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Modelling the risk of rainfall events leading to momentary pollution levels exceeding maximum allowed concentrations

A Swedish case study of urban runoff in the Fyris river

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Civilingenjörsprogrammet i miljö- och vattenteknik

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Abstract

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The purpose of this study was (1) to study the proportion (X) of the flow in a watercourse that consists of urban runoff during a rain event and (2) to evaluate the risk that a few chosen pollutants, transported by urban runoff, exceed the maximum allowed concentration in the watercourse according to the environmental quality standards (MAC-EQS). The Fyris river in Uppsala, Sweden, was selected as a case study.

Urban runoff quickflow was estimated with a water balance model using precipitation data and flow data from three stations. Precipitation data was used to identify 31 rain events with a minimum rain volume of 10 mm and at least a maximum rain intensity of three mm/h during the study period 2017-2020. Pollutants in urban runoff were sampled during the winter of 2020-2021. The highest concentrations obtained during sampling were used to estimate momentary pollution concentration and to evaluate the risk of exceeding MAC-EQS.

The highest X found during a rain event was 71%. Low flow conditions in the river prior to a rain event in summertime are circumstances when X can be expected to be high. It is therefore advised to include rain events under such circumstances when monitoring MAC-EQS or sampling momentary pollution concentrations in the Fyris river.

The pollutant category polycyclic aromatic hydrocarbons (PAH), and especially the pollutant fluoranthene, showed risk of momentary pollution concentration exceeding MAC-EQS. The highest risk was observed in the Luthagen catchment area. Therefore, the author recommends that mitigation measures for urban runoff should be considered and include PAHs.

Keywords: urban runoff, flow, rain event, pollution concentration, EQS, MAC-EQS
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Referat

Modellering av risken att regntillfällen leder till tillfälliga föroreningskoncentrationer som överskriver maximala tillåtna koncentrationer - En svensk fallstudie av dagvatten i Fyrisån
Tove Gannholm Johansson

Syftet med denna studie var (1) att studera hur stor andel (X) av flödet i ett vattendrag som utgörs av dagvatten vid ett regntillfälle, och (2) att utvärdera risken att ett utvalt antal föroreningar som transporteras med dagvattnet överskrider maximal tillåten koncentration enligt miljökvalitetsnormerna för vatten (MAC-MKN). Fyrisån i Uppsala, Sverige, valdes som fallstudie.

Snabbt dagvattenflöde (quickflow) uppskattades med en vattenbalansmodell som använde nederbördsdata samt vattenföring från tre stationer. Nederbördsdata användes för att identifiera 31 regntillfällen med en minsta regnvolym på 10 mm och minst en maximal regnintensitet på tre mm/h under perioden 2017-2020. Föroreningar i dagvatten provtogs under vintern 2020-2021. De högsta koncentrationerna som påträffades vid provtagningen användes för att uppskatta momentan föroreningskoncentration och för att utvärdera risken att MAC-MKN överskrids.

Det högsta X som beräknades under ett regntillfälle var 71%. Lågt flöde i Fyrisån innan ett regntillfälle under sommartid är omständigheter när X kan förväntas vara högt. Det rekommenderas därför att inkludera regntillfällen under sådana omständigheter när MAC-MKN övervakas eller när momentana föroreningskoncentrationer i Fyrisån provtas.

Föroreningskategorin polycykliska aromatiska kolväten (PAH), och särskilt föroreningen fluoranten, uppvisade risker för att MAC-MKN skulle överskridas. Den högsta risken identifierades för avrinningsområdet Luthagen. Därför rekommenderas att reningsåtgärder för dagvatten bör övervägas och inkludera avskiljning av PAH:er.

Nyckelord: dagvatten, flöde, regntillfälle, föroreningskoncentration, MKN, MAC-MKN
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Populärvetenskaplig sammanfattning

Våra vattendrag är viktiga eftersom de bidrar med betydelsefulla ekosystemtjänster såsom dricksvatten, biologisk mångfald, livsmiljöer för många vatten- och landlevande organismer samt rekreation. Tyvärr är många vattendrag känsliga för föroreningar som bland annat transporteras från städer och försämrar vattenkvaliteten. För att skydda våra vatten mot dålig vattenkvalitet finns lagstiftning som bland annat innehåller gränsvärden för vilka föroreningskoncentrationer som får finnas i ett vattendrag (miljökvalitetsnormer). Dessa gränsvärden finns både som årsmedelvärden och som maximal tillåten koncentration.

När det regnar i en stadsmiljö rinner vatten av från ytor och tar med sig smuts och föroreningar ner i vattendrag. Denna avrinning kallas dagvatten. Idag används oftast årsmedelvärden av föroreningars koncentrationer för att utvärdera dagvattnets påverkan på vattendrag, till exempel vid exploatering av ett nytt bostadsområde. Dagvatten tillkommer dock inte jämnt fördelat över året utan i tillfälliga pulser när det regnar eller när snö smälter. Därför kan det skapas kortvariga, höga föroreningskoncentrationer i ett vattendrag. Det finns idag förhållandevis lite kunskap om sådana föroreningstoppar i vattendrag eftersom det är kostsamt och tidskrävande att provta och analysera många vattenprover.

För att försöka uppskatta dessa tillfälliga toppar av föroreningskoncentration i ett vattendrag, undersöker denna studie om det finns ett användbart samband mellan regntillfälle och andelen dagvatten i ett vattendrag. En vattenbalansmodell användes tillsammans med nederbörds- och flödesdata från Fyrisån i Uppsala 2017-2020. Den största andelen dagvatten som hittades i studien var 71%. Andelen dagvatten kan antas vara hög när det är lågt flöde inför ett regn i Fyrisån under sommartid. Därför rekommenderas att övervakning av gränsvärden och provtagning sker just under sommartid när det är lågt flöde i Fyrisån.

Studien undersökte också risken för att miljökvalitetsnormer skulle överskridas av tillfälliga föroreningstoppar under regntillfällen. Provtagning av dagvatten genomfördes under vintern 2020-2021. Studien visade på att det fanns en risk att de organiska föroreningarna polycykliska aromatiska kolväten, PAH:er, och särskilt föroreningen fluoranten, kan överskrida miljökvalitetsnormerna. Störst risk identifierades i avrinningsområdet för Luthagen. Därför rekommenderas att dagvattenåtgärder bör övervägas och inkludera avskiljning av PAH:er.

Det kvarstår emellertid många frågor kring föroreningskoncentrationen i ett vattendrag vid ett regntillfälle och mer forskning behövs för att hitta ett användbart samband som kan förutsäga tillfälliga föroreningskoncentrationer i vattendrag.

Preface

This work was written as a 30 credit master thesis, concluding the Master of Science program in Water and Environmental Engineering at Uppsala University and the Swedish University of Agricultural Sciences. The project was initiated by WRS and supervised by Hannes Öckerman from WRS. The subject reader was Thomas Grabs, Senior lecturer/Associate Professor at the Department of Earth Sciences, Program for Air, Water and Landscape Sciences; Hydrology at Uppsala University.

I would like to thank the team at WRS for always being a source of inspiration and for providing equipment and data. A special thank you to my supervisor Hannes Öckerman and subject reader Thomas Grabs for interesting and helpful discussions.

A big thank you to Jenny Näslund at WRS for organising the sampling and to my master thesis colleague Matilda Ahlström, who's cheerfulness got us through those rainy days of sampling.

I would lastly like to express my gratitude to friends and family who have encouraged me and believed in my capabilities to undertake this project.

Tove Gannholm Johansson
Uppsala, June 2021

Definitions

’young’ water Water from a recent rain event

ADWP Antecedant dry weather period. The period before a rain event with no precipitation

baseflow Flow caused by processes which mobilize deliver water slowly to a watercourse

duration The time duration of a rain event

EQS Environmental Quality Standard

first flush effect The initial runoff during a rain event which has the potential to transport a large part of the total pollution load

fraction In what form the substance can be found. For example particulate

HaV The Swedish Agency for Marine and Water Management

hydrograph Graph of flow over time

hydrograph separation Method for separating the hydrograph into quickflow and baseflow. Can be graphical or tracer-based

landuse The main characteristics of an area. For example forest or residential area

MAC-EQS Maximum Allowed Concentration Environmental Quality Standard

PAH Polycyclic Aromatic Hydrocarbon. A group of pollutants

precipitation Rain and snow

Q Water flow

quickflow Flow caused by processes which mobilize water quickly to a watercourse

rain depth The rain volume referred to as a depth [mm]

rain event An occasion when it rains. A definition used in this project for analysing purposes with certain conditions

rain intensity The rain depth during one hour [mm/h]

residence time How long a substance spends in a lake or reservoir

runoff coefficient Used to predict how much runoff is created from precipitation

SMHI The Swedish Meteorological and Hydrological Institute

urban runoff Runoff from rain or snowmelt in an urban area

water balance Mass balance for water

WFD Water Framework Directive

X The maximum proportion of urban runoff during a rain event

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1 Introduction

Watercourses are a valuable asset in today's society, providing us with essential ecosystem services such as drinking water, biodiversity, habitat for flora and fauna, as well as human recreation (HaV 2017). For all of these ecosystem services, a good water quality is vital. To ensure a good water quality, the Water Framework Directive (WFD) was adopted by EU in 2000 (2000/60/EC). In Sweden, the Swedish Agency for Marine and Water Management (HaV) is responsible for the Swedish implementation of the WFD and it has issued limits for pollution concentrations called Environmental Quality Standards (EQS). There are both limits for yearly average concentrations and maximum allowed concentrations (MAC-EQS) (HaV 2019).

Today, pollution of watercourses from urban runoff is often modelled as yearly average concentration. However, urban runoff primarily reaches watercourses during individual rain events. As the urban runoff arrives in pulses, the consequence is that the momentary effect on the watercourse might be considerably larger than the yearly average. Since random sampling of urban runoff does not give representative values and analysing many samples is expensive (Fölster et al. 2019) there is little knowledge on momentary pollutant concentrations in watercourses due to urban runoff. It is therefore valuable to examine whether momentary pollutant concentrations could be toxic to the aquatic environment and/or exceed the environmental quality standards for waters.

To increase knowledge of when high momentary pollutant concentrations occur, there is a need to study the impact of different rain events and flow situations in watercourses. Finding a way to estimate the momentary pollution in a watercourse can bring knowledge and possibly save money. Ideally, one way could be to reliably determine the proportion of urban runoff in the watercourse. Known urban runoff concentrations during rain events could then be used to estimate momentary pollution concentrations. The combined information of momentary proportions of urban runoff and momentary pollution concentrations in the watercourse, would allow to prioritise which future urban runoff mitigation measurements are needed.

1.1 Aim and Research Questions

The main aim of this report is to estimate momentary concentration of pollutants in the watercourse and evaluate if these risk exceeding MAC-EQS. To estimate the momentary pollutant concentration, a model is needed. Therefore, the second aim of this report is to create a model from flow and rain data, which can predict the proportion of flow in a watercourse originating from urban runoff, during different rain events. This model will then be combined with urban runoff concentrations sampled in this study. For this project, the river Fyris in Uppsala is used as a pilot study. To achieve the aim, the following questions were developed.

1. What proportion of the flow in the Fyris river is made up of urban runoff at a rain event?

2. Do momentary pollutant concentrations in the river risk exceeding MAC-EQS?

2 Background

In this section, background knowledge and the current research situation is presented. First, following the path of a raindrop from rain to flow, then water quality and the EQS for water, and last some hydrological modelling tools.

2.1 Urban hydrology and urban runoff

Runoff from rain or snowmelt in an urban area is called urban runoff. As an urban area develops, previously permeable natural surfaces are built on and made impervious, which changes the natural hydrology to urban hydrology (Swedish Water 2011). Urban hydrology is characterised by decreased infiltration and an increase in surface runoff, both in intensity and volume (ibid.), see Figure 1 for a simplified illustration. This can affect both the magnitude of water flow and pollution concentrations in receiving waters (ibid.). Pollutants can originate from for example roads, roofs or other urban surfaces.

The focus in urban runoff management and design in Sweden has historically been to avoiding floodrisks. However, designing systems for both flood and pollution mitigation has developed in the last few decades (Swedish Water 2004, 2011, 2016). Therefore, many urban areas lack the infrastructure needed to mitigate the environmental effects of urban hydrology, such as polluted runoff.

This study focuses on urban catchments in Uppsala in which few urban runoff mitigation measures, such as stormwater ponds, exist and the effects on the receiving water body could possibly be large. For more information on urban runoff management in Uppsala and good examples of urban runoff infrastructure, see Uppsala Vatten's reference manual (2014) and example collection (2014).

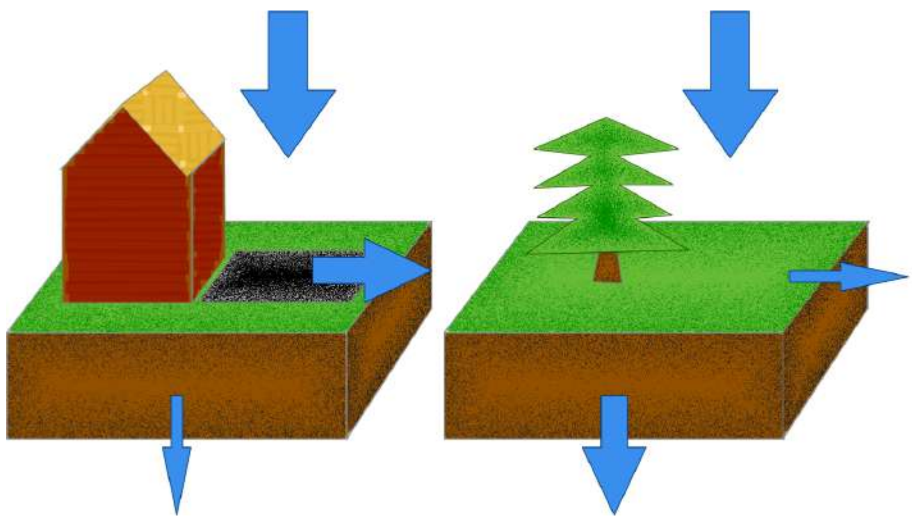


Figure 1: *Simplified illustration of urban hydrology compared to natural hydrology.*

2.2 Rain event

What is a rain event? The simple answer is when it is raining. However, rain events can vary both spatially and temporally, and in intensity and duration (Swedish Water 2011). Therefore, rain event as a term needs to be specified.

Rain or precipitation can be measured at stations using weighing buckets or tipping buckets (SMHI 2021a; Swedish Water 2011). They can be heated (Jansson 2021; SMHI 2021a) or contain defrosting chemicals (SMHI 2021a) to account for snowfall. The Swedish Meteorological and Hydrological Institute (SMHI) mostly uses weighing buckets while some municipalities use tipping buckets. The latter option is cheaper but can have uncertainties due to evaporation or loss of rain volume when the tipping buckets overflow during intense rains (ibid.).

There are other uncertainties associated with precipitation measurements (SMHI 2021a; Swedish Water 2011). Wind turbulence at the measuring station can affect the measurement and therefore a good placement of the station in a big open area is critical (SMHI 2021a). This is sometimes difficult in an urban setting with dense housing. Snow is problematic as it can clog the inlet to the measuring instrument if it is unheated (ibid.).

In water balance studies, the actual measured precipitation is often corrected using air temperature, wind speed, type of precipitation and type of measuring instrument but SMHI publishes uncorrected data (ibid.). A difference in volume is often found when comparing municipal tipping bucket data with SMHI station data but correcting data straight off with a statistical correction term is not recommended for high-resolution data (Swedish Water 2011). When analysing rain events for urban runoff purposes, high-resolution data is recommended as important information like rain intensity might otherwise be lost (ibid.). Rain is spatially unevenly distributed and there can be great variations even on a local scale (ibid.). Therefore, having a local network of measuring stations can be beneficial (ibid.). Measurements from several rain gauges can be distributed spatially over the study area in order to obtain representative data. If using an arithmetic mean, spatial information is lost in the process. Thiessen polygons on the other hand, also know as voronoi polygons, is a method which takes spatial information into account and which can be suitable for a relatively flat study area (Hendriks 2010).

Furthermore, data might need to be paired with temperature data and some knowledge of snow to distinguish rain events from snowfall and snowmelt in the measuring equipment. In contrast to rain, snow remains stored for extended periods, and accumulates pollutants over a longer time (Vijayan 2020). This indicates that urban runoff from snowmelt should be studied separately from rain events, to reliably estimate pollutant transport processes.

Moreover, rain event duration need to be established. To distinguish two separate rain events for analysis purpose, certain time must pass since the end of the last rain event. Previously used break durations have been between 2 and 36 hours, where 2 - 6 hours are normally used in rain data analyses in Sweden (Swedish Water 2011). Other studies or projects have used 6 h (Larm & Blecken 2019) and 12 h (Öckerman 2021). Rain events can also be classified according to total volume, intensity and duration (Swedish Water 2011). When the first raindrops fall on a dry surface, the rain wets the surface and fills up small pores and an initial rain volume does not create runoff (ibid.). Therefore, rain events with very low intensity or total rain volume might not produce much urban runoff, especially if there has been a longer time since the last wetting, the antecedent dry weather period (ADWP). So for urban runoff purposes, there is reason to set a minimum intensity or volume level for rain events being studied. Previously used limits are > 0.2 - 2 mm (Larm & Blecken 2019; Scherling, Svensson, & Sörelius 2020; Swedish Water 2011; Zgheib et al. 2011).

2.3 Hydrograph

A graph of flow (Q) over time is called a hydrograph (Hendriks 2010), see Figure 2. A hydrograph is often shown together with a hyetograph, precipitation over time, to visually illustrate the link between precipitation and flow. The flow can be divided into two different categories depending on the flow behaviour. Quickflow is caused by processes which mobilize water quickly to the watercourse, such as rapid soilwater throughflow, pipeflow or channel precipitation. While the afformentioned processes mobilize relatively 'young' water to the streams, quickflow can also be caused by processes such as the transmissitivity feedback that mobilize 'old' water. Such processes can be important for the runoff chemistry (Bishop et al. 2004). The other flow category is called baseflow. Baseflow is caused by processes which deliver water more slowly to the watercourse, continuously delivering water also during dry periods. Examples of such slow processes are slow soilwater throughflow and groundwater flow during dry periods (Hendriks 2010). In this study it is assumed that quickflow from urban areas is mostly associated with processes such as overland flow or pipeflow which deliver mostly 'young' water to the recipients.

A common hydrograph has some key characteristics. Before a rain event, there is baseflow recession (there is only baseflow and it is declining). When a rain event occurs, the flow increases until a peak flow (maximum quickflow) is reached. The flow then decreases until a separation point is reached, when there is again only baseflow recession.

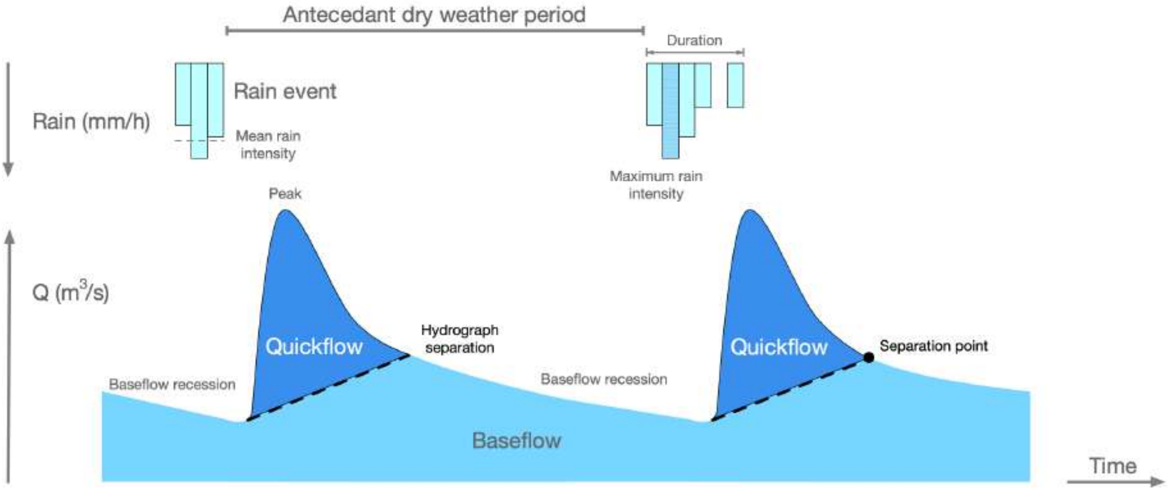


Figure 2: *Hydrograph.*

A study used a hydrograph to predict event based pollutants coming from urban catchments (Tao et al. 2019). They found it feasible that a hydrograph can predict event based pollutant loads to receiving waters (ibid.). The study suggests that once a yield function has been established for the catchment, rain data can be used to estimate pollutant load to receiving waters and therefore reducing the need to monitoring the pollutant load by sampling at each rain event (ibid.).

Both the hydrograph and the pollutograph, depicting pollutant concentration over time, depend on parameters such as rainfall intensity, ADWP, antecedent rainfall and the characteristics of the catchment (Bertrand-Krajewski, Chebbo, & Saget 1998).

2.4 Hydrograph separation

A hydrograph separation aims at separating the hydrograph into baseflow and quickflow. There are two types of hydrograph separation, graphical and tracer-based. A tracer-based method entails measuring some water quality parameter, for example conductivity (Hendriks 2010) or isotope composition (Grip & Rodhe 2016), in the watercourse and in sources and pairing this with a hydrograph, while a graphical method separates the hydrograph graphically, based only on the hydrograph. A tracer-based method would have been preferable for this study because it is process-based and it is used to trace the age and sources of the water. However, in the absence of tracer data, the choice fell on a graphical method, under the previously mentioned assumption, see previous section, that quickflow is assumed to be 'young' water delivered by pipeflow and overland flow.

There are several methods for graphical hydrograph separation and most are arbitrary (Hendriks 2010). The most important aspect when doing a graphical hydrograph separation is to use the same method consistently to make comparison possible (ibid.). Examples of graphical methods are the constant discharge method, the constant-slope separation point method and the concave curve separation point method (ibid.).

Lyne and Hollick (Lyne & Hollick) suggested using a digital filter for hydrograph separation. The Lyne and Hollick filter has later been standardised (Ladson et al. 2013). Advantages of using a standardised filter is that the result of the hydrograph separation is reproducible and comparable, and that suitable parameter values are suggested (ibid.). An example using the standardised Lyne and Hollick filter can be found on the author's website [1]. The parameters used in the standard filter are α, the number of values reflected at the start and end of the time series, and the number of passes back and forth (ibid.). The recommended α is 0.98 but 0.925 has been used historically (ibid.). α should be calibrated with tracers if possible (ibid.). The number of reflected days recommended is 30 (ibid.). The number of passes has to be uneven, with 3 passes being recommended for daily data resolution and 9 passes for hourly data resolution (ibid.).

2.5 Runoff coefficients

Runoff coefficients are used to predict how much runoff is created from precipitation. The higher the runoff coefficient, the more runoff is created. They can be site specific or based on landuse. Runoff coefficients are often higher for hardened surfaces than for natural landuse and there, agricultural land have higher runoff coefficients than forest (Swedish Water 2016). However, natural landuse can also have high runoff coefficients on occasion. At high rain intensities or big rain volumes, the ground can become saturated which means more runoff is created (ibid.).

The landuse based runoff coefficients provided by Swedish Water account for the degree of exploitation, impervious surfaces and the slope of the landscape (Swedish Water 2004, 2016). The stormwater model StormTac also provides data on runoff coefficients based on data from long time flow proportional sampling and urban runoff analysis (StormTac 2021).

A recent study in Stockholm found that standard runoff coefficients were larger than the runoff coefficients calculated in the study (Rennerfelt et al. 2020).

2.6 Urban runoff water quality

Summarising urban runoff water quality is difficult since the pollutant types are abundant, and there are numerous factors which can affect the presence of pollutants.

The most important pollutants in urban runoff are those which are usually found in an urban setting. They are common and/or persistent heavy metals or organic substances, often harmful to the environment. E. Eriksson et al. suggested 25 prioritised urban runoff pollutants to be included when evaluating risks from urban runoff (2007). Among the 25 pollutants were metals (Cd, Cr, Cu, Ni, Pb, Pt and Zn) and PAHs. This list of pollutants might have to be complemented with locally present pollutants. To study the presence of pollutants, a study of a Parisian suburb examined 88 pollutants(Zgheib et al. 2011). Of these, 45 were found in urban runoff (ibid.). A majority

[1](https://tonyladson.wordpress.com/2013/10/01/a-standard-approach-to-baseflow-separation-using-the-lyne-and-hollick-filter/)

of the pollutants found are monitored by the WFD but some are not included (Zgheib et al. 2011), for example PBCs, historically used in electrical applications.

Common urban runoff pollutants come in different fractions, where a standardised separation is made between the dissolved and the particulate fraction. The dissolved fraction consists of pollutants that remain when the analysed water is filtered through a 0.45 µm filter, and the particulate fraction cannot pass through the filter. Total concentrations refer to both fractions. The occurrence of pollutants in urban runoff can depend on which fraction is analysed (ibid.).

In a study from southeastern France, rain events were found to contribute with 90% of the annual output of particulate Cu, Zn, Cd and Pb and more than 60 % of the dissolved fraction (Nicolau, Lucas, et al. 2012). The study was carried out for rain events with a minimum total volume of 11 mm but with no clear definition of ADWP (ibid.). The correlation of parameters varied greatly between different rain events (ibid.). However, rainfall intensity, antecedent rainfall history and season were able to explain observed variations sufficiently (ibid.). Metals were mostly transported in the particulate fraction (ibid.).

The concentration in watercourses can vary greatly due to urban runoff pulses and therefore it is not possible to take representative random samples for urban runoff (Fölster et al. 2019). In other words, the pollution concentrations in watercourses can be different before and during a rain event. Additionally, a study from China found significant temporal and spatial variations in the pollutant wash-off process during the rain events (D. Li et al. 2015), i.e. two rain events can give different urban runoff concentrations and the concentration can differ for two catchment areas during the same rain event.

In the watercourse, point sources can contribute to an uneven pollutant distribution, in the water column depth and across the watercourse. This was for example seen in a study of micro plastics (Bondelind et al. 2020). The contribution of point sources at rain events can be visually seen in the change in water colour upstream and downstream of major urban runoff outlets in the Fyris river (Andersson 2021).

A study of an urban area river in France found alarming momentary metal concentrations (Nicolau, Galera-Cunha, & Lucas 2006). The study showed that low flow (baseflow) during non-rainy periods had low pollutant concentrations while heavy rains after dry periods, with high flow had higher pollutant concentrations (ibid.). Some metals were found in concentrations which can affect biota (ibid.). A seasonal dilution effect was seen for metals, where concentrations were lower during high flow periods (ibid.).

A case study in Uppsala found heavy metal concentrations in urban runoff decreased with a higher proportion of urban runoff baseflow (Karlsson & Öckerman 2016). The study found that concentrations of Pb, Cu and Zn greatly exceeded values in the Fyris river (ibid.). The study suggests the accumulation of heavy metals in the catchment area is important for the pollutant concentration at a certain rain event (ibid.), i.e. ADWP.

In brief, there are at least 25 pollutants which are highly relevant when studying urban runoff. The factors which affect their presence can be time related, location related, fraction related, and all of these relations can vary with pollutant.

2.7 First flush effect

Many studies refer to the so-called first flush effect. It is the initial runoff during a rain event which has the potential to transport a large part of the total pollution load. Both urban runoff event mean-concentrations and first-flush-40 (the first 40% of total runoff volume) have been found to correlate with maximum rain intensity, mean rain intensity, total rain volume and ADWP (D. Li et al. 2015). Another study uses the term first-flush-30, where it is said to be significant if 80% of the total pollutant mass is transported in this first flush (Bertrand-Krajewski, Chebbo, & Saget 1998). A study from France suggests this first flush is rare, however (ibid.).

Nevertheless, the same study found some first flush effects. In separate sewer systems (where stormwater is transported separately from the wastewater) 50% of the pollutant mass was transported in the first 38% of the total volume for 50% for the rain events, and 80% was transported in the first 74% (ibid.). The first flush depends on the site, pollutant, rain event and the sewer system (ibid.).

A study in Los Angeles found that particles showed a strong first flush effect where 40% of the particles were transported in the first 20% of the runoff volume (Y. Li et al. 2005).

2.8 Effects on biota

Several pollutants are potentially toxic to biota. In this context, the most common metals are Pb, Cd, Co, Cu, Cr, Hg, Ni, Ag, Sn, V and Zn (Naturvårdsverket 2008). They can for example damage the nerves, vital organs or cause reproductive issues ibid. Another pollutant type is PAH, which are carcinogenic organic substances ibid.

Because pollutants are often persistent, many can bioaccumulate, which means the pollutant can be found in greater concentrations in organisms compared to in the water. They can also biomagnify, meaning the concentration is higher in top-organisms such as predators. As a consequence, concentrations in the water which are not considered toxic can lead to toxic concentrations in biota over time.

Previously, the fraction of the total pollution concentration which could affect the biota was considered to be the dissolved fraction. However, today only a part of the dissolved fraction is considered potentially toxic to aquatic organisms and this fraction is referred to as the bioavailable fraction (HaV 2019).

Bioavailable concentrations should be calculated with an appropriate methods or models (HaV 2013). For Cu, Zn and Ni, the bioavailable concentration can be calculated using the biomet bioavailability tool which is a biotic ligand model (BLM) (Bio-met 2019). It uses total concentrations, DOC, pH and Ca as parameters (ibid.).

