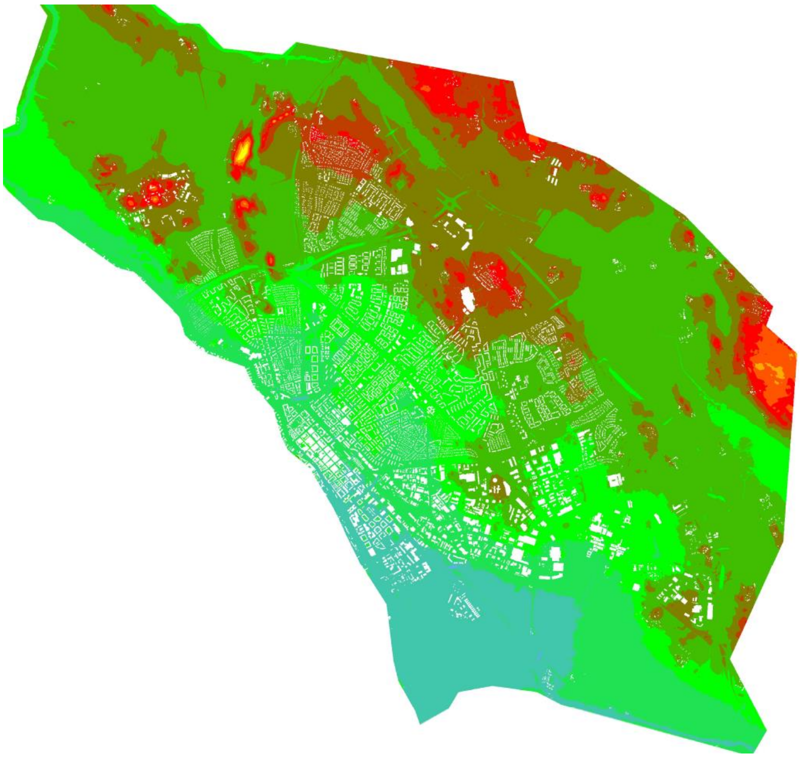

Sensitivity analysis of clogged stormwater inlets in a 1D-2D hydrodynamic stormwater model

Case study of Uppsala

Master's Thesis in the Master's Program Infrastructure and Environmental Engineering

REBECKA ENGSTRÖM GUSTAFSSON
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DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
DIVISION OF WATER ENVIRONMENT TECHNOLOGY

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022

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MASTER'S THESIS ACEX30

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Cover:
The cover presents the bathymetry of the original model area of Uppsala (DHI, 2021c). Further presented in section 3.1.

Department of Architecture and Civil Engineering
Gothenburg, Sweden, 2022

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Abstract

Pluvial flooding caused by cloudburst is predicted to increase due to climate change and the preconditions for flooding changes due to urbanization. The municipalities in Sweden are responsible to assess what land use an area is appropriate for and 1D-2D hydrodynamic stormwater modelling is one tool that can be used to assess this. In practice, it is not rare that debris flushes towards stormwater inlets when raining. The debris can cause clogging of the inlets and reduce its capacity. This thesis has researched through a survey the working method regarding consideration of clogged stormwater inlets of limited number of consultants in Sweden. This thesis also evaluated the effect of clogged stormwater inlets and reduced capacity in a 1D-2D hydrodynamic stormwater model. A model built in MIKE+ of Uppsala in Sweden was used. To represent clogged stormwater inlets the capacity was reduced with a clogging factor affecting the discharge coefficient of the 1D-2D couplings of the model. Four simulations were done with four different clogging factors based on literature research and the survey regarding consultants working method.

The responses of the survey presented that there is no common working method regarding if and how clogged stormwater inlets should be considered based on the group of consultants that answered the survey. A sensitivity analysis of the four simulations were made considering interaction volumes between the 1D collection system model and the 2D overland model, maximum water depth, water level and the discharge to surface in three nodes within the research area. The analysis concluded that the interaction volume from 1D to 2D is more affected by increasing clogging factor than the interaction volume from 2D to 1D. The extent and maximum water depth in the simulations are affected by the change of clogging factor but not largely. The analysis also concluded that the discharge in nodes is affected differently but the water level in nodes is not affected to a large extent by reducing capacity due to clogged stormwater inlets.

Keywords: Clogged stormwater inlets, clogging factor, MIKE+, 1D-2D hydrodynamic stormwater model, coupled model, 1D-2D coupling, discharge coefficient

Känslighetsanalys av igensatta rännstensbrunnar i en hydrodynamisk 1D-2D dagvattenmodell

Fallstudie av Uppsala

Examensarbete inom masterprogrammet Infrastruktur och Miljöteknik

REBECKA ENGSTRÖM GUSTAFSSON

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Sammanfattning

Översvämning orsakat av skyfall förväntas öka på grund av klimatförändringarna och förutsättningarna för att hantera översvämning förändras i och med urbanisering. I Sverige är kommunerna ansvariga för att bedöma vad som är lämplig användning av ett område. Ett verktyg som kan användas för att bedöma detta är hydrodynamisk 1D-2D dagvattenmodellering. Det är inte ovanligt att löv och skräp transporterad till rännstensbrunnar vid regn och orsakar igensättning och således reducerad kapacitet i rännstensbrunnarna. Detta arbete har i en enkätstudie utrett arbetsmetoden för igensatta rännstensbrunnar hos begränsat antal konsulter i Sverige. Arbetet har också undersökt effekten av igensatta rännstensbrunnar och således reducerad kapacitet i en hydrodynamisk 1D-2D dagvattenmodell. Modellen som användes var över Uppsala i Sverige och var uppbyggt i MIKE+. 'Discharge coefficient' i 1D-2D kopplingarna justerades med avseende till en igensättningsfaktor för att representera den reducerade kapaciteten vid igensatta rännstensbrunnar. Fyra simuleringar genomfördes med fyra olika igensättningsfaktorer vilka var baserade på litteraturstudie samt resultatet av enkätstudien.

