Birgitte Taugbøl Kragset

Modelling of the Interaction Between Storm and Foul Sewers in a Joint Model and Assessment of Infiltration and Inflow (I/I)

A Case Study at Risvollan, Trondheim

Master's thesis in Civil and Environmental Engineering
Supervisor: Sveinung Sægrov
June 2019

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Kunnskap for en bedre verden

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Abstract

One of the biggest challenges in management of sewer systems is the occurrence of infiltration and inflow (I/I). Extraneous water entering the sewer system have negative effects on both the capacity, performance, cost and reliability of the system. I/I can enter the pipe system in different ways, have different sources, and vary with seasons and weather conditions. The wastewater entering the treatment plants in Trondheim consist of more than 60% I/I, and is therefore a problem that should be addressed.

In this project the situation regarding I/I at a study area at Risvollan in Trondheim will be assessed, with the use of a computer model. Such models are used more and more in water engineering and have a wide range of application. The model that is built in this project is innovative because it combines the sewer system and stormwater system in the same computer model. The project involves two main parts: building the computer model and analysing its success and source data, and using the model to assess the situation regarding I/I at Risvollan.

The results of the project showed that combining the two systems in one model was successful. The model was able to run and be calibrated for both the sewer and stormwater system. Lack of data with sufficient quality made the results regarding I/I incomplete. Yet, a constant part of I/I of 22% during dry conditions and clear signs of increased discharge during wet conditions, confirmed the strong occurrence of extraneous water in the system at Risvollan.

Sammendrag

En av de største utfordringene ved forvaltning av avløpsnett i Norge er tilsig av fremmedvann. Innlekking og infiltrasjon av fremmedvann har negative konsekvenser for både kapasitet, ytelse, kostnad og pålitelighet til et avløpssystem. Fremmedvann kan komme inn på systemet på ulike måter, ha ulikt opphav og variere med sesong og værforhold. I Trondheim utgjør fremmedvann mer enn 60% av vannet som fraktes til renseanleggene.

I dette prosjektet analyseres forekomsten av fremmedvann på et felt ved Risvollan i Trondheim ved hjelp av en datamodell. Datamodeller blir mer og mer brukt innenfor vannfaget og har mange bruksområder. Modellen som er laget i dette prosjektet er innovativ ved at den kombinerer både avløps- og overvannssystemet i samme datamodell. Prosjektet består av to hoveddeler: bygging av datamodellen inkludert analyse av den ferdige modellens yteevne og datagrunnlag, og bruk av modellen til å analysere forholdene relatert til fremmedvann på Risvollan.

Resultatene fra prosjektet viste at det var vellykket å lage en modell som inneholdt både avløps– og overvannssystemet. Det var mulig å kjøre modellen, samt kalibrere den for begge type systemer. Data med varierende kvalitet gjorde at resultatene angående mengden fremmedvann på Risvollan ble mangelfulle. Likevel, en konstant innlekking under tørre forhold på 22 % og tydelige tegn på økt vannføring ved våte forhold, viser klart tilstedeværelsen av fremmedvann.

Preface

This project is my Master Thesis in water and wastewater engineering at the Norwegian University of Science and Technology (NTNU), as the final part of my Master of Science (MSc).

There are several people who have helped me and supervised me through this work. Sveinung Sægrov was the initiator behind this project, and has been my main supervisor. I want to thank him for good guidance and useful discussions. A special thanks to co-supervisor Marius Rokstad, who have assisted me with the modelling in PCSWMM and been very helpful with all of my questions during my work. Additionally, I want to thank Trondheim Municipality for good cooperation. The necessary data and information about the study area was key to successfully carry out this project.

Birgitte Taugbøl Kragset, 05.06.2019

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1 Project Background

1.1 Situation regarding I/I in Trondheim

The amount of infiltration and inflow in sewer systems in Norway is high compared to other European countries. A study done by Lindholm and Bjerkholt (2011) found that among wastewater systems across Norway, the average infiltration and inflow exceeds 50%. At the largest wastewater treatment plants, the amount of I/I was even higher, being from 50% to 80%. This includes the wastewater treatment plants in Trondheim.

Trondheim Municipality have in their “Water and Wastewater Masterplan 2013-2024” addressed the problem of I/I and the significance of extraneous water in the sewer system. The plan points out the negative effects of I/I, especially at the wastewater treatment plants. It lays out the need for further action and measures to improve the situation, e.g. through separation of combined sewer systems and rehabilitation of the existing system.

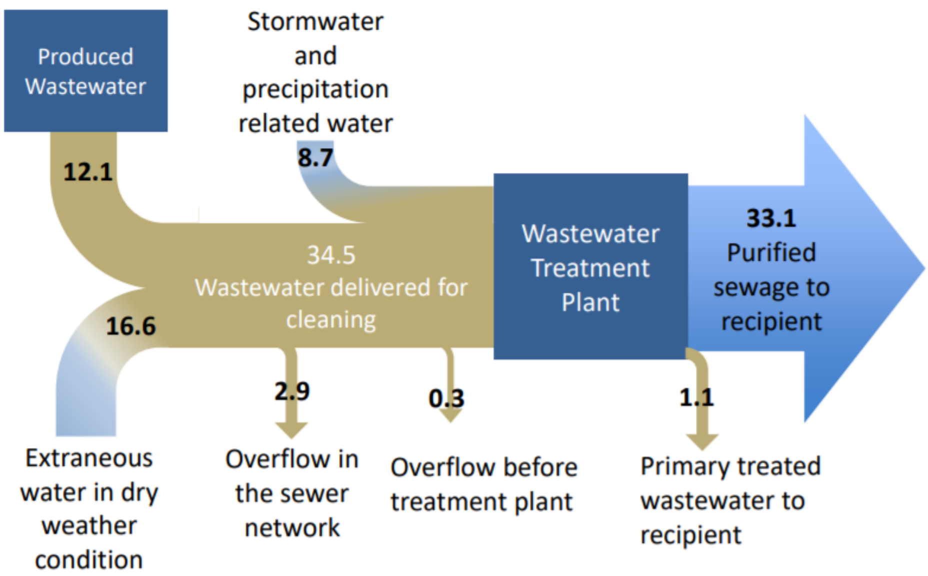

Figure 1.1. Origin and amount (in million m³) of wastewater in Trondheim (Beheshti and Sægrov, 2018)

Figure 1.1 shows the origin and the proportions of the water in the wastewater system when reaching the wastewater treatment plants in Trondheim. The infiltration and inflow in Trondheim is around 67% (in the period 2009-2011). The amount of I/I in dry conditions is almost twice as high as the infiltration related to precipitation and wet conditions. I/I affects the wastewater system in Trondheim significantly and should be addressed.

1.2 Computer Models

Computer models and GIS-tools (Geographical Information Systems) are being more and more used in the water sector (Johnson, 2009). It is applied in academia, in private sectors and are also widely used by municipalities and governmental departments around the world. Computer models have a wide range of applications, including assessing the situation regarding I/I.

Usually, when creating models for separated sewer systems, the sewer and stormwater system are not constructed together in the same model. This limits the possibilities to analyse the interaction between the two system. Even if the systems theoretically, and ideally should be fully separated, they can interact. This can occur when pipes are close to each other, or when elements of the systems are common, such as sewer and stormwater pipes going through the same manholes, which can be the case in Norway and Trondheim.

In this project a computer model is built for the separated sewer system at Risvollan, containing both the sewer and stormwater system. According to NTNU, it has not been constructed a model with both parts of a separated system previously at NTNU or in Trondheim Municipality. A search in literature for such models also gives no indication that it has been done before.

1.3 Project goal and Research Questions

This project aims at building a computer model that contains both parts of the separated system; the sewer system and the stormwater system. The model calibration will be based on flow measurements in the period February 2019 – May 2019. The goal is that the model is successfully calibrated, that it can be used for assessing the situation related to I/I, and additionally to look at the interaction between the sewer and stormwater system. The water balance method will be used to assess the situation regarding I/I, and the project aims at giving answers to the amount of I/I in the sewer system.

Research questions:

- Is it possible to build a computer model with the sewer and stormwater system together?
- Is the available data of sufficient quality to have a successful calibration of the model?
- What is the situation regarding I/I at Risvollan?

1.4 Disposition

The thesis will first present some general information about sewer systems, and the issue of infiltration and inflow. This includes what I/I is, its consequences, where it comes from, and seasonal variations. This part will be based on a literature study. Section 2.2.1. to 2.2.4 is based on work during the fall semester 2018, for a similar project on I/I at Lykkjbekken pumping station in Trondheim.

The theoretical section is followed by a description of the study area at Risvollan. Thereafter, the method used will be described. This includes a description of the utilised modelling tools, the process of building the model, the data collected and used in the project, and simulation and calibration of the model. The results will be presented and discussed, followed by the conclusion and recommendations for further work.

2 Theoretical background

2.1 Sewer systems

Sewer systems can be divided into two main types of systems; separated or combined systems (Brombach et al., 2005). A combined system transports both the dry weather flow, from households and industry, together with wet weather flow from precipitation. In separated system, the sewer convoys the dry weather flow and water coming from I/I, while the stormwater systems transports the wet weather flow (Mannina and Viviani, 2009). Several studies has tried to find out what the best system is, especially according to pollution load release (Brombach et al., 2005). The results from the studies show that for some pollutant indicators the combined system is better, and for others the separate system is a better solution. Therefore, the choice of system must be evaluated for each case and project. In towns and cities in Norway there are a mix of the two types, but separate systems are dominating and are mostly chosen when developing new areas (Norsk Vann, 2014).

2.1.1 Interaction between sewer and stormwater systems

In literature, there are plenty of research done on both combined and separate sewer systems. In the case of a separated system, the available literature often focuses on one of the systems isolated. There are in fact very little research done on separated systems that include analyses on both systems and that gives information about how they interact.

A study done on a small suburban watershed in Nantes in France does give some information about how the systems interact. It presents the response in both the stormwater system and wastewater system to rainfall events from September 2002 to March 2004 (Ruban et al., 2005). Over this period the pipe system, including both systems, drained 42% of the rainwater. The majority of this is collected by the stormwater system, making up 34% of the runoff, while the wastewater system drains 8% of the rainfall. This means that of the rainfall ending up in the pipe system, 81% is drained by the stormwater system and 19% ends up in the wastewater system. The study shows that the systems are not fully operating as they in theory are planned, and that the response of one system influences the response of the other.

2.2 Introduction to infiltration and inflow

2.2.1 What is I/I?

Infiltration and inflow of extraneous water is an important issue in sustainable wastewater management (Beheshti et al., 2015). Infiltration and inflow refer to extraneous non-sewer water that enters the sewer system. This water is also known as parasite water in separate storm sewers (Weiss et al., 2002). Infiltration occurs when groundwater or infiltrated stormwater is leaking into the pipe system through cracks, holes or broken parts of the pipes (Benninger, 1984). Inflow is referring to unwanted water that enters the sewer through direct connections. These can either be intended or illicit connections, the former situation in combined sewer systems and the latter in separated sewer systems (West Virginia University, 1999). The occurrence and magnitude of I/I is dependent on several factors. This includes geological conditions, sewer material, age of the system, surface condition and the hydrological situation (Hey et al., 2016).

2.2.2 Consequences of I/I

Infiltration and inflow lead to undesirable consequences for the sewage system and the society. I/I affect the efficiency, capacity and cost for both the pipe system and the treatment facilities. Increased water flow will lead to higher hydraulic stress in the system. This can result in flooding of surface areas and increased separate and combined sewage overflows (SSO and CSO) (Karpf and Krebs, 2011). Consequently, this increases the risk of polluting local areas and the receiving waters. Flooding and overflows can also lead to damage on infrastructure and property and can cause a health risk for the public (Hey et al., 2016). More water also means higher operational costs for pumping stations, increased energy costs and maintenance requirements (Beheshti et al., 2015). High amount of I/I means that the pipe system must be dimensioned for larger amount of water than otherwise needed, and thus increasing the total cost of the system.

Intrusion of extraneous water will in addition dilute the sewage water. This will have consequences for the efficiency, cost and capacity of the wastewater treatment plants (Wittenberg and Aksoy, 2010). The capacity of the treatment plant to treat wastewater will evidently be lower when additional extraneous water must go through the facility. If the capacity is reached, there can be cases of untreated sewage overflows, polluting the recipient (Hey et al., 2016). With increased incoming water amounts, the efficiency of the treatment process is reduced, while the operational cost is increased through higher energy demand and increased use of chemicals. Diluted water going through the treatment facility will convoy pollutants through the treatment plant and to the recipient. This water will be more polluted than when it entered the sewer as infiltration or inflow (Lindholm and Bjerkholt, 2011).

I/I has an impact on infrastructure, economics, the environment, and public health risk. Reducing infiltration and inflow will have a positive effect on pollution control, capacity and operation of the system, economy, and public health and safety.

2.2.3 Sources of I/I

There are numerous sources to infiltration and inflow. In general, it can be divided into two main categories; the I/I that is related to precipitation, and infiltration not related to wet conditions. The first category can further be split into two; inflow directly from precipitation, and rainfall induced infiltration (Wittenberg and Aksoy, 2010). The different sources are illustrated in Figure 2.1.

The direct inflow from rainfall have different ways of entering the system. The water can enter through illicit connections that brings stormwater from roof drains or street drains to the sewer. The inflow can also find its way through unsealed manholes. After a rainfall event, the inflow component will give a flow peak in the sewer pipes that are closely related to the time and length of the rainfall event (Weiss et al., 2002).

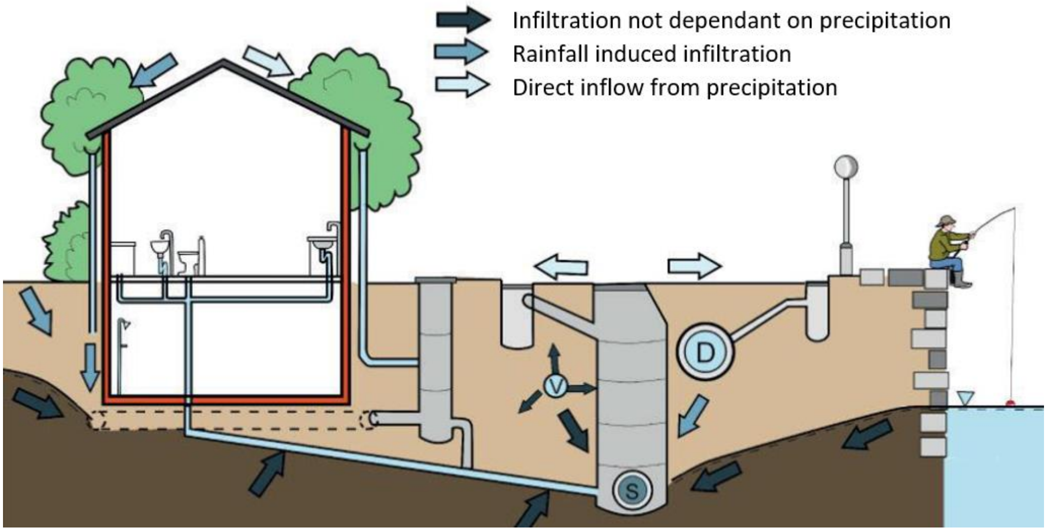

Figure 2.1. Sources of infiltration and inflow (Lundblad, U., Backö, J., 2014)

The rainfall induced infiltration means water that is related to precipitation but is not entering through direct connections from above the ground. This type of extraneous water comprises stormwater that infiltrates the ground, percolates through the soil until it reaches the sewer pipe and enters through cracks and holes. Seasonal variations, such as wet periods and potential snowmelt can cause a rise of the groundwater table and lead to increased infiltration (Belhadj et al., 1995). The rainfall induced infiltration can also be led to the sewer through drainage pipes surrounding residential houses. With a separated sewer system, the drainage pipes should either lead the water to the groundwater or be connected to a storm water pipe, but in practice many drainage pipes are wrongly connected to the sewer system (Weiss et al., 2002). The rainfall induced infiltration will have longer response time than the direct inflow. The effect of this type of infiltration will therefore be visible in the system with a delay after the rainfall, last over a longer time frame, and will not lead to a sudden peak flow (Weiss et al., 2002)

The third main category is constant infiltration not related to precipitation. Groundwater leaking constantly into pipes lying below the groundwater table is the main source (Belhadj et al., 1995). This infiltration is related to situations when the pipe is surrounded by groundwater independent of the hydrological cycle and seasons, as opposed to the rainfall induced infiltration, that is related to the rise of the ground water level because of precipitation or snowmelt. Streams and creeks can also be a similar source. Furthermore, leaks from nearby waterpipes can contribute to infiltration (Norsk Vann, 2014). Potential leakages from these pressurized pipes may find its way to the sewer system.