2.9 Environmental quality standards for water

The Water Framework Directive (WFD) 2000/60/EC exists to protect European waters (The European parliament and the Council of the European Union 2000). A goal of the WFD is that all surface waters should achieve at least good ecological status (GES), or good ecological potential, and good chemical status (GCS) (ibid.). The environmental quality standards (EQS) are a measurement tool to fulfil the goal of the WFD. An EQS is "the concentration of a particular pollutant or group of pollutants in water, sediment or biota which should not be exceeded in order to protect human health and the environment" (ibid.). The EQS for individual surface waters are defined based on how impacted the surface waters are by human activity, their ecological status, ecological potential, chemical status and a risk evaluation (HaV 2019).

The EQS for some common urban runoff pollutants for the Fyris river to achieve GES and GCS are presented in Table 1. Pollutants include some metals as well as two polycyclic aromatic hydrocarbons (PAH) for which the Fyris river do not achieve GCS; anthracene and fluoranthene (VISS n.d.). The EQS are given as annual average (AA) concentration and for some pollutants maximum allowed concentration (MAC) (HaV 2019). The EQS for the metals refer to the dissolved concentration and for Pb, Cu, Zn and Ni they refer to the bioavailable dissolved concentrations for the annual average concentration (ibid.). The EQS for Cd depends on the hardness of the water and is divided into 5 classes where the Fyris river falls into class 4 (VISS n.d.).

Table 1: *Common urban runoff pollutants and their respective EQS, annual average AA-EQS and maximum allowed concentration MAC-EQS (HaV 2019).*

Pollutant	**AA-EQS** [µg/L]	**MAC-EQS** [µg/L]
TotP		
Pb	1.2 bioavailable	14
Cu	0.5 bioavailable	
Zn	5.5 bioavailable	
Cd	0.15 (class 4)	0.9 (class 4)
Cr	3.4	
Ni	4 bioavailable	34
Anthracene	0.1	0.1
Fluoranthene	0.0063	0.12
BaP	0.00017	0.27

2.9.1 Swedish pollution concentration modelling practices

The informal Swedish practice for calculating and evaluating pollution concentrations from urban runoff generally does not take into consideration the risk of momentary pollution from rain events. Usually, the annual average pollutant concentrations and/or annual pollutant loads are calculated when evaluating the environmental impact of urban runoff. When modelling pollution concentrations, Swedish Water suggests looking at StormTac values for pollution concentrations (Swedish Water 2016) and the Stormtac database contain yearly average pollution concentrations, based on landuse type (StormTac 2021).

2.10 Hydrological modelling tools

Models can be more or less complicated, demanding and useful in terms of uncertainties and output. When choosing a model, pros and cons of models should be weighed against the purpose of the model and what is required to achieve this purpose. Model categories that were considered for this project include distributed models and lumped models.

Distributed models take spatial variation into account (Hendriks 2010). Examples of distributed models are MIKE and SWMM which have integrated powerful calculation tools and give spatial resolution. However, they require more input data and are hard to calibrate and validate. Consequently, the output from a distributed model might be uncertain if data is not sufficient.

Lumped models are spatially averaged (ibid.). For water flow, lumped models can be visualised as a bucket with inflow and outflow where the processes in the bucket cannot be distinguished. Lumped models usually require less data input and are therefore more manageable and often easier to calibrate and/or validate than distributed models. Therefore, the output of a lumped model can have less uncertainties than for a distributed model. On the other hand, lumped models do not provide any spatial resolution. Nonetheless, the spatially averaged output from a lumped model can still be satisfactory for the purpose of the project.

2.10.1 Water balance

A mass balance model is based on the law of conservation of mass and can be applied to water or pollution concentrations. The water balance entails all that inflows of water Q_{in} must equal all outflows Q_{out} plus the difference in storage $\Delta S/\Delta t$, see Equation 1 (Hendriks 2010). Put in a model frame, data on available inflows and outflows are input parameters and the output is the flow, in this case urban runoff contribution from a rain event.

$$\sum Q_{in} = \sum Q_{out} + \frac{\Delta S}{\Delta t} \tag{1}$$

When setting up a water balance, it is important to consider all possible flows and the storage difference (ibid.). The flows taken into consideration for a surface water in Hendriks's drainage basin hydrological system (2010) are discharge, channel precipitation, overland flow, flooding, evaporation, soil water throughflow and ground water flow and recharge, see Figure 3.

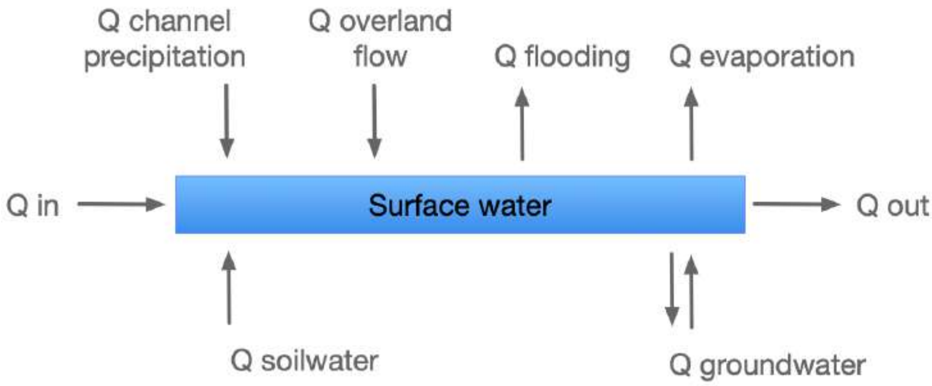


Figure 3: *The hydrological system of surface water, based on Hendriks (2010), as a water balance in a lumped model. The blue surface water can be visually represented as a bucket with inflows and outflows. Arrows pointing to the surface water are inflows and arrows pointing from the surface water are outflows.*

2.10.2 Concentration and mixing

A pollutant concentration can be calculated by the conservation of mass, see Equation 2. The mixing model used in this study assumes that the water body is mixed completely, and that mass is constant, i.e. no mass is added or removed by reactions or changes to particulate or dissolved fraction. This mixing model will be referred to as a conservative mixing model.

$$V_1 \cdot c_1 + V_2 \cdot c_2 = V_3 \cdot c_3 \tag{2}$$

However, the pollutant concentration in a river can vary between different parts of the water volume due to mixing. If water volumes do not mix, streaking can occur with big concentration gradients, see Figure 4. Downstream of waterfalls or weirs, there is often turbulent water. Turbulence increase mixing in the water column and it is common practice to assume complete mixing has occurred downstream of a fall or weir.

Stratification is likely to appear in slow moving water in deep lakes or reservoirs. Temperature differences between top layers of the water column in contact with the atmosphere, and deeper layers can cause stratification. Sweden has a dimictic stratification pattern were the entire water column mix in spring and in autumn and stratification is common in winter and in summer.

Figure 4: *Illustration of how complete mixing, streaking or stratification affect the concentration in a river.*

In a river, reactions or fraction changes might occur. Changes in water velocity and turbulence can cause particles to sediment or resuspend and water quality parameters such as pH or the chemical composition can affect solubility. If these processes are not in equilibrium, conservative mixing cannot be assumed.

2.10.3 Residence time

The residence time of a lake or reservoir describes how long time a substance or a water molecule on average spend in the lake or reservoir. The residence time (τ) can be calculated as the reservoir volume ($V_{reservoir}$) divided by the outflow (Q_{out}) (NE n.d.), see Equation 3. If τ is small, then the water in the reservoir is quickly replaced with new water.

$$\tau = \frac{V_{reservoir}}{Q_{out}} \tag{3}$$

3 Material and Methods

In this section, the study area, the data material and the methods used in this project are presented.

3.1 Description of Study Area

The Fyris river is located in Uppland in Sweden passes through the city of Uppsala, almost at the end of its course. The Fyris river has moderate ecological status according to the WFD (VISS n.d.) and is therefore sensitive to pollutants from urban runoff. The Fyris river drains a total catchment area of 2002 km^2 into lake Ekoln (Uppsala University 2021) which is part of lake Mälaren, a drinking water source for the city of Stockholm. Uppsala is the biggest city in the Fyris river catchment area with a population of 240 000 inhabitants. Uppsala has an annual total precipitation of 623 mm which is predicted to increase with 20 - 30% (SMHI 2015) to 2100. More extreme weather events due to climate change are also predicted (ibid.). The elevation ranges from 7 to 107 m.a.s.l. Forest and agriculture are the dominating land covers in the catchment. There is an esker that runs along the river Fyris and through the city. The Fyris river catchment area upstream of the study area can be seen in Figure 5

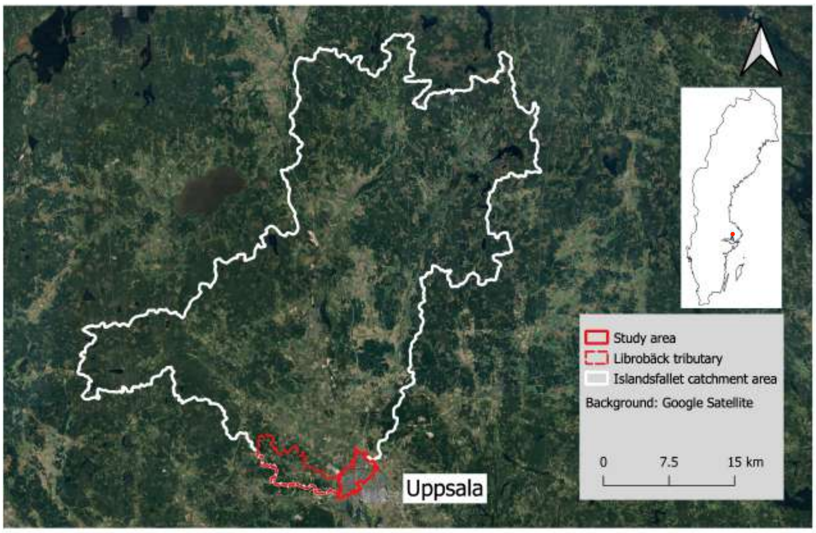


Figure 5: *The study area in red, and the Libroböck catchment area in dotted red line. The entire catchment area upstream of Islandsfallet in white. Small map of Sweden: Uppsala is located in eastern Sweden, red dot.*

In this study, the focus lies on a 3 km river stretch in the city of Uppsala, see Figure 6. The stretch starts as the river enters the urban area at Bärbyleden, (national road number 55). At Bärbyleden, water flow is being measured continuously since 2017 (Lennermark 2021). The stretch ends in central Uppsala at Islandsfallet, one of two falls in central Uppsala. At Islandsfallet, streamflow is also measured continuously (Uppsala University 2021). There are a number of urban runoff sewer system point outlets along the studied river stretch, accumulating 11.8 km^2 of urban catchment area. The river water surface area of this river reach is 60 000 m^2. The monthly average flow at Islandsfallet 2000-2020 varied between 17.3 and 2.2 m^3/s and can be seen in Figure 7. The flow typically peaks around April following snowmelt and is at its lowest during the summer month period, June to September.

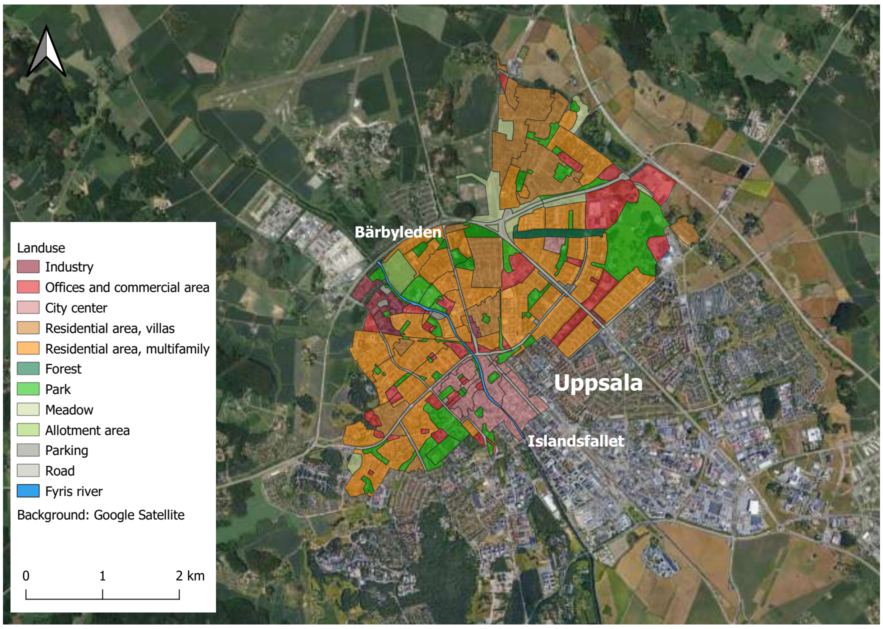


Figure 6: *The study area, colored according to landuse type.*

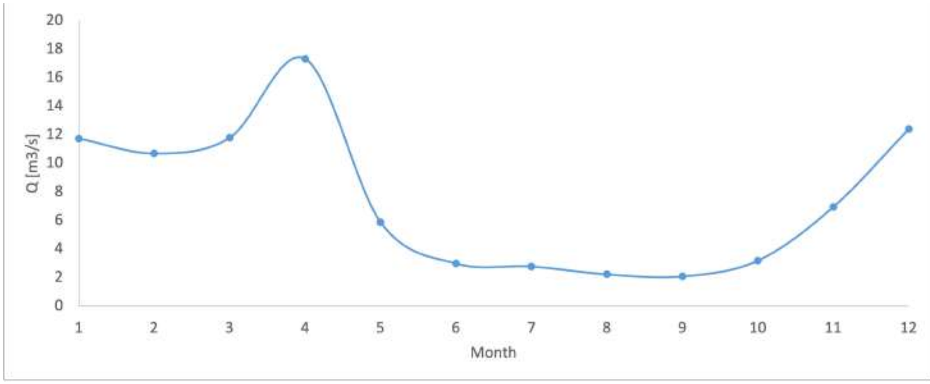


Figure 7: *The montly average flow at Islandsfallet 2000-2020.*

The landuse in the study area is dominated by residential area, see Figure 6 and A.4. The combined runoff coefficient for the study area is 0.40, using Stormtac's runoff coefficients (StormTac 2021).

The river reach in the study area is channelised. The section between Islandsfallet and Kvarnfallet has straight, reinforced sides while the section upstream of Kvarnfallet has sloped sides lined with trees, reed and other aquatic plants. See Figure A.6 for representative pictures of different river sections.

The maximum monthly mean potential evaporation in southern Sweden occurs in June and in 1961-1978 it was 130 mm (B. Eriksson 1981). This gives a maximum evaporation from the Fyris water surface of 0.003 m^3/s. In June, the water flow at Islandsfallet in 2017 and 2018 was never below 1 m^3/s. In total, this yields the maximum evaporation 3 ‰ of the water flow.

Upstream of Bärbyleden, the catchment consists of mainly natural rural landscape agricultural land and forests. There are also an airport, an industrial area and a smaller urban area with urban runoff outlets at the river just upstream the measuring station at Bärbyleden. Downstream of Bärbyleden, there are several urban runoff outlets from the separate stormwater sewer system. There are few treatment facilities such as stormwater ponds or sedimentation chambers in their catchment areas. In addition to this, the Librobäck tributary joins the Fyris river on the studied river stretch.

The flow from the Librobäck tributary is not continuously measured. However, there is another small river, the Stabby river, close to the study area, see Figure 8 where flow is measured continuously. The Librobäck catchment area was delineated using the free depression flow tool in SCALGO. The Stabby catchment area was obtained from the Swedish Water Archive (SVAR). The Librobäck catchment area is 26.56 km^2 and the Stabby catchment area is 6.18 km^2. The yearly average runoff in the region is 6 - 8 L/s ha (SMHI 2002). The landuse in the Librobäck tributary catchment area is dominated by agriculture and forest and the Stabby river catchment area is dominated by forest, see Figure C.3.

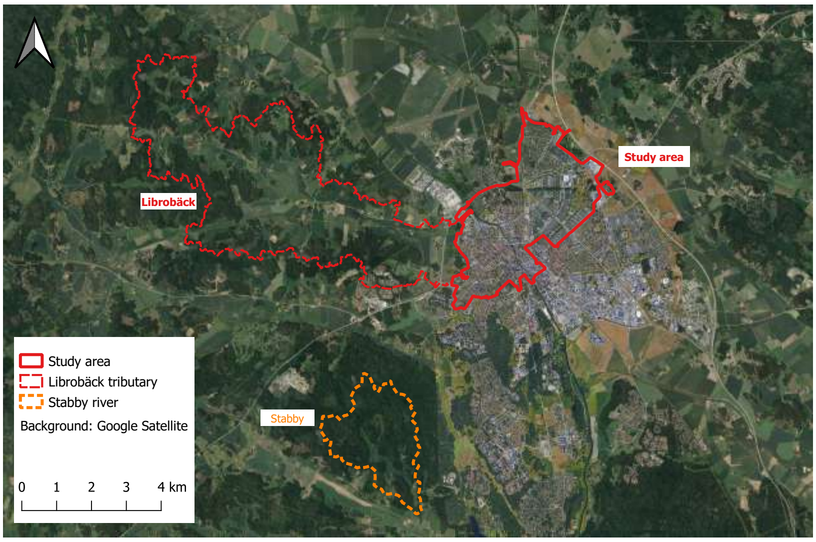


Figure 8: *The study area in red, and the Librobäck catchment area in dotted red line. The Stabby catchment area, in orange.*

The study area is almost exclusively affected by urban runoff while its upstream catchment is predominantly natural land cover. Flanked by two flow measurement stations, the river stretch makes for a suitable study area, see Figure 6.

In Uppsala, water quality parameters are monitored for the WFD by the Swedish University of Agricultural Sciences (SLU) (VISS 2019). There is one monitoring station upstream of the study area at Klastorp, see Figure B.1, and one downstream of the city (ibid.). The pollutants Pb, Cd and Ni are sampled 12 times a year (ibid.) according to a schedule. PAH pollutants are not sampled regularly (VISS 2019).

3.2 Data

Water flow data was obtained from Islandsfallet and Bärbyleden. The measurement at Islandsfallet is run by the Department of Earth Sciences, Program for Air, Water and Landscape sciences at Uppsala University in cooperation with the municipality of Uppsala and Uppsala Vatten (Uppsala University 2021). In summer, a threshold of 20 cm is added to the fall, see Figure 9, to ensure a certain water level upstream in the city, and the data has been corrected for this by Uppsala University (Herbert 2021). The station measures the water level which can be transformed into flow using a rating curve (ibid.). Data is recorded hourly (ibid.) and available at http://www.fyris-on-line.nu/.

(a) *Looking upstream.*

(b) *Looking downstream.*

Figure 9: *Extra threshold added to Islandsfallet in summer. (Photo: Roger Herbert)*

The monitoring of the Fyris river at Bärbyleden is run by SMHI. The monitoring started in 2017 and data is recorded every 15 minutes (Lennermark 2021). The measurement is done using the index technique as there is no deciding section (ibid.), see Figure 10d. The water level is measured using a ventilated pressure meter which is then converted to cross-section area (ibid.). Additionally, water velocity below the surface is measured using hydroacoustics (ADCP), see Figure 10a which is then transformed to mean water velocity (ibid.). The water flow is then calculated from the area and the mean water velocity (ibid.). Both the velocity measurement and the cross-sectiona area are continuously controlled and adjusted (ibid.), see Figure 10b and 10c.

(a) The hydroacoustic velocity meter submerged.

(b) Adjusting cross-section area.

(c) Controlling index station with ADCP boat.

(d) Looking downstream towards the index station.

Figure 10: *The index station at Bärbyleden. (Photo: Mikael Lennermark)*

A map of the technical catchment area in Uppsala was provided by WRS (Öckerman 2021), see Figure 6. It is based on Uppsala Vatten's stormwater pipe network and landuse types and it was used to delineate the study area.

Precipitation and air temperature data was obtained from SMHI (SMHI 2021b). Precipitation data was also obtained from Uppsala Vatten. The SMHI precipitation data is quality controlled (ibid.) while the Uppsala Vatten rain data is not quality controlled and might include substantial errors (Jansson 2021).

Flow data was also obtained from the Stabby river The monitoring of the Stabby river is run by SMHI. Data is recorded every 15 minutes. The measurement is done using a V-notch weir of 120° (Blomgren 2021), see Figure 11.

(a) Looking upstream. *(b) Looking downstream.*

Figure 11: *The V-notch weir used for measuring flow in the Stabby river. (Photo: Karin Blomgren)*

3.3 Methods

The method of the project consists of two main parts:

1. Estimating and modelling the proportion of urban runoff in the Fyris river during rain events.

2. Using the proportion of urban runoff in the Fyris river to estimate momentary pollution concentrations and evaluating the risk of these exceeding MAC-EQS.

3.3.1 Modelling the proportion of urban runoff

For this project, the availability of data, time limitations and the type of end usage lead to the choice of a lumped model based on a mass balance of water flow. This water balance model was made for the studied river stretch between Bärbyleden and Islandsfallet. Urban runoff was approximated by quickflow, assuming that quickflow from the urban study area is mostly associated with processes such as overland flow or pipeflow which deliver mostly 'young' water to the recipient.

The previously introduced surface water system, see Figure 3, was adjusted to accommodate for an urban setting with a high occurrence of impervious surfaces and and a conventional stormwater sewer system, see Figure 12. Slow soil water throughflow and overland flow were removed. Flow from tributaries and urban runoff baseflow, which also includes continuous industrial water discharge to the stormwater system, were added. Rapid soil water throughflow and overland flow were removed. Urban runoff quickflow caused by rain was added. Flooding is not included since the river is channelised and have high river banks, which makes flooding very rare. Also, the complexity of flow and pollution during flooding was not sought to be modelled within the boundaries of this project. Drinking water outtake and treated wastewater outlet were added as well as water added during lowflow periods to maintain a certain water level.

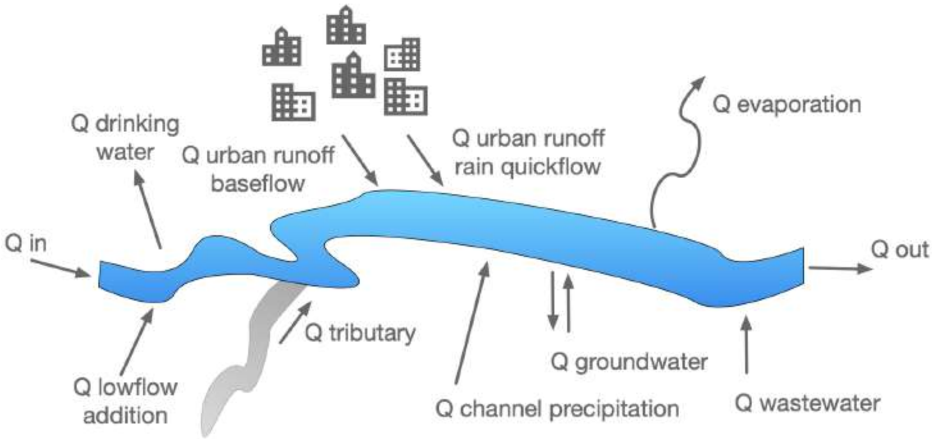


Figure 12: *The hydrological process considered for the water balance in this project. The blue watercourse can be visually represented as a bucket with inflows (arrows pointing to the watercourse) and outflows (arrows pointing away from the watercourse).*

All the flows in Figure 12 were considered for this project. Drinking water outtake and lowflow addition occur upstream of the selected study area (Beal 2021) and were therefore removed from the model. The wastewater treatment plant has its outlet downstream of the study area and removed as well. The maximum evaporation in the study area is negligible in comparison to the minimum flow at Islandsfallet so the evaporation was omitted. Because the city is located on top of a layer of relatively impermeable clay (Sidenvall 1970) and because the Fyris river is located on the valley bottom (which is typically a discharge area), the groundwater leakage from the river is thought to be low and was omitted too. For the hydrograph separation, groundwater flow and urban runoff baseflow were idealised as continuous baseflow components. The tributary Librobäck can contribute to quickflow from rainfall of high intensity or big volume but it will not contribute with water of urban runoff quality. It was therefore treated separatly to urban runoff quickflow. Lastly, direct channel precipitation could contribute to quickflow volume, especially at high rain intensities. Rain water contains fewer pollutants than urban runoff and was therefore treated separatly to urban runoff quickflow. Hence, the hydrological processes in Figure 12 were simplified into the water balance model for this project, see Figure 13.

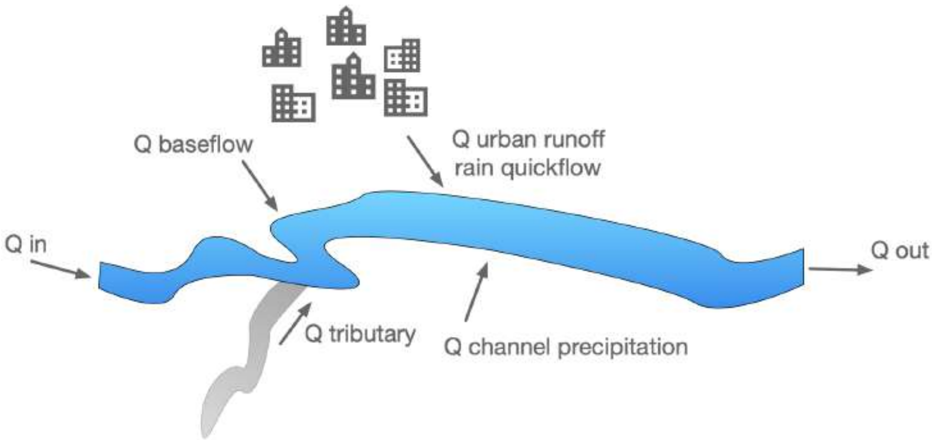


Figure 13: *The water balance model in this project.The blue watercourse can be visually represented as a bucket with inflows (arrows pointing to the watercourse) and outflows (arrows pointing away from the watercourse).* Q_{in} *is the flow at Bärbyleden and* Q_{out} *is the flow at Islandsfallet.*

Rain measurements from several raingauges were first intended to be spatially distributed over the study area using Thiessen polygons, see Figure 14, in order to obtain representative data for the studied area. This was deemed an appropriate method considering the data availability and the flat topography of the study area. However, when analysing the rain data, discrepancies in the Uppsala Vatten rain data were found. Moreover, the data differed considerably to data obtained from the SMHI rain gauges. For example there were long periods without precipitation in the Uppsala Vatten data. To avoid uncertainties, and to align with the method used in an other master thesis carried out simultaneously, only the SMHI measurements from Geocentrum were used, the station near the Department of Geosciences, Uppsala University. The Geocentrum station was selected as it was located closest to the study area and to Islandsfallet of the two SMHI stations.

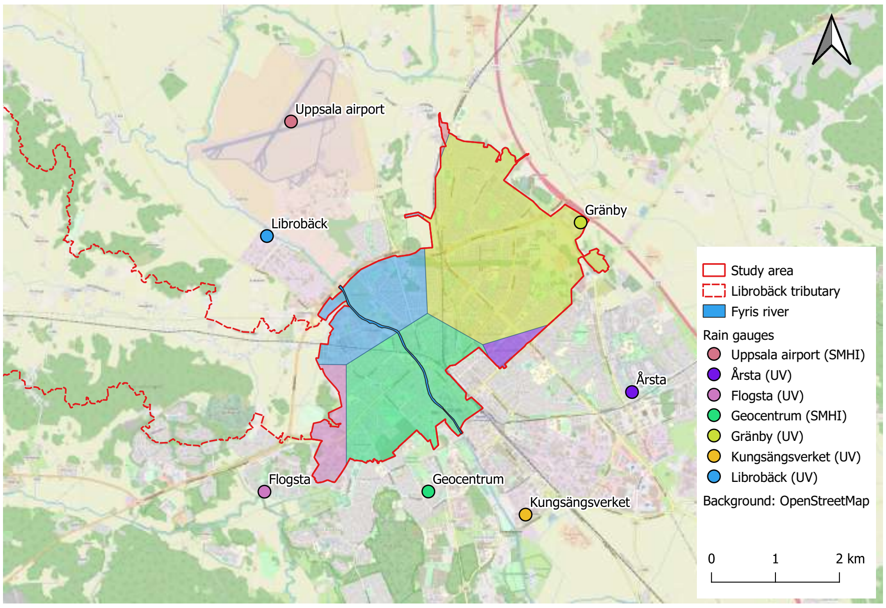


Figure 14: *The rain gauges close to the study area with their corresponding Thiessen polygons. The rain gauges are run by Uppsala Vatten (UV) and SMHI.*

In the first round of selection, potential rain events were identified with the criteria of a minimum total rain depth of 2 mm and a minimum of 6 h with no precipitation data between events. If there was a 5 hour gap, or less, in between precipitation, it was still considered to be the same event. Furthermore, rain events were identified to occur when the air temperature was above 0 °C and when the unheated raingauges at Libroбäck and Årsta were recording rainfall. Events that did not fulfil the above criteria were removed as they are possibly snowfall or snowmelt events.

Out of the 232 rain events that were identified, a second selection was done. The heaviest rains were chosen for further analyse because they were thought to incite detectable quickflow in the hydrograph, and produce the biggest proportion of urban runoff in the river. Therefore, based on the qualities of the 232 rain events, only rain events with a minimum total rain depth of 10 mm and a minimum maximum intensity of 3 mm/h were kept. 33 such rain events were identified. These will hereinafter be referred to as the rain events.