Enkätstudien visar att det inte finns någon gemensam arbetsmetod för om och hur hänsyn till igensatta brunnar bör tas baserat på de konsulter i Sverige som svarade på enkäten. En känslighetsanalys genomfördes på de fyra simuleringarna med avseende på interaktionsvolymer mellan 1D ledningsnät modellen och 2D markmodellen, maximalt vattendjup, vattennivå och flöde till markmodellen i tre noder belägna inom studieområdet. Analysen visar att interaktionsvolymen från 1D till 2D påverkas mer av ökad igensättningsfaktor än vad interaktionsvolymer från 2D till 1D gör. Utbredningen av översvämning och det maximala vattendjupet påverkas av igensättningsfaktorn men inte i hög grad. Analysen konkluderar även att påverkan på flödet i noder varierar men att vattennivån i noder inte påverkas i hög grad av kapacitetsreducering på grund av igensatta rännstensbrunnar.

Nyckelord: Igensatta rännstensbrunnar, igensättningsfaktor, MIKE+, hydrodynamisk 1D-2D dagvattenmodell, kopplad modell, 1D-2D koppling, discharge coefficient

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Rebecka Engström Gustafsson and Johanna Pålsson

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Terminology

1D model	-	A model with one dimension. In terms of stormwater modelling 1D aims at the direction of the flow in a pipe or in a ditch.
1D-2D coupling	-	A coupling between a 1D and a 2D model enabling the two models to interact with each other.
1D-2D hydrodynamic stormwater model	-	A coupled 1D-2D model, exchange flows between the 1D collection system and the 2D surface can be studied.
2D model	-	A model with two dimensions. In terms of stormwater modelling 2D describes the extent of a potential flood on the surface.
ASCII-file	-	File based on binary data format.
Bathymetry data	-	Data of topography.
Boundary conditions	-	Defines the boundary of a model area. Can describe precipitation, water levels over time, and evaporation.
Calibrated model	-	A theoretical model that has been adjusted to assimilate measured data.
Catchment connection	-	A link between the outlet of a catchment to the collection system within MIKE+.
Catchment	-	In general: an area which’s runoff is lead to a specific recipient. In MIKE+: one hydrological unit of the model area.
Chicago Design Storm (CDS)	-	One type of design storm.
Climate factor	-	A factor multiplied with the rain intensity to consider climate change.
Cloudburst	-	When a large volume of water precipitate during a short period of time. In this thesis cloud bursts concerns rain of at least 50 mm during 1 hour or 1 mm during 1 min.
Collection system	-	Pipe system for stormwater collection.
Combination of grated inlet and curb inlet	-	A stormwater inlet designed to be both vertical and horizontal to the street.
Combined collection system	-	Both stormwater and wastewater are collected in the same pipe.
Crest width	-	Parameter associated with 1D-2D couplings within MIKE+. Can physically correspond to the crest width of a manhole.
Curb inlet	-	A stormwater inlet designed to be vertical to the street.
Curb inlet function	-	Equation within MIKE+ describing the flow a 1D-2D coupling.
Digital Elevation Model (DEM)	-	Model over the terrain containing elevations of the surface
Design storm	-	Precipitation data not based on historical rain series.
dfs-file	-	File formats associated with the MIKE-series.
Danish Hydrological Institute (DHI)	-	Institute that developed the MIKE-series.

Discharge coefficient	-	Coefficient affecting the flow in 1D-2D model coupling within MIKE+.
Drain inlet	-	A stormwater inlet designed to be horizontal to the street. A long and narrow inlet.
Duplicate collection system	-	Wastewater and stormwater are collected in separate pipes
Exponential function	-	Equation within MIKE+ describing the flow a 1D-2D coupling.
GIS (Geographical Information Systems)	-	System that can be used to model pluvial flooding.
Grated inlet	-	A stormwater inlet designed to be horizontal to the street with grates that stretches across the inlet.
hotstart file	-	File that can be used within MIKE+ to containing results from previously simulations.
Hydrodynamic (HD)	-	Module within MIKE+ that enables simulations of flow in the defined 1D network.
Hydraulic conductivity	-	The soils capacity to transport water, also called permeability.
Hyetograph	-	Graph presenting the relationship between rainfall intensity and time.
Intensity-Duration-Frequency curve (IDF curve)	-	One type of design storm. Describes the relation between the rain intensity and duration for a specific return period
Initial conditions	-	Conditions applied before the simulation starts. Can describe water levels, groundwater levels, and flows.
Initial loss	-	Parameter associated with the Time-Area method within MIKE+.
Inspection well	-	A component of the collection system enabling controls, inspections, and maintenance. An inspection well is operated from the ground.
Instantaneous time series	-	Time series with values only valid for a precise time.
Kinematic wave method	-	A surface runoff model within MIKE+.
Linear reservoir method	-	A surface runoff model within MIKE+.
Link	-	An element of the collection system within MIKE+. A link is a conduct between two nodes.
Manhole	-	A component of the collection system enabling controls, inspections, and maintenance.
Manning's number	-	Describes roughness of a surface.
Mean step accumulated times series	-	Time series with average values valid in between two time steps.
Measurement station	-	In this thesis: station measuring precipitation data.
MIKE Zero Toolbox	-	Software that can be used to create, process, and convert dfs-files.
MIKE+		Software that can be used for 1D-2D hydrodynamic stormwater modelling.
Node	-	An element of the collection system within MIKE+. A node can be a manhole or an outlet.

