattendrag.* Retrieved April 10, 2026, from https://www.smhi.se/kunskapsbanken/hydrologi/sveriges-vattendrag/sveriges-storsta-vattendrag#:~:text=%C3%84lvsborgsbron%20%C3%B6ver%20G%C3%B6ta%20%C3%A4lv%20vid%20mynningen%20mot,totala%20m%C3%A4ngden%20vatten%20fr%C3%A5n%20G%C3%B6ta%20%C3%84lvs%20avrinningsomr%C3%A5de.

Sveriges meteorologiska och hydrologiska institut [SMHI]. (n.d.b). *RPC scenarier.* Retrieved January 29, 2026, from https://www.smhi.se/kunskapsbanken/klimat/klimatmodeller-ochscenarier/rcp-scenarier

Sveriges meteorologiska och hydrologiska institut [SMHI]. (2022). SVAR 2022: Delavrinningsområden [Dataset]. Sveriges lantbruksuniversitet, Geodata Extraction Tool (GET). Retrieved 2026-02-20 from https://www.smhi.se/data/sjoar-och-vattendrag/hydrografi

Sveriges meteorologiska och hydrologiska institut [SMHI]. (2024). *Års- och månadsstatistik - tabeller för temperatur, vind, nederbörd och solskenstid.* Retrieved March 31, 2026, from https://www.smhi.se/data/temperatur-och-vind/temperatur/ars--och-manadsstatistik

SVT Nyheter. (2023, 8 augusti). Göta älv har svämmat över. https://www.svt.se/nyheter/lokalt/vast/gota-alv-har-svammat-over

Trafikverket (2025). *Ny dragning av E45 genom Göteborg (del 2).* (2025:103). https://www.diva-portal.org/smash/get/diva2:1990187/FULLTEXT01.pdf

Trafikverket. (2024). *Vägars och gators utformning* (TRVINFRA-00396, Version 1.0). Trafikverkets infrastrukturregelverk. https://trafikverket.diva-portal.org/smash/record.jsf?pid=diva2%3A1909331&dswid=5433

Tyréns. (2016). *BADVATTENKVALITET GÖTA ÄLV - MODELLERINGSSTUDIE* (SLUTRAPPORT 2016-12-02). Göteborgs Stad. https://www5.goteborg.se/prod/Intraservice/Namndhandlingar/SamrumPortal.nsf/93ec9160f537fa30c1

2572aa004b6c1a/78e88fa27ddcd76cc1258c1f0034463f/$FILE/23.%20F%20Rapport%20Badvattenkvalitet%20Gota%20Alv.%20modelleringsstudie.pdf

United States Environmental Protection Agency [USEPA]. (2025a). Combined Sewer Overflow Basics. https://www.epa.gov/npdes/combined-sewer-overflow-basics

United States Environmental Protection Agency [USEPA]. (2025b). Superfund Chemical Data Matrix (SCDM) methodology. Office of Superfund Remediation and Technology Innovation. https://semspub.epa.gov/work/HQ/405538.pdf

United States Geological Survey [USGS]. (1998). *Transport, Behavior, and Fate of Volatile Organic Compounds in Streams* (U.S. Geological Survey Professional Paper 1589). United States Department of the Interior. https://pubs.usgs.gov/pp/1589/report.pdf

van Leeuwen, C., & Vermeire, T. (Eds.). (2007). *Risk assessment of chemicals: An introduction* (2nd ed.). Springer. https://doi.org/10.1007/978-1-4020-6102-8

Westergren, S., Rudling, M., Wenke, C. (2015). Underlag till förslag till linje av val av dagvattenlösningar/anläggningar i olika typer av gator (Ramboll-rapport 1320017373). *Ramboll Sverige AB Trafikkontoret, Göteborgs stad.* https://teknisk handbok.goteborg.se/Arkiv/2018-1/__site/Content/File/1E_9_F%C3%B6rslag%20p%C3%A5%20dagvattenanl%C3%A4ggningar_2018-04.pdf

Wijesiri, B., Liu, A., Goonetilleke, A. (2020). Impact of global warming on urban stormwater quality: From the perspective of an alternative water resource. *Journal of Cleaner Production, 262.* https://doi.org/10.1016/j.jclepro.2020.121330