The urban runoff quickflow was estimated in several steps according to the water balance model, Figure 13. These steps are explained in the following paragraphs. To begin with, the flow contributed from the study area ($Q_{Studyarea}$) was obtained by subtracting the flow at Bärbyleden ($Q_{Bärbyleden}$) from the flow at Islandsfallet ($Q_{Islandsfallet}$), see Equation 4. This was done by adding a time delay (t_{delay}) to the flow at Bärbyleden, corresponding to the rising limb at Bärbyleden to reach Islandsfallet. The time delay was set individually for each year. The time delay was needed as the lumped model omits the transport processes within the "bucket". Any inflow or outflow should be perceived as instantaneous regardless of the actual access point. The time delay was selected through ocular trial and error of overlaying the flow curves. According to the water balance, Figure 13, this leaves the baseflow, tributary flow and channel precipitation to be estimated and substracted in order to have the urban runoff quickflow.

$$Q_{Studyarea}(t) = Q_{Islandsfallet}(t) - Q_{Bärbyleden}(t - t_{delay}) - Q_{Libroback}(t) - Q_{precipitation}(t) \tag{4}$$

The flow from the tributary Libroböck ($Q_{Libroböck}$) was estimated using flow data from a close-by monitored river, the Stabby river. The river dries out in summer, as does the tributary Libroböck. The specific flow of the Stabby river was calculated by dividing the flow with the catchment area. The Libroböck flow was then estimated by multiplying the specific flow with its catchment area. For more information about this estimation, see Appendix (C).

The channel precipitation $Q_{precipitation}$ was estimated as the rain intensity multiplied with the estimated area of the Fyris river (60 000 m^2).

The baseflow was obtained from hydrograph separation using the standard approach Lyne-Hollick filter (Ladson et al. 2013) in R. The parameters were set to α 0.98 with 30 reflected values and 3 passes. The number of passes recommended for hourly values, as in this study, is 9, but this was found to be unsuitable by visually inspecting the resulting baseflow. 3 passes is the recommended number of passes by Ladson et al. for daily values but was here found to give a satisfactory baseflow. The baseflow ($Q_{Baseflow}$) was then subtracted from $Q_{Studyarea}$ to obtain the urban runoff quickflow ($Q_{urbanrunoff}$), see Equation 5.

$$Q_{urbanrunoff}(t) = Q_{Studyarea}(t) - Q_{Baseflow}(t) \tag{5}$$

The proportion of urban runoff in the Fyris river at Islandsfallet (X) was calculated by dividing $Q_{urbanrunoff}$ with $Q_{Islandsfallet}$, see Equation 6.

$$X(t) = \frac{Q_{urbanrunoff}(t)}{Q_{Islandsfallet}(t)} \tag{6}$$

Data for different parameters were gathered for each the rain event, see Table 2. Data analyses were then performed in Excel and R. Correlation between parameters were examined using the non-parametric Spearman's rho test. Coupled parameters showing significants correlations were further considered for a linear regression model. X was also plotted against other parameters such as month, see Table 2, to analyse patterns not visible from the correlations analysis.

Table 2: *The parameters used for the study of X.*

Parameter	Definition
$Month$	Season of the rain event.
Airtemp.	Air temperature at the beginning of a rain event.
R_d	Total rain depth for the duration of the rain event.
I_{max}	Maximum rain intensity.
I_{mean}	Mean rain intensity for the duration of the rain event.
$Duration$	Duration of rain event.
$ADWP$	Antecedant dry weather period. Time since the last precipitation.
Q_{prior}	Q at Islandsfallet prior to a rain event.
Q_{ur}	Maximum urban runoff quickflow.
X	The maximum proportion of urban runoff for a rain event.

X, the proportion urban runoff quickflow of the total flow, was assumed to be representative of the volume proportion in the river. This would be the case if the river was free flowing. However, within the study area, the Fyris river has two weirs, Kvarnfallet in the middle of the study area, and Islandsfallet at the end of the study area, both creating water reservoirs upstreams each weir. The stored water in these reservoirs could have an impact on the proportion X.

To estimate if the above assumption was acceptable, the residence time (τ) was investigated in the reservoir created upstreams of Islandsfallet. As the water becomes turbulent directly after falling over the crest of Kvarnfallet, complete mixing was assumed to occur between Kvarnfallet and Islandsfallet. Urban runoff from 4% of the study area joins the Fyris river between Kvarnfallet and Islandsfallet so most of the urban runoff form the study area was assumed to joins the river upstream of Kvarnfallet. Using previous measurements of the reservoirs bottom and width (Persson, Loreth, & Johansson 2009), the average width was estimated as 21 m and the average depth below the weir crest as 0.97 m. The length was estimated to 385 m. The riversides in this section are vertical, so the width of the channel could be assumed constant with the water level. The water level at Islandsfallet is measured as height above the weir crest. Therefore, the total average water depth in the reservoir was calculated as the depth below the weir crest plus the water level. τ was calculated by dividing the reservoir volume by $Q_{Islandsfallet}$, see Equation 7.

$$\tau(t) = \frac{21\text{m} \cdot 385\text{m} \cdot (0.97\text{m} + waterlevel(t))}{Q_{Islandsfallet}(t)} \tag{7}$$

Lastly, to qualitatively estimate the uncertainty of the method, a runoff coefficient (φ) was calculated from the estimated $Q_{urbanrunoff}$. It was then compared to the runoff coefficient of 0.40 estimated with Stormtac. φ was only calculated for the rain event with the highest reliable X found in the project. φ was calculated by dividing the total urban runoff volume by the theoretical maximum volume, see Equation 8. The total urban runoff volume was estimated as an integral of $Q_{urbanrunoff}$. The theoretical maximum volume was estimated as the area of the study area ($A_{studyarea}$) multiplied by the rain depth.

$$\varphi = \frac{\int Q_{urbanrrunoff}(t)\, dt}{A_{studyarea} \cdot R_d} \tag{8}$$

3.3.2 Estimation of momentary pollution concentration

Not all pollutants which were sampled in the Fyrisån river have MAC-EQS, see Table 1. Thus, the parameters chosen to evaluate the risk of momentary pollution concentarations exceeding MAC-EQS were the metals Pb, Cd and Ni, and the PAHs anthracene, fluoranthene and BaP.

Urban runoff pollution concentrations were sampled over six months from november 2020 to April 2021 together with WRS and Matilda Ahlström. For the sampling procedure, see Appendix B. Pre-event concentration $c_{preevent}$ was sampled at Islandsfallet in between precipitation events on the 15th of February 2021. This concentration was considered unaffected by pollution from urban runoff quickflow. Urban runoff was sampled from two technical catchment areas within the study area. These were Luthagen and Svartbäcken, see Figure B.1. The study area landuse is mainly residential area. A more industry heavy landuse might give different a urban runoff water quality. Therefore, urban runoff from two industrial areas outside the study area was also sampled, Librobäck industrial area and Boländerna.

A conservative mixing model was used, see Equation 2, to calculate the maximum allowed concentration in the urban runoff (MAC_{ur}), see Equation 9. All the urban runoff quickflow was assumed to have the same concentration. The flow that was not urban runoff quickflow was assumed to have pre-event concentrations. Because a risk was being evaluated, a worst case scenario was applied. Thus, X was chosen as the highest reliable X found in this study. The concentration in the river was set equal to MAC-EQS ($c_{MAC-EQS}$).

$$MAC_{ur} = \frac{c_{MAC-EQS} - c_{preevent} \cdot (1 - X)}{X} \tag{9}$$

The MAC_{ur} were then compared to the highest urban runoff concentrations found during sampling. A risk was estimated based on how the sampled concentrations compared to the estimated MAC_{ur}. To visualise how they compared and to quantify risk, a set of risk definitions including a color scheme were created. See Table 3 for risk-definitions used.

Table 3: *Definitions of risk used for MAC-EQS evaluation.*

Risk	Definition
Exceeding MAC-EQS	Exceeding MAC_{ur}
High risk of exceeding MAC-EQS	>50% of MAC_{ur}
Moderate risk of exceeding MAC-EQS	>25% of MAC_{ur}
Low risk of exceeding MAC-EQS	<25% of MAC_{ur}

4 Results

In this section, the results from the project are presented in the same order as the research questions were presented in section 1.1.

4.1 Proportion of urban runoff

The rain events were evenly distributed in number and size over the study period 2017 to 2020, see Figure 15. All rain event parameters can be seen in more detail in Appendix E.

One rain event stood out in magnitude from the rest, however: the skyfall event of 2018-07-29. It caused media headlines especially for the inundation of the underpass at Uppsala train station but the river was never flooded. The rain event was included in the analysis.

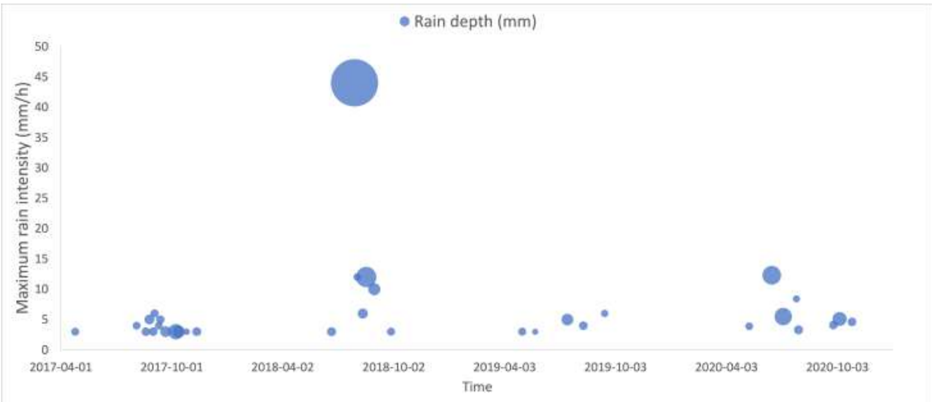


Figure 15: *The rain events analysed in this project during the years 2017 to 2020. The rain events had a minimum total rain volume of 10 mm and a minimum maximum intensity of 3 mm/h. The width of the blue bubbles are the rain depth. The minimum rain depth was 10.3 mm and the maximum was 77 mm.*

A good example of when the model worked as intended can found in the 2018-08-17 rain event, see Figure 16. The rising limbs of $Q_{Bärbyleden}$ and $Q_{Islandsfallet}$ start simultaneously at the start of the rain event and both have similar baseflow recessions. X for this event was 71%.

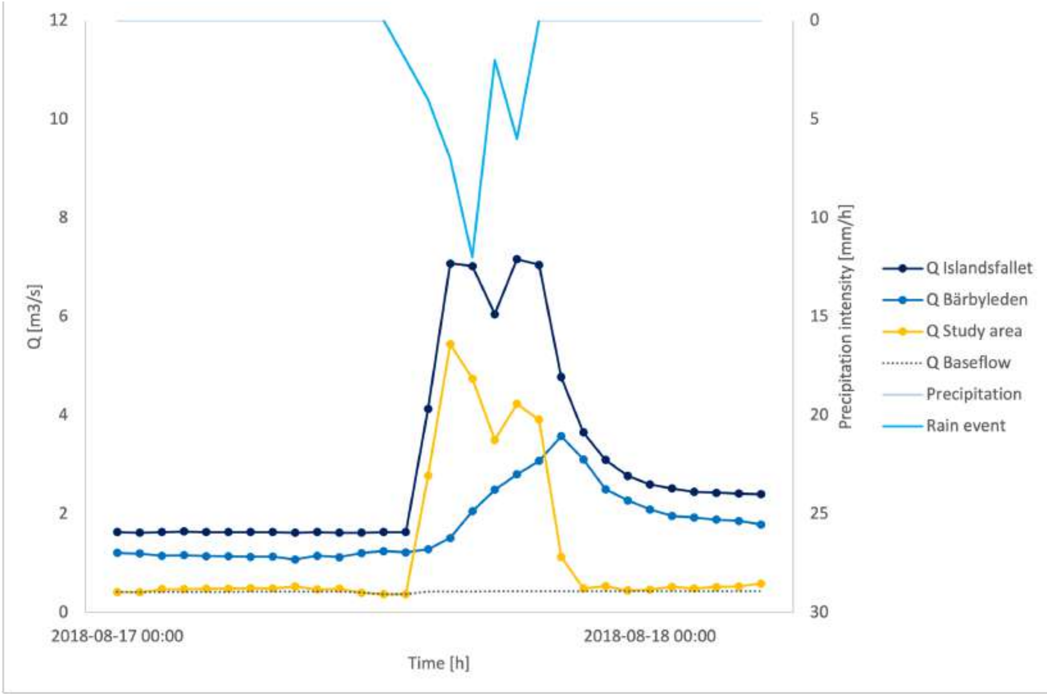


Figure 16: *The rain event starting 2018-08-17. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow. "Rain event" is the precipitation during a rain event and "Precipitation" is the precipitation when there is no rain event.*

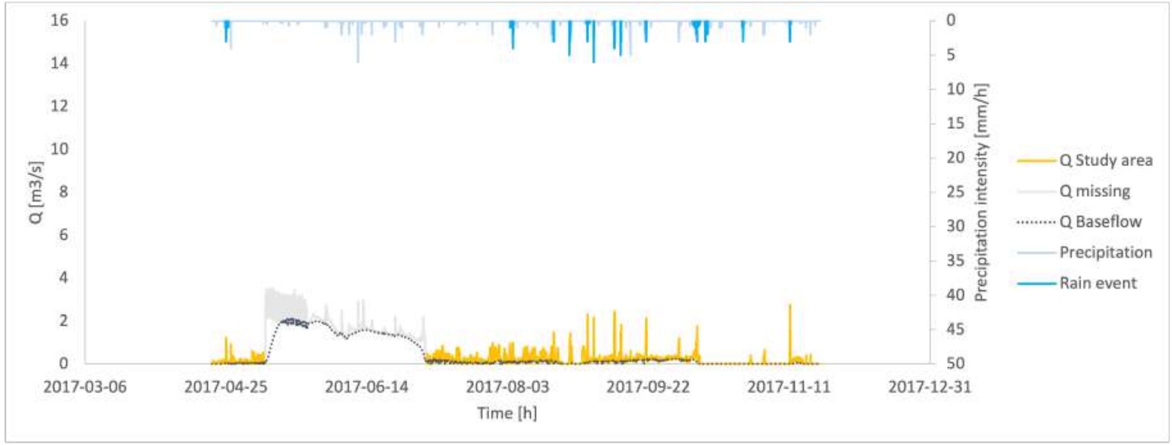
An overview of flow and precipitation of the four years included in the study years show how almost all rain events lead to peaks in $Q_{studyarea}$, see Figure 17. Two rain events in October 2017 did not show any study area flow contribution because $Q_{Bärbyleden}$ was greater than $Q_{Islandsfallet}$, see Figure E.11 and E.12. These two rain events were therefore excluded from further analysis.

During two periods, in 2017 and 2020, data from $Q_{Bärbyleden}$ was missing, see the grey lines "Q missing" in Figure 17. This did not coincide with any rain events in 2017 but it did coincide with three rain events in 2020, see Figure E.28, E.29 and E.30 for more detail. For these three rain events, $Q_{studyarea}$ can not be said to be only the study area contribution but the full upstream contribution. Nevertheless, the rain events were included in the analysis.

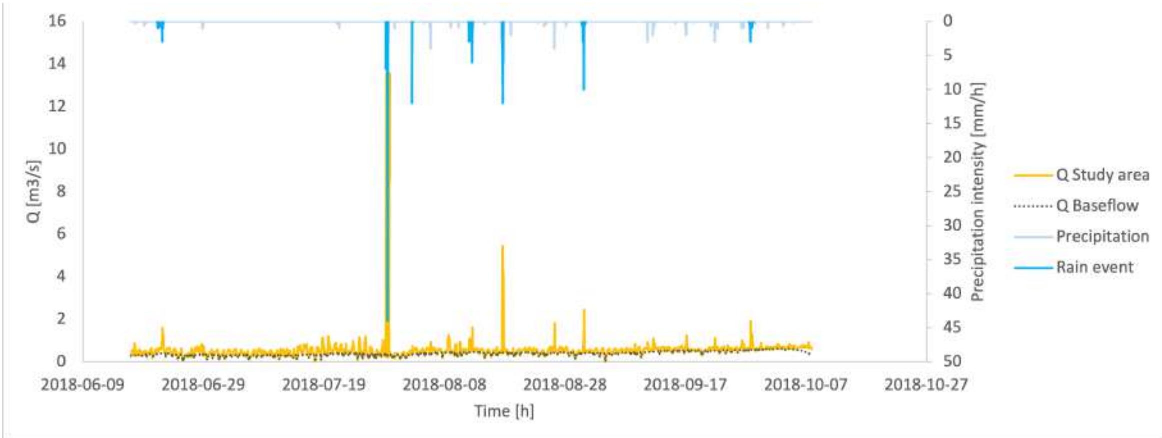
In summary, the total number of rain events used in further analysis is 31. The number of rain events each year can be found in Table 4.

Table 4: *Number of rain events in each year and the full study period.*

Period	Rain events
2017	11
2018	7
2019	5
2020	8
Full study period	31

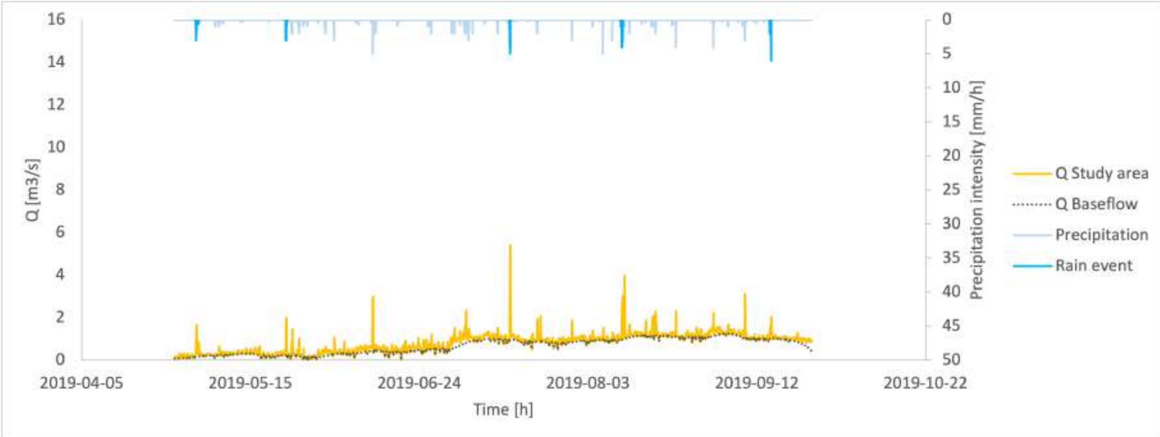


(a) 2017

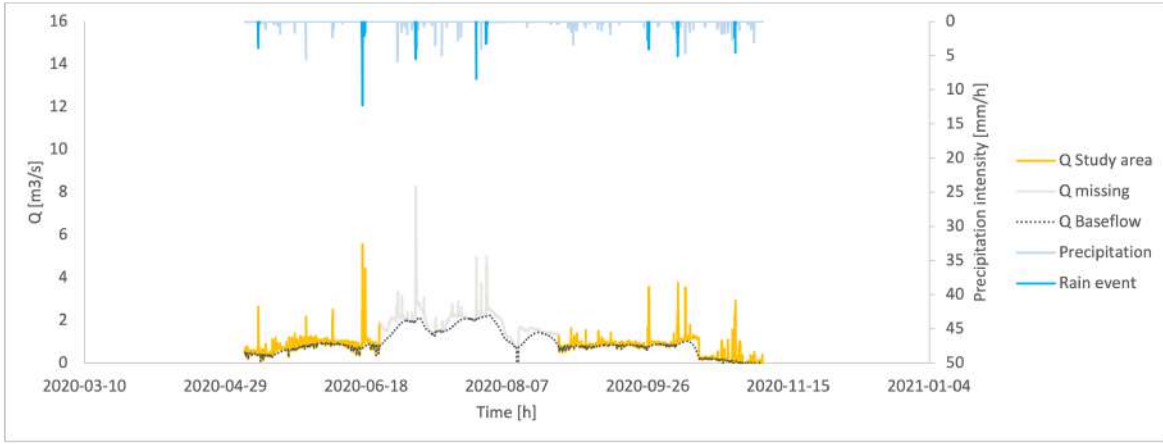


(b) 2018

Figure 17: *Estimated Q for the study area during the rain event months each year in the study period.*



(c) 2019



(d) 2020

Figure 17: *Estimated Q for the study area during the rain event months each year in the study period (cont.).*

The standard Lyne-Hollick baseflow separation filter (Ladson et al. 2013) was used for the study period. Each year was treated separatly. The difference in baseflow over a year is best shown in Figure 17c. The estimated baseflow follows the general outline of $Q_{studyarea}$, with the baseflow slowly increasing when $Q_{studyarea}$ increases. Some noice (quick fluctuations) in the baseflow can be seen when $Q_{studyarea}$ suddenly decreases. When studying the baseflow in more detail for each rain event, see Appendix E, the baseflow appears less noisy.

The time delay, t_{delay}, was chosen as 0 hours for all years. This choice was based on the fact that no suitable t_{delay} could be found for a full year. This is best exemplified by the 2017-08-09 rain event, see Figure E.3, where t_{delay} would first have needed to be positive and then negative to follow the general outline of $Q_{Islandsfallet}$. 70% of the rain events would have needed y to be negative. This can be seen in Appendix E when the rising limb in $Q_{Islandsfallet}$ starts before $Q_{\text{Bärbyleden}}$ shows a rising limb.

In 50% of the rain events, $Q_{\text{Bärbyleden}}$ dipped, decreased and then increased, when $Q_{Islandsfallet}$ was at its peak, see Figure E.6 for a clear example. Changing the time delay by one hour can greatly change the $Q_{studyarea}$ peak, and as a consequence change the maximum urban runoff quickflow Q_{ur}. For the rain event 2017-09-02, an increase in t_{delay} by one hour would have decreased Q_{ur} by approximately 30%.

The correlation analysis showed a significant, strong, negative correlation between Q_{prior} and the maximum proportion of urban runoff, X. There was also a significant, weak, positive correlation between air temperature and X. A correlation is considered significant if its p-value is <0.05 for a confidence level of 95%. See all the significant correlations for the parameters in Figure 18. In the figure, a red colour signals negative correlation and a blue colour positive correalation. A stronger (darker) colour implies a stronger correlation. The ellipse symbol is shaped narrower the stronger the correlation is and it is tilted in the direction of the correlation. All correlations and their respective p-values can be found in Appendix D.

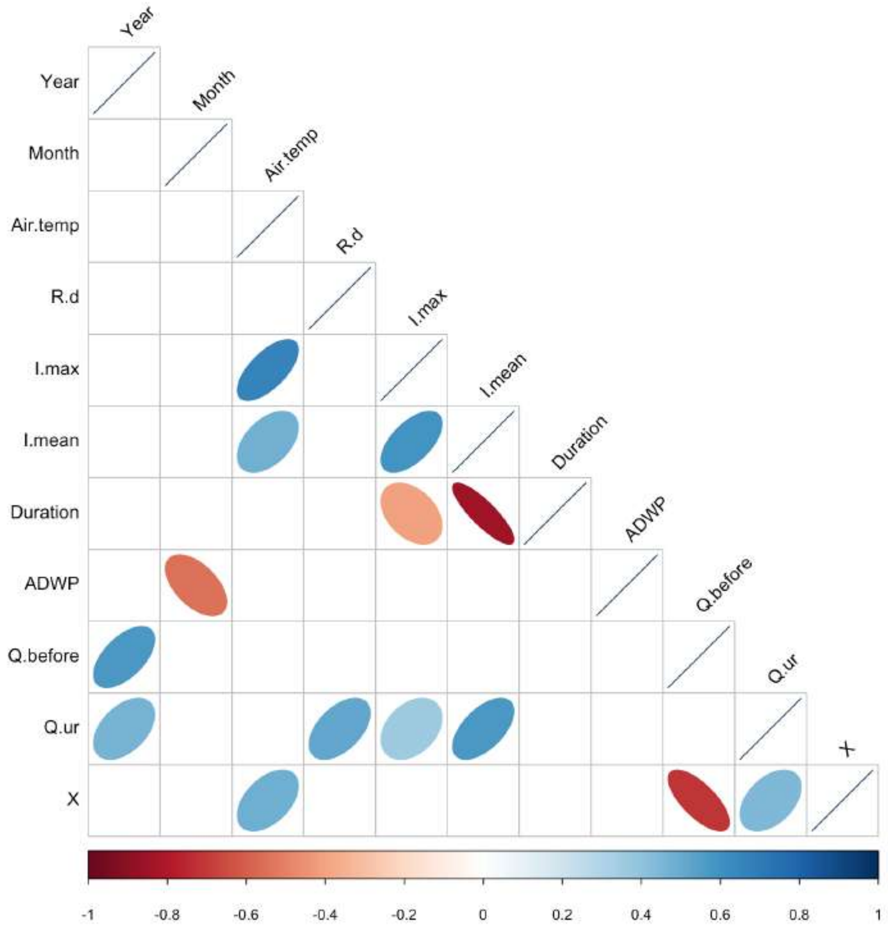


Figure 18: *The significant correlations for the parameters, indicated in color. The confidence level is 95%.*

The maximum proportion of urban runoff in the river during a rain event X seemed to decrease with a larger flow prior to a rain event, Q_{prior}, see Figure 19. However, no acceptable transformation, to obtain linearity, nor trend could be found.

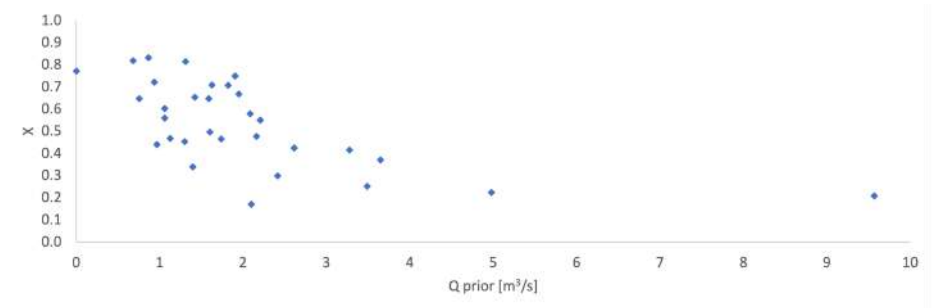


Figure 19: *The proportion of urban runoff X appears to decreased with Q_{prior}.*

X was increasing with air temperature before the rain event. This continued until the air temperature reached 20 °C, see Figure 20, when one data point deviated and gave a lower X.

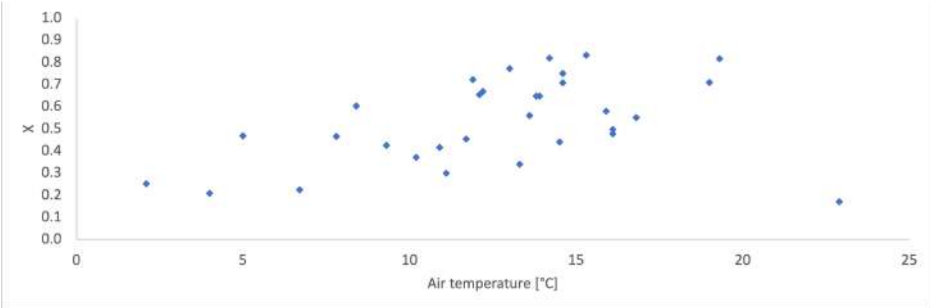


Figure 20: *The proportion of urban runoff X increased with air temperature.*

The parameter $Month$ did not show any significant correlation with X but when plotting X against month, a pattern of an upside down parabola could be distinguished, with X being higher in summer months, see Figure 21. When looking at individual years, the pattern is consistent, see Figure 22.

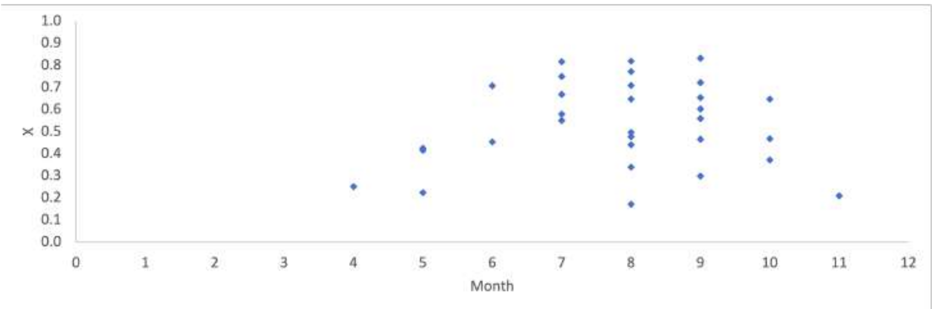


Figure 21: *The proportion of urban runoff X seemed to be higher during summer months.*

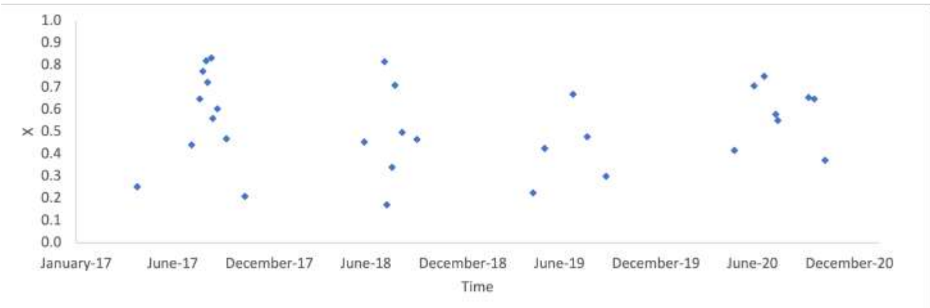


Figure 22: *The proportion of urban runoff X seemed to be higher during summer months.*

No other parameter showed significant correlation nor pattern with X. In summary, Q_{prior}, $Month$ and $Airtemp.$ showed a connection with X.

Furthermore, the correlation analysis showed that the total rain depth ,R_d, maximum rain intensity ,I_{max}, and mean rain intensity, I_{mean}. are weakly, but still significantly positively correlated with the maximum urban runoff quickflow Q_{ur} (confidence level 95%). Out of these, R_d showed a clear linear trend, see Figure 23. I_{mean} and I_{max} showed increasing patterns as well, but not as distinguished, see Figure D.2 and D.3. However, as already mentioned, these three parameters did not show any significant correlations or pattern with X.