Orifice equation	-	Equation within MIKE+ describing the flow a 1D-2D coupling.
Permeability	-	The soils capacity to transport water, also called hydraulic conductivity.
Pluvial flooding	-	Flooding caused by precipitation.
Rainfall Runoff (PR)	-	Module counting hydrological models for simulation of rainfall runoff within the 1D model in MIKE+.
Precipitation	-	Comes from clouds and is related when vapor of water condensate, rain and snow are two examples of precipitation
Rain intensity	-	Amount of precipitation per unit of time.
Rainfall catchment load	-	A method for applying precipitation in the 1D model within MIKE+.
Raster data	-	Data format associated with GIS. Raster data includes rectangular cells organized in rows and columns.
Return period	-	Relation between the volume of precipitation and the duration and the precipitation event.
Runoff coefficient	-	Coefficient describing the portion of stormwater that is surface runoff.
SCALGO Live	-	Software that can be used to model pluvial flooding.
Skewness factor	-	A factor used when creating a CDS-rain. The factor describes the time from the starting point to the maximum intensity in ratio to the total duration.
Stormwater	-	Temporal flow of water can be due to precipitation.
Stormwater inlet	-	A component of the collection system which aims to intercept the stormwater from the surface to the collection system.
Thieessen polygon	-	Triangular irregular network with polygons that can be used within MIKE+ to create catchments. Thiessen polygons are also called Voronoi cells.
Time-Area method	-	A surface runoff model within MIKE+.
Tipping-bucket	-	A type of gauge for measurement of precipitation.
Unit hydrograph method	-	A surface runoff model within MIKE+.
Vector data	-	Data format associated with GIS. Vector data includes polygons, lines, and points.
Voronoi cells	-	Triangular irregular network with polygons that can be used within MIKE+ to create catchments. Voronoi cells are also called Thiessen polygons.
Weir equation	-	Equation within MIKE+ describing the flow a 1D-2D coupling.
xyz-file	-	File containing columns for coordinates (x, y) and z-value.

Notations

A	-	Available opening area of a grated inlet
c_0	-	Reduction factor due to clogging of a stormwater inlet
C	-	Orifice constant
D	-	Water depth at a grated stormwater inlet
E	-	Hydraulic efficiency of a stormwater inlet
E_{clean}	-	Hydraulic efficiency of a clean stormwater inlet
$E_{clogged}$	-	Hydraulic efficiency of a clogged stormwater inlet
ΔE	-	Difference in hydraulic efficiency between clean and clogged stormwater inlets
g	-	Gravity of Earth
i	-	Rain intensity or precipitation rate
i_a	-	Average rain intensity or average precipitation rate
M	-	Manning's number
n	-	Manning's roughness coefficient
Q_a	-	Approaching flow towards a grated stormwater inlet
Q_i	-	Intercepted flow by a grated stormwater inlet
Q_b	-	Bypassed flow of a grated stormwater inlet
R	-	Water depth
S	-	Slope of surface
t_r	-	Duration
Δt	-	Time length of considered period
T	-	Return period
v	-	Velocity
V	-	Volume of precipitation

1 Introduction

The Swedish Meteorological and Hydrological Institute, (SMHI, 2020), predicts that the amount of extreme rain events will increase as a consequence of climate change. Extreme rain events can cause harm in urban areas (SMHI, 2020). The harm can be both direct and indirect and, some consequences can be described as monetary value, and some cannot (Hernebring & Mårtensson, 2013). A consequence that is direct and has a monetary value is damage of buildings and infrastructure. Other direct consequence can be health related. One indirect consequence is disruption of traffic due to for example flooded roads. Moreover, the present urbanization is changing the preconditions for floodings (SMHI, 2020). To be able to minimize the harm of increased rain events and urbanization, more knowledge of extreme rain events and flooding is necessary.

Flooding can be caused by precipitation, snow melting or cloudbursts (MSB, 2020). When an area that is usually not under water, is covered with water temporally it is flooded. When the flooding is due to precipitation it is called a pluvial flooding (Hernebring & Mårtensson, 2013). If large volumes of water precipitate during a short period it is called a cloudburst (SMHI, 2011).

According to the Swedish Planning and Building Act (SFS 2010:900), it is the municipalities responsible to assess if the land is suitable for a certain land use. Thereby they should among other things assess the risk of flooding for the land. The Country Administrative Board acts as a supervisory authority towards the municipalities regarding risk assessment of floods. Therefore, it is of importance for the municipalities to have good knowledge of the risk of flooding. 1D-2D hydrodynamic stormwater modelling is one way to gain more knowledge about potential flooding and the predicted extent for a rain with a certain return period (MSB, 2017).

With a 1D-2D hydrodynamic stormwater model the interaction of flow between the surface (2D) and the collection system (1D) can be analysed (Blomquist et al., 2016). Flow paths and water depth at the surface as well as water levels in the collection system is received and hence more knowledge about potential flooding is gained. A stormwater model commonly contains several assumptions (Blomquist et al., 2016). According to a publication by Salomonsson et al. (2017) published by Svenskt Vatten Utveckling (SVU), assumptions about the capacity of the collection system should be highly conservative.

One assumption generally made in terms of stormwater modelling is that all stormwater inlets that intercept the flow on the surface to the collection system are free of clogging (Leitão et al., 2017; Salomonsson et al., 2017) even though clogging of stormwater inlets is a common phenomenon (Palla et al., 2018). Clogged stormwater inlets affect the capacity of the collection system and can have a significant impact on the model result (Leitão et al., 2017). Therefore, assumption about stormwater inlets is of great importance.

Since it is of major importance for the municipalities to assess the risk of potential flooding it is crucial to have a reliable work procedure regarding the assumptions made in 1D-2D hydrodynamic stormwater model. It is also important to have good knowledge about the consequences of the assumptions made. Therefore, this thesis will evaluate the work procedure applied by Swedish consultants regarding clogged stormwater inlets in a 1D-2D hydrodynamic stormwater model. The thesis will also evaluate the effect of the generally made, non-conservative, assumption that the stormwater inlets in a 1D-2D hydrodynamic stormwater model are free of clogging.