Xu, J., Zheng, L., Yan, Z., Huang, Y., Feng, C., Li, L., Ling, J. (2020). Effective extrapolation models for ecotoxicity of benzene, toluene, ethylbenzene, and xylene (BTEX). *Chemosphere, 240.* https://doi.org/10.1016/j.chemosphere.2019.124906

Yang, Y., Zhu, D. Z., Loewen, M. R., Zhang, W., van Duin, B., Mahmood, K. (2024). Impacts of climate change on urban stormwater runoff quantity and quality in a cold region. *Science of the Total Environment, 954.* https://doi.org/10.1016/j.scitotenv.2024.176439

Zheng, Z. Y., & Ni, H. G. (2024). Predicted no-effect concentration for eight PAHs and their ecological risks in seven major river systems of China. *Science of The Total Environment, 906.* https://doi.org/10.1016/j.scitotenv.2023.167590

Appendix

Table A1

Pollutant concentrations (C_j) per input source (MEC) [μg/l]

Pollutant	Ryaverket	CSO	KB	GÄ (US)	SÅ	MÅ
PFOS	0.00	0.0	0.00876	0.00065	0.00155	0.0025
TBT	0.00	0.0	0.00024	0.00006	0.00004	0.00004
Trichloroethylene	0.00	0.0	0.2	0.3	0.05	0.2
Benzene	0.00	0.0	0.12	0.032	0.1	1.0
Benzo[a]pyrene	0.00	0.0	0.00037	0.0002	0.0075	0.00539
Cu	7.30	51.0	3.24	1.05	1.6	3.0
Zn	9.70	77.0	11.7	1.66	3.4	8.11
Cr	0.36	2.4	0.25	0.5	0.34	0.29
As	0.00	0.0	0.35	0.24	0.28	0.31
Pb	0.15	2.5	0.231	0.078	0.09	0.214
Cd	0.02	0.1	0.01	0.006	0.009	0.023
Hg	0.02	0.06	0.00	0.00066	0.00	0.00243
Ni	2.70	3.3	1.754	0.433	0.79	0.614

Sources: RV (Gryaab, 2025), KB (Länsstyrelsen, 2023d), GÄ (US) (Länsstyrelsen 2023e), SÅ (Länsstyrelsen 2023c), MÅ (Länsstyrelsen 2023b).

Table A2

Road dimensions and traffic data.

Road type	Length [m]	Width [m]	Annual average daily traffic
Expressway	25934	20	45000
Expressway Tunnel	6740	20	45000
Primary Road	197017	15	6000
Primary Road HT	5379	15	11000
Primary Road LHT	1562	15	8000
Local street	7878	10	3500

Sources: Length (Lantmäteriet n.d.b), Width (Göteborgs Stad, 2017; Trafikverket, 2024), Annual average daily traffic (Trafikverket, 2025; Göteborgs Stad, 2017).

Table A3

Annual water discharge in Göta älv, its tributaries, combined sewer overflow and Ryaverket WWTP.

Input source	Discharge (Q) [m^3/year]
Ryaverket	134137899
CSOs	1567891
Göta älv	6189671710
Kvillebäcken	9460800
Säveån	630720000
Mölndalsån	68433120
Göta älv US	5345352000

Sources: Ryaverket (Gryaab, 2025), CSOs (J. Brunsten, personal communication, February 4, 2026), Kvillebäcken (Exploateringsförvaltningen. 2025), Säveån (Miljöförvaltningen, 2025c), Mölndalsån (Miljöförvaltningen, 2025c), Göta älv US (Miljöförvaltningen, 2025b).

Table A4

GREAT-ER Calculations - Pollutant Variables.

Variable	H-L Const	$t_{1/2,d}$ [h]	Θ [-]
Pollutant			
PFOS	4.34E-08	359160	NA
TBT	2.07E-07	5880	NA
Trichloroethylene	0.00902	NA	0.617
Benzene	0.00556	NA	0.638
Benzo[a]pyrene	4.57E-08	552	NA
Cu	NA	NA	NA
Zn	NA	NA	NA
Cr	NA	NA	NA
As	NA	NA	NA
Pb	NA	NA	NA
Cd	NA	NA	NA
Hg	4.84E-07	NA	NA
Ni	NA	NA	NA

Sources: H-L Const (NCBI, 2026), $t_{1/2,d}$ (NCBI, 2026), Θ (USGS, 1998).