2.2.4 Seasonal variations

Because infiltration and inflow is dependent on hydrological conditions, it also varies with seasons (Wittenberg and Aksoy, 2010). The infiltration coming from groundwater shows a clear seasonal variation related to the fluctuations of the groundwater level (Staufer et al., 2012). This constant infiltration typically has its maximum level during spring, due to snowmelt, and lowest level during summer with warmer and drier conditions (Weiss et al., 2002). The magnitude of these variations is highly dependent on local conditions, and cannot be generally quantified. Weiss et al. (2002) found that for some systems in Germany, the I/I can be as much as ten times as large in spring as in summer. Inflow does not follow a similar seasonal variation, as the response is directly related to precipitation and with a much faster response (Staufer et al., 2012). When precipitation fall as snow, the inflow is low which is often the situation in Trondheim during the winter season.

2.2.5 How to measure and locate I/I?

Several methods for assessing I/I in sewer systems have been developed. They can be divided into quantitative and qualitative methods (Beheshti et al., 2015). The quantitative aim to determine the volume of I/I, while the qualitative aim to find the locations where I/I appears. Among the quantitative methods, there are two that are most commonly used in Norway; the dilution method (DM) and the water balance method (WBM) (Jenssen Sola et al., 2018).

2.2.5.1 The Dilution Method

The dilution method is based on measurements of total Phosphorus (Tot-P) at the inlet of wastewater treatment plants to find the portion of I/I. Tot-P is used as a tracer based on assumptions of how much phosphorus one person produces per day, water consumption per person per day, and the number of people and industry connected to the pipe system. From this the sewage can be divided into water originating from drinking water and water from extraneous I/I. Even though this is considered a rough method, it gives a good indication on the amount of I/I in the system and are based on easily accessible data (Lindholm et al., 2012).

2.2.5.2 The Water Balance Method

The water balance method is also called the flow rate method and is the most conventional and widely used method internationally. It is a statistical analysis, with varying complexity, based on hydrographs of wastewater flow over a period of time. There are different ways of doing the analysis; the time scale differs from daily to annual and there are variations in how dry weather flow (DWF) is used in the calculations (De Bénédittis and Bertrand-Krajewski, 2005).

The concept of the method is to divide the total wastewater flow (Q_T) into two parts; wastewater from households and industry (Q_{WW}), and infiltration and inflow (Q_{INF}), shown in Equation 1.

$$Q_T = Q_{WW} + Q_{INF} \rightarrow \; Q_{INF} = Q_T - Q_{WW} \qquad (2.1)$$

A widely used assumption for this method is that the infiltration is constant in the daily dry weather flow (DWF), and that the diurnal minimum at night is equal to the extraneous infiltration of groundwater (Beheshti et al., 2015). In this case the calculations follow Equation 2.2, with an example of results in Figure 2.2.

$$DWF = P * G + I + E \qquad (2.2)$$

P=population, G= daily average water consumption per capita, I=daily average I/I, E=daily average industrial effluent flow

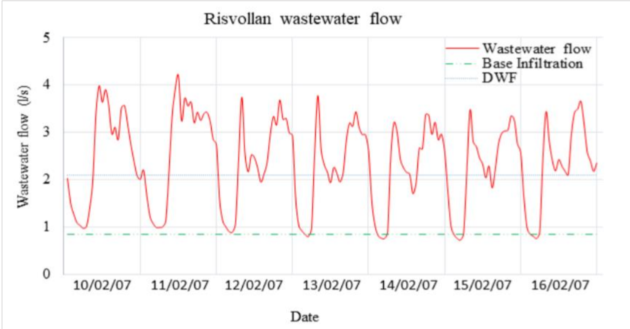

Figure 2.2. Wastewater flow, theoretical DWF and base infiltration at Risvollan (Beheshti et al., 2015)

The fact that wastewater flow hydrographs are the only input makes it an easy and convenient way of quantifying I/I. On the other hand, there are limitations because of the lack of complexity. Several assumptions and simplifications must be made, e.g. that the diurnal minimum is equal to constant infiltration. This assumption might not be valid as the catchments can be large and therefore have a long travel distance, and also because today's society has a 24 hour water consumption, at least in urban areas (Kracht et al., 2008).

The dilution method gives a higher amount of I/I than the water balance method (Jenssen Sola et al., 2018). This might be because in case of heavy rainfall, some water may be transported to recipients through a CSO or SSO, but still contributing to dilution of the sewage Vråle (1993).

2.2.5.3 Qualitative Methods

There are a wide range of methods available to detect where I/I occurs (Tuomari and Thompson, 2004). They vary in complexity, accuracy and cost. Some of the most widely used methods are dye testing, smoke testing, CCTV (closed-circuit television) inspection, fibre-optic distributed temperature sensing (DTS), intensive sampling and sewer damming. DTS is the only method among these that also can be used to quantify I/I. Which method to apply depends on the specific situation, there are not given that one method is always better than another (Benninger, 1984).

3 Study Area, Risvollan

The study area is situated in the southern part of Trondheim Municipality. The area was developed around 1970 and was established as a residential area dominated by apartment buildings. A hydrological research station was established at the downstream end of the catchment at Risvollan in 1986 by a cooperation between NTNU, The Norwegian Water Resource and Energy Directorate (NVE) and Trondheim Municipality. The station measures meteorological data and flow data from both the sewer and stormwater system.

Figure 3.1. Map of Trondheim with the study area indicated

The catchment size is 19.6 ha or 0.196 km^2, with a combination of impervious areas (roads and roofs) and vegetated area. The amount of impervious area is 26%, of which half is roofs and half is roads (Bøyum et al., 1997). As the area has not changed significantly the last 20 years, this is assumed to be similar to today's situation. The altitude varies across the area, as there are small hills and varying topography. The lowest part of the area is about 80 meters above sea level, while the highest is at 135 m. This is lower than the former sea level in Trondheim at 171 meters above todays level. This influences the soil condition and the infiltration capacity in the area. The soil consists of thick oceanic deposits, which are unsuitable for infiltration (Geological Survey of Norway, 2019).

The pipe system in the study area is a separated system, with both a sewer system and a stormwater system. The system was gradually established over six years from 1968, when the development of the residential area started. The pipes are mostly concrete pipes, but also PVC (polyvinyl chloride) pipes are used. As it is a residential area, most of the connected buildings are residential, but there is also a kindergarten connected to the system. According to data from the municipality, the number of people that are connected to the system is 1112. The main parts of the system are owned by the Municipality of Trondheim, while the pipe connecting each house to the system is privately owned. The length of the stormwater system is 4.77 km, including all pipes. The sewer system is 2.67 km long, excluding the connecting pipes.

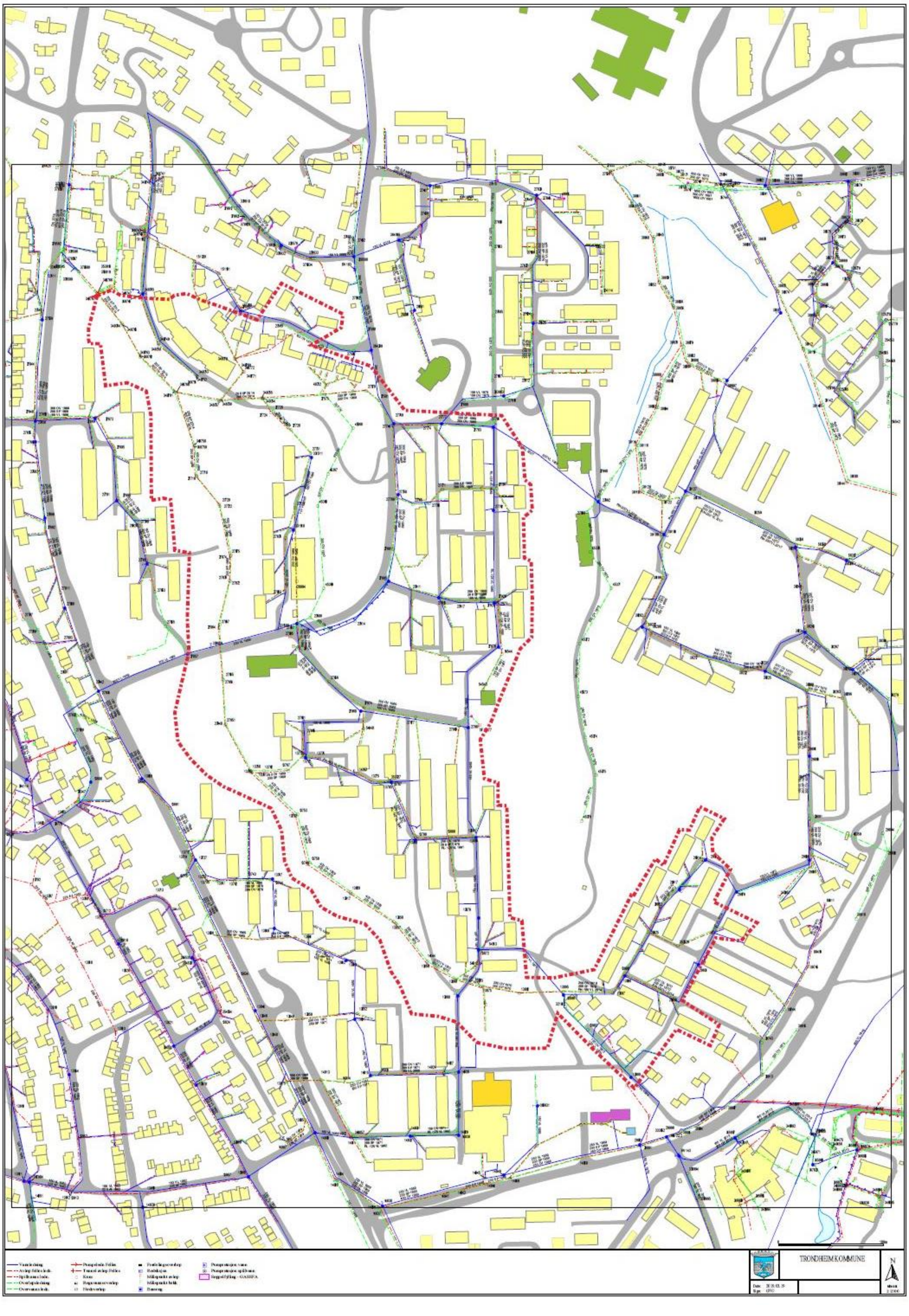

Figure 3.2. Map of the study area with pipe system and catchment area

4 Modelling

4.1 Storm Water Management Model (SWMM)

This project and the assessment of I/I will be carried out with the help of a computer model. The modelling program used is the Storm Water Management Model (SWMM), more specified the version PCSWMM, developed by the EPA (United Stated Environmental protection Agency). This model is a dynamic rainfall-runoff simulation model that has a large variety of hydrologic applications (Rossmann, 2015). The model can simulate runoff from subcatchments and contains hydrological routing through a user defined system of pipes, manholes, storages, channels etc. SWMM can be used for analyses, planning and design applications related to runoff generation, flooding, sewer overflows, pollution control etc. In this project PCSWMM was used to create a model of the study area and as a modelling tool for assessing the situation regarding infiltration and inflow, and the interaction between the two systems. The model will consist of both the sewer system and the stormwater system in a combined model.

Chapter 4.1.1 to 4.1.5 will explain briefly how SWWM is built up and the most important applications related to this project. All the information is from the SWMM manual (Rossmann, 2015).

4.1.1 Conceptual Model

Conceptually, SWMM divides the hydrological processes and the drainage system into four different environmental compartments; the atmosphere, the land surface, the groundwater and the transport compartment. The atmosphere compartment is where precipitation is generated and deposited onto the land surface department, which generates outflow to the groundwater compartment through infiltration, or to the transport compartment as surface runoff. The transport compartment is a network of conveyance and storage elements (pipes, nodes, channels, pumps etc.) that can receive water from surface runoff, groundwater inflow or dry weather sanitary flow, and leads the water to an outlet. Thus, SWMM has a wide range of applications and different modelling capabilities. When using PCSWMM it must be decided what parts of the modelling tools to apply. Models can be built with a wide range of complexity, from simple models using few of the modelling options, to complicated models accounting for all parts of the hydrological cycle and all physical processes. For instance, the modelling of stormwater runoff can include all of the following physical processes: surface runoff, groundwater, flow routing, water quality routing, infiltration, snowmelt and surface ponding.

Because of the limiting time for this project, not all modelling capabilities will be used. Nevertheless, the model can always be extended and improved for projects in the future. The most important modelling capabilities applied to the model for Risvollan are explained briefly in the next chapter.

4.1.2 Surface Runoff

The concept of how surface runoff is calculated on each subcatchment is shown in Figure 4.1. The subcatchments are nonlinear reservoirs where the inflow comes from precipitation and with three different outflow mechanisms; evaporation, infiltration and surface runoff. The surface runoff will be generated when the depth of the water exceeds the depression storage depth (d_s). The runoff is computed with Manning's equation.

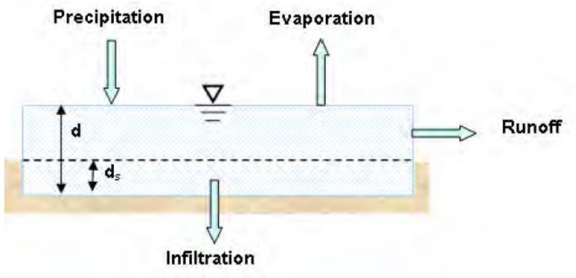

Figure 4.1. Conceptual view of surface runoff in PCSWMM (Rossman, 2015)

The infiltration component represents the water that infiltrates the pervious parts of the ground surface and percolates through the unsaturated zone of the soil. The infiltration can be calculated with different methods. SWMM offers four methods; Horton's method, modified Horton method, Green-Ampt method and modified Green-Ampt method.

The modified Horton method will be used in this project. This is because it requires less input than the Green Ampt-method, and is more accurate than the original Horton method, without requiring more input data.

4.1.3 Dry Weather Inflows

Dry weather inflows are continuous inflows and will in this project represent the sanitary sewage that is produced by households and discharged to the sewer system. The flow is added to the relevant nodes as an average flow rate, and can further be adjusted according to a designated time pattern for either hourly, daily or monthly variations.

4.1.4 Rainfall-Dependant Infiltration and Inflow (RDII)

This is the flow component entering the system as either infiltration or inflow in relation to wet weather (as explained in chapter 2.2.3). SWMM calculates the RDII-component based on a defined set of triangular unit hydrographs (UH). These hydrographs must be determined through a calibration process. More information about how the unit hydrographs are defined, how they are used in this project and the calibration of them is discussed in chapter 4.4.2.1.

4.1.5 Flow Routing

The flow through the pipe system is managed with the principles of conservation of mass and momentum equations for gradually varied and unsteady flow. These equations can be solved with different methods. SWMM offers three choices; steady flow routing, kinematic wave routing and dynamic wave routing. The latter will be used in this project, because it is the method that gives the most accurate results and is suitable for flow through a closed pipe system, which is the case for the model at Risvollan.