1.1 Aim

The aim of the thesis is to evaluate the effect of clogged stormwater inlets in a 1D-2D hydrodynamic stormwater model. Potentially, the result of the study can contribute to improvements of 1D-2D hydrodynamic stormwater modelling and hence lead to more resilient urban areas towards pluvial flooding. The objectives are to:

- Review theory about pluvial flooding, stormwater modelling, and the function of stormwater inlets.
- Investigate, based on a survey, how consultants in Sweden consider clogged stormwater inlets in a 1D-2D hydrodynamic stormwater model.
- Within a sensitivity analysis applied on the case study area Uppsala (Sweden) evaluate different reduction factors of the flow capacity in the couplings between the 1D and the 2D model in a hydrodynamic stormwater model. The reduced flow capacity in the 1D-2D model couplings represents clogged stormwater inlets.

1.2 Research questions

The research questions to be answered within this thesis are:

RQ 1. What are the working methods adapted by consultants in Sweden regarding clogged stormwater inlets in a 1D-2D hydrodynamic stormwater model?

RQ 2. How is the result of a 1D-2D hydrodynamic stormwater model affected when considering clogged stormwater inlets by reducing the flow capacity in the 1D-2D model couplings?

1.3 Limitations

The following limitations were made:

- The thesis was limited to only consider pluvial flooding, that is flooding due to rainfall.
- The survey was sent to a limited number of consultant companies.
- The impact of reduced flow capacity in 1D-2D model couplings was only considered in the software MIKE+.
- Only one CDS-rain event was included in the simulations of the sensitivity analysis.
- The sensitivity analysis was based on one research area.

2 Theory

This chapter provides a theoretical background to the topics presented in this thesis. Firstly, this chapter provides information about rainfall and design storms. Secondly, parameters affecting the surface runoff are described. Thirdly, the function of the collection system is described generally, and the stormwater inlets are presented more in detail. Concerning stormwater inlets, the factors affecting the likelihood of clogging, the frequency of clogging, hydraulic performance, and approaches regarding modelling of stormwater inlets are covered. Moreover, the chapter also covers modelling of pluvial flooding in urban areas where different levels of details is explained. Lastly, the chapter covers how modelling of pluvial flooding is performed in the software MIKE+.

2.1 Rainfall

Precipitation can be both in liquid and solid form, as for example rain and snow (Swedish Water, 2011). Precipitation comes from clouds that is created when vapor of water condensate. Precipitation releases from the clouds due to different reasons, one reason is increased temperature and air pressure which can happen if a cloud travels towards a mountain, this is called orographic precipitation. The orographic precipitation can also occur by the coast since the high wind velocity moves upwards when it reaches land. One other reason to precipitation is that two masses of air meets, one warm and one cold (SMHI, 2013; Swedish Water, 2011). When the two masses meet a front is created. The warmer air raises and cools down which creates clouds that can precipitate. A third reason to precipitation is convection, when cold air is above warmer ground or water. The air starts to move upwards which create clouds that can precipitate. According to SMHI (2013), convection is often the reason to the rain during the summer.

Within the topics of precipitation, three concepts are important: return period, duration, and rain intensity. Rain intensity is the amount of precipitation per unit of time, often as millimetres per hour [mm/h] but it can also be presented as litre per second and hectare [l/s, ha] (Swedish Water, 2011). The average rain intensity (i_a) can also be called average precipitation rate and is calculated considering the volume of precipitation (V) and time length of the period of consideration (Δt), see Equation 1. To consider the climate changes a climate factor is multiplied with the rain intensity (Swedish Water, 2016). Svensson (2020) writes that the climate factor is suggested by SMHI and Swedish Water to be 1.2-1.25 depending on the duration. The duration is the time length of the rain event. The return period describes a prediction of how often a specific rain event will occur (Swedish Water, 2016). The return period is based on historical data from measurement stations and the longer time series of data used when determining the return period, the more accurate is the determined return period. Swedish Water (2016) writes that, for example a rain with a return period of 100 years, can happen today and it can also happen tomorrow since the occurrence of rain events are random. The return period is a relation between the volume of precipitation and the duration (Swedish Water, 2016). The return period for a specific volume of precipitation differs depending on the duration, a shorter duration leads to a higher return period and a longer duration leads to a lower return period.

$$i_a = \frac{V}{\Delta t} \tag{1}$$

SMHI (n.d.) have compiled meteorological data of precipitation and presents that the normal monthly precipitation during the years 1991–2020 for July and August are 60–70 mm and 70–80 mm, respectively. When a large volume of water precipitate during a short period it can be called a cloudburst (SMHI, 2011). A cloudburst is by SMHI (2011) defined as a rain with a rain intensity of at least 50 mm during 1 h or 1 mm during 1 min. Swedish Water (2011) write that the high intensity cloudburst is due to convection. When water from precipitation cover an area which result in a flooding it is called a pluvial flooding (Hernebring & Mårtensson, 2013).

When modelling rain events the input data can be historical data, hyetographs created in a stochastic model or synthetic hyetographs (Licznar et al., 2011). The input precipitation data that is not based on historical rain series is called a design storm (Calabrò, 2004). Mazurkiewicz and Skotnicki (2018) writes that synthetic hyetographs are often used when modelling collection systems and pluvial flooding. When no historical data is available, synthetic hyetographs are an adequate option (Mazurkiewicz & Skotnicki, 2018).

2.1.1 Historical rain

Historical data with high resolution is one type of input data representing the precipitation in a hydrodynamic model (Licznar et al., 2011). Licznar et al. (2011) writes that resolution of every 5 min or less is essential if urban systems are hydrodynamically modelled. But time series of a rain event is usually not available (Calabrò, 2004; Licznar et al., 2011). Measurements of rain are often measured per 10 min or 15 min with gauges called tipping-buckets, therefore, the high-resolution historical data are sometimes not available (Licznar et al., 2011).