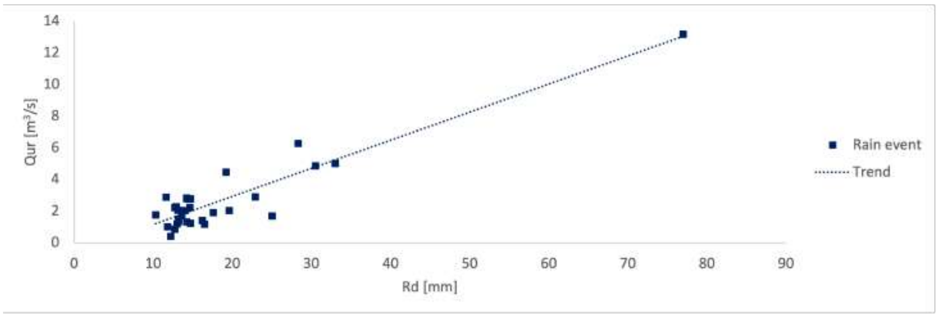


Figure 23: *Q_{ur} increased linearly with R_d. n = 31, R^2 = 0.86, y = 0.18x-0.62, p = $9e^{-14}$.*

The maximum urban runoff quickflow Q_{ur} was also significantly weakly positively correlated with year, see Figure 18, suggesting the maximum urban runoff quickflow for a rain event has increased during the study period. When removing the extreme event 2018-07-29 and rain events when $Q_{Bärbyleden}$ was missing, there was a positive trend, see Figure 24. The increase in Q_{ur} during the study period was 1.8 m^3/s. This is only true when accounting for the full study period. The majority of rain events in 2018 and 2019 have slightly lower Q_{ur} than the majority in 2017, while 2020 has sligtly higher Q_{ur} than 2017. Notice the difference in number of rain events each year, for instance 11 in 2017 and 5 in 2020.

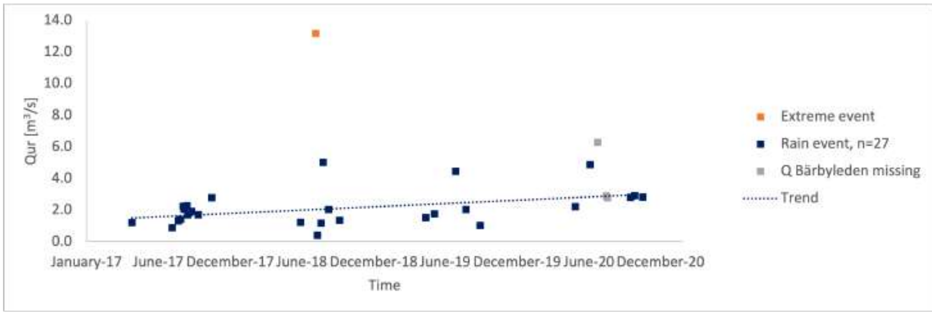


Figure 24: *The urban runoff quickflow Q_{ur} increase with time. n = 27, R^2 = 0.18, +0.44 $m^3/s/year$.*

For 65% of the rain events, the residence time τ was shorter than 1 hour. τ appeared to decrease with time, see Figure 25. Three rain events in 2017 had τ around 100 min.

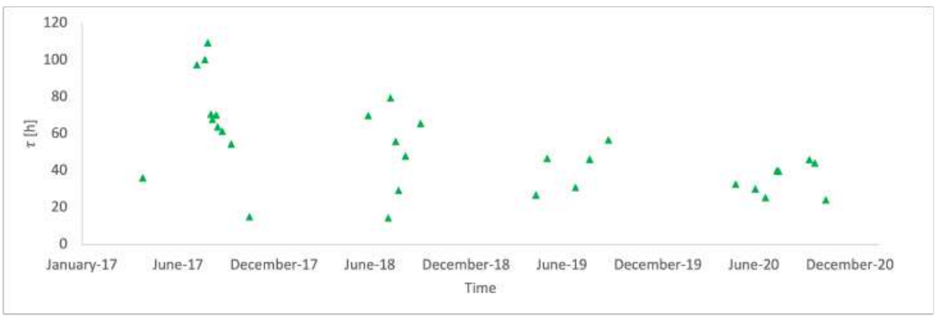


Figure 25: *The residence time τ.*

The maximum urban runoff quickflow, Q_{ur}, occured within one hour after the maximum rain intensity, I_{max}, in 87% of the rain events. At most the delay was five hours.

One rain event, 2018-07-17, had Q_{ur} the hour before I_{max}, see Figure 16. All parameters and τ can be seen in Appendix D.

The maximum proportion of urban runoff in the river, X, found in this study was 83% for the rain event 2017-09-09. However, this was one of the rain events where $Q_{Bärbyleden}$ "dipped". When excluding such rain events, the extreme skyfall event of 2018-07-29 as well as the rain events when $Q_{Bärbyleden}$ was missing, the maximum X was 71%, for the rain event 2018-08-17.

The runoff coefficient φ was estimated to 0.21 for the rain event 2018-08-17. This is lower than the 0.40 estimated by using Stormtac, although it is at the same end of the scale. The total urban runoff volume for this rain event was estimated to 82 000 m^3 and the theoretical maximum volume was estimated to 390 000 m^3.

4.2 Momentary pollution concentrations

The maximum proportion of urban runoff quickflow in the river,X, was chosen as 71% for the pollution concentration analysis. The pre-event concentrations at Islandsfallet were sampled on 2021-02-15 can be seen in Table 5. They were sampled during a period with low precipitation and low runoff. The PAHs (Anthracene, Fluoranthene and BaP) were all found to be below the detection limit. For these, the concentration is estimated as half the detection limit. The table also summarises the MAC-EQS for the pollutants used in the risk evaluation.

Table 5: *Concentrations sampled in between precipitation events 2021-02-15 at Islandsfallet and the MAC-EQS for the pollutants.*

Pollutant	**Concentration** [µg/L]	**MAC-EQS** [µg/L]
Pb	0.089	14
Cd	0.012	0.9
Ni	1.8	34
Anthracene	0.005	0.1
Fluoranthene	0.005	0.12
BaP	0.005	0.27

The maximum allowed concentration in the urban runoff, MAC_{ur}, calculated for each pollutant can be seen in Table 6. Since urban runoff is diluted with baseflow water in the river, MAC_{ur} can be of higher concentrations than the concentrations for environmental quality standards, MAC-EQS in Table 5.

The highest concentration obtained during sampling of urban runoff in the study area can be seen in Table 6. Sampling also took place in two industrial catchment areas outside of the study area and the highest concentrations from this sampling can be seen in Table 7. From the pollutant concentration analysis, it is clear that the pollutant concentrations can vary temporally, spatially and with pollutant, since no date, location nor pollutant presented the same result.

Of the metals (Pb, Cd, Ni), only Ni concentrations sampled in the urban runoff in the Libroback industrial area presented a moderate risk (yellow) of exceeding MAC-EQS. However, this sampling, 2021-02-22, took place during the main spring snowmelt event.

Of the PAHs (anthracene, fluoranthene, BaP), fluoranthene presented the highest risk. Fluoranthene exceeded MAC-EQS in both Luthagen and Boländerna (red) and presented a high risk (orange) or moderate risk in the other two catchment areas. Anthracene only presented a moderate risk in Boländerna while BaP presented a high risk in Luthagen and a moderate risk in Boländerna.

Table 6: *Esimated MAC in urban runoff with X being 71% and the highest concentration obtained within the study area during sampling as well as the date on which that sampling occured. Red means MAC-EQS is exceeded, orange means high risk, yellow means moderate risk and white means low risk of exceeding MAC-EQS.*

Pollutant	**MAC_{ur}** [µg/L]	**Luthagen** [µg/L]	**Date**	**Svartbäcken** [µg/L]	**Date**
Pb (dissolved)	20	0.061	2021-02-22	0.063	2021-04-12
Cd (dissolved)	1.3	0.044	2021-03-12	0.033	2021-03-12
Ni (dissolved)	47	2.6	2021-02-22	2.2	2020-11-21
Anthracene	0.14	<0.030	2021-01-21	0.011	2021-01-21
Fluoranthene	0.17	0.36	2021-01-21	0.15	2021-01-21
BaP	0.38	0.26	2021-01-21	0.045	2020-12-04

Table 7: *Esimated MAC in urban runoff with X being 71% and the highest concentration obtained in industrial areas outside the study area during sampling as well as the date on which that sampling occured. Red means MAC-EQS is exceeded, orange means high risk, yellow means moderate risk and white means low risk of exceeding MAC-EQS.*

Pollutant	**MAC_{ur}** [µg/L]	**Librobäck** [µg/L]	**Date**	**Boländerna** [µg/L]	**Date**
Pb (dissolved)	20	0.25	2021-04-12	0.4	2020-11-19
Cd (dissolved)	1.3	0.094	2021-03-12	0.31	2020-11-19
Ni (dissolved)	47	15	2021-02-22	2.2	2021-02-22
Anthracene	0.14	<0.010	All dates	0.036	2021-01-21
Fluoranthene	0.17	0.047	2021-04-12	0.31	2021-01-21
BaP	0.38	0.011	2021-03-12	0.15	2021-01-21

During the sampling occasions, streaks of urban runoff were clearly visible in the Fyris river, see Figure 26 for two example pictures. In other words, there was not complete mixing of urban runoff and river water for all rain events.

(a) 12th of March 2021 *(b) 22nd of April 2021*

Figure 26: *Streak of urban runoff in the Fyris river during two snowmelt and rain events in spring 2021. Both pictures are taken at the site where the Luthagen catchment area joins the Fyris river, see Figure B.1.*

On 2021-04-22, the urban runoff was sampled in the morning and the afternoon, making it possible to compare two temporally different samples of the same precipitation event. The water color of the urban runoff in the morning was visibly much darker than the water color in the afternoon, see Figure 27. This implies the first flush effect was present during this sampling occasion.

(a) Morning *(b) Afternoon*

Figure 27: *Water color difference in the morning and afternoon sampling of urban runoff on 2021-04-22. From left to right is Libroback industrial area, Luthagen and Svartbäcken.*

5 Discussion

In this section, the research questions are discussed in order. For each research question, the (i) associated methodology, (ii) results, future perspectives and recommendations are discussed. The latter are summarised in section 6.

5.1 Proportion of urban runoff

5.1.1 Methodology discussion

The model is not verified because of the few years available. The model should be verified with independent data for quality control.

Several flows were omitted from the model, including flooding, ground water recharge and evaporation. These flows should be measured for the model to be less uncertain.

The model is specific for the study area. The method and result might not be applicable elsewhere because of the many site specific conditions. To name one key condition, the requirement of two flow measurement stations.

The flow from the Librobäck tributary was estimated instead of measured. To check whether the Stabby river could be representative for the Librobäck tributary, flow, landuse and location were analysed. First, the average flow was compared to a proposed value. The average discharge in Stabby river during the study period was 7.7 L/s ha which correspond well to 6 - 8 L/s ha for the study area proposed by SMHI (2002). Furthermore, both the Stabby river and the Librobäck tributary are known to dry out in summertime. Secondly, the landuse of Stabby is dominated by forest, see Figure C.3, while the landuse in Librobäck is has both agricultural land and urban area as well as forest. The difference in landuse, and therefore different runoff coefficients, could mean some runoff dynamics are not captured by this approximation. Lastly, the Stabby river is located close enough to the Librobäck tributary see, Figure 8, to have a similar precipitation pattern but the difference in location means the exact rain dynamics, like volume and intensity, will probably vary and therefore the flow estimation might not reflect the temporal pattern or the magnitude of the real flow in the Librobäck tributary. In summary, the Stabby river can be used to estimate the flow in the Librobäck tributary for average flow dynamics, but for momentary flow dynamics, the estimation should be used with restraint. However, if the real flow from the Librobäck tributary is of the same scale as the esimated $Q_{Librobäck}$, see Figure C.4, then the quickflows from the tributary are quite small in summertime compared to the river flow at Islandsfallet and the estimation could therefore be considered acceptable. The flow in the Librobäck tributary should be measured, for example with tracer or ADCP to make the approximation less uncertain.

The method is highly sensitive to choice of time delay, t_{delay}, since increasing t_{delay} by one hour for rain event 2017-09-02 would have decreased Q_{ur} by 30%. t_{delay} was selected as 0 because both a positive and a negative t_{delay} was needed for all years. When a negative t_{delay} is needed, in practice, it means that the peak of the floodwave first passes the downstream station and then the upstream station. This is unlikely in reality and could be a sign of some unknown processes affecting the model. It can also be a result of a more natural landuse upstream of Bärbyleden, resulting in a low runoff coefficient, delaying the peak flow. When the needed negative time delay is one hour, this could also be a resolution issue, as the resolution of the flow data is one hour. In reality the time delay could be 30 minutes or 1,5 hours while the data does not have this resolution. Regardless of the cause, the number of occurrences of negative t_{delay} (70%) and the difficulty to find a suitable time delay have consequences on the proportion of urban runoff quickflow in the river, X, because of t_{delay}'s impact on the maximum urban runoff quickflow Q_{ur}.

The advantage of the method is knowing that the quickflow only comes from the study area. As such, it can be assumed that the quickflow has urban runoff water quality in terms of pollution. The disadvantage of the method is that the quickflow can vary greatly with choice of time delay, which makes the result uncertain. This uncertainty also makes the pollution evaluation uncertain and the usefulness of the method could be questioned. A simpler model without a water balance would remove the need for time delay. However, the quickflow could not be assumed to have urban runoff water quality then. A more complex model such as SWMM or MIKE could be used to try to find a better estimation of Q_{ur} and X. However, this was not done because of the lack of data, for example bathymetric (bottom and depth) data which would have been too time consuming to collect in this study.

The maximum urban runoff quickflow Q_{ur} often occured within one hour of the maximum rain intensity. One hour is the time step resolution and the quick response in the hydrograph highlights the need for higher temporal resolution when studying urban runoff quickflow.

The residence time was shorter than the time step 1 hour for most rain events and some rain events had τ just above the hour, see Figure 25. Three rain events in 2017 had longer residence times, around 100 min. Nonetheless, the residence time analysis indicates that the reservoir volume has a limited impact on the water chemistry and the proportion of urban runoff in the river during rain events. The assumption that X can represent the proportion of urban runoff in the river is thought to be acceptable for most rain events during the study period.

The estimated runoff coefficient, φ, differed compared to the runoff coefficient estimated by using Stormtac (0.21 compared to 0.40). The lower runoff coefficient is in line with a recent study (Rennerfelt et al. 2020). Because both are estimations, but using different methods, the deviation is considered acceptable since they are in the same range of the runoff coefficient scale (0 to 1). To improve the analysis, a tracer-based methodology which can track the source of the water could be useful to decrease the uncertainties.

5.1.2 Results, future perspectives and recommendations

Summer season and low flow prior to a rain event are the conditions that are associated with high proportion of urban runoff, X, according to the analysis of Q_{prior}, $Airtemp$ and $Month$. It seems quite natural, as a low flow in the river prior to an event means that the baseflow is low during the event. This means Q_{ur} will be higher and thus X will be greater. This is also consistent with previous studies (Karlsson & Öckerman 2016; Nicolau, Lucas, et al. 2012). Additionally, summer months have the lowest yearly average flow, see Figure 7. If X is proportional to pollution concentration in the river, then MAC-EQS should be monitored at low flow conditions in summer during rain events. It is therefore worrying that water quality monitoring is carried out on a schedule (VISS 2019) and not during rain events.

That Q_{ur} occurred before the maximum rain intensity I_{max} for 2018-08-17 could be due to the slower rise in quickflow from the natural area upstream of Bärbyleden than from the urban study area, see Figure E.18. This is consistent with increased runoff intensity and volume in urban areas (Swedish Water 2011).

The maximum urban runoff quickflow, Q_{ur}, increased with rain depth R_d, maximum rain intensity I_{max} and mean rain intensity I_{mean}, see Figure 23, D.2 and D.3. This is consistent with runoff coefficient theory, where more rain leads to more runoff. However, no trend could be found between these three parameters and X. The presence of these Q_{ur} correlations indicates that another parameter is more important for X, than Q_{ur} and the three rain parameters. Such a parameter could for example be the flow at Islandsfallet which is not urban runoff quickflow, which is connected to Q_{prior}. That Q_{ur} increased with R_d, I_{max} and I_{mean} could therefore strengthen the observed correlation between X and Q_{prior}.

Q_{ur} had an increasing trend over the study period. It was not the intention of this project to study this but it is an interesting result. However, the study period was too short to establish a significant trend and it could still be due to natural yearly variance. The study period would have to be longer to establish such a trend. The difference in the number of rain events each year might have affected the trend. The number of rain events per year should ideally be more equal. The causes behind an increase in Q_{ur} could be climate change as rain intensity is predicted to increase, or landuse change since Uppsala has been expanding rapidly and densifying the city during the study period. Studying this possible trend at a larger scale could give more knowledge about urban runoff management and further studies are encouraged.

The study area worked well for applying the water balance model since most inflows and outflows considered were not relevant, could be omitted or estimated. The study area also included two gauging stations for flow measurements in suitable locations. This made it possible to assume that the quickflow was urban runoff quickflow once having removed tributary flow and direct channel precipitation. Applying the model in a different study area might not have these advantages. The possibility to monitor urban runoff quickflow in this manner could be taken into account when planning new gauging stations.

Summarizing the research question, what can be said about the proportion of the flow in the Fyris river which is made up of urban runoff? The method was not fully adequate but a reliable maximum proportion of urban runoff in the Fyris river was still found to be 71%.

5.2 Momentary pollution concentrations

5.2.1 Methodology discussion

This project has confirmed that sampling urban runoff is challenging and that random sampling (sampling one time under unknown water chemistry conditions) might not be appropriate even during rain events. Weather forecasts were unpredictable during the study period which made planning difficult. A practical experience from this project is to prepare equipment in advance, so that sampling can be conducted soon after a rain event starts.

It was also difficult to know if runoff processes had started when initiating a sampling session. This meant that it was difficult to establish whether urban runoff baseflow or quickflow was being sampled. Furthermore, one random sample during a rain event will most probably not give the maximum urban runoff pollution concentration. It is not possible to know the time of the maximum concentration without continuous sampling. Alternatives to random sampling could be taking several samples over time in the same location using automated samplers. They could be programmed to start sampling after triggered by an event, such as water level rising. Sampling could also be done using a sampling time interval or flow proportional sampling device. This would also make it easier to sample all rain events no matter when they start, for example during nighttime. These sampling method improvements are however a matter of time and costs.

It should be noted that the sampling did not take place during the period of the studied rain events but after the study period. Most sampling sessions during spring 2021 had mixed precipitation, snow and rain. However, only the sampling of 2021-02-22 was a snowmelt event where pollutants would have had time to accumulate in the snow layer. The other precipitation events saw bare ground before the event and snowfall at the beginning of the event or snowfall during sampling. For these events, no extra accumulation of pollutants would have occured. Therefore, the sampled urban runoff pollution concentrations for these events are thought to be representative of urban runoff from rain events.

The assumption that the urban runoff quickflow was mainly 'young' water could not be evaluated because of the lack of tracer data. The quantity of 'young' versus 'old' water could have an impact on the pollutant concentration of a rain event, since they can have different chemical composition (Bishop et al. 2004). Therefore, it would be interesting to further investigate the 'young' water assumption for urban runoff in this context.

A conservative and complete mixing process was assumed for estimating momentary pollution in the river. Yet, there were clear signs of urban runoff forming streaks or plumes in the river during sampling, see Figure 26, indicating that complete mixing did not occur. If sampling takes place in such a streak, or outside it, the sample would not be representative of the whole river. If urban runoff concentrations exceed MAC-EQS, they will also likely be exceeded in streaks in the river since the waters do not mix fully. How such a situation should be handled when monitoring MAC-EQS is not clear to the author. Furthermore, the mixing might not be conservative in regards to pollutant fraction. Preliminary results from a study of using the same sampling show that the fraction of particulate and dissolved pollutants might differ in the urban runoff and in the river (Ahlström 2021). This means that a more advanced mixing model is needed.

It was also assumed that the highest pollution concentration in the river occurred when X occurred. This might not be the case because of fraction change, streakin, stratification and first flush effects. Streaking was present upstream of Kvarnfallet, see Figure 26. While this can affect the pollution concentrations in the river stretch upstream of Kvarnfallet, it is thought that complete mixing occurs downstream of Kvarnfallet. Thus it should not affect the concentration at Islandsfallet. First flush effects were indicated by the water colour, see Figure 27. Because of the long time between sampling and obtaining the result of the lab analysis, the first flush effect for each pollutant could not be analysed for this sampling session. Since X was not analysed for this sampling occasion, the pollutant concentration, and first flush effect was not put in relation with X either. However, the indication of the first flush effect might complicate establishing a yield function, the suggested approach by Tao et al. (2019), because the urban runoff has to be sampled with high temporal resolution.

For the MAC-EQS analysis, the highest measured concentrations during sampling were used to evaluate the risk of a pollutant exceeding MAC-EQS. As previously discussed, the actaul maximum concentrations of pollutants in the urban runoff quickflow could be higher still. For this reason, the risks might also be even higher in reality. The risk could also be lower. For example, not all urban runoff quickflow might have the highest concentration.

The MAC-EQS analysis of the industrial areas should be viewed with caution since the industrial areas are outside of the study area. The industrial areas were sampled because the landuse is different to the sampled residential areas in the study area. The sampling showed that the water chemistry was different in these areas. However, industrial areas have higher runoff coefficients than residential areas because of the higher amount of impervious surface. This means that the maximum urban runoff quickflow Q_{ur} could be different, probably higher, if the study area had been industrial. Therefore a different X should have been used for these areas. However, this was not possible in this study.

5.2.2 Results, future perspectives and recommendations

Of the pollutants analysed in the study area, especially fluoranthene concentrations exceeded or had high risk of exceeding MAC-EQS. BaP also had high risk of exceeding MAC-EQS in the catchment area of Luthagen. In the industrial areas, fluoranthene again had a high risk of exceeding MAC-EQS and the other PAH pollutants presented moderate risk. None of the metals lead, nickel and cadmium showed more than low risk, with the exception of nickel in the Librobäck industrial area. However, this concentration was obtained at the snowmelt event 2021-02-22 and could include accumulation effects from times of cold weather, making it unrepresentative of a rain event.

The sampling was carried out during winter and spring which usually are a period of higher flow, see Figure 7. Previous studies (Karlsson & Öckerman 2016; Nicolau, Galera-Cunha, & Lucas 2006) suggest metal concentrations might be higher at other times during the year. Consequently, the low metal concentrations might be a result of the sampling period. Therefore, the low risk should be reevaluated in future studies.

Conclusively, the results from the MAC-EQS analysis show that mitigation measures should possibly first be prioritised in Luthagen with focus on PAH pollutants.

Previous studies suggest using the hydrograph together with an established yield function (Tao et al. 2019). However, establishing pollution concentration relations in urban runoff to be able to use X might not be cost efficient. The sampling in this project confirms that pollution concentration vary temporally during a rain event, see Figure 27 for indications of the first flush effect, and in between rain events, which is consistent with previous studies (Nicolau, Lucas, et al. 2012). Pollution concentrations can also vary spatially depending on the catchment and on pollutant properties, which is also consistent with previous studies (D. Li et al. 2015). It would take a lot of sampling, time and money to establish useful pollution concentration correlations which take these aspects into account. Furthermore, a more complicated mixing model would be needed. Even so, due to the first flush effect, the maximum urban runoff pollution concentration might not even occur when X occurs. This possibility makes the method less relevant for evaluating risks as the risk will be overestimated.

In summary, besides increasing the knowledge and certainty of X, the usefulness of improving the method for estimating X can be questioned, as it would require significant funding and effort to minimize the uncertainties of the model. The first flush effect also puts the use of the quickflow fraction X into question when analysing momentary pollution concentrations.

While sampling urban runoff pollution concentrations can be useful for prioritising stormwater mitigation measures, sampling directly in the river would be more appropriate for monitoring MAC-EQS, if sampled at appropriate times. regarding the risk evaluation in this report, assumptions were made about urban runoff concentrations and conservative mixing as well as maximum X - all which carry uncertainties. Sampling directly in the river would remove all such uncertainties and this is recommended for future studies focusing on monitoring MAC-EQS or sampling momentary pollution concentrations. This sampling would be recommended to be carried out during low flow conditions in summer time with a short sampling interval during rain events. The time resolution should be higher than one hour and the sampling should be carried out downstream of a turbulent area to avoid streaks, to reduce the risks of getting less representative measurements. While a short sampling interval will make sure to capture pollution concentration over time, it will also infer numerous samples to analyse. Therefore, it would be useful to find a relation between pollution concentrations and an easily analysed parameter, in order to select which sample(s) is relevant to further analyse for pollutants. Parameters to add to the parameter list in Table 2 could be a first flush parameter, turbidity (water color), conductivity (ions), and 'young' water.

Summarizing the research question, what can be said about the risk of a few chosen pollutants exceeding MAC-EQS? The risk analysis of MAC-EQS shows fluoranthene is at risk of excceding MAC-EQS.

6 Conclusion and future perspectives

Even though the chosen method was based on a very strong simplification of reality, the project still produced some results and useful insights.

This study found that there was an actual risk of momentary pollution concentrations exceeding MAC-EQS, based on urban runoff from rainfall events. PAHs, and especially fluoranthene, were the pollutants that showed the highest risk of exceeding MAC-EQS in the Fyris river. To ensure better water quality in the Fyris river, the author recommends that mitigation measures for urban runoff pollutants, such as PAHs, should be considered.

The proportion of urban runoff, X, in the Fyris river can be as high as 70%. A high proportion of urban runoff in the river is most likely to occur during low flow conditions in summertime. The relation between X and pollution concentration in the river still needs to be investigated, but awaiting that, the author recommends that sampling momentary pollution concentrations and monitoring of MAC-EQS should include rain events with these circumstances.

Another future investigation of interest would be to examine the possible trend of maximum urban runoff quickflow Q_{ur} increasing with time. More knowledge about Q_{ur} could help in urban runoff management.

Moreover, signs of the first flush effect and clearly visible urban runoff streaks, indicate that a more complex mixing model is needed, as well as more knowledge about how urban runoff pollution concentration changes over time. Since direct sampling of urban runoff is not cost efficient, a different approach is proposed in which sampling of urban runoff is replaced by sampling directly in the river.

While sampling momentary pollution can be challenging, the risks of momentary pollution exceeding MAC-EQS presented in this study show that momentary pollution concentrations should not be overlooked.

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Appendices

A Study area

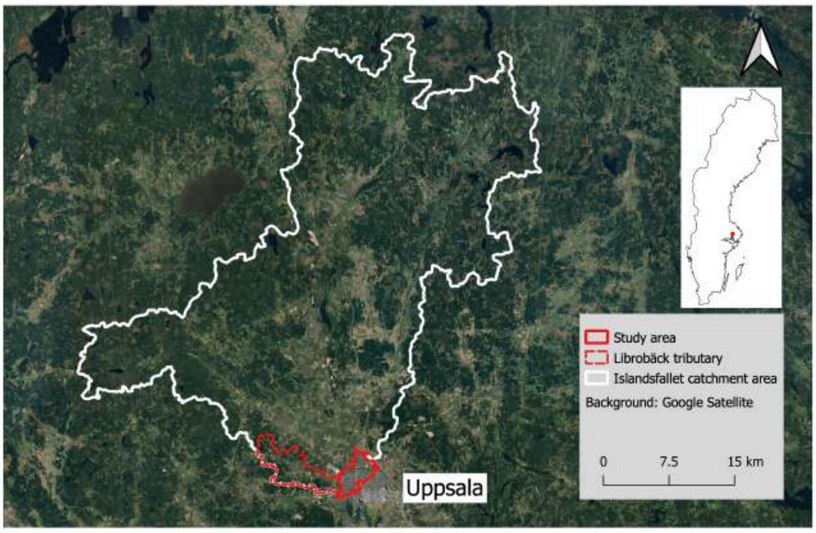


Figure A.1: *The study area in red, and the Libroback catchment area in dotted red line. The entire catchment area upstream of Islandsfallet in white.*

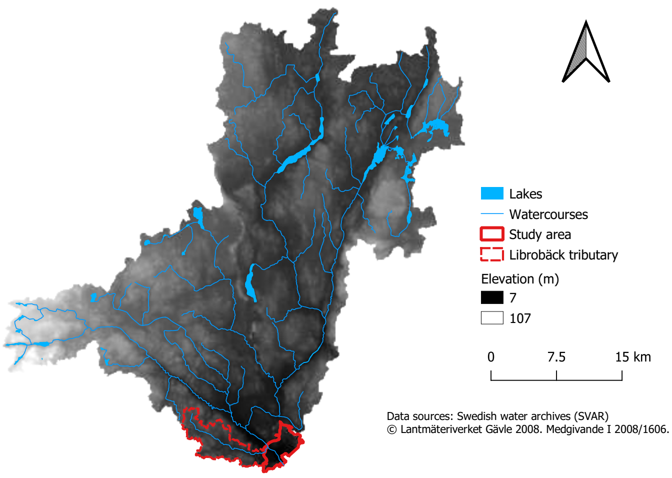


Figure A.2: *The study area in red, and the Libroback catchment area in dotted red line. The elevation difference is small and ranges within 100 m.*

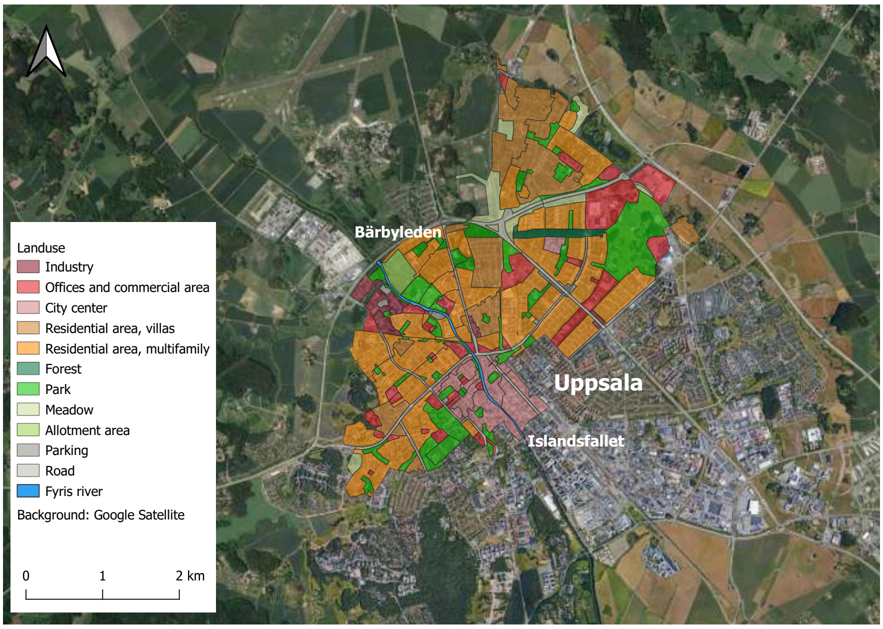


Figure A.3: *The study area, colored according to landuse type.*

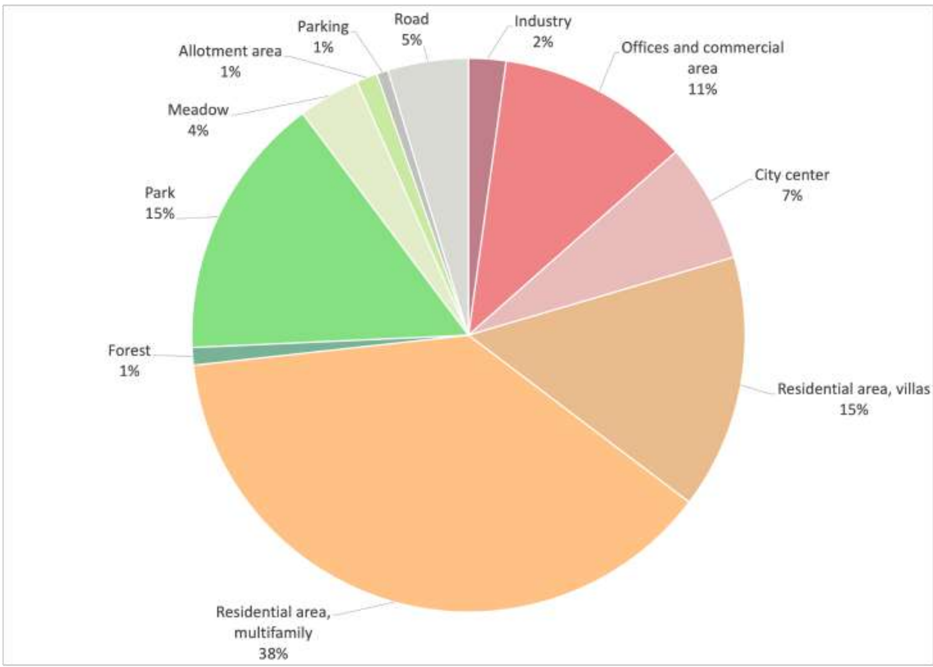


Figure A.4: *The landuse of the study area in percent, colored according to landuse type in A.3.*

Figure A.5 shows where representative pictures of the studied river reach in Figure A.6 are located.