4.2 Building the model

For building the model of the pipe system in PCSWMM, detailed data of the system was needed. This data was provided by Trondheim Municipality, as spatial data for nodes (manholes) and conduits (pipes), with its attribute data. Before importing the data to PCSWMM, some work had to be done on the data by using the GIS (Geographical Information Systems) tool ArcMap. The reason for this is because the data set was not adequate for direct import to PCSWMM. Some assets had missing data, and certain parts of the data set were not relevant for the analysis in PCSWMM. For instance, assets belonging to the drinking water system were removed. The model will include all the pipes in the stormwater system, also private pipes such as roof drains and drainage pipes to the system, while the sewage system will consist of the public parts of the system. In addition to adjust the data for the pipe system, ArcMap was also used to define subcatchments in the study area for simulation of surface runoff.

4.2.1 Work in ArcMap

The work done in ArcMap can be divided into two main parts: work related to the assets of the system and their attributes, and defining the subcatchments for the model.

4.2.1.1 Pipes and Manholes

Trondheim Municipality's data for terrain elevation and invert elevation of each node were taken from Gemini VA, their mapping database. The elevation data are assumed to be fully correct, but deviation from reality might occur. More than half of the nodes, about 53%, had missing data for elevation. All of them had missing values for the invert elevation, and the majority also had no values for the terrain elevation of the asset. To fill in the missing values, a digital elevation model (DEM) was downloaded from The Norwegian Mapping Authority. The DEM had grid cells with size 1 m x 1 m. The DEM will be used to define approximate elevation for nodes with missing data. For these nodes an assumption was made that the node invert is situated 2.5 meters below terrain surface, which is chosen based on standards and the depth of the other manholes in the system.

The dimension of some of the pipes also had to be modified. PCSWMM uses the inside diameter when running simulations. The diameter for concrete pipes is given as the inside diameter, but for PVC pipes it is the outside diameter. Therefore, wall thickness of the PVC pipes had to be determined. Relevant information on this was found from companies selling the type of pipes used in this system. Standard wall thickness for a variety of dimensions were found and thus the inner diameter could be calculated. Data on dimensions and material were available for all the public pipes, while most of the private pipes were missing this data. It was therefore made suitable assumptions based on the overall knowledge about the system.

Roughness of the pipe material also needed to be defined. The roughness is given with Manning's roughness coefficient. Standard values for different pipe materials can be found in hydraulic handbooks. For the concrete pipes the roughness is set to 0.015 and 0.009 for PVC (Norsk Vann, 2014). The pipe roughness can vary with the condition of the pipe, and therefore it is one of the values that must be evaluated and may be adjusted further in the modelling process.

4.2.1.2 Subcatchments

In order to add surface runoff to the model, the study area must be divided into subcatchments. The subcatchments will connect the overland flow to the stormwater system, this includes both roof drains and additional surface runoff. All the residential buildings in the area has roof drains connected to the stormwater system, thus each roof area will be defined as a subcatchment. The rest of the subcatchments could be decided in different ways with varying accuracy. It is possible to sketch them by hand with the use of contour lines or it can be done with tools in ArcMap. The latter was chosen as method for this project.

ArcMap uses the DEM as a basis to find the subcatchments. First the flow direction for each cell is calculated, which can create sinks where water is collected. These sinks are then filled before the flow direction map is used to create a flow accumulation map. Then the watersheds are found based on a selection of nodes in the stormwater system, and an acceptable snap distance from the accumulated flow to the nodes. This means that a suitable selection of nodes must be defined, together with the acceptable distance from a node to the accumulated flow.

After a field trip and an inspection at the study area, it was clear that simplifications and certain assumptions must be made in the process of defining the subcatchments. It is not possible to create a model that will reproduce the overland flow exactly the way it appears, due to the complexity of both the study area and the hydrological situation. It appeared that some part of the area had drains to collect the stormwater, while other parts did not have surface drains. Nevertheless, it was assumed that the entire area will contribute to the flow in the stormwater system, thus the subcatchments will together cover the entire study area. Based on this assumption and the knowledge about the drains and the vegetation, a selection of 25 nodes was made across the area.

Considering that a drain or manhole is often 0.8 m wide, the acceptable distance from the calculated accumulated flow to the nodes was initially set to 1 m. This turned out to give bad results for the construction of the watersheds, with some being very small, and other vary large. After trying different distances, it was found that a distance of 3 meters gave the best and most applicable result for use in the model.

Each subcatchments must be given a set of attributes that SWMM uses to simulate the overland flow. The attributes and how they will be set for the model at Risvollan are listed below:

1. Width (m)
   SWMM treats the subcatchments as rectangles, not as their drawn shape, as a simplification when calculating the overland flow. The width of the area must be set, and from this SWMM calculates the flow length as the area divided by the width. The flow length should represent the average maximum overland flow length, and represent the slow flow from pervious surfaces to a greater extent than fast flow from impervious surfaces.

2. Slope (%)
   This is a challenging parameter to decide because the slope is not uniform over the area of a subcatchment. ArcMap can use the DEM to calculate the slope for each cell. This was carried out, and the mean value of all the cells in one subcatchment area was chosen as the slope. For the roof areas it was set as 0.025%, as the roofs are flat and a standard slope for flat roofs are 1:40 in Norway.

3. Impervious areas (%)

The amount of impervious area was set based on both knowledge from the field trip, and orthophotos of the area.

4. Roughness
   SWMM uses Manning's roughness coefficient to define the roughness of the surface, and must be set for both impervious and pervious areas. The majority of the impervious areas are roofs, roads and playgrounds with asphalt or similar surfaces, and are given a Manning's coefficient of 0.015. The pervious areas are mostly grass and lawns, which was given a coefficient of 0.05 (Chow, 1959).

5. Depression storage (mm)
   The depth of the depression storage must also be set for both impervious and pervious areas. The SWMM manual has default values for a selection of surfaces, given as a range of values (Rossmann, 2015). For the roofs the depression storage is chosen to be 1.25 mm, and for the rest of the impervious areas it is set a little higher at 2 mm. Most of the pervious areas are lawns of different type and is given a value of 3.5 mm.

6. Zero impervious (%)
   This parameter represents the percentage of the impervious areas in each subcatchment that has no depression storage. In subcatchments where there are different types of impervious areas, of which some has no depression storage, this parameter is useful. In this case all the impervious areas are of the same surface type and has depression storage and this parameter will therefore be set to zero.

7. Subarea routing
   There are three different ways that the surface runoff can be routed within a subcatchment. The runoff can either go directly from both impervious and pervious surfaces to the outlet, or the runoff from pervious areas can flow to the impervious areas or vice versa, before reaching the outlet. At Risvollan, nine of the 25 subcatchments clearly has runoff going from pervious areas to roads and carparks, while for the rest of the subcatchments the option to lead all the water to the outlet will be used.

8. Infiltration parameters
   The Horton infiltration model requires four input parameters; maximum and minimum infiltration rate, a decay constant and drying time. The SWMM manual gives normal ranges for drying time (2-14 days) and decay rate (2-7 1/hr), and is initially set to 10 days drying time and a decay constant of 4/hr for this project. The minimum infiltration rate is set to 1.8 cm/hr as this is a typical value to use for the clay soil in Trondheim (Balstad et al., 2018). The maximum infiltration rate is harder to estimate without field tests and there are large variations in values recommended in literature. As Risvollan is a developed area the chosen initial value for this parameter is 30 mm/hr, thus a higher rate than undeveloped clay soil (Birmingham et al., 1999).

There are evidently differences between the subcatchments, and the parameters are difficult to set correctly. All the parameters described must be evaluated when calibrating the model. They should be changed and adjusted in order to fit the model to the measured stormwater hydrographs. After processing the data in ArcMap, it was ready to be imported to PCSWMM. The data set still contained some errors and data that needed to be assessed and adjusted further before the model is ready for simulations and calibration.

4.2.2 Work in PCSWMM

4.2.2.1 Pipes and Manholes

The first thing that was done in PCSWMM was to ensure that the flow direction of the system was correct. The program automatically defines direction of flow for each pipe section, this caused some errors. The flow had in some cases opposing direction in the same pipe branch. Based on the knowledge about the terrain and the overall pipe system, the flow direction of all the pipe sections were examined and corrected if needed.

Other inaccuracies in the data were related to connections between pipes and nodes. Some pipes had small gaps between them, other connections did not have a node, which PCSWMM demands, and some sections had nodes, but they were not connected to the correct pipes. Errors related to elevation and slope also appeared, some slopes were negative, and some manholes were unrealistically deep. These problems were corrected manually according to available knowledge of the system and the terrain. In this work there had to be made some necessary assumptions, that might affect how well the digital pipe system reflects reality.

The modelled sewer system is shown in Figure 4.2, while the modelled stormwater system, together with the defined subcatchments are shown in Figure 4.3. The two systems are in the same model, but to illustrate the differences between them and to give a clear picture of the two system, they are illustrated separately.

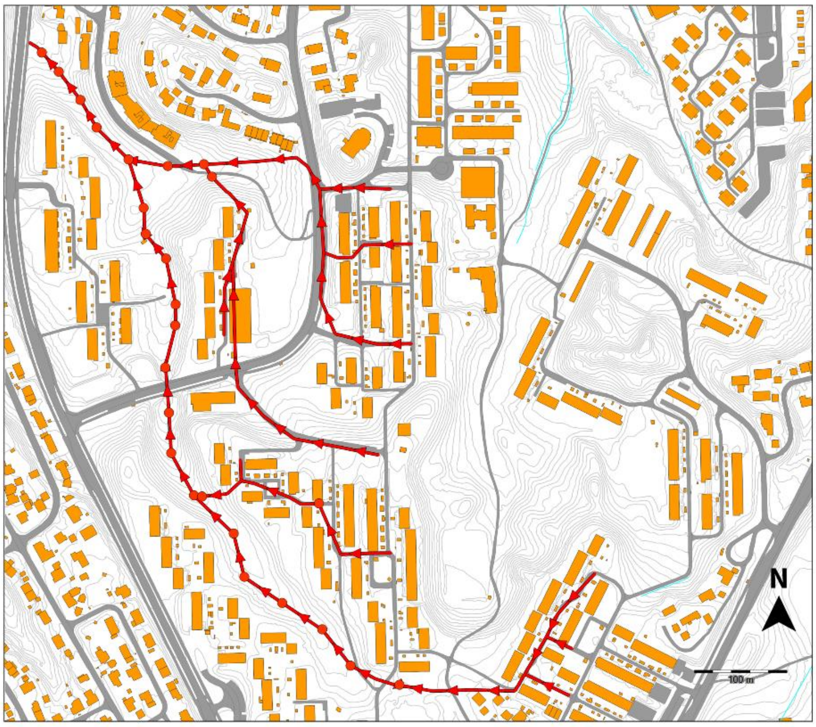

Figure 4.2. PCSWMM model of the sewer system at Risvollan

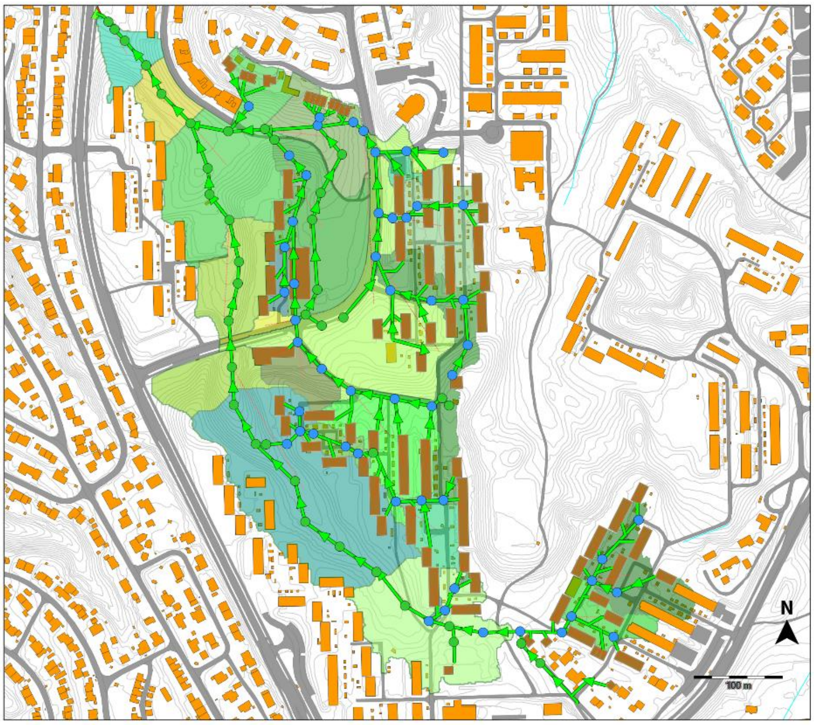

Figure 4.3. PCSWMM model of the stormwater system at Risvollan

4.2.2.2 Two Systems in one Model

It is common to make sewer models and stormwater models separately, and not combine the two system in one model. As this system is separated, it is natural to think that the pipes sections in the computer model also will be separated and result in two independent systems, but this is not the case. The reason is because some of the manholes are combined manholes with both stormwater pipes and sewer pipes going through them. Therefore, PCSWMM will merge the two systems together, and do not understand that to separated systems can pass through the same nodes. PCSWMM do not have an easy way of combining the two systems in one model. Therefore, this problem had to be worked around manually.

It is desirable to end up with a system that will manage to separate the water going through the two systems, but at the same time be connected in the case of overflow from one system to the other. To manage this, there had to exist two nodes for each of the combined manholes instead of one. It was therefore created new nodes next to the existing combined manholes, with a distance of 0.3-0.4 meter. It was created a pipe connection between the two nodes, enabling for overflow from one system to the other. This was designed in the model as a rectangular, open conduit. The width was set to 0.8 m, representing the diameter of a regular manhole, and the height was set to 2 meters. Figure 4.4 shows the separation and connection of the two systems for a small part of the pipe system.

Figure 4.4. Illustration of the model separation in PCSWMM

Before proceeding with the modelling process, the system was run with both rainwater and household spill water through it as a test to find out if the model approach was successful. The test was showing that there was no interaction between the two systems with small amounts of water flowing in the systems. Therefore, the modelling process on the pipes and manholes were considered finished, and the next step in the modelling process was to define subcatchments.

4.2.2.3 Subcatchments

The subcatchments created in ArcMap can be imported to PCSWMM together with their defined attributes. The subcatchments created from the DEM do not consider the buildings, thus in some cases accumulated flow is assumed to go through them, which will not occur in reality. Because of this, some of the subcatchments has to be adjusted to fit the actual surface conditions in the study area.

4.2.3 Use of the model at Risvollan

The finished model at Risvollan will have several useful applications. For the sewer system, the results from the modelling will be assessed related to I/I, both for dry and wet conditions. For the stormwater system on the other hand, an assessment related to I/I is not as relevant. Infiltration will be discussed related to dry weather, but for wet conditions, assessment related to infiltration for the stormwater system will be left out of this project. This is natural, as the stormwater system is designed to drain rainwater.

A successfully calibrated stormwater system is still important because it opens up for other applications of the model. The model can be used to analyse the interaction between the stormwater system and the sewer system, which is one of the goals of this study. Because of limiting time and data for this project, the only way this will be assessed is through a stress test of the system to find out in what situations there would be overflow from one system to the other.

4.3 Data

In order to do the planned analyses in this project, different types of data are required. Flow data for both pipe systems; the sewer system and the stormwater system, form the basis of the analyses. Meteorological data on precipitation and temperature is needed and it is also important to gather information about the residential situation. Information about the different data types are discussed separately in the following sections.