Historical data of a certain rain event is often presented as an accumulation of the precipitation data (Swedish Water, 2011). The starting point of the accumulation is difficult to decide and according to Swedish Water (2011) it is common that the accumulation is presented for one day and the precipitation is set to zero at the beginning and end of the day. Swedish Water (2011) write that a rain event can be defined by the length of the break between two persistent periods of precipitation, the break can vary between 0.5 to 6 hours.

2.1.2 Design storm and CDS-rain

The design storms are often used and can be divided into two groups (Balbastre-Soldevila et al., 2019). One group is only based on intensity-duration-frequency curves (IDF curve) while the other additionally considers temporal patterns (Balbastre-Soldevila et al., 2019). IDF curves describe the relation between the rain intensity and duration for a specific return period (Swedish Water, 2011). The precipitation before and after the studied time of duration is not included in the IDF curves. Some geographic locations do have developed IDF curves but for those areas that have not, the use of Dahlström's equation from year 2010 is suggested (Swedish Water, 2011), see Equation 2 (Dahlström, 2010). In Equation 2 the return period in months is presented as T, t_r is the duration in minutes and i is the rain intensity [l/s, ha]. The intensity and duration curves calculated with Equation 2 for return periods between 0.5 and 100 years are presented in Figure 1. Dahlström's equation can be used for durations between 5 min and 1 day (Swedish Water, 2011).

$$i(t_r) = 190 \times \sqrt[3]{T} \times \frac{ln(t_r)}{t_r^{0.98}} + 2 \tag{2}$$

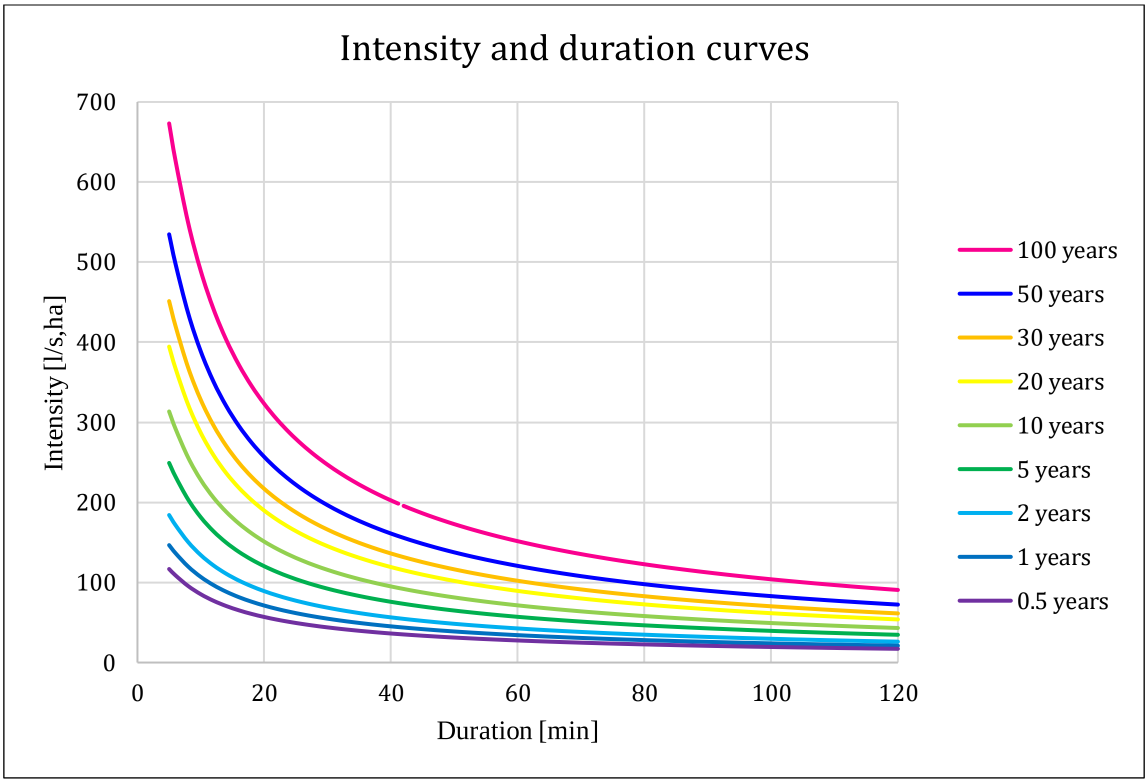

Figure 1. Intensity and duration curves calculated with Equation 2.

There are many different design storms that can be used, for example Chicago Design Storm, Alternating Block Method, Uniform Intensity Storm, Triangular or Linear/exponential storms (Balbastre-Soldevila et al., 2019). According to MSB (2017), the Chicago Design Storm (CDS-rain) is a suitable design storm event to use when modelling cloudbursts.

CDS-rain is a design storm within the group that only considers IDF curves (Balbastre-Soldevila et al., 2019). Rosbjerg and Madsen (2019) write that CDS-rain was elaborated in 1957 by Keifer and Chu. For the design storm, CDS-rain, it is important that the maximal average intensity for different durations follows a IDF curve (Swedish Water, 2011). The CDS hyetographs presents a specific return period and can be seen as several blocks that changes over time (MSB, 2017). For each block the intensity and duration vary. A skewness factor is used when creating a CDS-rain and the factor describes the time from the starting point to the maximum intensity in ratio to the total duration (Swedish Water, 2011). Swedish Water (2011) recommend that the factor of skewness is 0.37.