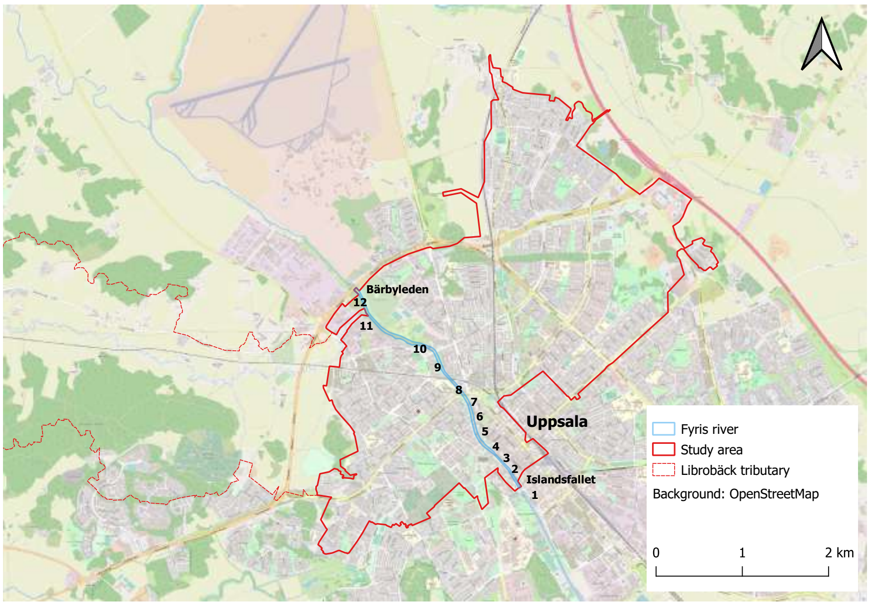


Figure A.5: *The study area in red, and the Libroböck catchment area in dotted red line. The numbers describe the location of pictures in Figure A.6.*

(1) Islandsfallet.

(2) Directly upstream Islandsfallet.

(3) Upstream Drottninggatan.

(4) Kvarnfallet.

Figure A.6: *The studied river reach, looking upstream.*

(5) *Upstream Järnbron.*

(6) *Upstream Skolgatan.*

(7) *Upstream Eddaspången.*

(8) *Upstream Fyrisspången.*

(9) *Upstream Strandängsspången.*

(10) *Upstream Fyrishov.*

(11) *Librobäcken tributary joining the Fyris river.*

(12) *Bärbyleden.*

Figure A.6: *The studied river reach, looking upstream (cont.).*

B Sampling procedure

Sampling locations

There are seven sampling locations, three in the Fyris river and four of urban runoff, enumerated according to the list:

- 1F - Klastorp (Fyris river)
- 0D - Librobäck industrial area (urban runoff)
- 1D - Luthagen (urban runoff)
- 2D - Svartbäcken (urban runoff)
- 2F - Islandsfallet (Fyris river)
- 3D - Boländerna (urban runoff)
- 3F - Upstream the waste water treatment plant (WWTP) (Fyris river)

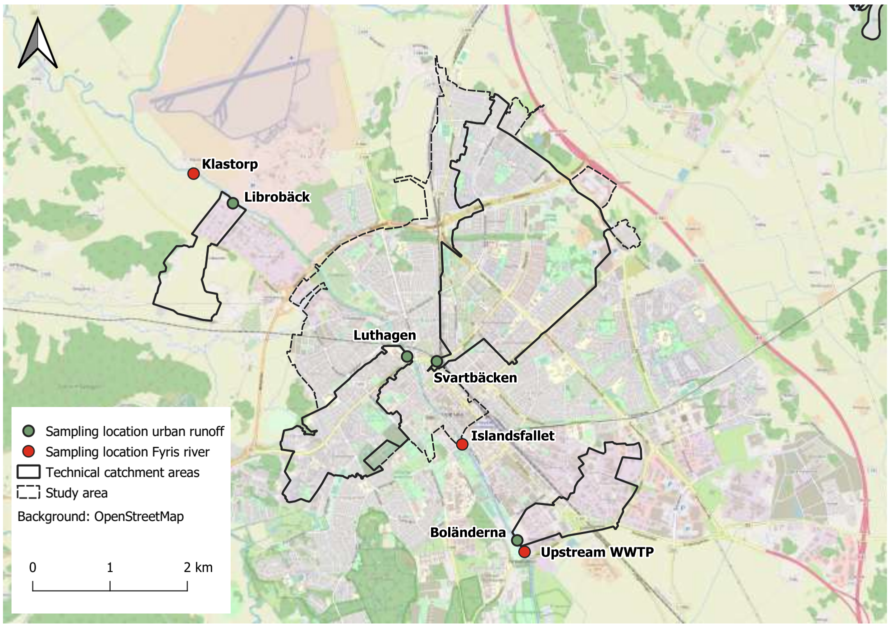
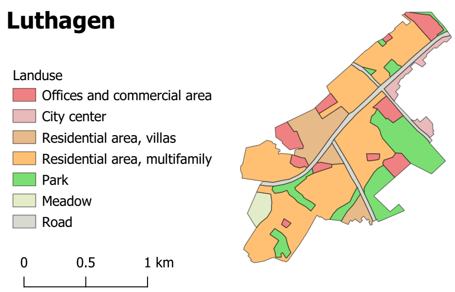
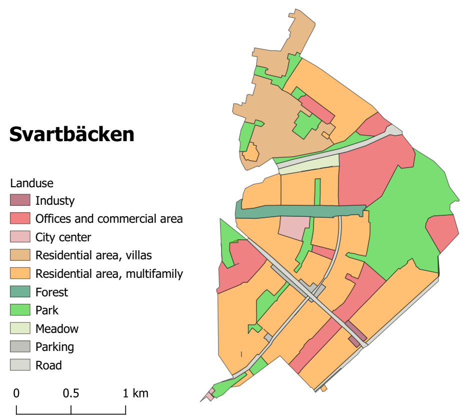


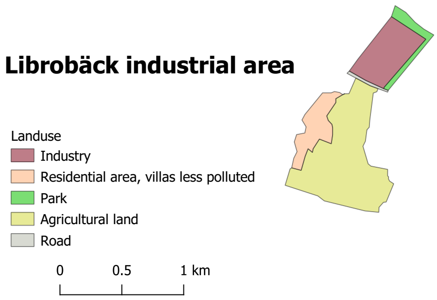
Figure B.1: *The sampling locations.*



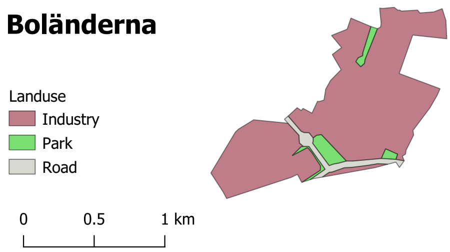
(a) Landuse in Luthagen.



(b) Landuse in Svartbäcken.



(c) Landuse in Librobäck industrial area.



(d) Landuse in Boländerna industrial area.

Figure B.2: *Landuse in the sampled urban runoff locations.*

Descripition of the sampling locations from north to south:

1F) Klastorp, river water. Same location as in sampling carried out by SLU. 17 minutes on bike from the WRS office. The sample is taken under the bridge on the western side of the river.

0D) Librobäck industrial area, urban runoff. 3 minutes on bike from Klastorp. The sample is taken in the culvert outlet by the river.

1D) Luthagen, urban runoff. 13 minutes on bike from Librobäck industrial area. The sample is taken in the manhole, closest to the culvert outlet. The culvert outlet is under water in the river. The manhole is too small to sample with the Fyris river sampling stick. Therefore, use a thinner sampling stick.

2D) Svartbäcken, urban runoff. 3 minutes on bike from Luthagen. The sample is taken in a manhole behind the Mikael's church, a few hundered meters from the river.

2F) Islandsfallet, river water. 5 minutes on bike from Svartbäcken. The sample is taken from the western side of the river, upstream of the bridge. The location is the same as in sampling carried out by Uppsala University.

3D) Boländerna industrial area, urban runoff. 5 minutes on bike from Islandsfallet.

The sample is taken in the culvert outlet by the river. Suspected oil film is often visible on the surface. Therefore, use specially designated sampling stick, to avoid cross contamination.

3F) Upstream of the WWTP, river water. 2 minutes from Boländerna. The sample is taken from the eastern side of the river, from the pier, upstream of the waste water treatment plant outlet.

(a) Luthagen sampling location.

(b) Svartbäcken sampling location.

(c) Islandsfallet sampling location.

Figure B.3: *Sampling locations in the study area.*

Material

The material for one sampling session (seven sampling locations):

- 14 plastic bottles 1000 ml for taking samples
- 7 plastic bottles 1000 ml
- 7 plastic bottles 500 ml
- 7 plastic bottles 250 ml
- 14 brown glass bottles 100 ml
- 14 plastic tubes 50 ml
- 14 brown glass bottles 40 ml
- 3 insulated shipping containers and 18 frozen gel packs

(a) Sampling bottles and sample bottles. *(b) Sampling equipment in the field.*

Figure B.4: *Sampling material.*

Preparations

1. Print sampling protocol on waterproof paper
2. Prepare the bottles and mark with date, individual sample number and customer number
3. If needed, order more material
4. Put gel packs in the freezer
5. Order sample pick-up for shipping
6. Prepare shipping labels

Equipment to bring to the field

1. For one sampling location, bring:
    - 2 plastic bottles 1000 ml for taking samples (One is used for measuring pH and turbidity in the office. The other is used to fill sampling bottles not brought to the field.)
    - 1 plastic bottle 1000 ml
    - 2 brown glass bottles 100 ml
    - 2 brown glass bottles 40 ml
2. Fyris river sampling stick (used for 1F, 0D, 2D, 2F and 3F), 3D sampling stick, and 1D sampling stick
3. Conductivity and water temperature meter for measuring on location
4. Small beaker for conductivity and temperature measurement
5. Clean tap water for cleaning conductivity/temperature meter and beaker
6. High visibility saftey vest
7. Marker, pencil, clipboard, plastic pocket and protocol
8. Manhole openers
9. Thick gloves and weather proof clothing

To do at every sampling location

1. Rinse the sampling bottles several times before taking the sample
2. Take the sample and fill the sample bottles. Then, fill both sampling bottles
3. Fill in the sampling protocol
4. Measure conductivity and water temperature. Rinse the instrument and the beaker with tap water

To do at the office instantly after fieldwork

1. Store the samples in the fridge. Store one sampling bottle in room temperature, for measuring pH and turbidity
2. Fill all bottles and pack the insulated shipping containers with all samples and frozen gel packs
3. Measure pH and turbidity
4. Fill in the digital protocol and weather history
5. Read turbidity measurement from the measuring station at Islandfallet

6. Upload pictures to the server
7. Clean sampling bottles with tap water and let dry

Water quality analyses

Table B.1: *Water quality analyses and their analysis code at Eurofins.*

Analysis code	Description
	Urban runoff
SL866	Total suspended material
SLD47	Total phosporus
SLD68	Ammonium nitrogen in water
SLL23	Chloride in water
PSLE6	Sum of PAH16 in water and single PAH
PSLE8	Acid digested metals
SLD61	Total phosporus, filtered
PSLE6	Sum of PAH16 in water and single PAH (decanter 12 hours)
PSL3R	Filtered metals (0,45 µm)
	River water
SL866	Total suspended material
SLD47	Total phosporus
SLD68	Ammonium nitrogen in water
SL836	DOC in water
SLL23	Chloride in water
PSLE6	Sum of PAH16 in water and single PAH
PSLE8	Acid digested metals
SL00L	Calcium in water (digested)
SLD61	Total phosporus, filtered
PSLE6	Sum of PAH16 in water and single PAH (decanter 12 hours)
PSL3R	Filtered metals (0,45 µm)

C Estimation of flow from Libroback tributary

Flow from the Libroback tributary ($Q_{Libroback}$) was estimated with data from the gauged Stabby river. See the location of the catchments in Figure C.1. The Libroback catchment area was delineated using the free depression flow tool in SCALGO. The Stabby catchment area was obtained from the Swedish Water Archive (SVAR). The Libroback catchment area is 26.56 km^2 and the Stabby catchment area is 6.18 km^2.

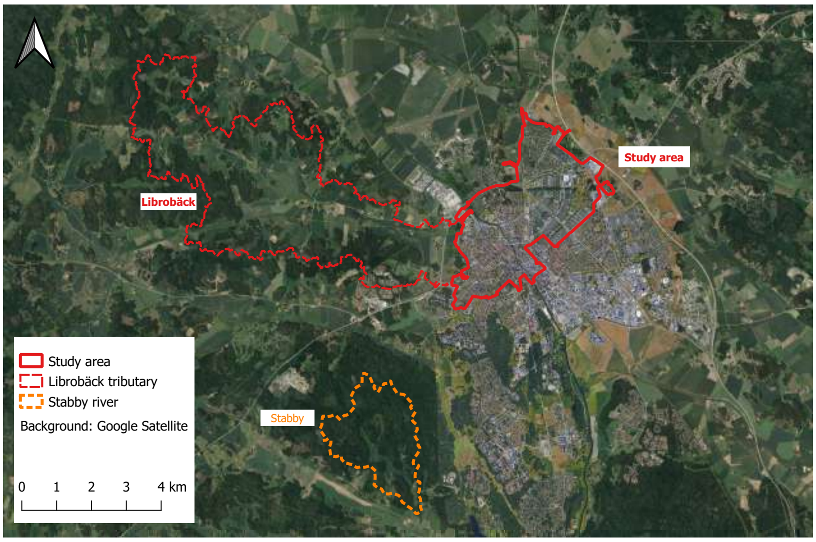


Figure C.1: *The study area in red, and the Libroback catchment area in dotted red line. The Stabby catchment area, in orange, was used to estimate the flow from the Libroback catchment area.*

The estimation can be seen in Figure C.2 for the full study period and in Figure C.4 for the rain event months each year. Notice that some rain events lead to quickflow, indicated by a rising red curve, and that some do not, indicated by a stable red curve. The plot for 2017 has a different scale which makes the curve appear more stable than in reality. Also notice that the quickflow is quite small during summer months.

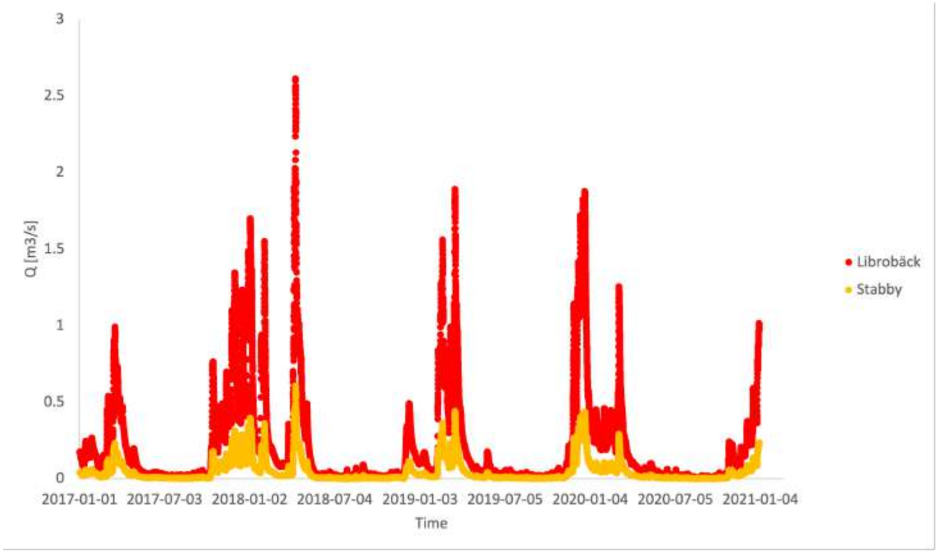


Figure C.2: *The flow in the Stabby river and the estimated flow in Librobäck, using the specific discharge from the Stabby river.*

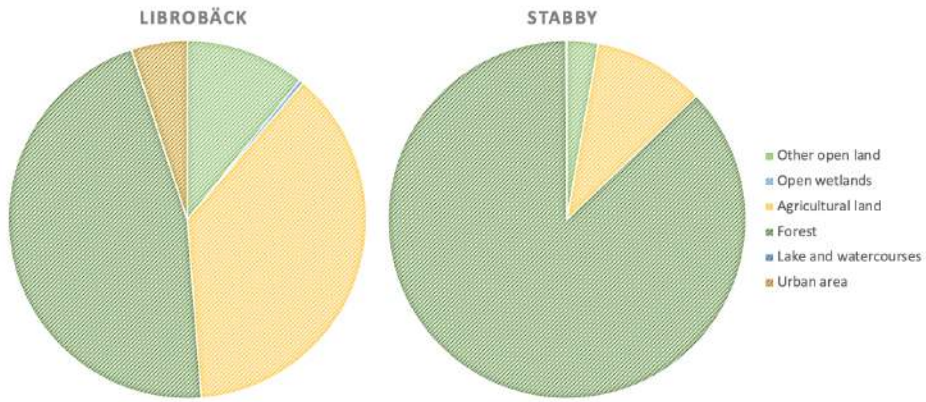
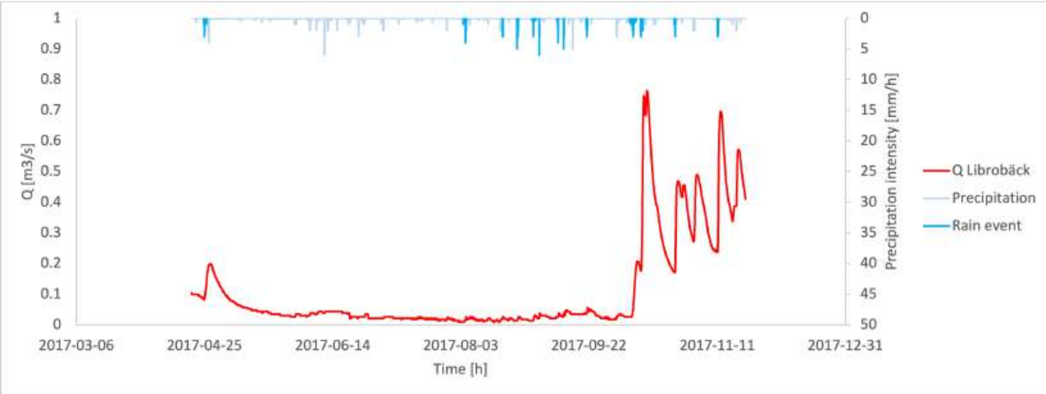
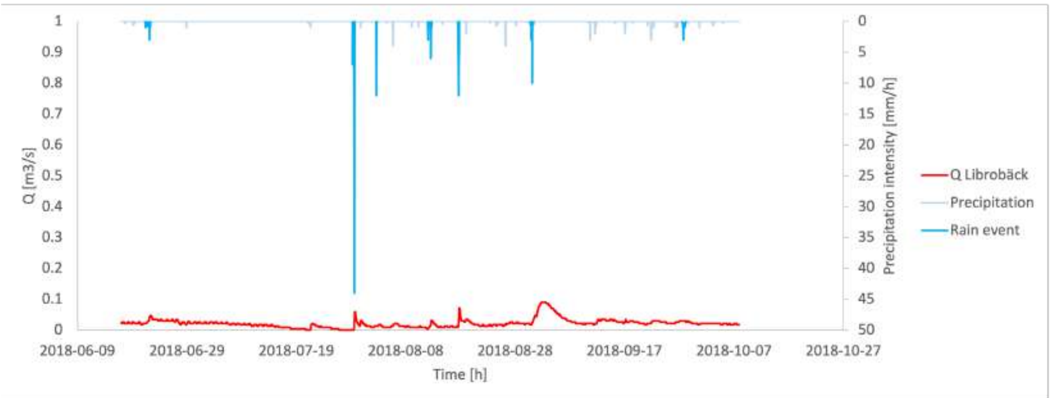


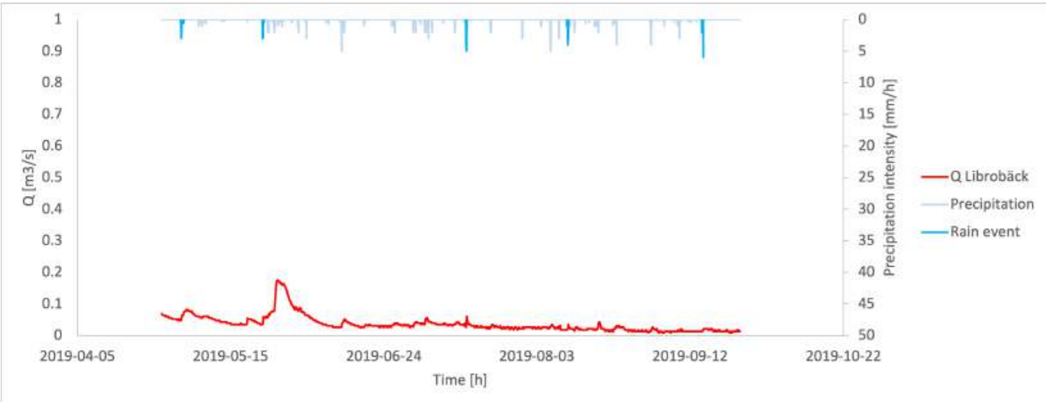
Figure C.3: *Libroböck has more agricultural land and urban area than Stabby.*



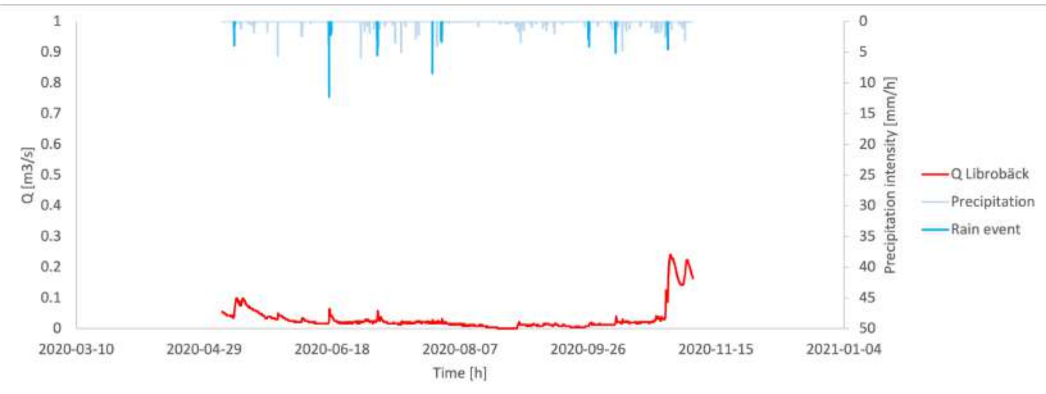
(a) 2017



(b) 2018



(c) 2019



(d) 2020

Figure C.4: *Estimated flow from the Librobäck tributary during the rain event months each year in the study period. Red lines indicate the start of a rain event.*

D Parameters

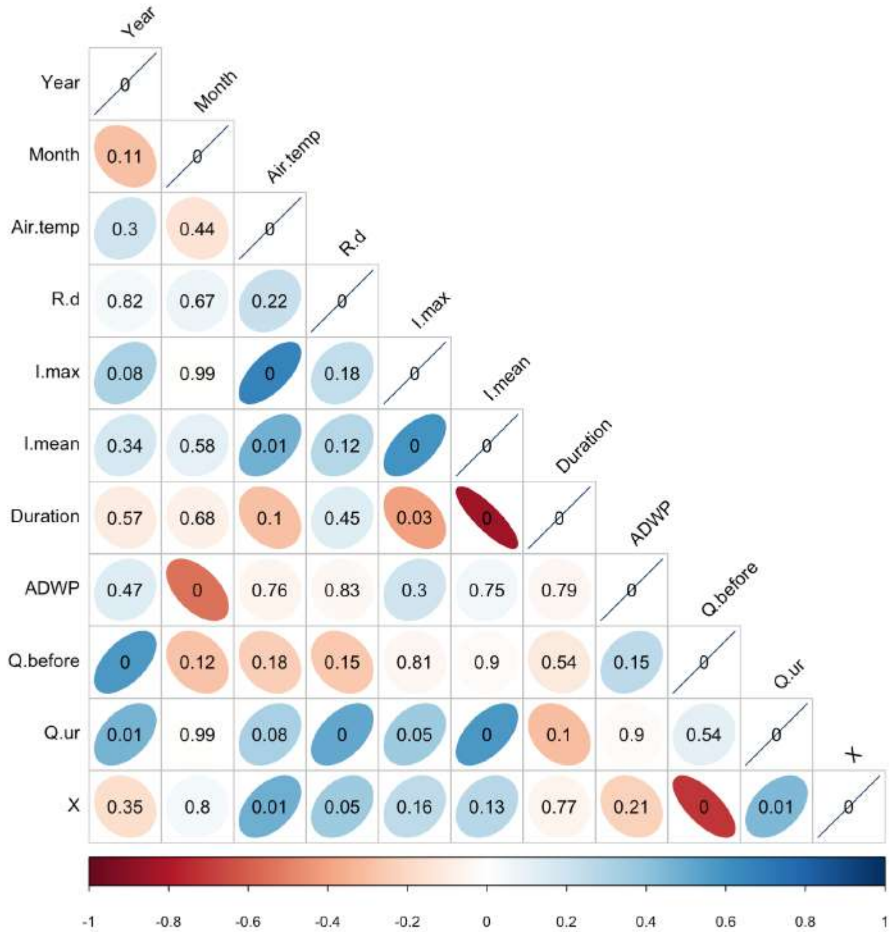


Figure D.1: *All correlations for the parameters, indicated in color, and their p-value. p<0.05 indicate significant correlations with a 95% confidence interval.*

Table D.1: *All parameter values for all rain events and the residence time for each rain event.*