4.3.1 Flow Data

The most important data needed for this project is the flow data from the pipe system. The foundation and reason for initiating this project was that NTNU had installed a new pressure sensor in the sewer system at Risvollan in May 2018. The pressure sensor was installed in a cylinder tank connected to the sewer pipe. The water level in the tank and the sewer pipe will therefore be equal. An illustration of the arrangement of the sensor is shown in Figure 4.10. The sensor was installed 02.05.2018, but was first calibrated 07.05.2018. The sensor is giving a time series with water level recorded every minute. Originally, the plan was to use recorded flow data from the calibration of the sensor from May 2018 and until January 2019. Unfortunately, it was discovered in January 2019 that the data from the sensor turned out to not be of good enough quality to be used in the project. This is further explained and discussed in chapter 4.3.4. After revealing the problems, the sensor was adjusted and started recording usable data from 19.02.2019.

In order to analyse the quantity of flow in the system and do analyses on the amount of I/I, the data from the sensor, measuring the water level, must be converted to sewer discharge. How the conversion from water level to discharge is done, is discussed in chapter 4.3.5.

In addition to sewer flow, the flow in the stormwater system was obtained. This data is collected by NVE. Data for the stormwater system is both given as water level and discharge. The data is originally recorded as events, meaning changes that are bigger than 2 mm, together with measurements every hour. NVE also provides data with a time step of one minute, which is desirable to use in this project. An issue with using the minute data is that there are timesteps with missing data. About 5% of the values in the period 01.01.2019-20.05.2019 are missing. The missing values are relatively evenly distributed over the time period, and the dataset is considered suitable enough for the project despite the missing values (found in Appendix C).

4.3.2 Meteorological Data

The precipitation data is taken from the rain gauge at NTNU's research station. The rain gauge is a Lambrecht gauge with a tipping bucket. It records continuously when the bucket tilts. The number of times the bucket tilts is corrected every two minutes and every hour, and the amount of rain is calculated with the use of an algorithm from the Norwegian Meteorological Institute (MET). The time resolution is one minute.

The precipitation data from NTNU was compared with data series from MET, downloaded from www.eklima.no. Both daily data and minute data was downloaded and assessed. The comparison was done as a control of the data series from NTNU. It was found that the daily data from MET was one day delayed compared to the data from NTNU's gauge. It was concluded that the data from NTNU has the correct date associated with it. In addition, the time series with one-minute time resolution from NTNU is exactly one hour later than the data from MET. The reason for this is that NTNU uses wintertime constantly through the year, while MET uses summertime. These findings will not affect the use of the precipitation data from NTNU, but it is still useful knowledge for the project. In general, it was found some small deviations in the recorded values. This means that there are uncertainties in the data, and that it is difficult to know what the most correct value is. As the differences are small, and uncertainty in the data is inevitable, the data from NTNU will be used directly without adjustments. Data series for temperature is also taken from NTNU's research station.

4.3.3 Residential Data

Knowing something about the residential situation is necessary to be able to add the residential wastewater component to the model. This component will be based on the population equivalent (PE) and specific water consumption.

One population equivalent reflects the produced sewage for one person over one day. Since the sewage is produced not only at home, but also in schools, offices, hotels etc., the PE-factor will vary according to the situations where the sewage water is produced. In Norway, residents will have a PE-factor of 0.8, while students and employees at schools and offices is set to 0.2. Thus, from knowing the number of residents, students etc. in a desired area the total PE value can be calculated. Trondheim Municipality has provided information about the situation at Risvollan. There are both residents, students, and workers in the area, making up a total of 1112 people. The calculated population equivalent ends up at 922 PE, divided into 41 different sub areas.

The specific water consumption, and an associated time pattern should be determined. Water consumption is a difficult component to decide accurately without water meters and it is common to make assumptions. A study done in Drammen had water meters in the entire study area and showed a consumption between 109 and 135 l/PE/day (Jenssen Sola et al., 2018). There has not been used water meters in this project at Risvollan and the water consumption must therefore be estimated. Norsk Vann recommends to use 140 l/PE/day in dimensioning, and this is what will be used in this project.

The water consumption is not constant throughout a day. It follows a pattern, with typically higher consumption in the morning and with a second peak in the afternoon, with lower water usage during the night (Norsk Vann, 2014). Trondheim Municipality have given information on the consumption pattern for Risvollan, see Figure 4.5.

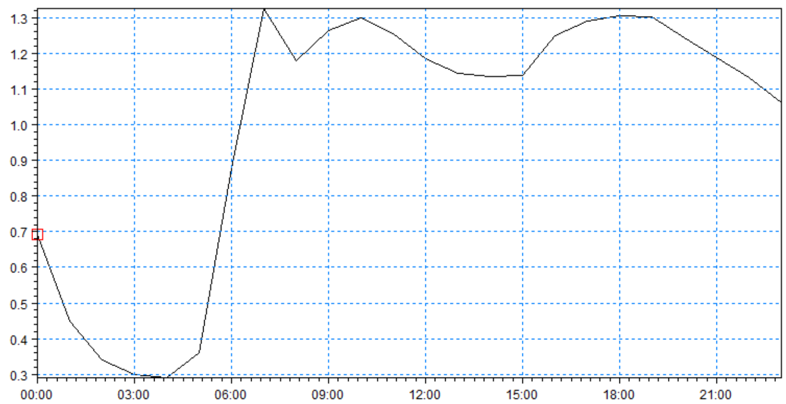

Figure 4.5. Daily variation in water consumption at Risvollan

The variation in water usage is defined by a unitless factor, in this case ranging from 1.33 at maximum water usage, to 0.29 at minimum, with an average of 1. These will be combined with the assumed daily water usage of 140 l/PE/day to find hourly consumption.

4.3.4 Assessment of the Flow Data

Before starting the analyses related to I/I, the flow data must be examined and assessed. This is done to detect possible errors or problems with the data. This assessment is based on visual inspection of the data, looking for values that do not make logical sense, or differs greatly from expected patterns etc.

In dry weather, the sewer discharge is expected to follow a daily pattern related to the residential water consumption (Norsk Vann, 2014). Over the course of a year, the consumption is higher during the summer, and lower in winter. The sewer system is often affected by wet conditions; precipitation, snowmelt or high groundwater level, this applies to both separated and combined systems.

The measured water level in the sewer from 08.05.2018-03.01.2019 is presented in Figure 4.6. Because of the long time period, it is difficult to observe the fluctuations on a daily basis. Nevertheless, the graph reveals two problems with the data. The first thing is that there is a sudden increase in the values the 4th of June, a day with no significant precipitation. The cause behind this increase was discussed with the Municipality of Trondheim, to investigate if there might have been an additional water source connected to the system at the time or other changes in the system. This was not the case, and as it was not done any calibration or adjustments by NTNU, the cause of the sudden change is unknown.

The second problem is that the time series seems to be cut off at a certain level. The pressure sensor has been unable to measure values above 79.2 cm. This results in unrecorded peaks and faulty measurements. It occurs occasionally before August, while from the 10th of August, it is dominating the data series. An example of this is shown in Figure 4.7, with records for two weeks in August. Through the fall and winter, the water level increases, and reaches a level such that the pressure sensor only records the daily minimum values, or no valid values at all. When the problems with the data were discovered, the pressure sensor was lifted higher in the tank, to a height where the water level would be within the operating range of the sensor.

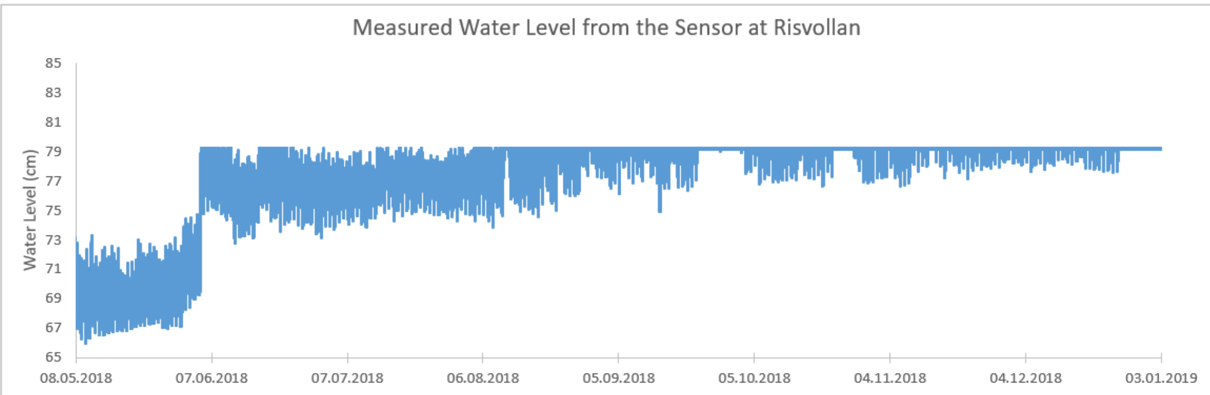

Figure 4.6. Measurements from the sensor at Risvollan, May 2018- January 2019

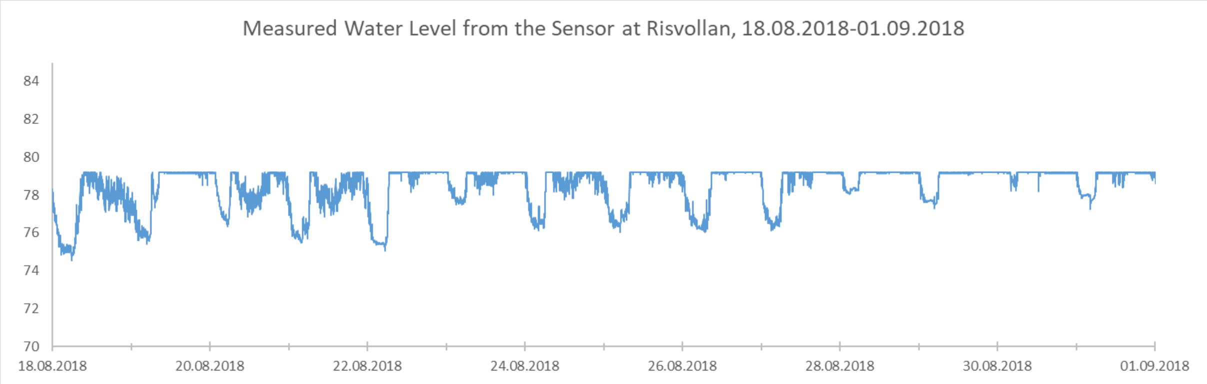

Figure 4.7. Measurements from the sensor at Risvollan, 18.08.2018-01.09.2018

The problems limit the use of the data in this project. The sudden increase in recorded values makes it difficult to convert the data to reliable discharge values. Therefore, the water level recorded cannot be used in the assessments directly and the flow cannot be quantified. The data collected after the adjustment of the sensor (19.02.2019) will be of better quality and will be data used in this project.

4.3.5 Conversion from Water Level to Discharge

The measured water level from the pressure sensor must be converted to discharge given in liter per second. A stage-discharge relationship will be used to convert the measurements from the pressure sensor, and thus this relationship must be decided.

At the research station at Risvollan there is installed a Palmer-Bowlus flume, shown in Figure 4.8 and Figure 4.9, in order to measure flow rates in the wastewater system. The storage cylinder containing the pressure sensor is connected to the channel upstream the flume. Information about the flume and its stage-discharge relation is described in a master thesis written for NTNU by Nordvåg (2017). The flume was installed in 1984 and comes with an initial stage-discharge curve. The thesis uses different calibration methods to find out if this stage-discharge relation is valid. It found that laboratory calibration and calibration results from a SINTEF report gave mean deviation from 0.11 to 0.18 l/s. These two methods thus confirmed the initial stage-discharge relation. Theoretical calibration, with the use of Bernoulli’s equation, and calibration from tracer dilution measurements did not give good enough results to confirm the relation, but there were uncertainties connected to these methods.

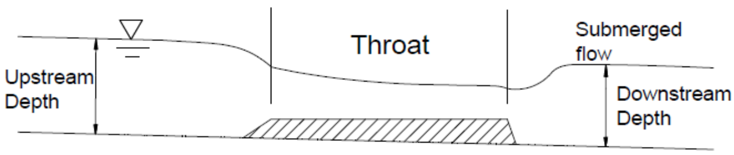

Figure 4.8. The Palmer-Bowlus flume at Risvollan (Nordvåg, 2017)

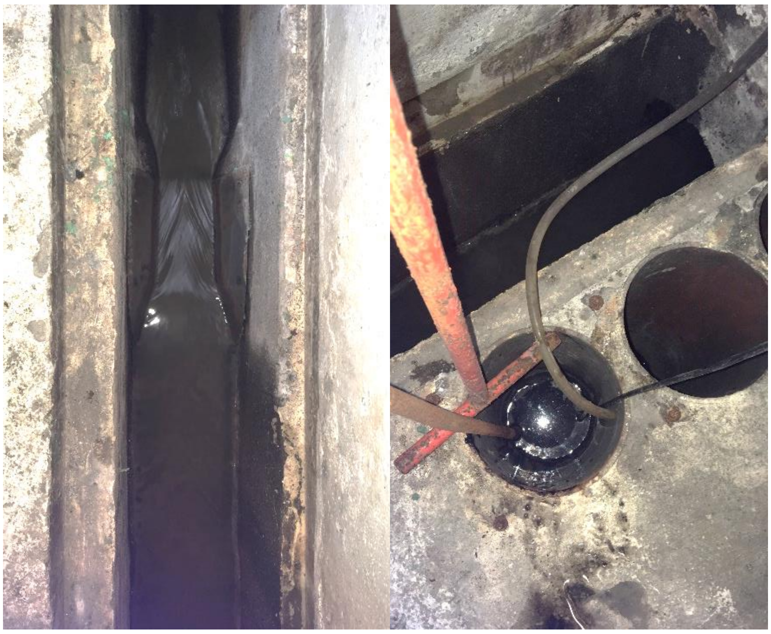

Figure 4.9. Left: Flow through the Palmer-Bowlus flume. Right: the cylinder with the measuring sensor (Photo Birgitte Taugbøl Kragset)

The initial stage-discharge relation for the flume is therefore valid to use in this project. It is given in Equation 4.1, where Q (l/s) is the discharge through the flume and d_i (cm) is the measured water level from the channel bottom in the U-cross section upstream the flume contraction. This relationship has a correlation of R^2=0.997.

$$Q\left(\frac{l}{s}\right) = 0.0241 * d_i^{2.3052} \tag{4.1}$$

The pressure sensor does not measure the water level in the channel, which is the input in the stage-discharge relationship. Therefore, the measurements from the sensor must be converted. This can be done when knowing where the sensor is situated in relation to the channel bottom. An illustration of the channel and the cylinder with the pressure sensor is illustrated in Figure 4.10. Note that this is a rough illustration, thus the different components and marked parameters does not necessarily have correct size in relation to each other.