The return period of a CDS- rain can be longer than some measurements' return period in the corresponding IDF curve (Swedish Water, 2011). The reason to this is that the IDF curve is based on measurement from several different rain events and that the top of the CDS-rain's curve tends to be unnaturally pointy. Swedish Water (2011) writes that the length of each timestep depends on for example the size of the catchment area but by increasing the timestep the pointy top of the CDS-rain's curve can be compensated.

2.2 Stormwater surface runoff

According to SMHI (2019), stormwater is temporal flows of water due to for example precipitation and snow melting. Stormwater can generally be described as the water that can cause damage on a city's infrastructure, for example erosion and flooding (Leeuwen et al., 2019). The stormwater can also damage the ecosystems, be a risk for a city's health, and be a transportation for pollutants. Surface runoff is the stormwater on the surface that have not infiltrated after a rain event and therefore flows on the surface (Grip & Rodhe, 2016). Four parameters that affect the surface runoff are topography, land use, infiltration, and surface roughness.

2.2.1 Topography

Stormwater flows on the land surface depending on topography, for example the water flows from high to low elevations (Grip & Rodhe, 2016). In addition, topography can include higher elevations that stretches over an area and creates a divider that separates the runoff (Andréasson, 2006). If the dividers are illustrated on a topographic map they would stretch along the heights and would orthogonally cross the contouring lines (Grip & Rodhe, 2016). These dividers create areas called catchment areas (Andréasson, 2006). The catchment areas represent an area which's runoff water is lead to a specific recipient.

2.2.2 Land use

One important parameter in hydrological modelling is land use (Daramola et al., 2022). Many studies have shown that the land use affects the hydrological response and properties of an area (Daramola et al., 2022; Gashaw et al., 2018), for example the surface runoff, infiltration and evapotranspiration (Berihun et al., 2019). When changing the land use it can change the coefficient of runoff (Basri et al., 2022). The runoff coefficient describes the portion of stormwater that is surface runoff (Fetter, 2014; Swedish Water, 2016). The other part of the portion has for example infiltrated, evaporated or absorbed (Swedish Water, 2016). When an area gets urbanized its runoff coefficient increases due to higher impermeability of the surface which leads to more runoff on the surface (Fetter, 2014; Lima et al., 2022). The coefficient depends on the type of land use, the gradient of the surface and the intensity of the precipitation (Fetter, 2014; Swedish Water, 2016). A higher gradient and/or a higher rain intensity increases the runoff coefficient. Two examples of coefficient are for asphalt/concrete and lawns which are 0.8 and 0-0.1 [-] respectively (Swedish Water, 2016).

2.2.3 Infiltration

The infiltration into soil depends on land use and land cover (Berihun et al., 2019) and the properties of the soil type in the area (Basri et al., 2022). Different soils have different possibilities to transport water due to their hydraulic conductivity, also called permeability (Fetter, 2014). The hydraulic conductivity for unconsolidated clay and unconsolidated well-sorted gravel are 10^{-9}-10^{-6} cm/s and 0.01-1 cm/s, respectively. These numbers support that well-sorted gravel have a higher hydraulic conductivity and therefore the infiltration and possibility to absorb precipitation is higher in well-sorted gravel compared to clay. The soil's capacity of infiltration decreases over the time of a rain event and how it decreases is dependent on the conditions of the soil (Lima et al., 2022).

2.2.4 Surface roughness

When calculating the velocity (*v*) of the stormwater on the surface Equation 3 can be used (Swedish Water, 2016). The velocity (*v*) is calculated with the Manning's number (*M*), the slope (*S*) and the water depth (*R*) in meters.

$$v = M \times R^{2/3} \times S^{0.5} \quad (3)$$

Manning's number describes the roughness of the surface which affects the velocity (see Equation 3) and the extent of the flooding (Mårtensson & Gustafsson, 2014). Areas with grass have high roughness and covered areas, for example concrete or asphalt, have lower roughness. Two examples of *M* are 20 [-]for fields of grass and 65 [-] for canals of fine concrete (Swedish Water, 2016). M number can also be expressed dependent on Manning's roughness coefficient (*n*) (Persson et al., 2014), see Equation 4.

$$M = \frac{1}{n} \quad (4)$$

Studies have investigated how the vegetation and slope affect the roughness coefficient (*n*), two examples are Gad et al. (2022) and Zhang et al. (2020). Gad et al. (2022) writes that *n* increases if the height of the vegetation increases, which results in a smaller M number. According to the study by Zhang et al. (2020) the slope's effect on *n* depends on if the water depth is deep or shallow. For shallow depth the increase of slope lead to increased *n* and for deep depth the study showed a decrease of *n* when the slope increases. Mårtensson and Gustafsson (2014) writes that higher roughness, in other words a lower Manning's number, results in a larger flooded area but a shallower water depth and a lower roughness result in smaller flooded area but deeper water depth.

2.3 Collection of stormwater

The stormwater that precipitates in urban areas is collected in stormwater inlets (SMHI, 2015) and lead to the collection system (SFS2006:412). The collection system also collects drainage water and wastewater. The collection system can be divided into three different types, including combined and duplicate collection system (Blomquist et al., 2016; Swedish Water, 2016). In a combined collection system both stormwater and wastewater are collected in the same pipes. In a duplicate collection system, the wastewater and stormwater are collected in separated pipes. Even if the purpose of duplicate systems is to keep the wastewater and stormwater separate, there is usually some stormwater in the wastewater pipe due to leakage and drainage in the system's pipes or wells (Swedish Water, 2016). Due to this, basements risk to be flooded when there are high flows of stormwater. In some duplicate collection systems, the wastewater is connected to the stormwater network in case of overflow (Blomquist et al., 2016). The third type of collection system is called separate system (Blomquist et al., 2016; Swedish Water, 2016). Separated systems collect wastewater in pipes but the stormwater is collected on the surface in ditches (Swedish Water, 2016). Swedish Water (2016) highlight the importance of maintenance of the ditches, if the maintenance is not enough the ditches do not fulfil their function to collect the stormwater which can lead to flooding. When it is large volumes of precipitation the stormwater network's pipes have much lower capacity than ditches and other collection systems on the surface (Swedish Water, 2016). Swedish Water (2016) and Salomonsson et al. (2017) present the flow capacity for a pipe, a canal and some grass ditches, all with the dimensioning diameter/depth of 1 m, at different water depth. It can be concluded that the ditches have much higher flow capacity than both the pipe and the canal (Swedish Water, 2016).