Rain event start	$Month$	$Airtemp.$ [°C]	R_d [mm]	I_{max} [mm/h]	I_{mean} [mm/h]	$Duration$ [h]	$ADWP$ [h]	Q_{prior} [m3/s]	τ [min]	Q_{ur} [m3/s]	X
2017-04-24 17:00	4	2.1	13	3	0.43	30	72	3.49	36	1.20	0.25
2017-08-03 21:00	8	14.5	12.7	4	0.42	30	25	0.96	97	0.87	0.44
2017-08-19 02:00	8	13.8	14.2	3	1.42	10	13	0.75	100	1.31	0.65
2017-08-24 21:00	8	13	16.2	5	1.35	12	45	0.00	109	1.41	0.77
2017-08-30 22:00	8	14.2	14.6	3	0.46	32	16	0.68	71	2.22	0.82
2017-09-02 12:00	9	11.9	13.1	6	2.62	5	30	0.93	68	2.05	0.72
2017-09-09 16:00	9	15.3	12.9	4	0.99	13	7	0.87	70	2.27	0.83
2017-09-12 00:00	9	13.6	13.6	5	1.51	9	18	1.06	64	1.70	0.56
2017-09-20 21:00	9	8.4	17.6	3	1.47	12	38	1.06	61	1.91	0.60
2017-10-07 18:00	10	5	25	3	0.38	66	22	1.12	54	1.69	0.47
2017-10-12 01:00	10	6.4	20.2	3	0.81	25	37	5.26	-	-	-
2017-10-25 05:00	10	6.5	10.9	3	0.84	13	38	8.89	-	-	-
2017-11-11 01:00	11	4	14.4	3	1.44	10	32	9.57	15	2.77	0.21
2018-06-21 09:00	6	11.7	14.7	3	0.59	25	45	1.30	70	1.22	0.45
2018-07-29 07:00	7	19.3	77	44	7.70	10	183	1.31	14	13.18	0.82
2018-08-02 14:00	8	22.9	12.2	12	2.44	5	61	2.10	79	0.40	0.17
2018-08-12 01:00	8	13.3	16.5	6	0.97	17	39	1.40	56	1.17	0.34
2018-08-17 13:00	8	19	33	12	5.50	6	67	1.63	29	5.02	0.71
2018-08-30 19:00	8	16.1	19.6	10	1.40	14	13	1.60	48	2.03	0.50
2018-09-27 15:00	9	7.8	13.2	3	0.94	14	10	1.74	66	1.35	0.47
2019-05-01 23:00	5	6.7	13.2	3	0.66	20	527	4.98	27	1.51	0.22
2019-05-23 07:00	5	9.3	10.3	3	1.03	10	94	2.61	47	1.76	0.43
2019-07-15 10:00	7	12.2	19.2	5	2.74	7	12	1.95	31	4.45	0.67
2019-08-10 18:00	8	16.1	14	4	1.17	12	12	2.16	46	2.03	0.48
2019-09-14 23:00	9	11.1	11.8	6	0.98	12	31	2.41	57	1.01	0.30
2020-05-10 12:00	5	10.9	12.7	3.9	0.98	13	89	3.27	33	2.22	0.42
2020-06-16 13:00	6	14.6	30.5	12.3	1.09	28	166	1.82	30	4.87	0.71
2020-07-05 09:00	7	14.6	28.3	5.5	2.57	11	19	1.91	25	6.28	0.75
2020-07-27 02:00	7	15.9	11.6	8.4	3.87	3	127	2.08	40	2.88	0.58
2020-07-30 14:00	7	16.8	14.7	3.3	1.23	12	21	2.21	40	2.77	0.55
2020-09-26 01:00	9	12.1	14.2	4.1	1.18	12	19	1.42	46	2.80	0.65
2020-10-06 10:00	10	13.9	22.9	5.1	1.64	14	28	1.59	44	2.90	0.65
2020-10-26 19:00	10	10.2	14.2	4.6	1.18	12	11	3.65	24	2.82	0.37

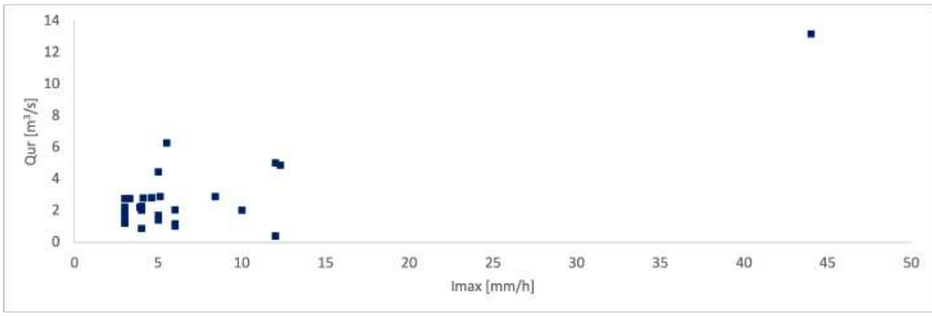


Figure D.2: *Q_{ur} increased with I_{max}.*

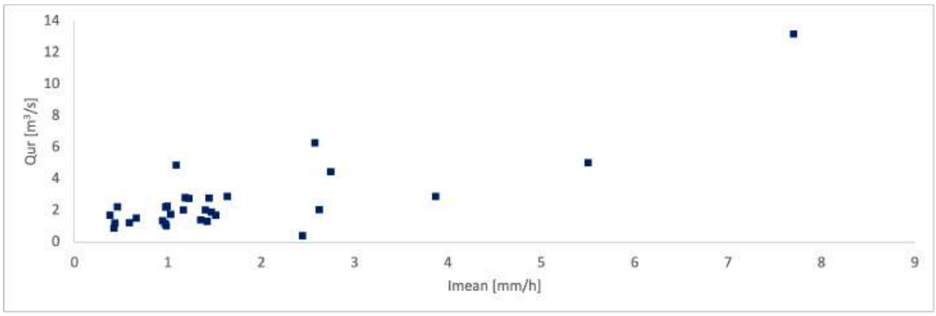


Figure D.3: *Q_{ur} increased with I_{mean}.*

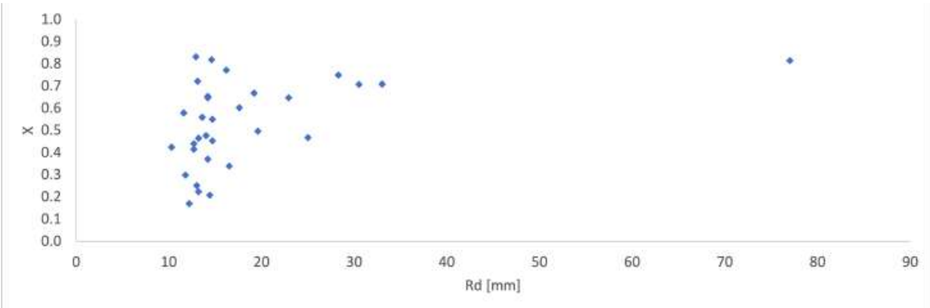


Figure D.4: *X showed no pattern with R_d.*

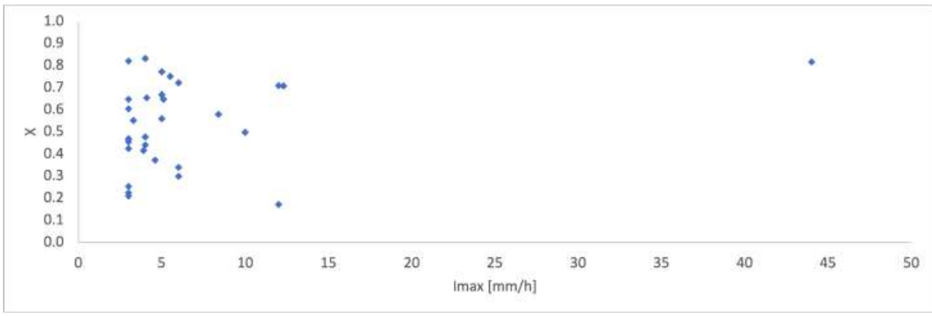


Figure D.5: *X showed no pattern with I_{max}.*

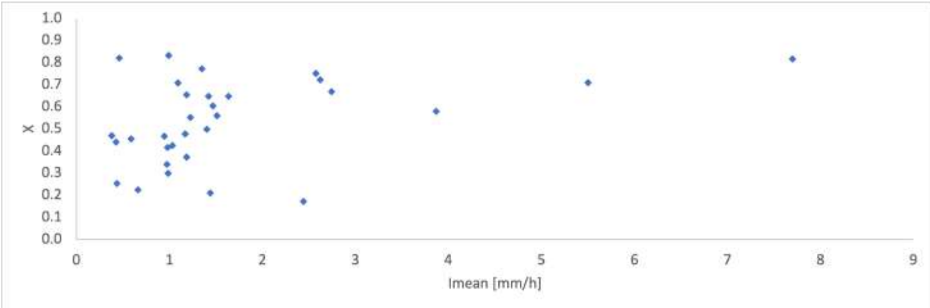


Figure D.6: *X showed no pattern with* I_{mean}.

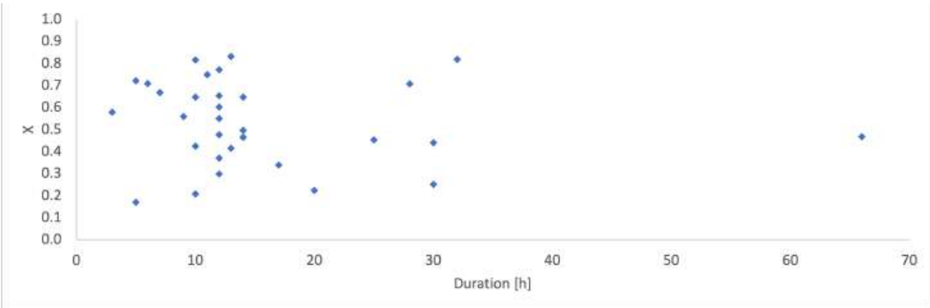


Figure D.7: *X showed no pattern with Duration.*

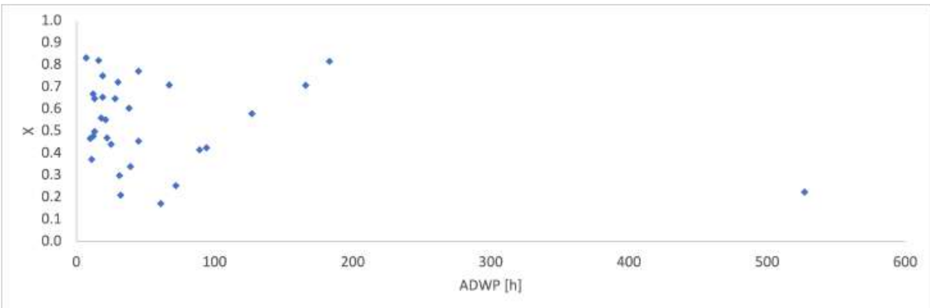


Figure D.8: *X showed no pattern with* $ADWP$.

E Rain events

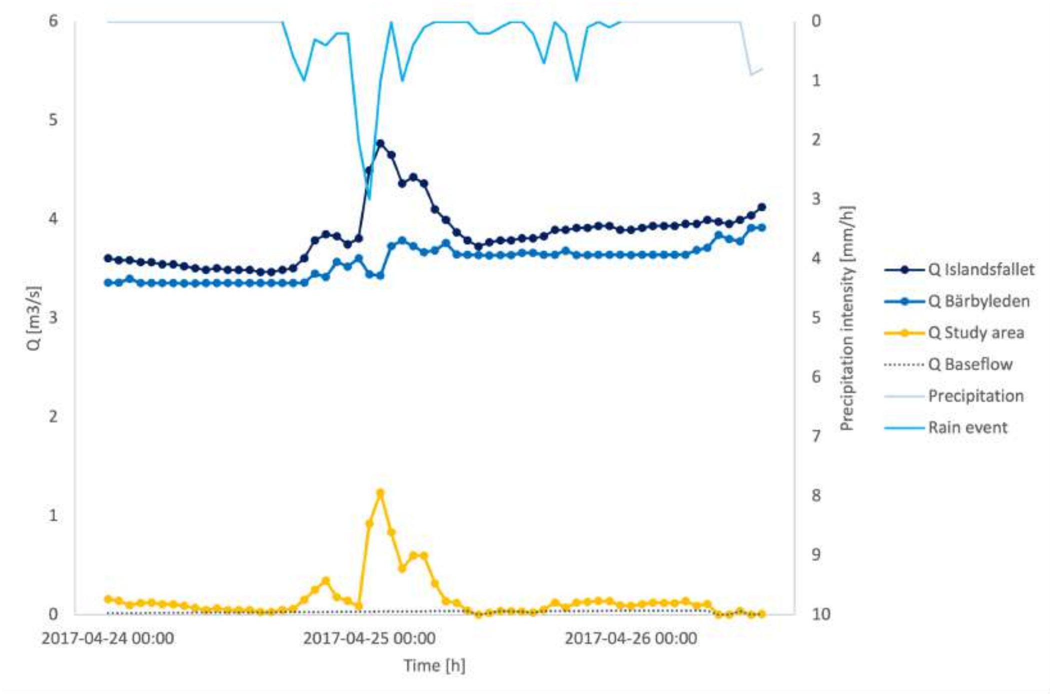


Figure E.1: *The rain event starting 2017-04-24. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow.*

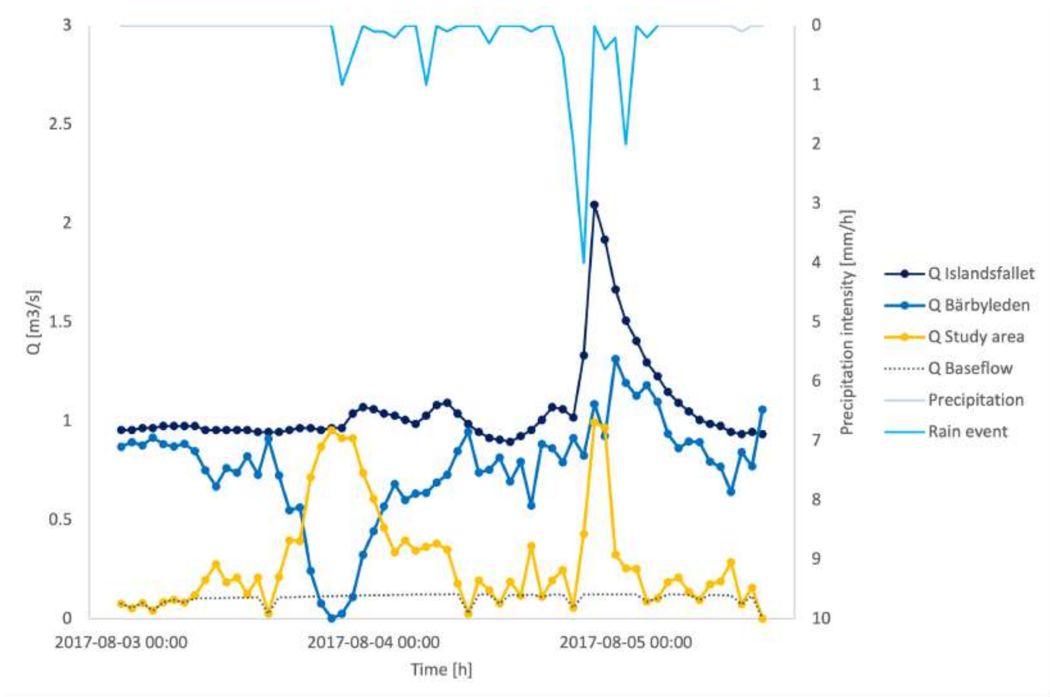


Figure E.2: *The rain event starting 2017-08-03. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow. The low Q Bärbyleden at the start of the rain event was considered faulty and the maximum urban runoff proportion was therefore chosen at the peak hour.*

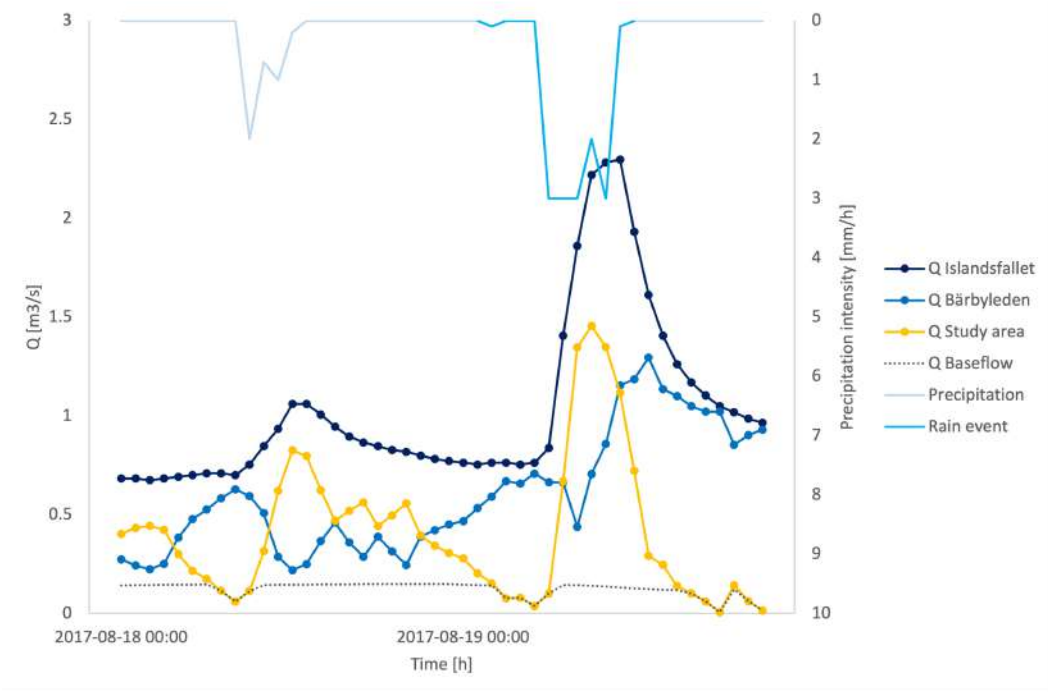


Figure E.3: *The rain event starting 2017-08-19. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow.*

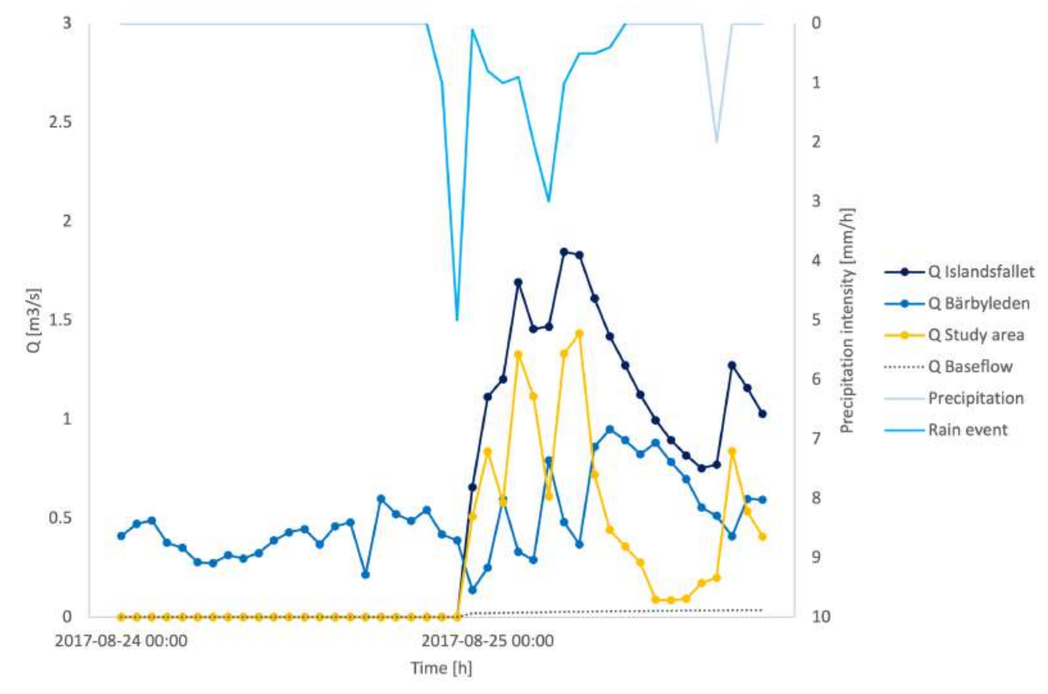


Figure E.4: *The rain event starting 2017-08-24. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow.*

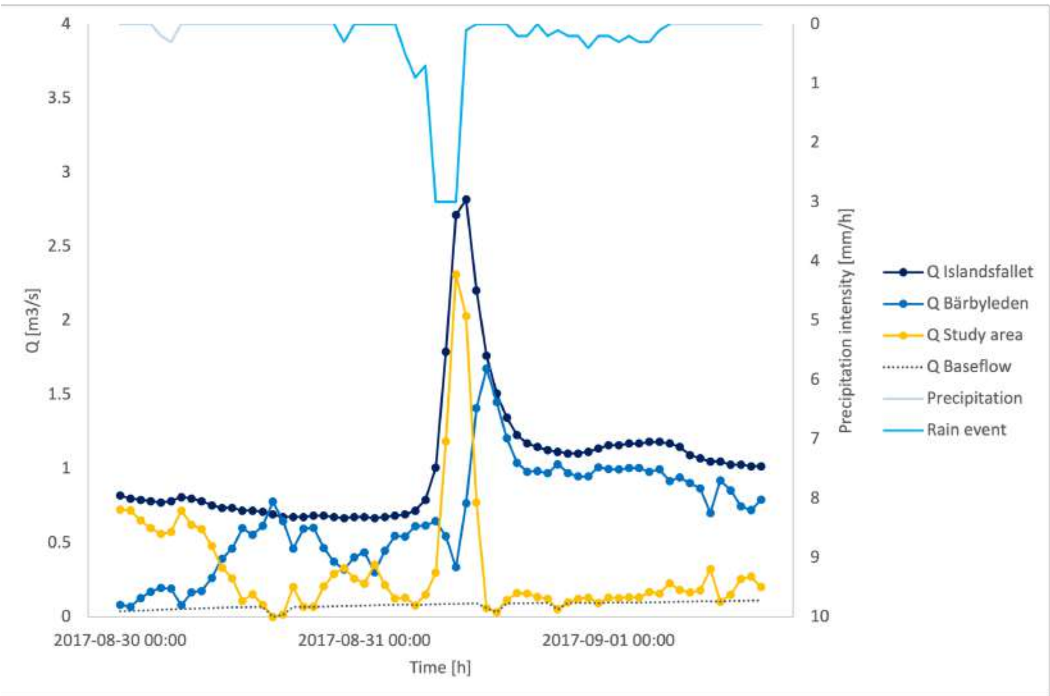


Figure E.5: *The rain event starting 2017-08-30. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow.*

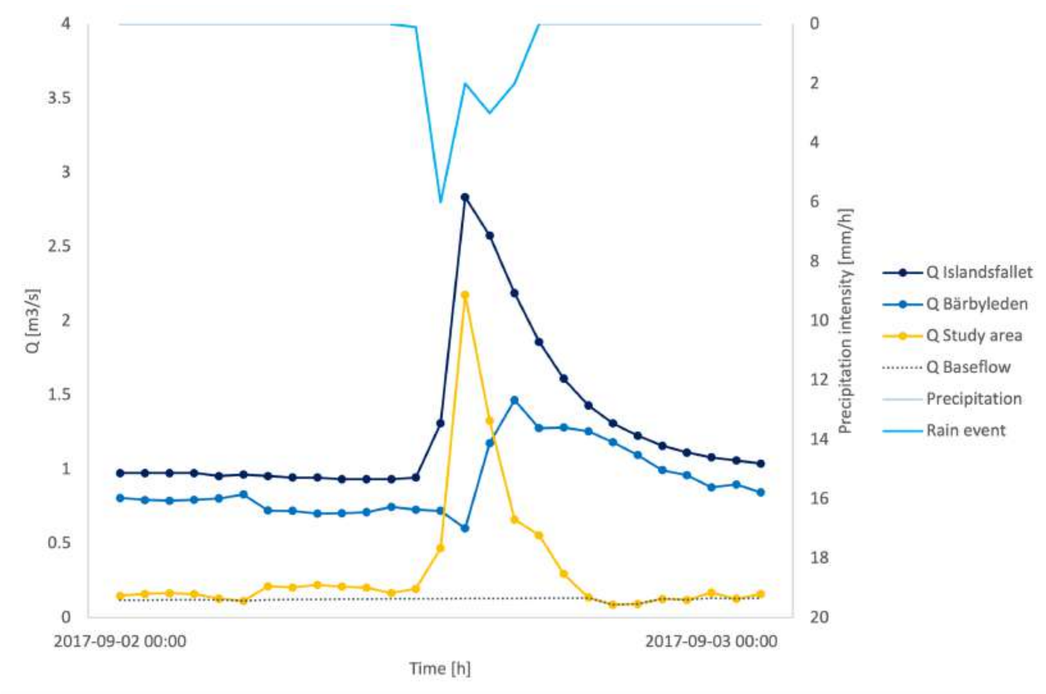


Figure E.6: *The rain event starting 2017-09-02. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow.*

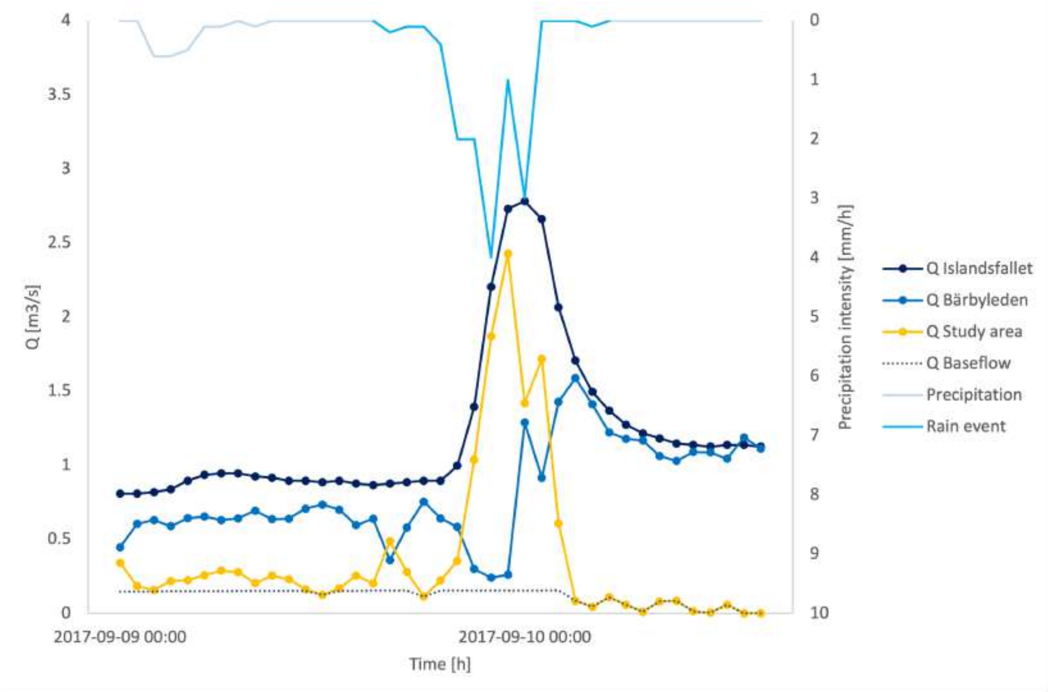


Figure E.7: *The rain event starting 2017-09-09. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow.*

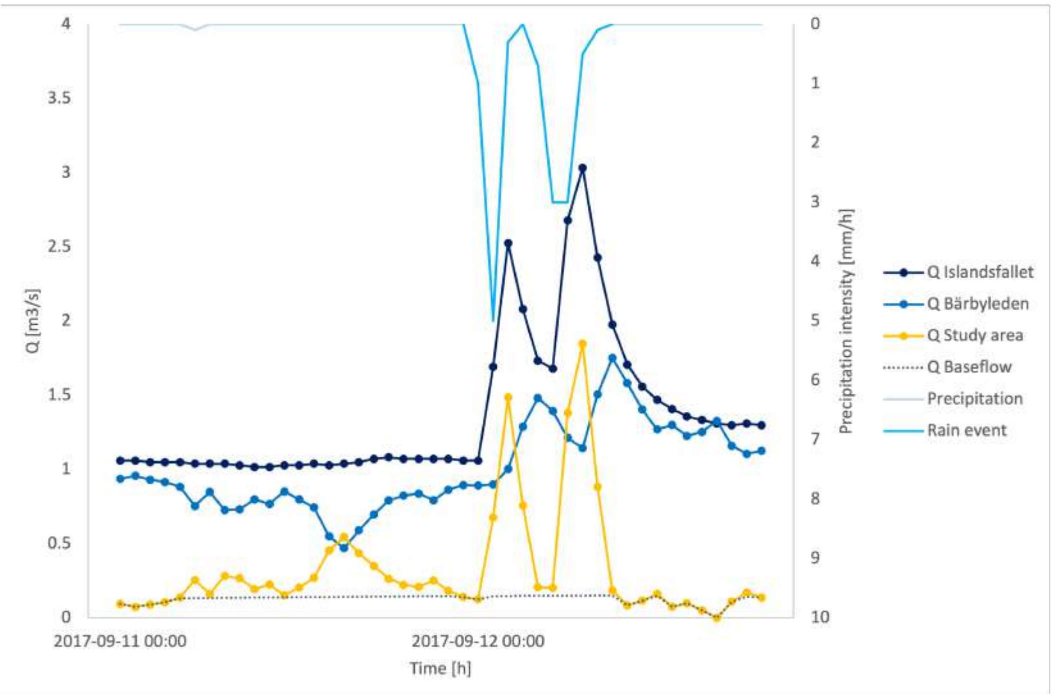


Figure E.8: *The rain event starting 2017-09-12. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow.*