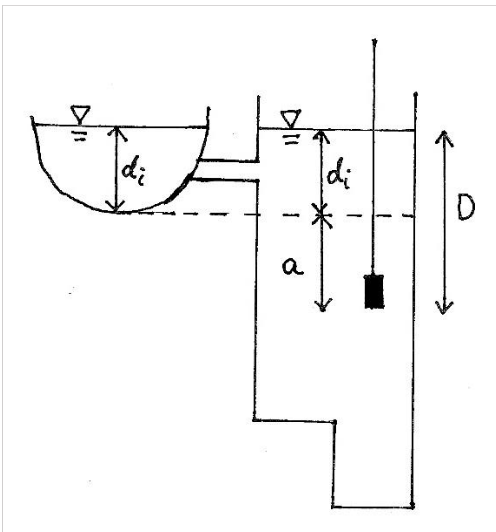

Figure 4.10. The measuring sensor, its position and relation to the channel

The sensor is the black rectangle in the illustration and measures the depth *D*. This depth will increase as the discharge and water level in the channel increases, as the channel and cylinder have the same water level. The relation between D and d_i must be found to convert the measurements from the sensor into channel depth and further to discharge. The sensor is situated at a constant lower level than the channel bottom, with distance *a*. This means that the relationships shown in Equation 4.2 is valid.

$$D = d_i + a \;\rightarrow\; a = D - d_i \;\rightarrow\; d_i = D - a \tag{4.2}$$

If distance *a* can be determined, d_i can be calculated from the measurements from the pressure sensor. This distance can be determined from measurements of the water depth in the channel and from the pressure sensor at the same time. This was done on March 20th at 10:36. The depth in the channel was measured with a measuring stick. When this is put into the water, it will disturb the flow slightly and the mark on the stick will be higher on the upstream side than the downstream. Therefore, the average was taken with level measurements from upstream, downstream and the sides of the measuring stick. The depth was found to be 8.2 cm. The recorded depth from the sensor at this time was 42.92 cm. It can then be found that the sensor is situated with distance a = 42.92 - 8.2 = 34.72 cm lower than the channel bottom. The relationship that will be used to convert the measurements from the sensor to channel depth is shown in Equation 4.3.

$$d_i = D - 34.72 \tag{4.3}$$

4.4 Simulation and Calibration

The simulations done in PCSWMM can be divided into four different situations; during dry conditions and wet conditions, for both the sewage and the stormwater system. For all cases, the model should be run, the results assessed, and the model calibrated if needed. Calibration is the process of getting the behaviour of the model to match the observed data by changing model parameters (Gupta et al., 1999). Manual calibration is carried out, by using a "trial-and-error" method. The simulation output is calibrated against the measured flow data.

Originally, the plan was to use a data series which contained data from May 2018 to January 2019, thus mostly periods without snow or snow melting processes. It is desirable to avoid snow melting in the initial calibration of the model because this complicates the runoff process. It is better to calibrate the model for dry and wet periods first, without snow processes, and then after having a functional, calibrated model, the snow modelling capability in SWMM could be added to the model. Therefore, periods from summer to beginning of winter (June-November) is desirable for the initial calibration.

Because the original data series could not be utilised, the data series that will be used for the calibration is from 19.02.2019-20.05.2019, which is during the period with snow melting. This complicates and limits the calibration process. Instead of using a continuous time period of 2-3 months for the calibration, which is often the desired minimum length of a continuous calibration period (Staufer et al., 2012), the model will be calibrated against selected, shorter time periods. The selection of the calibration periods will be discussed in section 4.5.

The result from the calibration will be inspected both visually and by use of correlation factors. The Nash-Sutcliffe model efficiency (NSE) is the most widely used factor in hydrology (Croke, 2009), presented in Equation 4.5. This factor gives a measure of how well the model fits the observed data, where NSE=1 represents a perfect fit. A negative NSE correlation indicates that the observed mean of the data is a better prediction than the model, as the mean will give NSE=0 (Gupta et al., 1999).

$$NSE = 1 - \frac{\sum_t^T (Q_S^t - Q_O^t)^2}{\sum_t^T (Q_O^t - \overline{Q_O})^2} \tag{4.5}$$

The correlation factor R^2 will also be used as a correlation factor. The performance of the model, and its usefulness, are highly dependent on the calibration process (Gupta et al., 1999). The calibration will be done in different ways for the different situations, and are explained in the following chapters.

4.4.1 Calibration for Dry Conditions

4.4.1.1 Sewer System

For simulation and calibration during dry periods, the model does not need precipitation data as input. It only requires the baseflow coming from the connected buildings. The household component is added according to the number of PE in each sub area. The calculated PE-value is given in decimal numbers from the municipality, and will be used to calculate the added baseline flow to the model according to the assumption of a water consumption of 140 l/PE/day.

The calibration process, in this case, is aiming at fitting the time of peak and minimum flows from the model with the measured data. The quantity of the input parameter will not be adjusted as the assumption of 140 l/PE/day has been chosen as final. This assumption might not be accurate and could influence the results. A possible difference in quantity between measured and simulated flow will be discussed in relation to rainfall independent I/I (Chapter 6). The calibration process involves adjusting the factors in the daily consumption pattern. Even if this data is given from the municipality, and not assumed, it is still considered open for adjustments. The flow downstream in the study area can for example be different from the consumption pattern upstream the measuring point.

4.4.1.2 Stormwater System

During dry weather, the discharge in the stormwater system is expected to be very low. The only expected water could come from people washing their cars, watering their gardens, cleaning the streets etc., but this is considered a very small contribution compared to the flow during wet conditions, and is also mostly expected during summer.

In the model, there are no flow component added for this situation, and thus the model does not need to be calibrated for this situation. Nevertheless, the measured flow data for this situation should be assessed, as there could be infiltration water entering the stormwater system as well.

4.4.2 Calibration for Wet Conditions

4.4.2.1 Sewer System – RDII

Calibration of the model in wet hydrological situations requires more input and adjustment of additional parameters, compared to a dry situation. Time series for precipitation must be added to the model.

The rainfall dependant I/I will contribute to the measured flow and must be implemented in the model simulation. In SWMM, this type of infiltration is referred to as RDII (rainfall dependant infiltration and inflow), and is estimated by using unit hydrographs (Rossman, 2015). These unit hydrographs are added as sets of three; for short-term response, medium-term response and long-term response. Each of the unit hydrographs are defined by three parameters, RTK:

- R: the fraction of rainfall volume that enters the sewer system
- T: the time from the inset of rainfall to the peak of the unit hydrograph
- K: the ratio between time to recession of the unit hydrograph to the time to peak

The estimation of RDII is done for nodes in the system, not pipes. A node can be given a sewershed area that contributes to RDII flow. In this project, instead of doing this for every node, a similar selection of nodes as the ones used to generate the subcatchments were used together with their respective area.

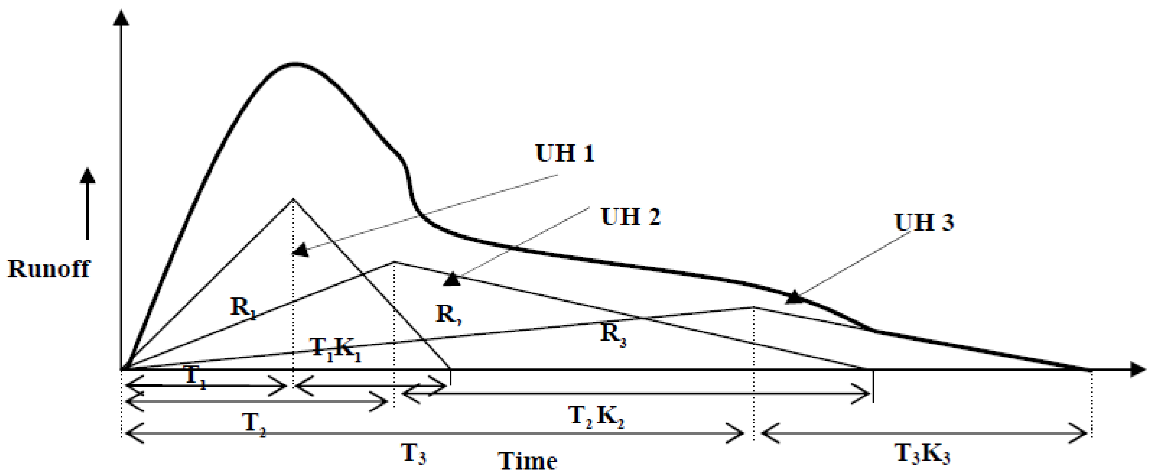

Figure 4.11. RTK-parameters in the unit-hydrograph (Mulata and Boulos, 2008)

In addition to the RTK-parameters, each unit hydrograph can be given a set of Initial Abstraction (IA) parameters (Rossman, 2015). IA parameters represent the amount of precipitation that is lost to depression storage and interception. The parameters are:

- D_{max}: maximum possible depth of IA (mm)
- D_{rec}: recovery rate (mm/day) at which stored IA is depleted during dry periods
- D_0: initial depth of stored IA (mm)

For this project, these parameters will not be used. This is to reduce the complexity of the calibration process, and because their contribution is considered small when using discrete periods for calibration and not longer time periods.

The calibration of RDII runoff by setting the RTK-parameters will be done manually. This can be a time consuming and complicated process. As there is a vast number of combinations of the parameters, it is not possible to try every possible combination, and different options might give similar results (Muleta and Boulos, 2008). To decrease the complexity of this calibration process, the parameters for medium-term response and long-term response are merged to one set of RTK-parameters. This means that there are six parameters that must be decided in the calibration of the RDII flow component. The fast response unit hydrograph will represent the contribution from inflow, while the slow response unit hydrograph represents the rainfall dependent infiltration.

4.4.2.2 Stormwater system

Precipitation data is also the input when generating the flow in the stormwater system during wet conditions. The rainfall will generate the surface runoff that ends up in the system, based on the subcatchments and their attributes. The modelled flow will be compared to the measured flow, both the quantity of flow and the time of peaks will be assessed. As the surface runoff process is complex, it is expected that the model will need thoroughly calibration. As explained in section 4.2.1.2, there are numerous parameters that have been set for the subcatchments, based on assumptions and standard values, that will be adjusted in the calibration process.

4.5 Selection of Calibration Periods

As earlier discussed, the transported water through sewage and stormwater pipes have many different origins. The main sources contributing to flow are baseflow coming from households, surface runoff, water from groundwater intrusion, I/I related to stormwater, and water form snowmelt. In order to analyse the different parts of the flow, it is useful to choose periods for calibration that will isolate separately the types of flow that is relevant for the analyses. Time series for rainfall, temperature, and discharge (found in the Appendix) have been examined to choose the different simulation periods for dry and wet conditions.

4.5.1 Dry Conditions

The first simulation of the model is done to examine the situation in dry weather. For the sewer system this includes the baseflow from households and the constant infiltration not related to precipitation. The latter will also be the contributing part in the stormwater system. To examine this, flow related to precipitation must be eliminated, thus a period with little rainfall must be chosen. As earlier mentioned, it is also important to avoid periods with snowmelt.

The driest period in the time series is during the Easter holiday, but because it is desirable to avoid public holidays for the calibration, this period will not be used. Instead, the week after is chosen, resulting in a calibration period of seven days from 22.04.2019 to 28.04.2019. This period has no precipitation and no snowmelt.

4.5.2 Wet Conditions

Assessment of the rainfall derived infiltration and inflow (RDII) in the sewer system requires a calibration period with rainfall. In order to look at both the quick and slow response, it is desirable to use a period containing a heavy rainfall event that shows a clear impact on the flow in the system. After examining the time series of temperature, precipitation and discharge, problems related to snow and snowmelt were apparent, as expected. There are two main periods with large precipitation events (28.02-02.03 and

20.03-31.03), but they are both in periods with significant snowmelt. This makes it difficult to find an appropriate calibration period. There are days with smaller rain events, but the response in the sewer system is too modest for these events. It was therefore concluded to not follow through with the calibration of RDII, as there is no suitable calibration period. Thus, there will not be given results for the RDII-component in the sewer system.

A suitable simulation period for the stormwater system for wet conditions does not need to contain an equally heavy rain event as for the sewer system. As the response in the stormwater system is clearer and faster, smaller and shorter rain events could be used for calibration. To avoid snowmelt, it is desirable to use events as late in the time series as possible. A long period with precipitation is found from 29.04.2019-08.05.2019, this will be used for calibration. One adjustment is made to the precipitation data, as there is recorded 22 mm precipitation the 8^{th} of May, which was a day without precipitation. This is considered a measuring error, and is removed from the data. After this adjustment, the precipitation during these ten days is 34 mm.

4.6 Validation

In order to assess the performance of the model, validation is needed in addition to the calibration. Validation is the process of assessing the performance of the calibrated model when using input data that is not used in the calibration process (Refsgaard, 1997). This means that the model is run for other time periods with similar hydrological conditions as the chosen periods. For dry conditions, the validation period is 11.03.2019-18.03.2019. For wet conditions the validation period is 10.05.2019-13.05.2019.

4.7 Stress test

Having both the stormwater system and the sewer system in the same model opens up for analyses on the interaction between the systems. A stress test will be conducted, to find out when the stormwater system will be overloaded, and stormwater will flow into the sewage system.

The approach to assess this is to make a symmetrical hyetograph, and upscale this until the system capacity is reached. The found precipitation event will then be related to a return period according to the IDF-curve for Risvollan (Intensity-Duration-Frequency curve) (Figure 5.11). To create the hyetograph, the duration of the rain event must be decided. It is common practice to use a duration close to the time of concentration of the catchment, because this is when the maximum flow will occur (Bøyum et al., 1997). The time of concentration will be found by running a "block rain" through the model, meaning a rain event with constant intensity, and assess how long it takes before the flow reaches its peak. This time will be the duration of the hyetograph.

5 Results

This section presents the results from the calibration process, together with results from validation and the stress test of the model. The results from the simulation in PCSWMM is taken from the node closest to the research station where the measurements in the pipe system are recorded.

5.1 Dry conditions

5.1.1 Sewer System

The initial simulation in PCSWMM with household consumption as input, with the initial consumption pattern, showed a need for adjustments (Figure 5.2). The peaks of the original simulation did not match well with the observed values. Therefore, the daily consumption pattern had to be changed, to change the magnitude and time of the peaks. When doing this it was important to keep the average equal to one, since the assumption of 140 l/PE/day will not be changed. The consumption at night and at noon was reduced, in order to raise the factors for the two peaks.

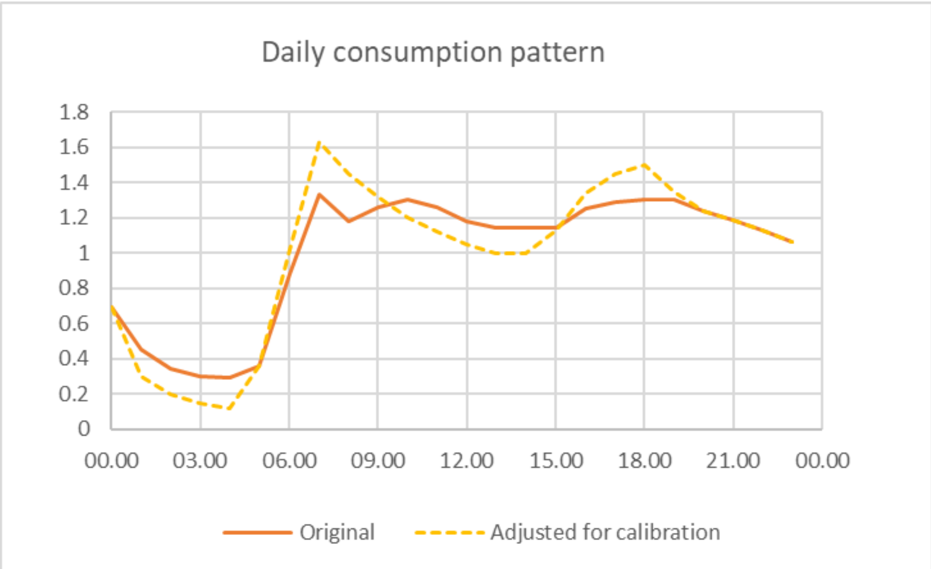

Figure 5.1. Daily consumption pattern before and after calibration

The widely used assumption that the nighttime minimum equals the constant part of I/I will in this case give an I/I not related to precipitation of approximately 0.7 l/s. It is not easy to determine, from the available data, how much of this is actually I/I and what come from households. It is assumed that the household consumption at night is low, but not zero, in a study area with almost 1000 PE. An assumption was made, that 0.2 l/s come from households and that the constant part of I/I makes up 0.5 l/s. This number was confirmed by the measured discharge in the stormwater system during the same period, see chapter 5.1.2.