Salomonsson et al. (2017) write that pluvial flooding can be due to that the soil saturation is high and the collection system's capacity is limited and is reached, which leads to that the precipitation will flow on the surface. The municipality or organisation responsible for the collection system in Sweden is according to Swedish Water (2016) responsible to provide a collection system with a capacity corresponding to a return period of 10 years. The surface runoff will flow towards low points and if the area is confined a flooding can occur (Salomonsson et al., 2017). If the capacity of the collection system is reached the water in the system can flow up from the system to the surface through open components, for example manholes. This happens when the pressure level is above the ground level. Two components of the collection system are manholes and inspection wells, both are intended to do controls, inspections, and maintenance (Swedish Water, 2015). The difference between the two components is that the inspection well is operated from the ground. Salomonsson et al. (2017) write that it is important that the stormwater collection system is maintained to prevent dams upstream due to clogged system with reduced capacity.

2.4 Stormwater inlets

One component of the collection system is the stormwater inlets which aim to intercept the stormwater from the surface to the collection system (Gómez et al., 2013; Salomonsson et al., 2017). Generally in urban areas, stormwater runoff flows in the direction of the slope of the street until reaching an inlet which can be placed either on a grade or in a low point (Zaman et al., 2021). Inlets placed in low points can have two functions and act as either an orifice or weir. Moreover, there are several categories of stormwater inlets such as grate, curbs, a combination of grate and curb, and slotted drain inlets. A grated inlet is designed to be horizontal to the street with grates that stretches across the inlet (UDFCD, 2016). A curb inlet is vertical in relation to the street. A grated inlet and a curb inlet can be combined, the combination has opening to the collection system both horizontal and vertical in relation to the street. A fourth type of stormwater inlet is a slotted drain inlet which is a long and narrow inlet designed to be horizontal to the street. An illustration of the different types of inlets is presented in Figure 2.

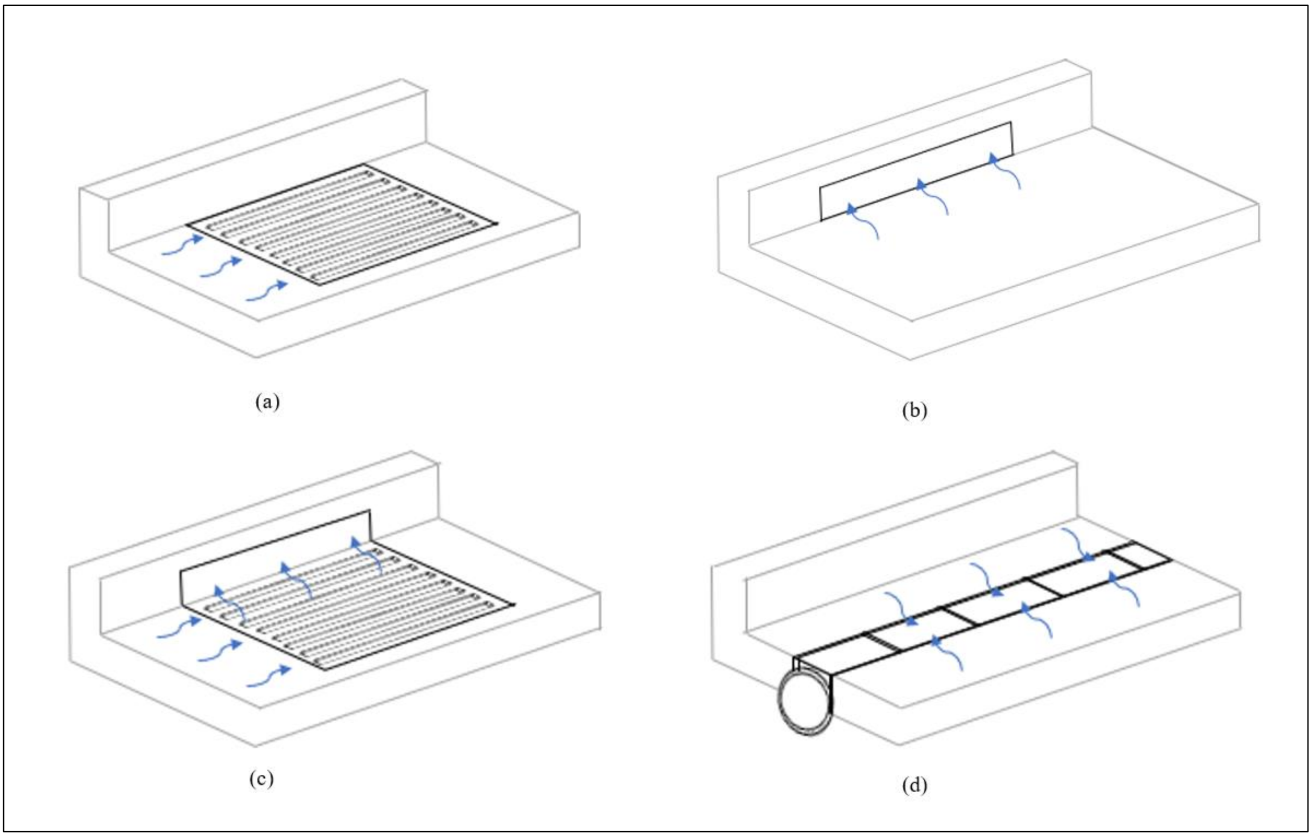

Figure 2. Illustration of stormwater inlets. (a) Grated inlet, (b) a curb inlet, (c) a combination of grate and curb, (d) and a slotted drain inlet. The illustration is inspired by UDFCD (2016) and made by the authors.