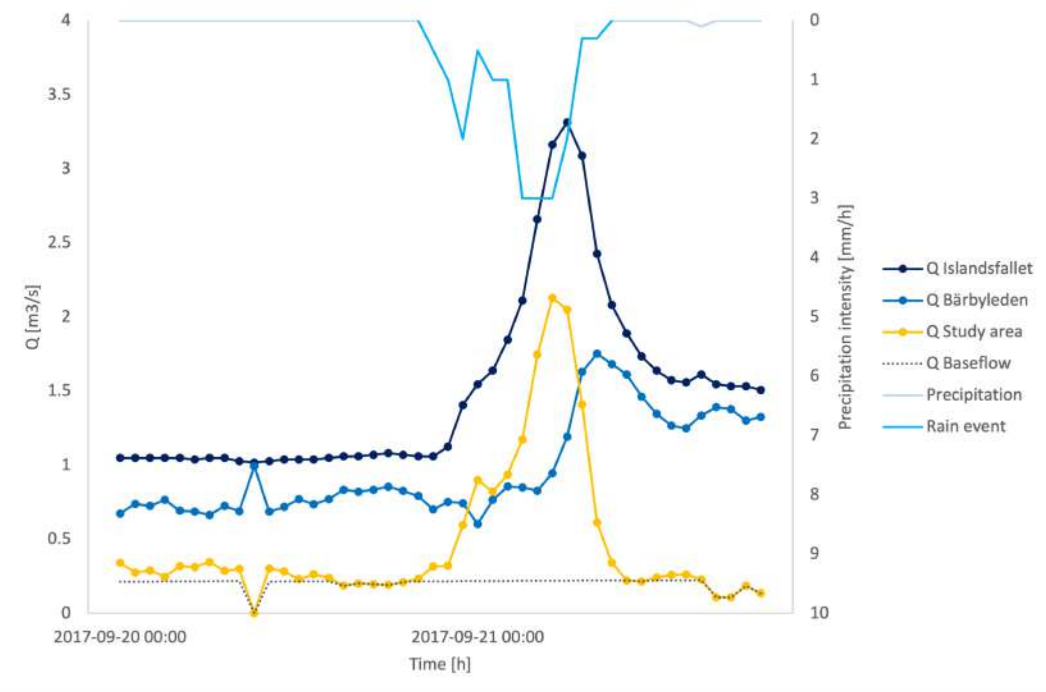


Figure E.9: *The rain event starting 2017-09-20. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow.*

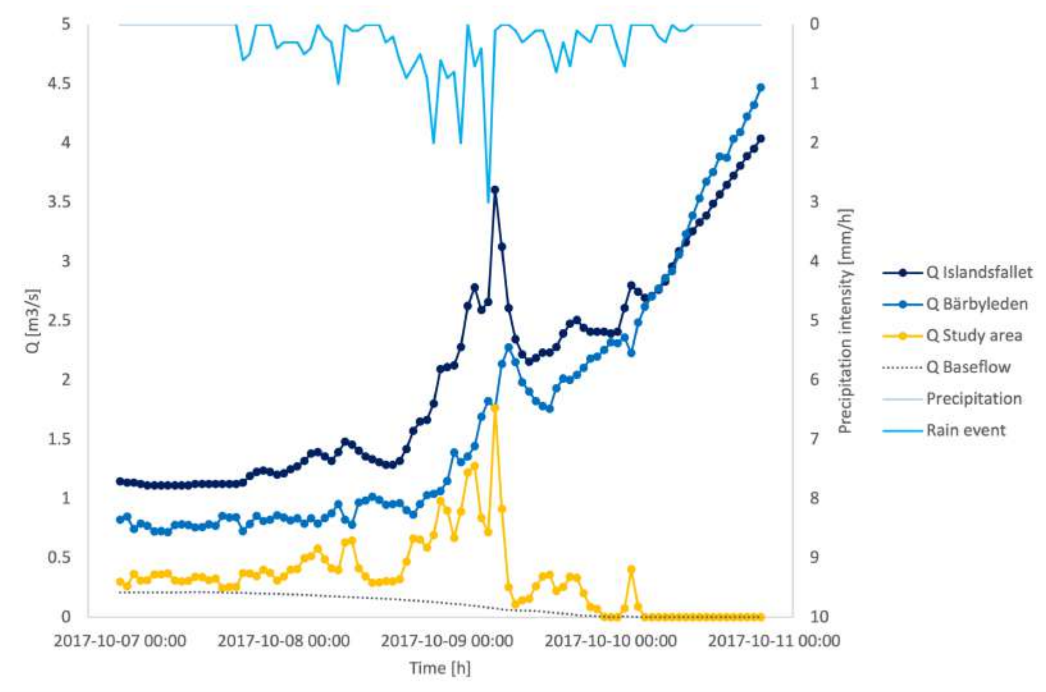


Figure E.10: *The rain event starting 2017-10-07. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow.*

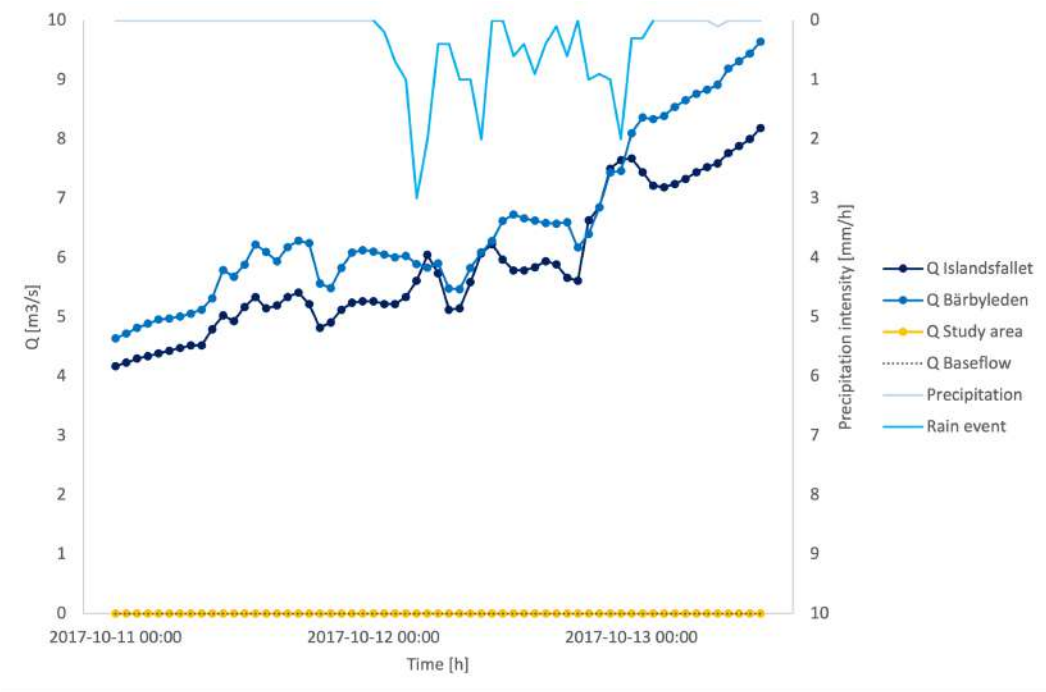


Figure E.11: *The rain event starting 2017-10-12. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow. Q Bärbyleden was greater than Q Islandsfallet. Therefore, this rain event was not included in the analysis.*

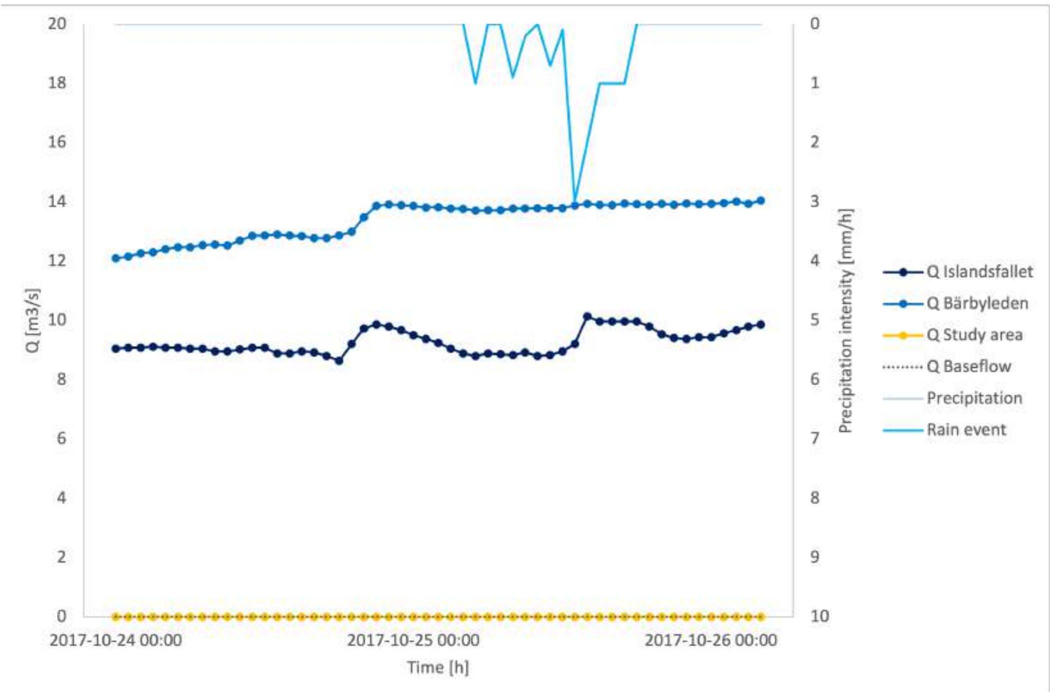


Figure E.12: *The rain event starting 2017-10-25. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow. Q Bärbyleden was greater than Q Islandsfallet. Therefore, this rain event was not included in the analysis.*

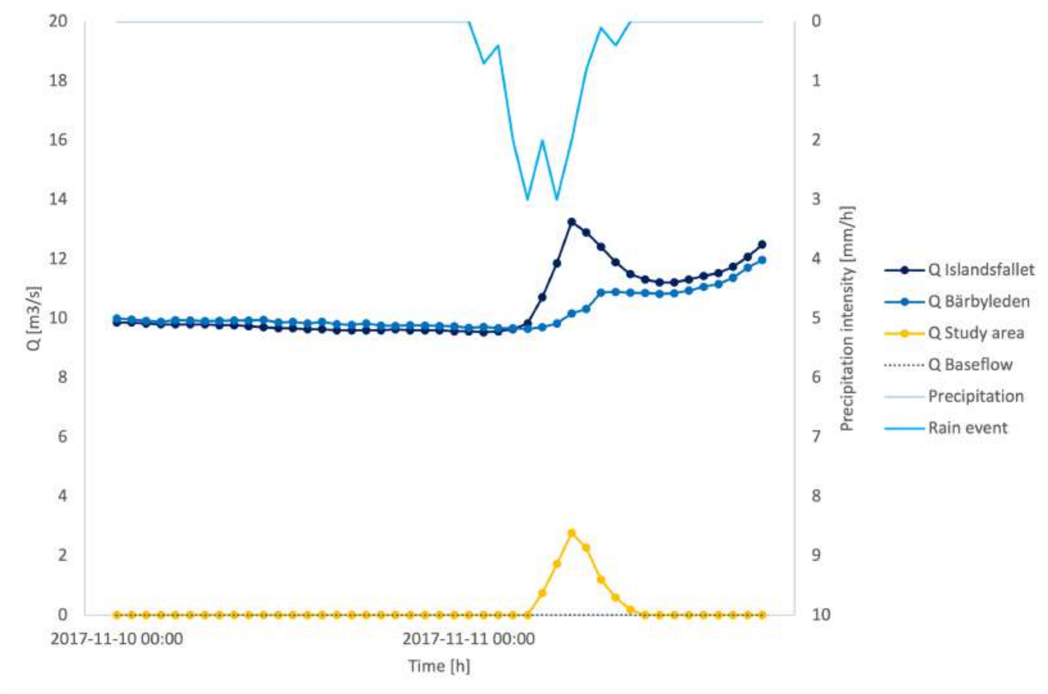


Figure E.13: *The rain event starting 2017-11-11. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow.*

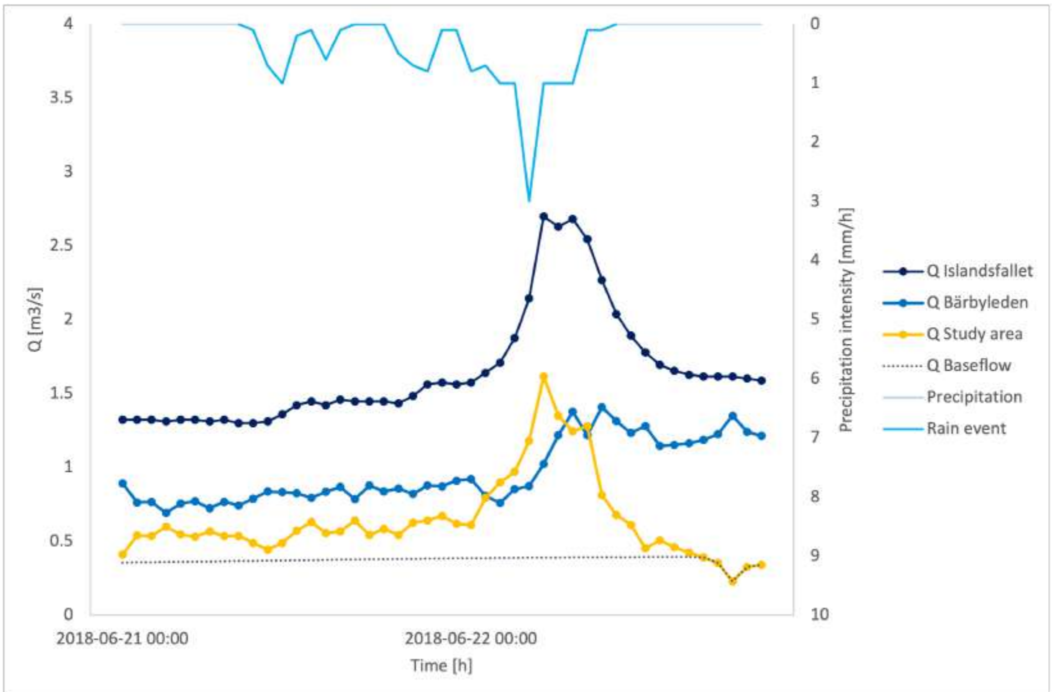


Figure E.14: *The rain event starting 2018-06-21. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow.*

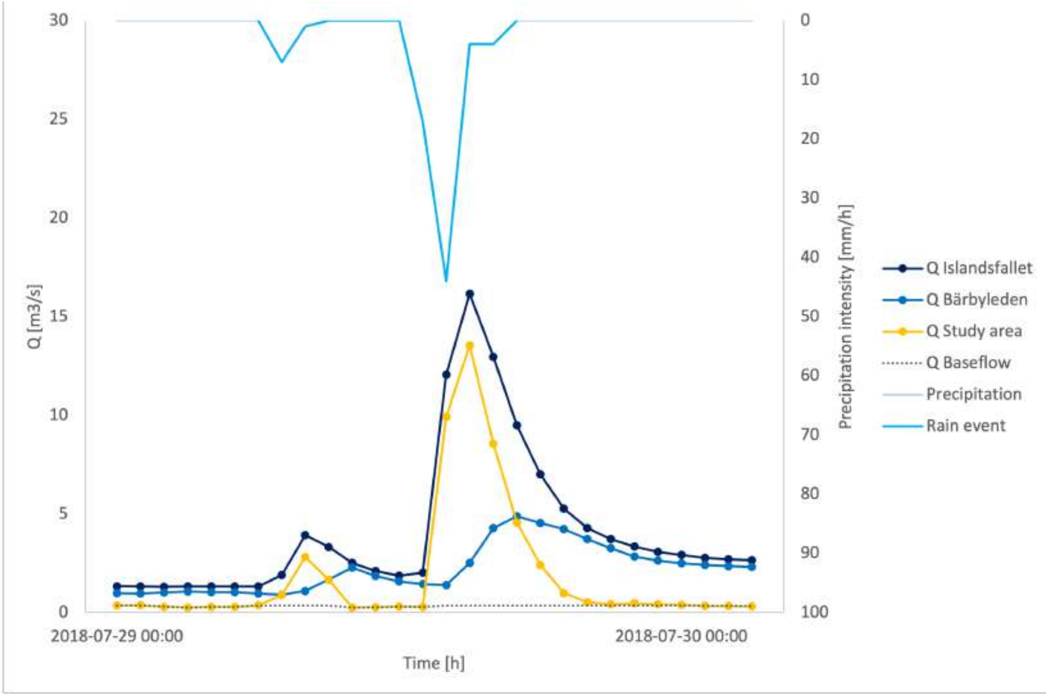


Figure E.15: *The rain event starting 2018-07-29. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow. This was an extreme rain event which caused headlines for inundating the Uppsala train station.*

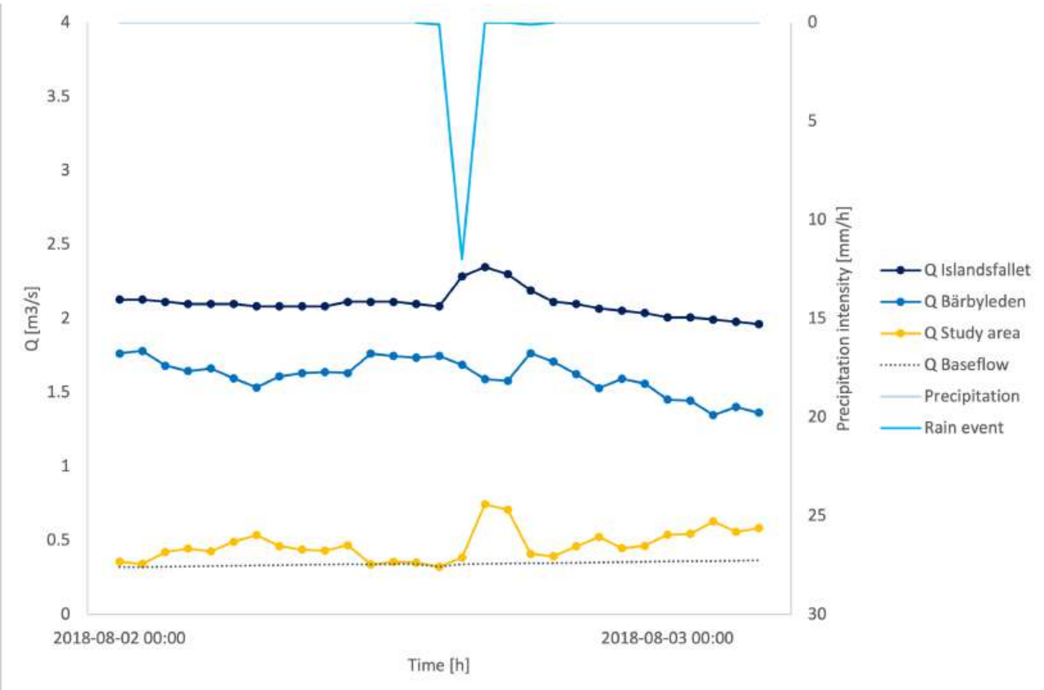


Figure E.16: *The rain event starting 2018-08-02. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow.*

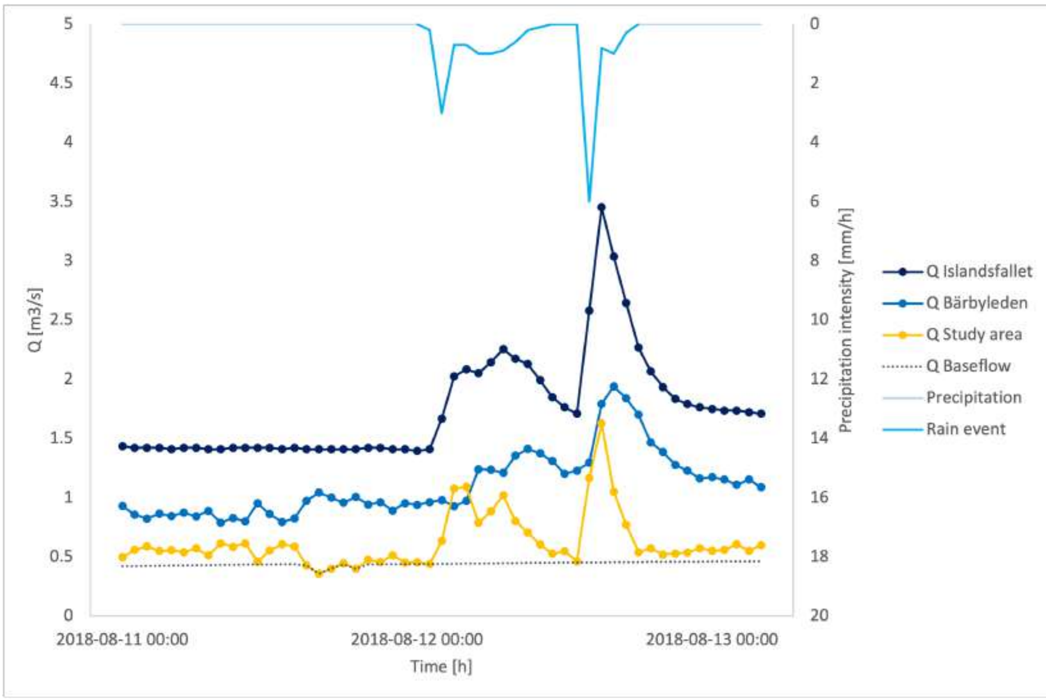


Figure E.17: *The rain event starting 2018-08-12. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow.*

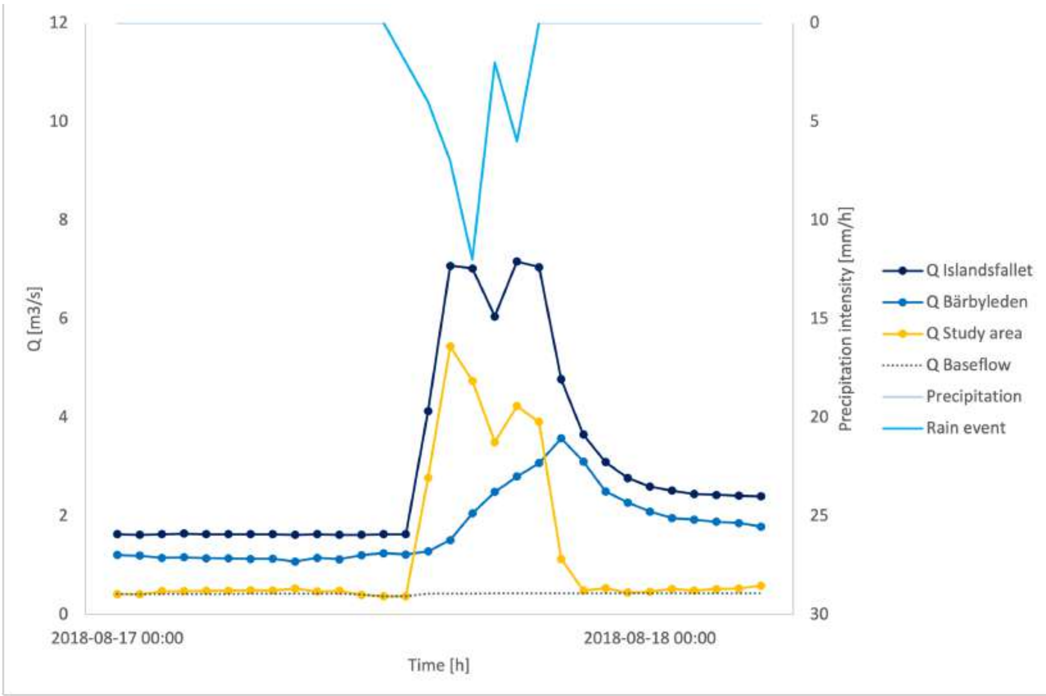


Figure E.18: *The rain event starting 2018-08-17. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow.*

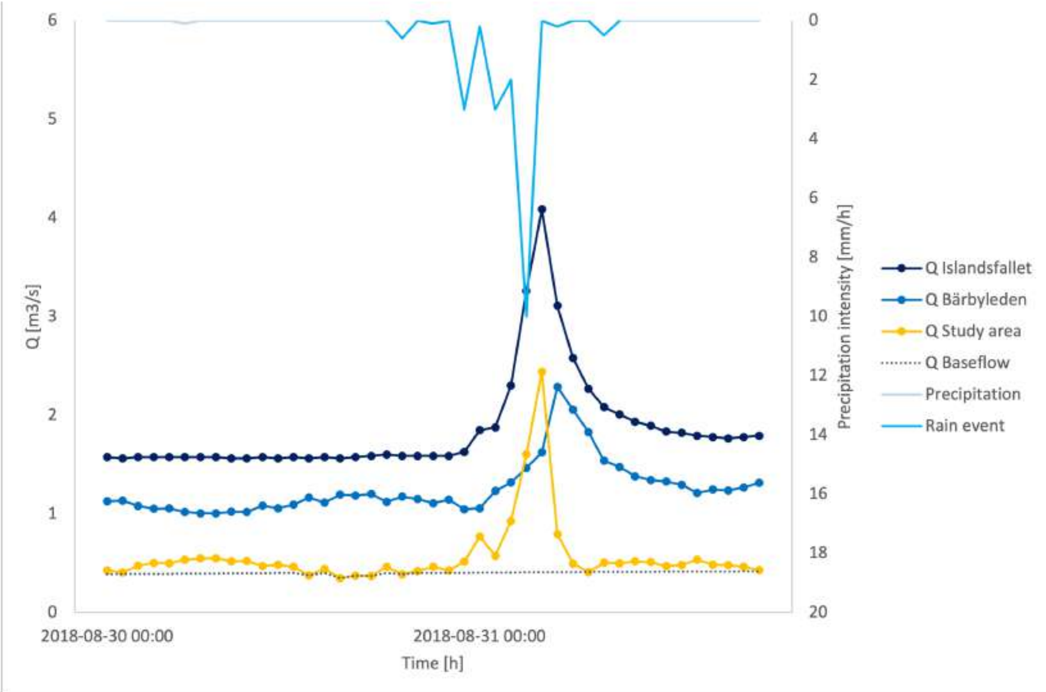


Figure E.19: *The rain event starting 2018-08-30. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow.*

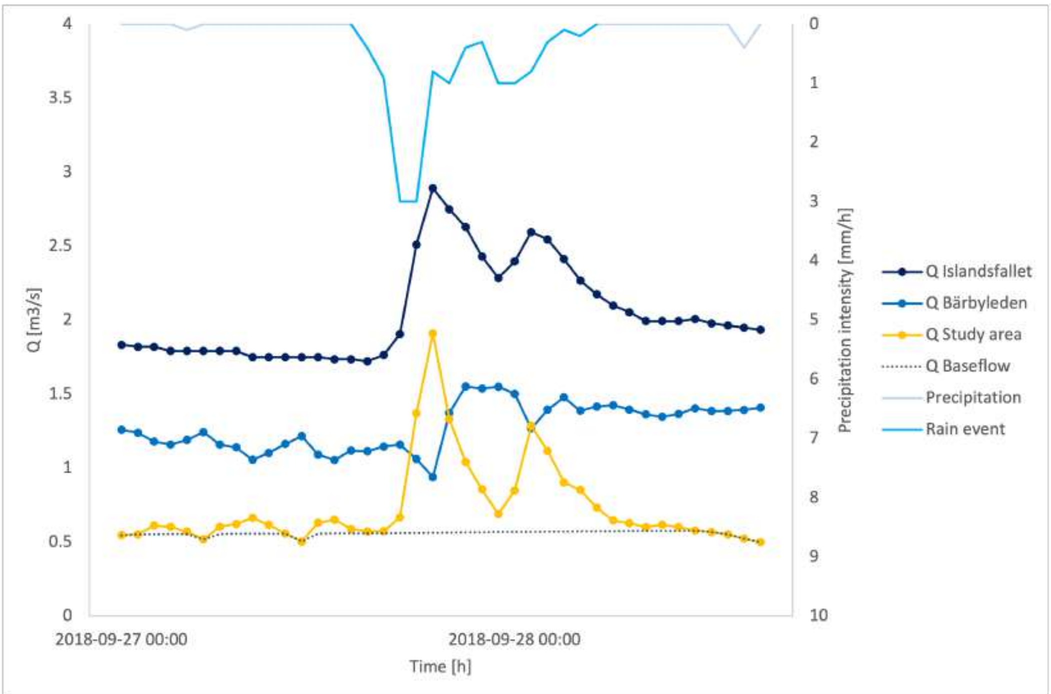


Figure E.20: *The rain event starting 2018-09-27. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow.*

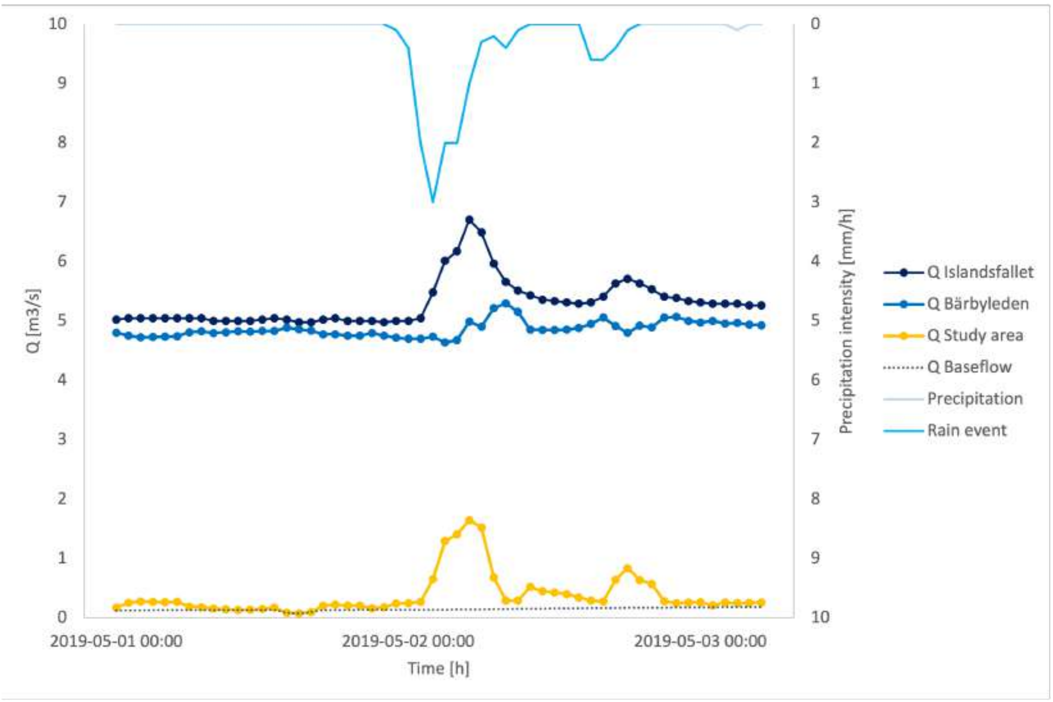


Figure E.21: *The rain event starting 2019-05-01. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow.*