In order to fit the model results to the measured data, the constant I/I-component of 0.5 l/s was added to the model. The results of the simulation after calibration and with the added I/I-component is presented in Figure 5.2. The calibrated model has an NSE=0.45 and R^2=0.54. The original simulation with the added I/I-component gave a correlation with NSE=0.42 and the same R^2 at 0.54. The model performance was slightly improved through the calibration and is now able to recreate the two peaks better than initially, even though the model still gives a maximum flow significantly lower than the measured maximum.

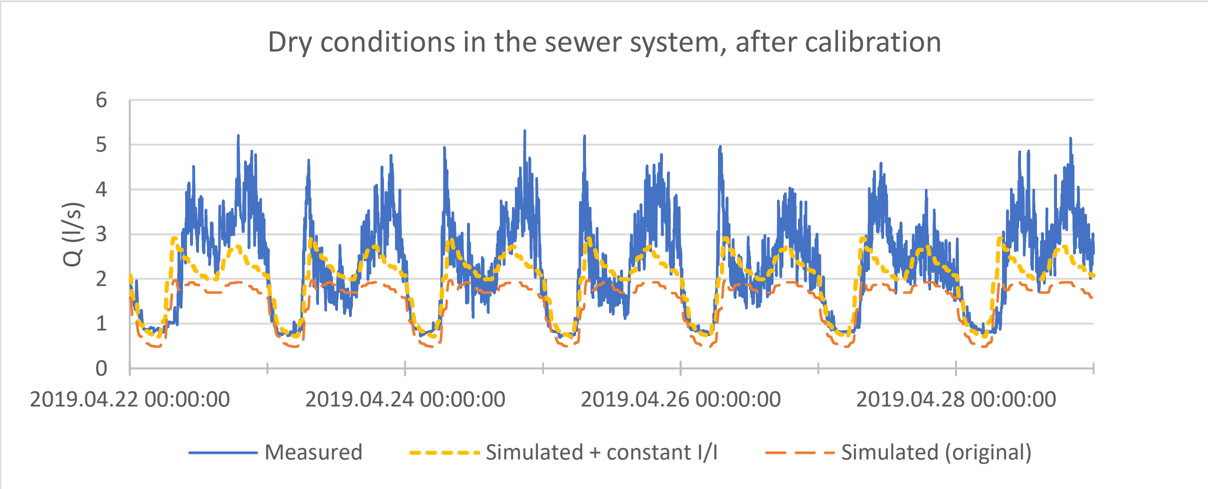

Figure 5.2. Simulated and measured flow in the sewer system during dry conditions, before and after calibration

Over the seven days the total measured flow is 1371 m^3, while the flow from the simulations in PCSWMM gives a total of 1206 m^3. This shows that the total simulated flow is 165 m^3 less than the measured, or an average of 23.6 m^3 per day. The I/I component of 0.5 l/s gives a total of 302,4 m^3 over the period, and makes up 22 % of the total flow over the 7-day period.

5.1.2 Stormwater System

The recorded discharge in the stormwater system during dry conditions are presented in Figure 5.3. The discharge is stable at around 0.5 l/s during the seven-day period. The maximum value is 0.7 l/s during the little increased flow the 26th of April, while the minimum value is 0.3 l/s. The graph shows a slight decrease in flow during the period, which can indicate that the soil is drying. The average discharge is 0.42 l/s.

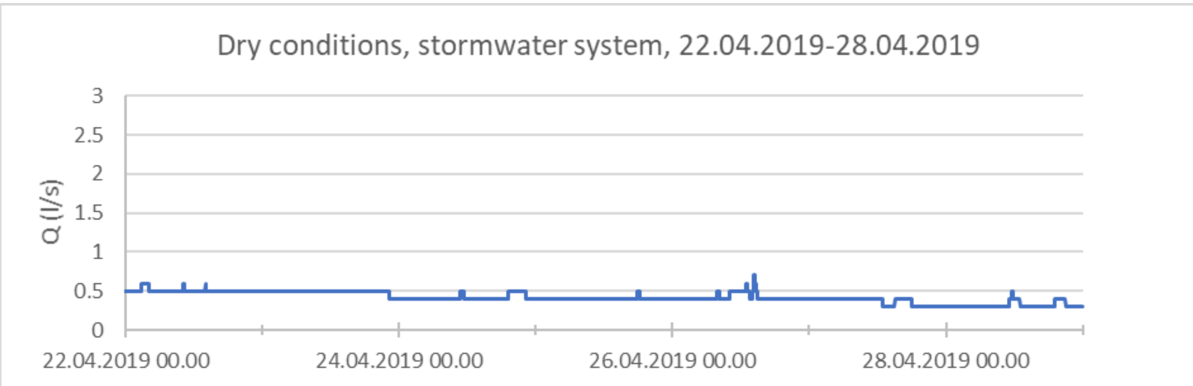

Figure 5.3. Discharge in the stormwater system during dry conditions

These results show that there is a constant flow of water through the stormwater system, and thus confirms that there is a constant part of I/I present. This is equal to the results from the sewer system. The I/I-component of 0.5 l/s is added to the model in the same way as for the sewer system.

The model is not calibrated for this situation, and will therefore not need to be validated either. Nevertheless, it is useful to look at the validation period used for dry conditions in the sewer system, 12.03.2019-18.03.2019, to compare the results. Figure 5.4 shows that the discharge during this period is higher, and with small peaks caused by small amounts of precipitation (1.4 mm in total).

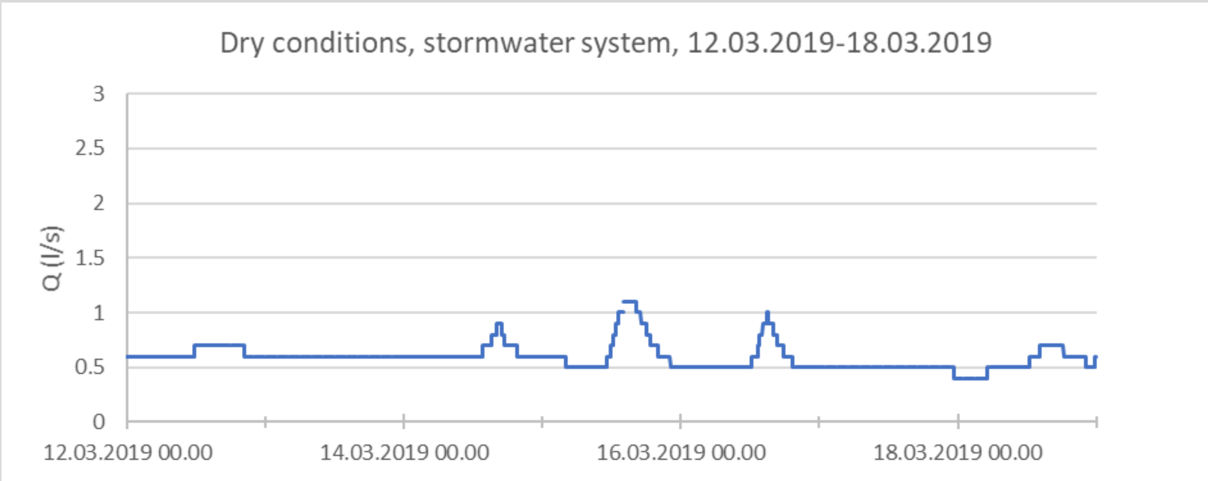

Figure 5.4. Discharge in the stormwater system during the validation period for dry conditions

Except for the peaks, the flow is relatively constant at 0.5-0.6 l/s, thus a little higher than the dry period in April, and confirms the finding of a constant I/I-component in the system. The increased flow rate can be caused by snowmelt and thus a more wet soil in March than April.

5.2 Wet Conditions

The model will be calibrated a second time, for the response of the stormwater system during wet conditions. As earlier mentioned, the calibration of the RDII-component for wet conditions in the sewer system will not be followed through, as the data is not good enough. Still, the sewer flow data (Figure 5.5) will be discussed around I/I related to precipitation even though the model is not calibrated for wet conditions, see chapter 6.3.

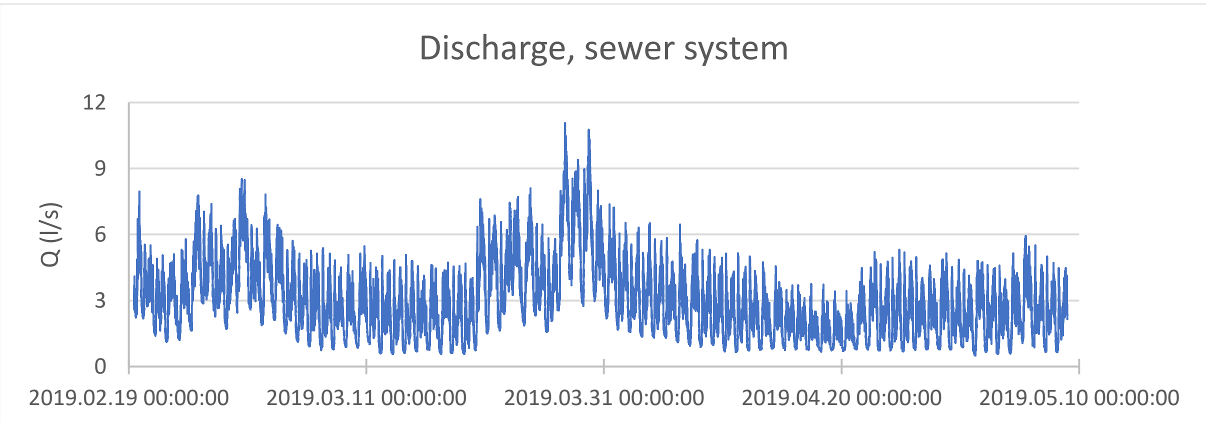

Figure 5.5. Discharge in the sewer system, February - May 2019

The stormwater data from NVE is recorded with summertime and the rainfall data from NTNU in wintertime, thus creating a mismatch in the records. The flow data from NVE is shifted one hour later to match the time of the rainfall data. As mentioned, the flow data contains some missing values. Over the ten-day period from 29.04.2019-08.05.2019, 13% of the data are missing. The plotted graphs of the measured flow have connected straight lines between the known datapoints to obtain a visually continuous graph. Nevertheless, the missing data create problems for calculating the NSE correlation. The majority of the missing data are at times when the flow increases or decreases, thus during the rainfall events, and not as much when the flow is constant at a low level. The average value of the observed data used to calculate the NSE will therefore be affected and lower than the actual average flow value. Thus, calculating the NSE, excluding the time steps with missing values, will not give a true representation of the model success. Still, the NSE is calculated together with R^2 for this calibration.

The model is first run with the initially chosen parameters, with the result shown in Figure 5.6. This gives a correlation of R^2=0.55, and visually it looks like the simulated peaks are too high and that the model generates more runoff than the measured flow, except for the first peak. The NSE correlation is -1.2, which indicates a poor fit, but as discussed earlier, it does not represent the true NSE value.

The process of calibration is done by trial and error, by adjusting different parameters. The first parameter that was adjusted was the maximum infiltration rate; increased from 30 mm/hr to 40 mm/hr, in order to reduce the amount of runoff. The reason why the first simulated peak is smaller is probably because of the depression storage is initially filled, therefore, this parameter is reduced to increase the peak. The depression storage for impervious areas (not including the roofs) are reduced from 2 mm to 1.3 mm. To reduce the amount of flow further, the percentage of impervious areas were reduced for many of the subcatchments. The roofs generated to much quick runoff and were therefore adjusted to have impervious areas of 60% instead of 100%.

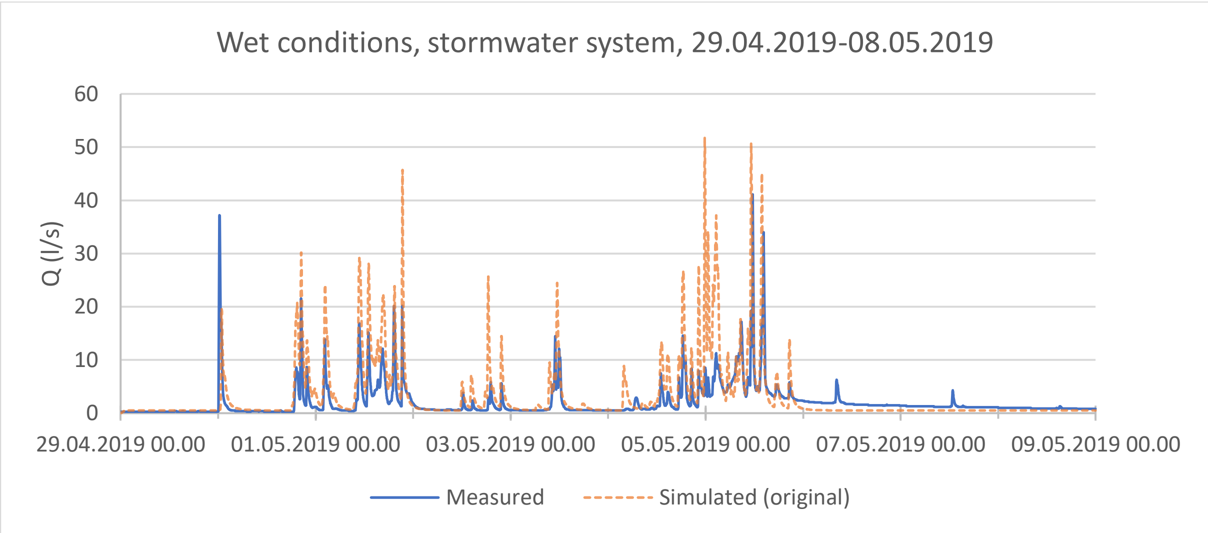

Figure 5.6. First simulation of the stormwater system during wet conditions

The result of the calibrated model is shown in Figure 5.7. The peaks are clearly reduced from a maximum above 50 l/s, to about 35 l/s. The R^2 value is only increased slightly to 0.57, while the NSE value has increased much more to reach a positive value of 0.27. Visually, the results look better in the first half of the time period. In the second half there are two problems; too high simulated peaks around midnight 05.05.2019, and low correlation at the end of the rain event, where the simulated flow decreases to a too low level to fast.

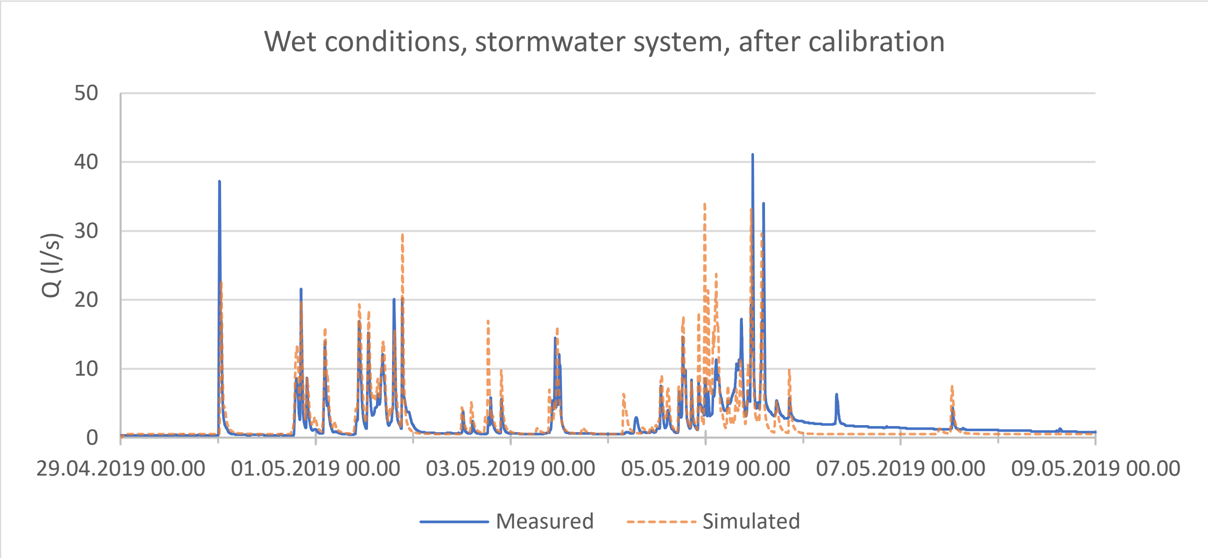

Figure 5.7. Simulation of stormwater system during wet conditions, after calibration

If the correlation is calculated for the only the first half of the period, 29.04.2019-04.05.2019, the correlation is higher, with NSE=0.3 and R^2=0.65.