Table A5

GREAT-ER Calculations - River segment characteristics.

River segment	Length (L) [m]	Depth (Y) [m]	Flow velocity (U) [m/s]
L_{L-S}	4800	7	0.35
L_{S-M}	2800	7	0.35
$L_{M-\ddot{A}}$	4200	7	0.35

Sources: Length (Länsstyrelsen 2023a; Länsstyrelsen 2023b), Depth (Sjöfartsverket, 2024), Flow velocity (Tyréns, 2016).

Table A6

Run-off pollutant concentration (C_{run}) per land-use and road type [μg/l] (StormTac Database, 2026).

Land-use & road types / **Pollutant**	Urban high density	Industrial	Urban low density	Block urban	Forest coniferous	Forest deciduous	Water inland	Open land	Paved open space	Expressway	Expressway tunnel	Primary road	Primary road heavy traffic	Primary road light heavy traffic	Local street
PFOS	0.018	0.0075	0.012	0.024	0.0075	0.0075	0.0058	0.0075	0.0075	0.013	0.013	0.013	0.013	0.013	0.013
TBT	0.002	0.2	0.002	0.064	0.002	0.002	0	0.002	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016
Benzene	0.09	0.1	0.09	0.09	0.09	0.09	0	0.09	0.09	4	4	4	4	4	4
Benzo[a]pyrene	0.05	0.15	0.05	0.1	0.01	0.01	0.0035	0.01	0.01	0.42	0.42	0.13	0.17	0.13	0.073
Cu	30	42	20	32	9	9	2.3	10	15	97	97	32	40	32	19
Zn	100	240	80	160	25	25	23	28	23	610	610	140	200	140	46
Cr	12	14	5.8	5	5	5	0.42	2.5	7	40	40	20	22	20	16
As	3	4	3	2.4	3	3	0.3	4	2.4	3.9	3.9	3.9	3.9	3.9	3.9
Pb	15	20	12	18	6	6	4	6	6	46	46	14	18	14	7.7
Cd	0.7	1.5	0.5	1	0.2	0.2	0.09	0.3	0.027	0.65	0.65	0.47	0.5	0.47	0.44
Hg	0.025	0.07	0.015	0.05	0.01	0.01	0.017	0.013	0.05	0.14	0.14	0.091	0.097	0.091	0.082
Ni	9	16	6	8.5	6.3	6.3	0.6	1.3	4	24	24	11	13	11	8.5

Table A7

Baseflow pollutant concentration (C_{base})per land-use and road type [μg/l] (StormTac Database, 2026).

Land-use & road types	Urban high density	Industrial	Urban low density	Block urban	Forest coniferous	Forest deciduous	Water inland	Open land	Paved open space	Expressway	Expressway tunnel	Primary road	Primary road heavy traffic	Primary road light heavy traffic	Local street
Pollutant															
PFOS	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
TBT	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012
Benzene	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
Benzo[a]pyrene	0.0083	0.025	0.0083	0.017	0.001	0.001	0	0.001	0.17	0.0042	0.0042	0.0042	0.0042	0.0042	0.0042
Cu	8.3	12	5.5	8	3.5	3.5	0	6.7	5	13	13	13	13	13	13
Zn	33	90	27	47	10	10	0	14	10	55	55	55	55	55	55
Cr	2	2.3	0.66	0.83	0.4	0.4	0	1	0.5	1.8	1.8	1.8	1.8	1.8	1.8
As	0.23	0.23	0.23	0.23	0.23	0.23	0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Pb	1.8	3.6	1.2	2.4	0.35	0.35	0	0.76	0.5	3	3	3	3	3	3
Cd	0.064	0.1	0.045	0.091	0.02	0.02	0	0.036	0.025	0.034	0.034	0.034	0.034	0.034	0.034
Hg	0.01	0.028	0.006	0.02	0.004	0.004	0	0.006	0.002	0.032	0.032	0.032	0.032	0.032	0.032
Ni	4.9	8.7	3.2	4.6	0.5	0.5	0	1	1	5.4	5.4	5.4	5.4	5.4	5.4

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF ENVIRONMENTAL SYSTEMS ANALYSIS
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se

CHALMERS
UNIVERSITY OF TECHNOLOGY