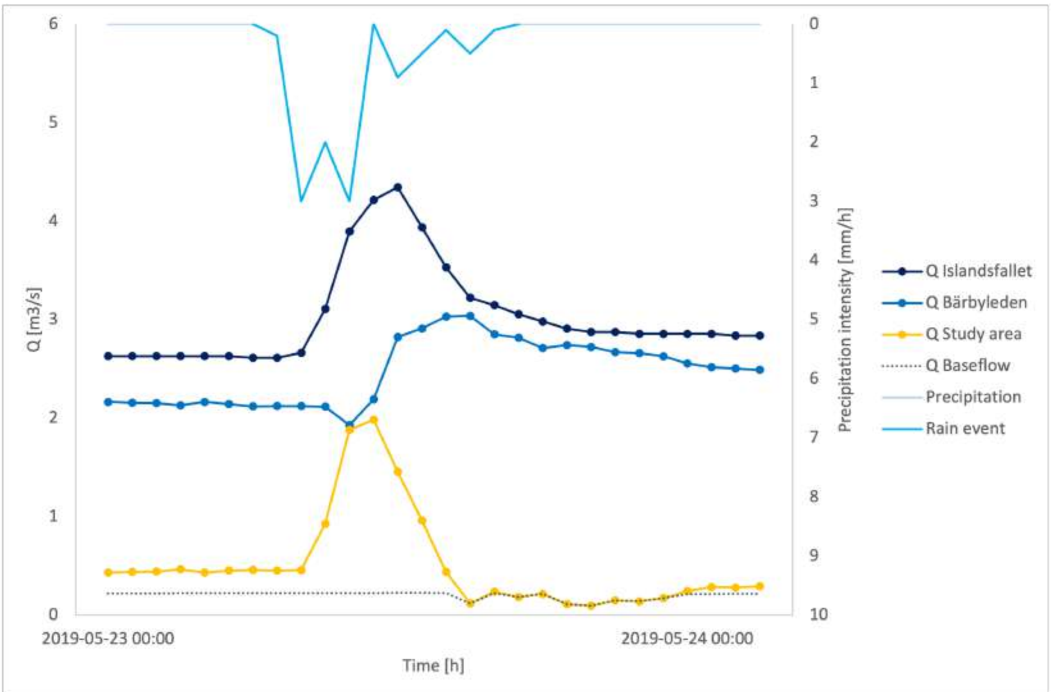


Figure E.22: *The rain event starting 2019-05-23. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow.*

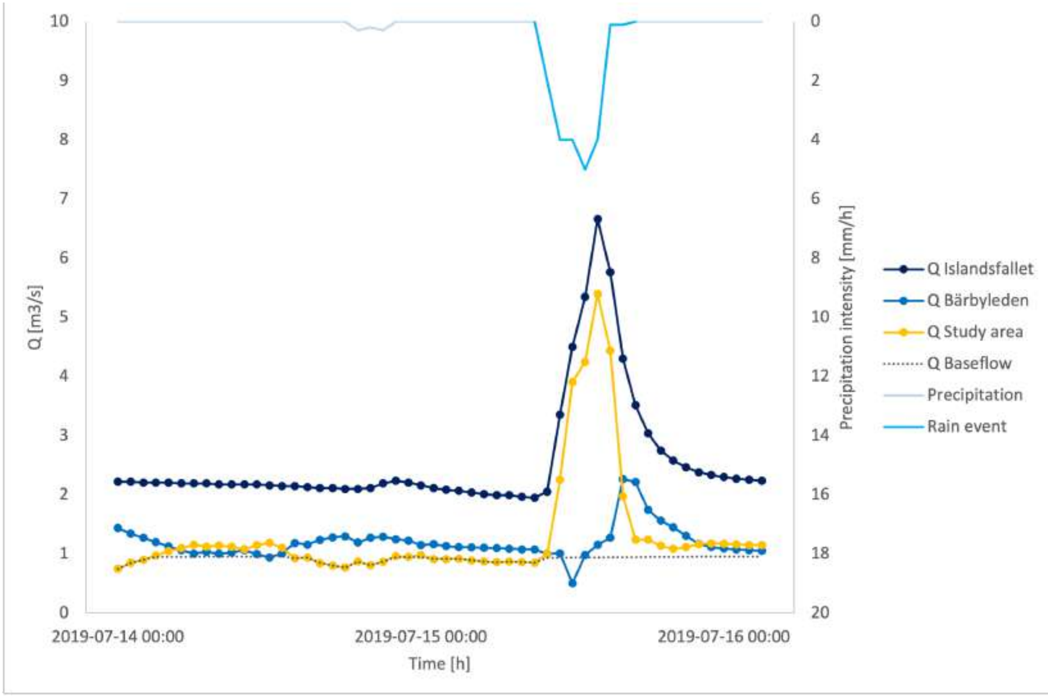


Figure E.23: *The rain event starting 2019-07-15. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow.*

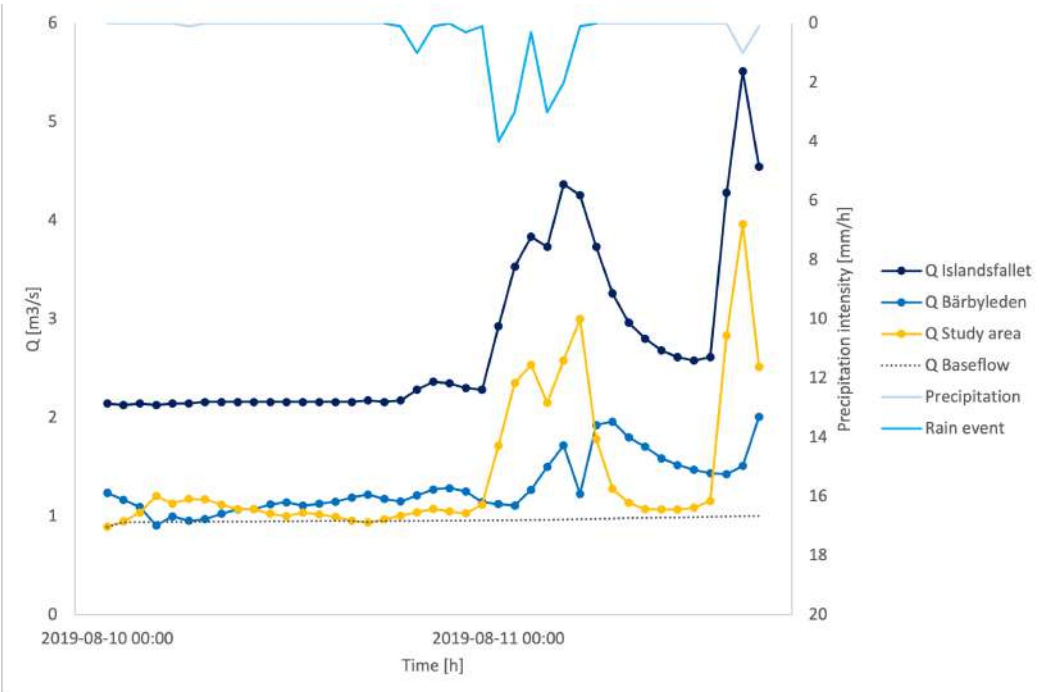


Figure E.24: *The rain event starting 2019-08-10. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow.*

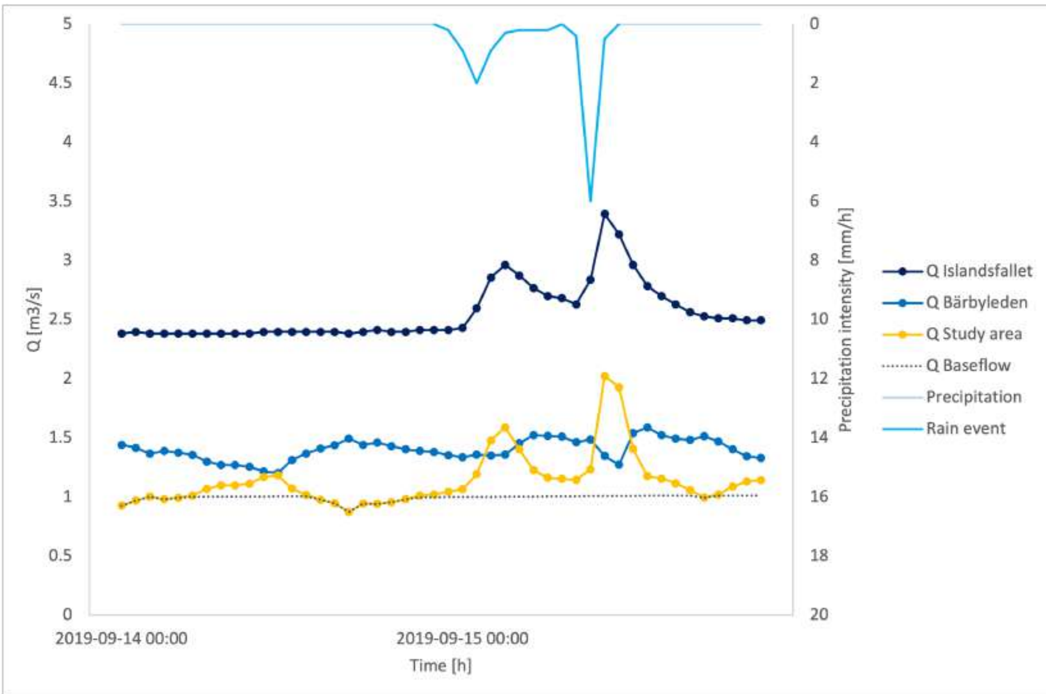


Figure E.25: *The rain event starting 2019-09-14. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow.*

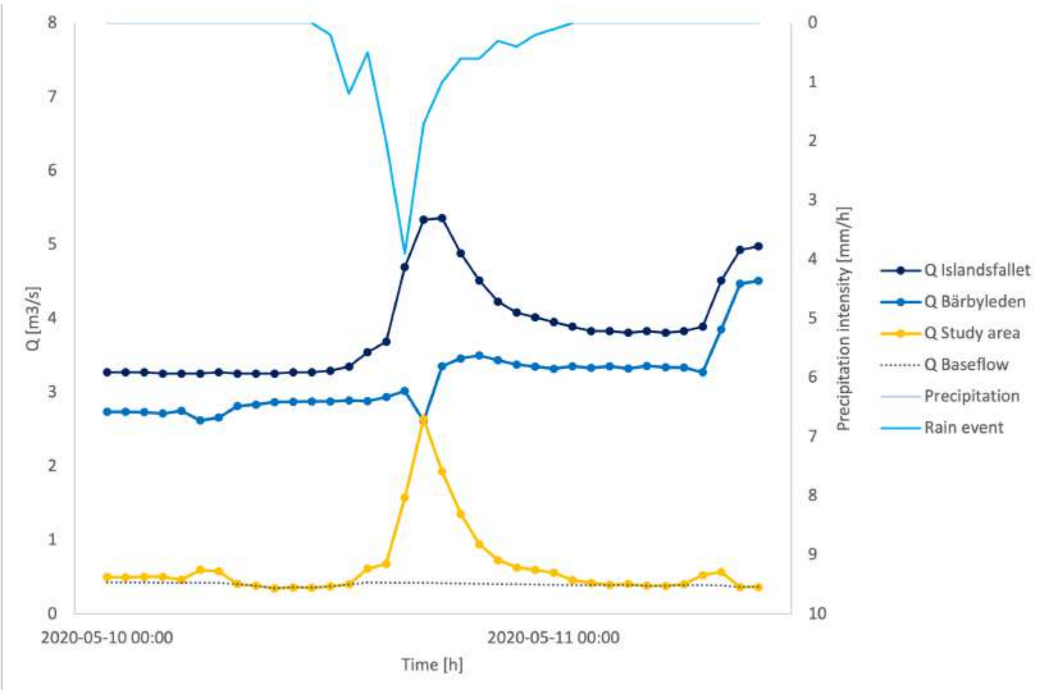


Figure E.26: *The rain event starting 2020-05-10. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow.*

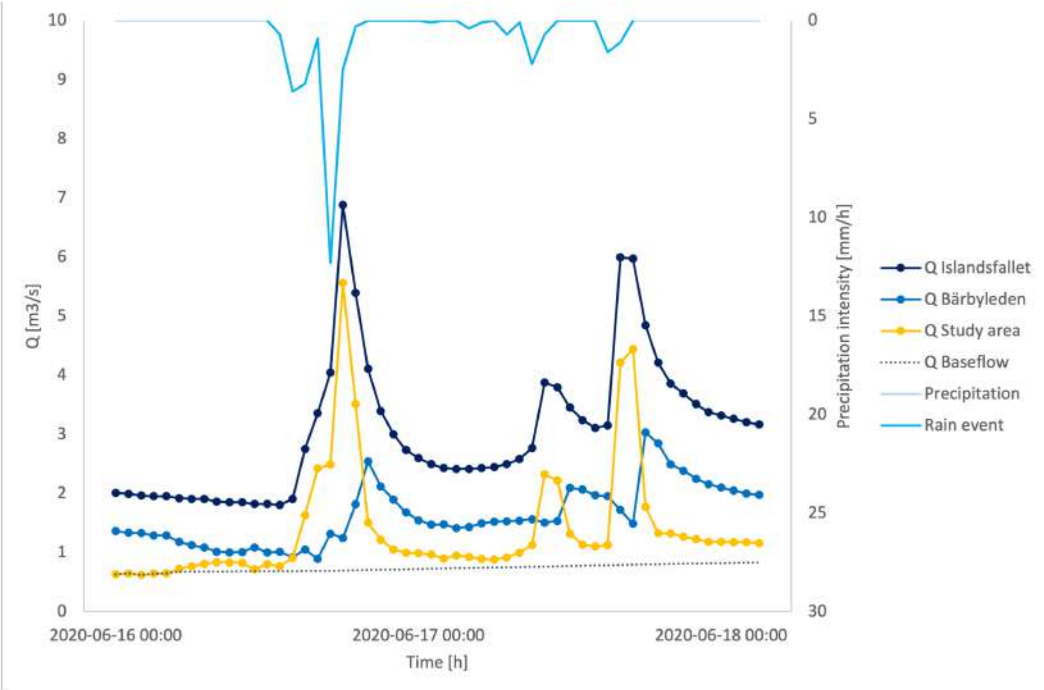


Figure E.27: *The rain event starting 2020-06-17. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow.*

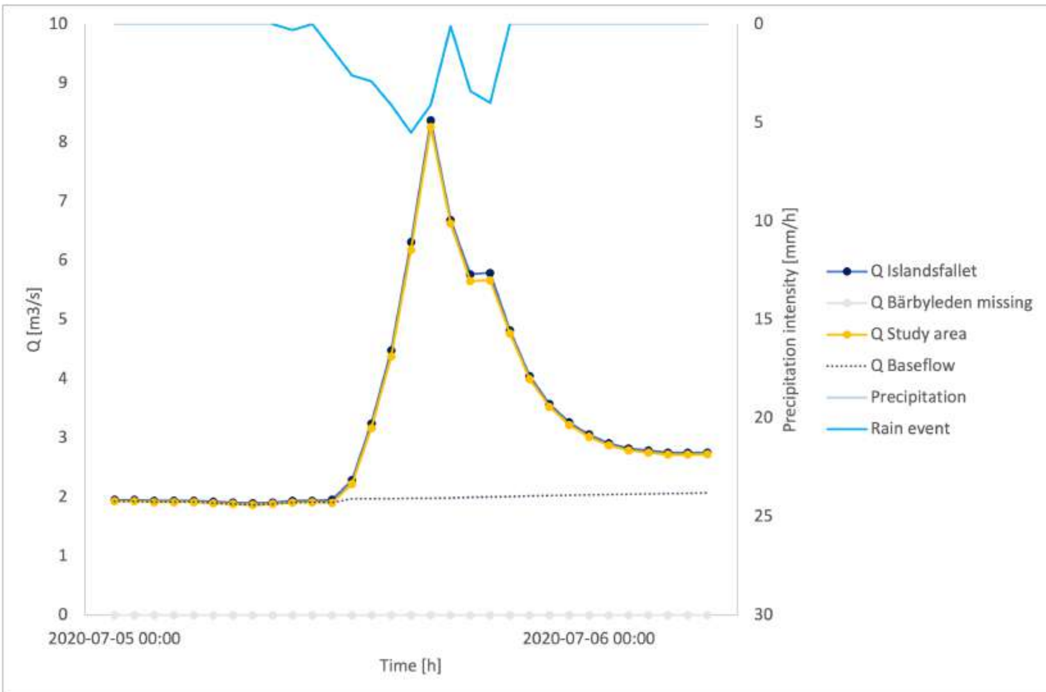


Figure E.28: *The rain event starting 2020-07-05. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow. Q Bärbyleden is missing. The quickflow therefore cannot be said to be only urban runoff from the study area. However, this rain event was still included in the analysis.*

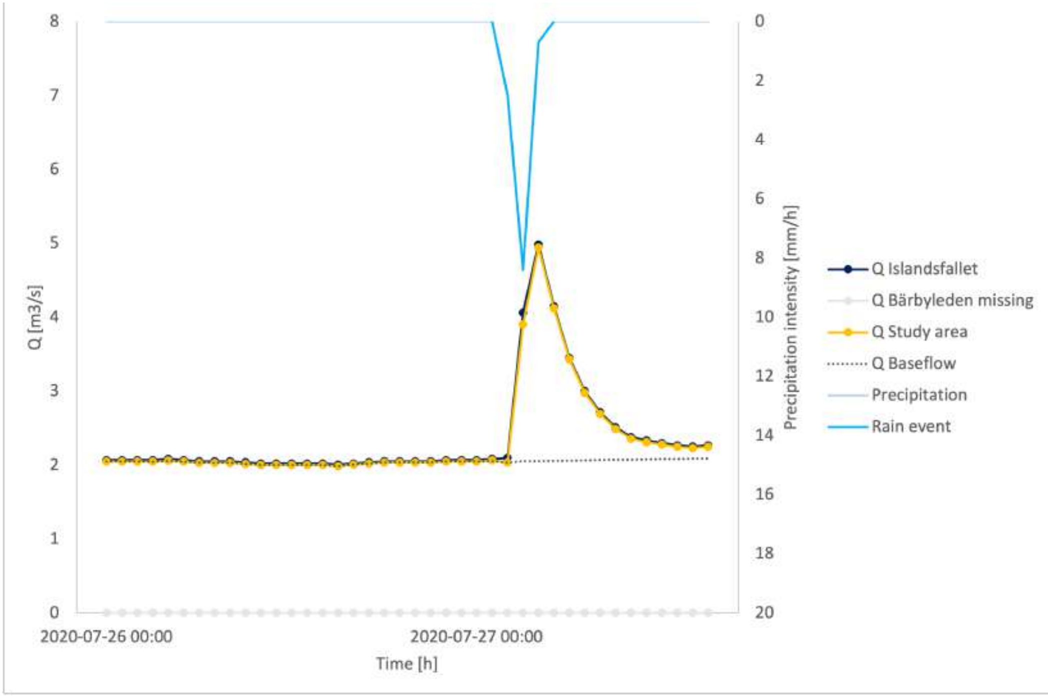


Figure E.29: *The rain event starting 2020-07-27. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow. Q Bärbyleden is missing. The quickflow therefore cannot be said to be only urban runoff from the study area. However, this rain event was still included in the analysis.*

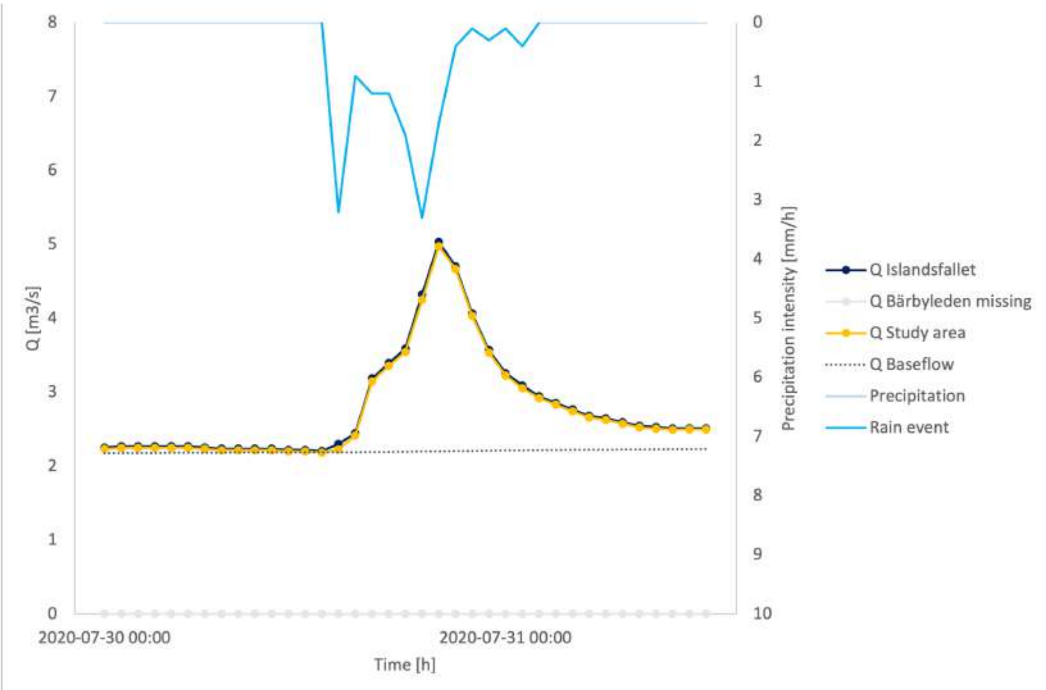


Figure E.30: *The rain event starting 2020-07-30. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow. Q Bärbyleden is missing. The quickflow therefore cannot be said to be only urban runoff from the study area. However, this rain event was still included in the analysis.*

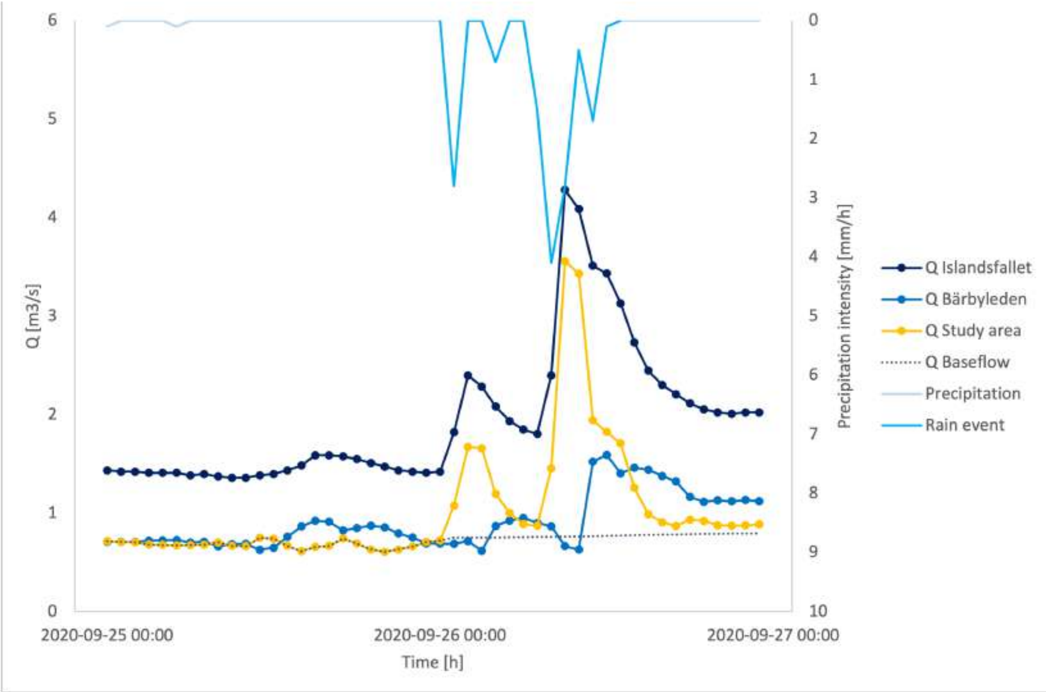


Figure E.31: *The rain event starting 2020-09-26. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow.*

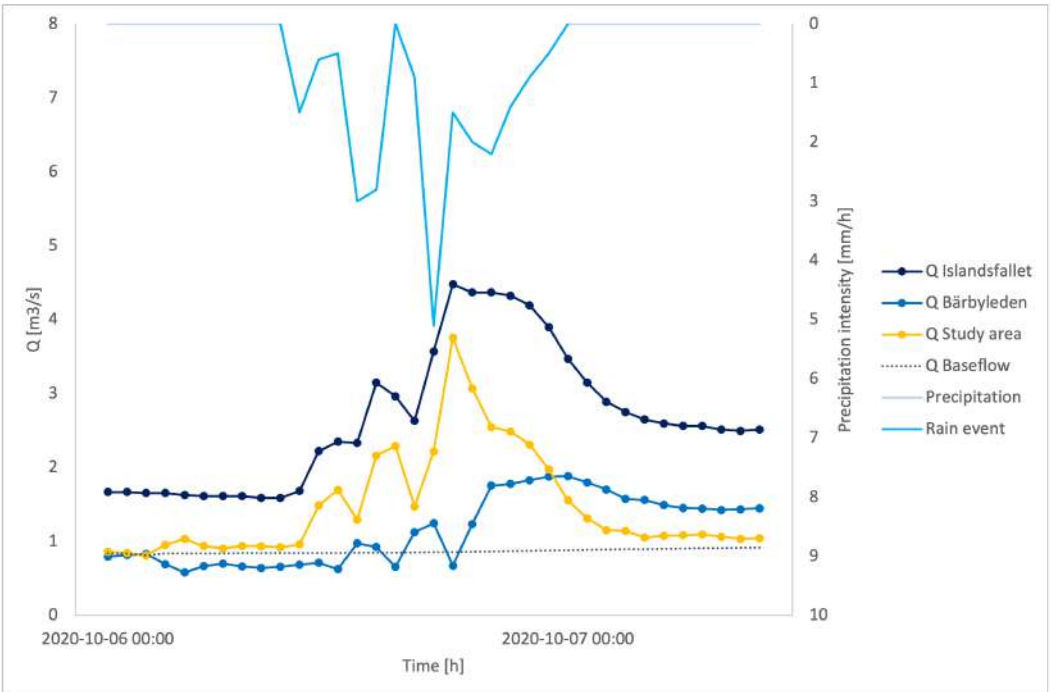


Figure E.32: *The rain event starting 2020-10-06. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow.*

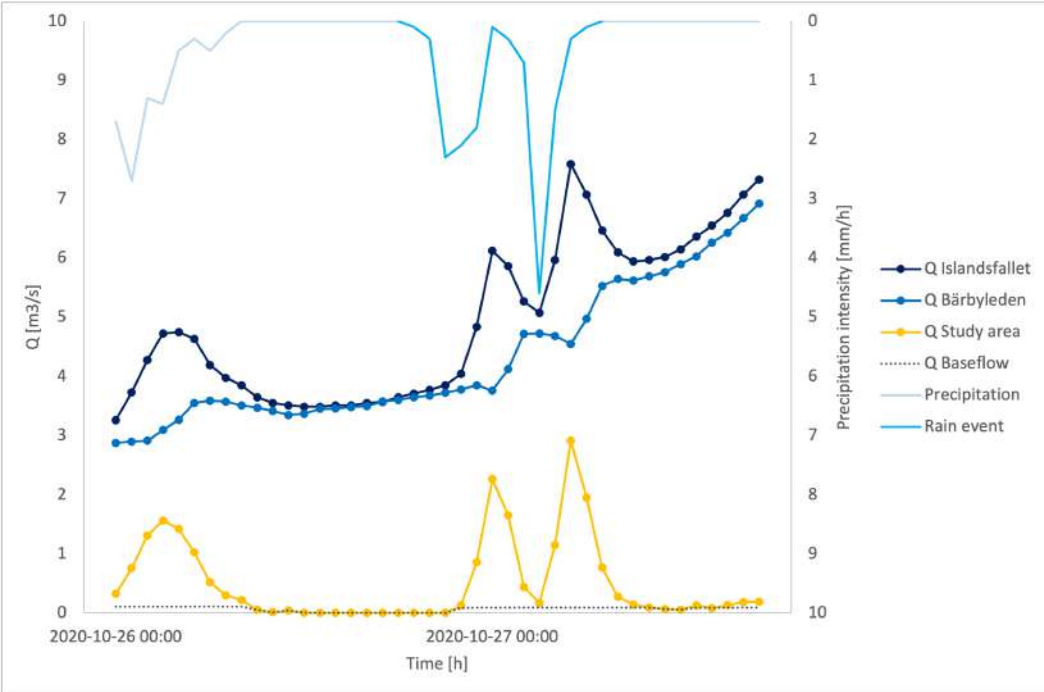


Figure E.33: *The rain event starting 2020-10-26. The difference between Q Study area (yellow) and Q baseflow (dotted) is the urban runoff quickflow.*