The impervious areas at Risvollan have been set to 26% in earlier studies (Bøyum et al., 1997). This means a runoff coefficient of 0.26. The calibrated model gives a total runoff coefficient relatively close to this, at 0.22.

5.3 Validation

Validation of the model is done for the two situations where the model was calibrated; dry conditions for the sewer system, and wet conditions for the stormwater system.

The dry period for validation is the same length as for the calibration, and with no precipitation. The validation results are presented in Figure 5.8, and visually looks similar to the results form calibration. The NSE correlation is slightly higher at 0.49, while R^2 is reduced to 0.51. The two days in the validation period with the least good results are the 16th and 17th, which is during the weekend. If the correlation is calculated for the four preceding weekdays, the correlation is even higher with NSE=0.59. The period is in the middle of March, which was expected to affect the discharge because of snow melt and more infiltration from soil water. Nevertheless, the validation shows an equally good results as the calibration and indicates that the model can be used with similar success for other periods than the calibration period.

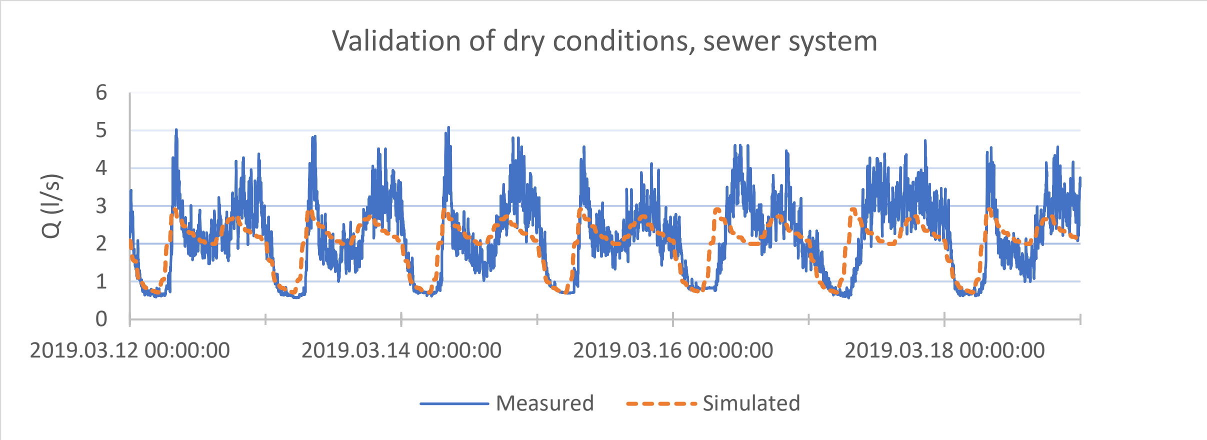

Figure 5.8. Validation of model performance of the sewer system during dry conditions

The validation of the stormwater system during wet conditions shows a good result, presented in Figure 5.9. The correlation factors confirm this with NSE=0.76 and R^2=0.87. The simulated peaks are close to the measured, both in terms of magnitude and time. An exception of this is the simulated first peak, which is 30 minutes after the measured. This indicates that the model has issues with the start of a precipitation event, and that the parameters affecting this could be improved further.

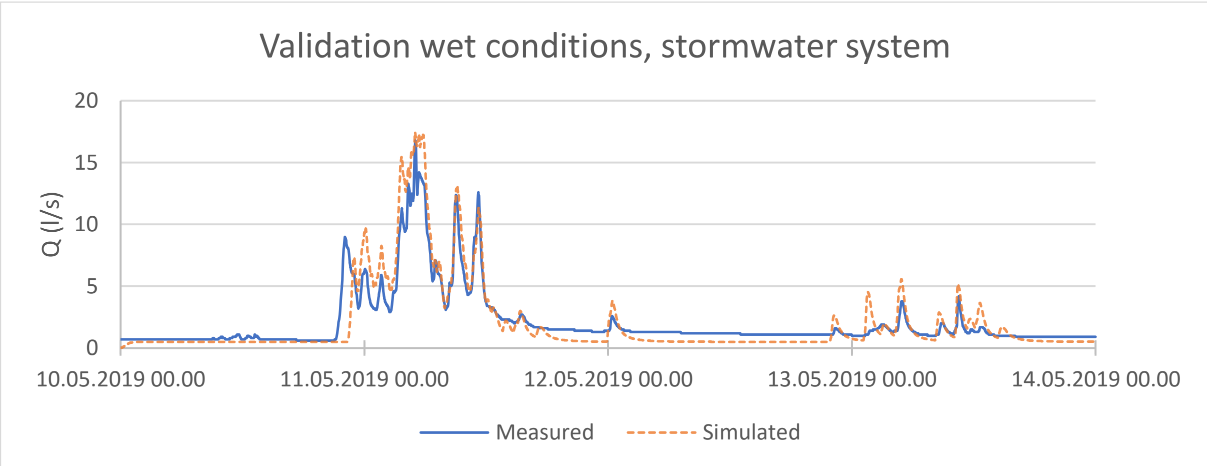

Figure 5.9. Validation of model performance of the stormwater system during wet conditions

5.4 Results of stress test

The concentration time for the fast response of the catchment at Risvollan was found to be 40 minutes. The duration of the hyetograph used in the stress test will thus be 40 minutes, with timesteps of 5 minutes. The required rain event to overflow the stormwater system is found by trial and error. First, a hyetograph is made for a return period of 5 years. This resulted in flooding of the system, and 31,5 m^3 liters of stormwater was transported through the sewer system. After several attempts, the precipitation event with a return period of approximately 2 years (presented in Figure 5.10) gave an adequate result. With a total of 9 mm rain over 40 minutes, the stormwater system is just flooded at one node for 4 minutes, with 0.8 m^3 of water.

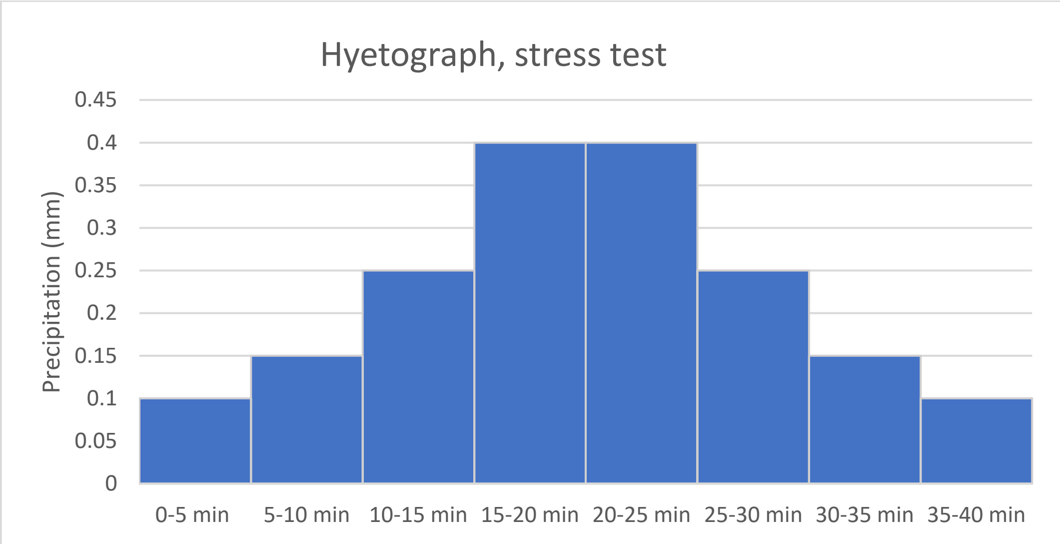

Figure 5.10. Hyetograph used in stress test of the system

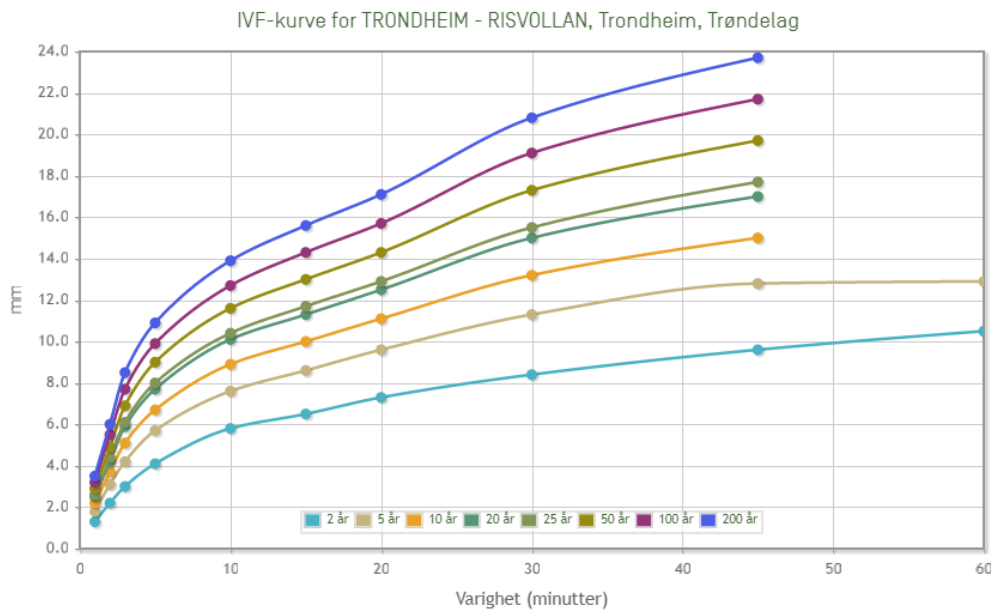

Figure 5.11. IDF-curve for Risvollan

6 Discussion

In this section the results will be discussed and analysed, and the research questions will be answered. The limitations in the project will also be covered, both in terms of quality of the data and the methodology.

6.1 Model success

One of the main goals for this project was to build a functioning model, containing both the sewer and stormwater system. The fact that this had not been done before at NTNU or elsewhere in Trondheim or Norway, made it challenging and new solutions in terms of model build-up had to be found. The challenge was to find a way of separating the system, but at the same time keep them connected at places where overflow from one system to the other can occur. The model simulations and the stress test showed that the model was able to run successfully and give applicable results. The solution of creating pipe connections between the two system, turned out to work. In the stress test, the excess water when the stormwater system was flooded ended up in the sewer system as desired.

The model success must also be assessed according to the results from calibration and validation. Based on the available data (which will be further discussed in next chapter), the model was calibrated and validated. For dry situations in the sewer system, and for wet situations in the stormwater system, the model calibration was fulfilled. The validation of these situations showed promising results, with similar or higher correlation results than the calibration. Because of limitations in the data, the calibration process also has limitations and thus room for improvements. The correlation factor for the simulation of the sewer system in dry conditions gave an acceptable result, but in the lower end of what is considered a good correlation and model performance.

For wet conditions in the stormwater system the validation is done for a shorter period with less precipitation than the calibration period, which must be considered when assessing the validation result. It shows that the model performance is good for the validation period, but does not give a clear answer to the performance of longer and heavier precipitation event. Ideally, the model should be validated over a longer time period, containing precipitation events with different characteristics. For this situation, there were also problems related to the NSE correlation. Missing values made it difficult to obtain a correct correlation value. The NSE is also sensitive to high, sudden peak values. Thus, for the simulations during wet conditions the R^2 is a better correlation value, and showed good results with 0.57 for the calibration and even higher at 0.87 for the validation.

Unfortunately, the calibration for the sewer system during wet conditions was not completed. The lack of results regarding rainfall derived infiltration and inflow (RDII) in the sewer system is a clear drawback for the project. The model therefore lacks an important flow component. Further discussion regarding the result related to I/I will be done in chapter 6.3.

It is important to mention that the performance of the model is related to how well the model replicates the measured values at the outlet of the study area. Therefore, the model might not necessarily give accurate results for all parts of the system. The parameters in the model might not be the same as they are in reality; some might be too high, other too low. What is most important is that the result of all the components and parameters of the model together creates an output that is as good as possible. For example, the fact that evaporation is not included in the model must be compensated for through the calibration of the other included processes and parameters. In the process of changing the parameters during the calibration, it has been focused on keeping the parameters within what can be assumed plausible and realistic.

One of the reasons for doing this project was to create a model that can be used for other applications and research projects at NTNU in the future. The model gave reasonable results and can be used for applications both related to the sewer system and the stormwater system, or both of them combined. Still, the model can be improved, and should be developed further in order to give even better results (see chapter 8).

6.2 Discussion of the data

The data used in this project is a crucial factor for the results. Different types of data have been collected and used. The data have varying quality, which will affect the uncertainty in the project results. After starting the project, it was soon discovered that the pressure sensor in the sewer system gave measurements of very poor quality. The initial plan to use data from May 2018 – January 2019, had to be modified. Even if this was a setback for the project, it was an important finding in terms of improving the data collection at Risvollan research station. NTNU collects large amounts of data from different research stations around Trondheim, and student projects play an important part in quality assurance of the data. Thus, an important result from this project was that the measuring sensor was recalibrated and now gives reliable data for the flow in the sewer system.

The usable flow data from the sewer turned out to be from the middle of February 2019 to May 2019. This data showed flawless quality in terms of having no missing values, and no problems with outliers etc. However, this period is not ideal for calibrating a hydrological model because of being during spring and thus be influenced by snow and snowmelting. It is also desirable to have a longer period of data, not just three months. The limited quality of the sewer flow data has affected the calibration process, and thus the results of this project. Another uncertainty related to the sewer flow data is the conversion from level measurements to discharge. The found relationship between the values from the measuring sensor and the channel depth was based on a single measurement done manually at the research station. This could have been assured through several measurement on different days and under varying conditions.

The flow data from the stormwater system also contained some issues. The data series had missing data throughout the time series from January to May 2019. Despite the missing values, the data could be visualized through plots and graphs in a satisfying way. Nevertheless, it created issues for the calculation of the NSE correlation factor. Thus, it is difficult to assess the success of the calibration and validation process. It was decided not to fill the gaps in the data for this project, yet this could be a useful thing to do in order to improve the model calibration. This could be done through interpolation of the data.

Issues related to the precipitation data was also apparent. Differences in the data from NTNU's rain gauge and the recorded data from MET (eklima.no) clearly increases the uncertainty related to the precipitation data. This influenced the calibration of the model in wet conditions, as there were occurrences of mismatch between the measured stormwater flow and the precipitation.

The data related to the residential situation at Risvollan is also a source of uncertainty. The number of residents living in the study area might be different from the number registered by the municipality. As found in the calibration of the sewer system for dry conditions; the consumption pattern might not give an accurate representation of the flow pattern. The assumption that was made related to daily water consumption is one if the factors that has the most influence on the results. The assumption of 140 l/PE/day was chosen as final, based on recent studies (Jenssen Sola et al., 2018). The consumption can, however, have great variation both temporally and between households. Water consumption also varies over a year, but this has not been considered in this project. All these things influence the simulated flow in the sewer system, and might be a reason for the limited success of the calibration in dry conditions.

6.3 Discussion of I/I

After having a functional, calibrated model, another goal for this project was too assess the situation regarding I/I at Risvollan. The main focus here is on the sewer system, as I/I is clearly more of an issue for the sewer system than the stormwater system. The different simulations done in PCSWMM for dry and wet conditions were aimed at giving answers for the different types of I/I. As I/I have different sources, and can be divided into different types, the approach was to try to isolate each type through several rounds of simulation and calibration. Ideally, the types of I/I that could be assessed is I/I not related to precipitation, and indirect and direct I/I related to precipitation and wet conditions.

The model was first run and calibrated for dry situations, aiming at finding the constant part of I/I that are not related to precipitation events. Results from the sewer flow measurements showed a minimum night-time flow of approximately 0.7 l/s. It is difficult to estimate exactly how much of this is I/I, as there will probably be some water coming from households even at night. The measurements from the stormwater system also indicated a constant flow in dry conditions, being around 0.5 l/s. It was therefore estimated and concluded that the constant part of I/I during dry conditions is 0.5 l/s. This makes up 22% of the flow in the sewer system during the calibration period, which is a considerable part of the flow being transported to the treatment plants in Trondheim. Nevertheless, according to Figure 1.1, the extraneous water in dry conditions in all of Trondheim is about 57%. This indicates that the results from Risvollan is better than for the pipe system in Trondheim as a whole. This could be related to the groundwater condition at Risvollan, which is difficult to say much about as there are no records of the groundwater level close to the study area. The lower amount of constant I/I could also indicate that the condition of the pipe system is better than the average in Trondheim. The correlation result of NSE=0.45 and 0.59 for the calibration and validation, respectively, reveals that the model performance should be improved to get more reliable results.

The simulation and calibration for wet conditions were aiming at giving answers to the amount of I/I related to precipitation, both direct inflow and rainfall induced infiltration. This was planned to be done with the RDII-tool in PCSWMM. Unfortunately, the flow data was not of suitable quality to do this, as previously discussed. Therefore, the are no direct results from the model regarding I/I to the sewer system in wet conditions. Nevertheless, the data series for the measured flow clearly shows that the discharge is not keeping a constant level over the spring months, which would be the case if wet conditions had no influence on the system. The flow clearly varies according to precipitation and snowmelt, with increased flow around end of February to beginning of March, and end of March to beginning of April. It can also be seen that after a wet period is over, the minimum flow is still higher than during the longer dry periods. In other words, there is a visible long-term effect of the wet soil and rainfall induced infiltration. It can be firmly concluded that the sewer system is influenced by I/I related to precipitation, but this flow component has not been quantified in this project.

The results from the stress test gave a return period for only about 2 years for a 40 minutes precipitation event, for the stormwater system to be flooded and flow into the sewer system. This means that flooding of the stormwater system can be expected to occur relatively frequently, and increase the problems related to I/I in the sewer system. It is also probable that the required rain event to flood the stormwater system is even smaller if it occurs together with snowmelt. Even if the flooding for the found precipitation event only occurs at one manhole, the system is not better than its weakest link. Consequently, the stress test shows that the model can be used to find problematic sections or points in the system. This could be useful when assessing possible improvements of the system and rehabilitation purposes.

7 Conclusion

The scope of this project has been to develop a digital model, containing both the sewer and stormwater system at Risvollan, calibrate the model, and use it to assess the situation regarding I/I. The innovative model build-up turned out successful, and proved that it is indeed possible to combine the two systems in one model in PCSWMM. This opens up for a range of new applications and new ways of doing analyses on separated sewer systems with computer models.

The calibrated model at Risvollan showed promising results through the validation process. Nevertheless, the model needs improvement and further work to increase its reliability and to be suitable for other application and further research purposes. The results regarding I/I was incomplete, as the calibration for rainfall derived I/I was not fulfilled. Still, 22% I/I during dry conditions and clear indications of significantly increased flow during wet conditions, confirmed that I/I is present and is an issue that should be addressed.

8 Recommendations for Future Work

One of the reasons for doing this project was to build a computer model that could be useful for other research projects in the future. As the results in this project showed, there is need for further work on the model to obtain a better model success. The model can also be extended in terms of adding modelling capabilities to open up for other modelling applications. Certain important aspects of such work are described in this section.

Data

- The calibration should be done with data from periods unrelated to snow and snowmelt.
- The RDII-component should be calibrated, for both the sewer and the stormwater system. In order to calibrate the RDII-component in the sewer system, a heavy precipitation event that shows a clear impact on the discharge in the system is desired.
- The model parameters related to infiltration was estimated based on standard values. Infiltration tests could be done over the study area to examine infiltration rates.
- When assessing the situation related to I/I, and the interaction between the systems, it could be useful to have measurements of water quality in both systems. This also opens up for assessment of possible pollution issues.

Adding modelling capabilities

As snow and snowmelt is an important part of the hydrological cycle in Norway and Trondheim, it would be useful to add this to the model. This should be done after the model shows sufficient results for periods without snow. In addition, evaporation was not included in the model. This can be considered added.

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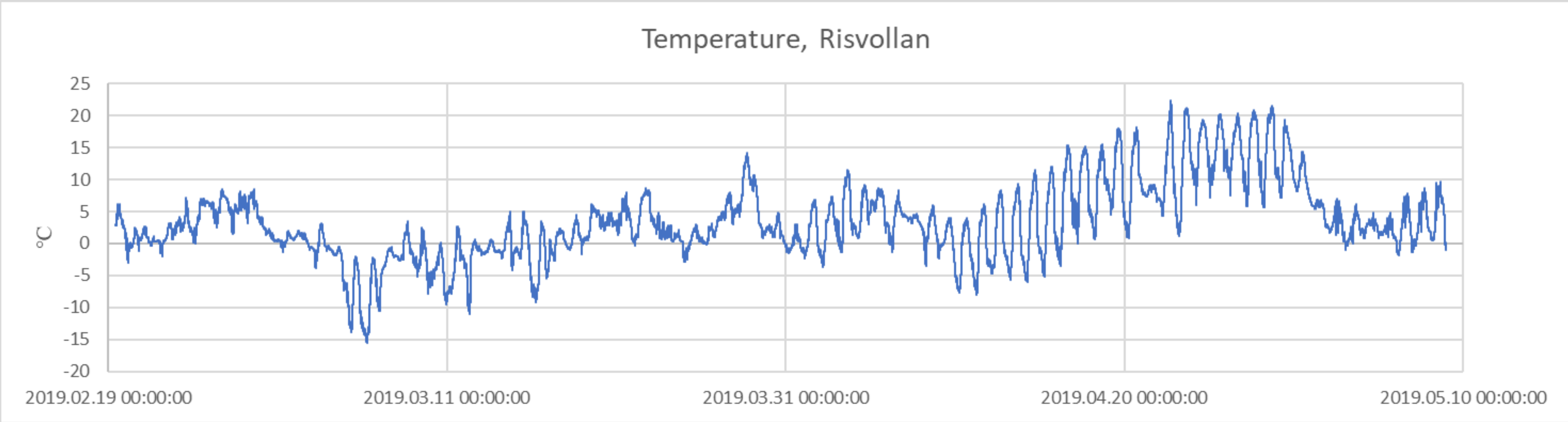
Appendix

Appendix A: Temperature data Risvollan

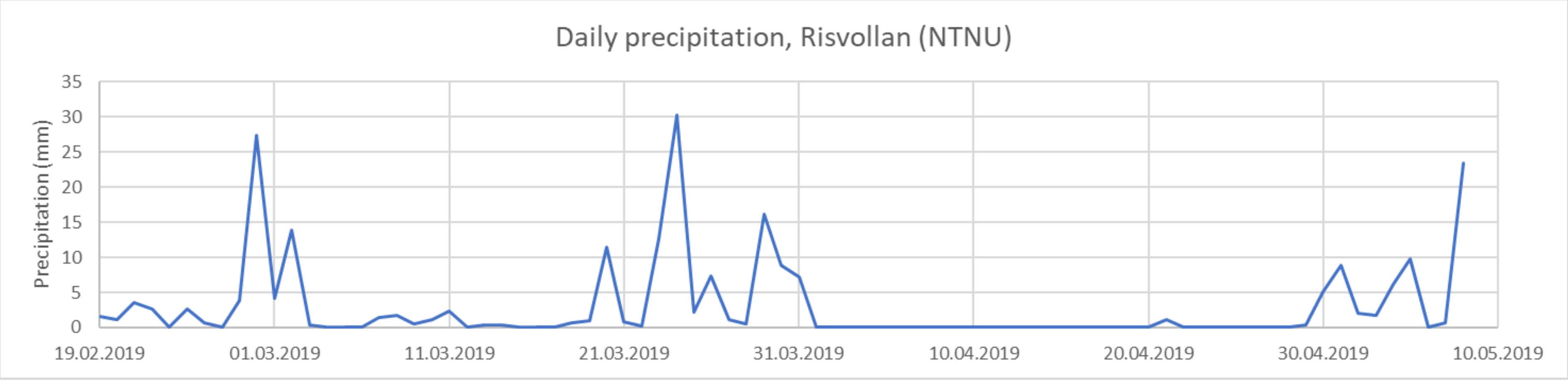
Appendix B: Precipitation data Risvollan

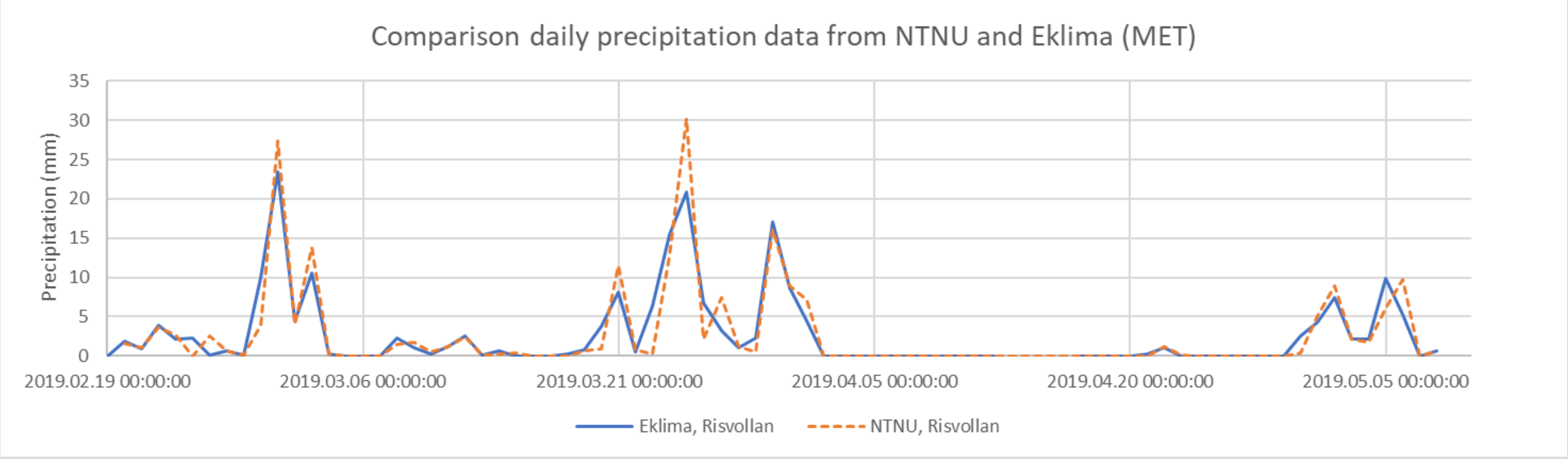
Appendix C: Flow data stormwater system, Risvollan

Appendix A – Temperature data, Risvollan

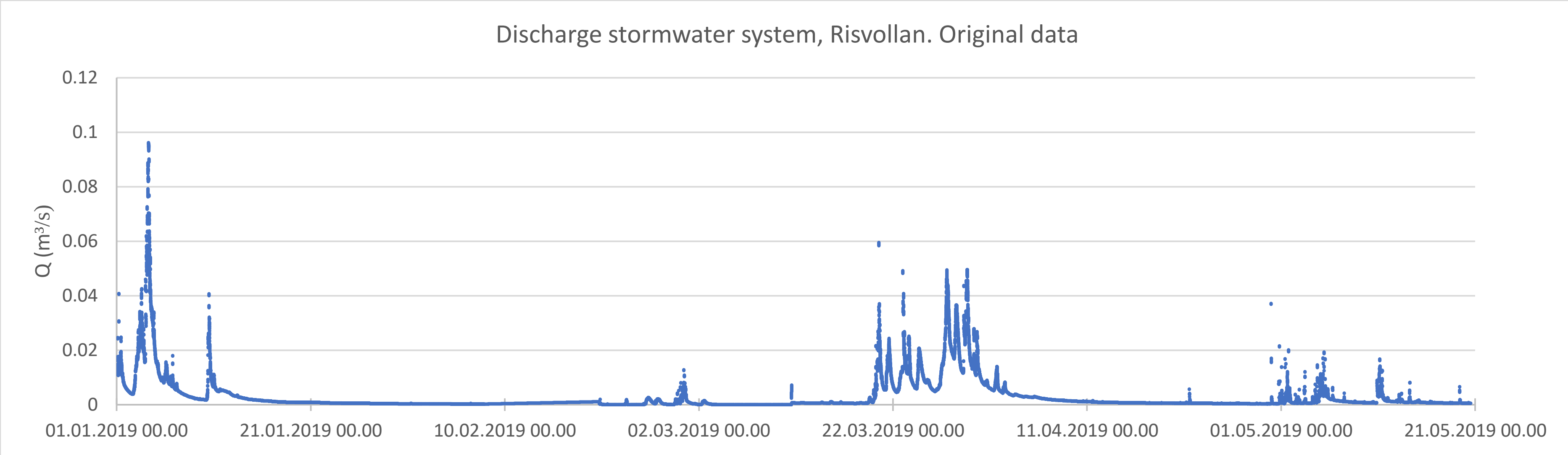


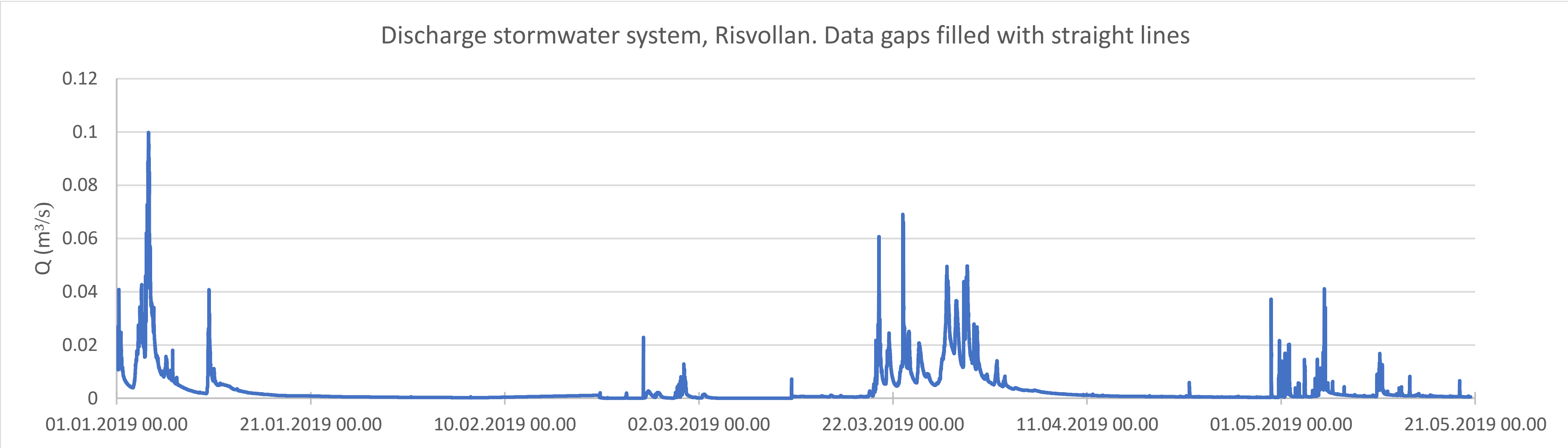
Appendix B – Precipitation data, Risvollan





Appendix C – Discharge stormwater system, Risvollan





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