The stormwater inlets can be clogged due to aggregation of debris like leaves etc (Gómez et al., 2013; Leitão et al., 2017; Palla et al., 2018). Clogged or partly clogged stormwater inlets can result in reduced efficiency of the inlets. It can also lead to the rest of the collection system not reaching its capacity (Gómez et al., 2013; Palla et al., 2018). Another consequence of clogged stormwater inlets is the occurrence of local flooding (Palla et al., 2018).

2.4.1 Factors affecting the likelihood of clogging

The likelihood of a stormwater inlet to be clogged depends on several factors like maintenance routine, season, and the surrounding environment (Gómez et al., 2013; Leitão et al., 2017; Palla et al., 2018). Catchments with a large portion of impermeable surfaces results in less material that can aggregate and cause clogged stormwater inlets (Gómez et al., 2013). However, there is sufficient material that can cause clogging even if the proportion of impermeable surfaces is high. The likelihood for an inlet to be clogged also depends on weather conditions (Palla et al., 2018). For example, storms increase the supply of debris that can aggregate in the inlets. Another factor that affects the likelihood of clogging is the type of grate that the inlets are equipped with (Gómez et al., 2013). Since maintenance of the inlets is not fully effective, debris tends to aggregate under a long-term perspective. Hence the time since the inlet were installed can affect the likelihood of clogging. Besides clogging caused by debris, cars and other obstacles can prevent the stormwater from entering the collection system through the inlets. Moreover, obstacles covering the inlets can indirectly reduce the efficiency of the inlets by complicate maintenance routines.

2.4.2 Frequency of clogged stormwater inlets

Stormwater inlets are commonly clogged or partly clogged (Palla et al., 2018). In a study performed by Gómez et al. (2013) clogging patterns for different types of grated stormwater inlets in the Riera Blanca basin in Barcelona (Spain) were analysed. The slope of the streets in the basin are by the authors described as steep and mildly with 82% impervious area. The study evaluated eight different types of grated inlets and for two types no clogging patterns could be identified. The inspections were executed during the period May to August which is the most critical rain season in Barcelona (Gómez et al., 2013). The period is also associated with leaves. Three of the inspections were executed the days after precipitation and one inspection were carried out after a period without precipitation. The portion of inlets that were clogged differed largely based on the type of grated inlet.

In the study performed by Gómez et al. (2013), clogging patterns were categorized into three classes, C1, C2 and C3. Clogging pattern C3 described the most serious clogging with the greatest portion of the area being clogged while pattern C1 described the least serious pattern. Pattern C1 and C2 were similar to each other, both describing clogging patterns after precipitation. The third class, C3, described a seasonal clogging pattern during the summer. According to the authors of the study both the number of cars and the cleaning of inlets decreased during the summer. The cumulated frequency of the clogging patterns C1-C3 were 27%-91%. One of the six inlet types were installed no later than 5-10 years before the study while the remaining five types of inlets in most cases were installed more than 30 years before the study. Taking only the five types of inlets that in most cases were installed more than 30 years before the study into consideration the cumulated frequency was 66%-91%.

Gómez et al. (2013) found that the slope of the street where the inlet was located had no impact on the type of clogging pattern. The occurrence of each clogging pattern for the six types of inlets are presented in Table 1. As displayed in the table, the least serious clogging pattern C1 were the dominant pattern for all types of inlets. The inlets are denoted with local references used in the study performed by Gómez et al. (2013).

Table 1. Clogging conditions and type of inlets in the Riera Blanca basin reported by Gómez et al. (2013).

Type of inlet according to local references	Pattern C1 [%]	Pattern C2 [%]	Pattern C3 [%]	Cumulated frequency of pattern C1-C3 [%]
Ebro	75	3	11	89
Delta	13	12	2	27
Impu	50	19	16	85
Diagonal	30	13	23	66
Teide	81	7	3	91
E-11	36	13	24	73

The frequency of clogged stormwater inlets has also been studied by Palla et al. (2018) who analysed approximately 1140 inlets in the Force subcatchment in Genova (Italy). According to the authors, the Force subcatchment is completely urbanized and the topology has a weak slope. The inspection of the inlets took place during the period October to December. According to the authors this period is the critical rain season for Genova as well as a period with a lot of leaves and sediment transport. The maintenance routine for the inlets were not known by the authors. In the analysis, the inlets were divided into three categories: grate inlets, curb inlets or a combination. Most of the analysed inlets were of the type grate followed by the type of curb. The majority of the inlets were of the dimension 40x30 cm but other dimensions occurred.

The result of the inspection of the Force subcatchment is presented in Table 2. 5% of the inlets were found to be completely clogged and 10% were partially clogged (Palla et al., 2018). The share of completely clogged inlets was found to be 5%. The study does not present the portion of clogged inlets in relation to the different types of inlets.

Table 2. Clogging condition and type of inlets in the Force subcatchment reported by Palla et al. (2018).

Type of inlet [numbers]	
Grate	981
Curb	114
Combination	40
Clogging condition [%]	
Free	85
Partially clogged (available area reduced to 50%)	10
Completely clogged	5

2.4.3 Hydraulic performance of a grated inlet

There are three types of flows associated with the hydraulic performance of a grated stormwater inlets; the approaching flow (Q_a), the intercepted flow (Q_i) and the bypassed flow (Q_b) (Zaman et al., 2021). See Figure 3 for an illustration of the three flows.

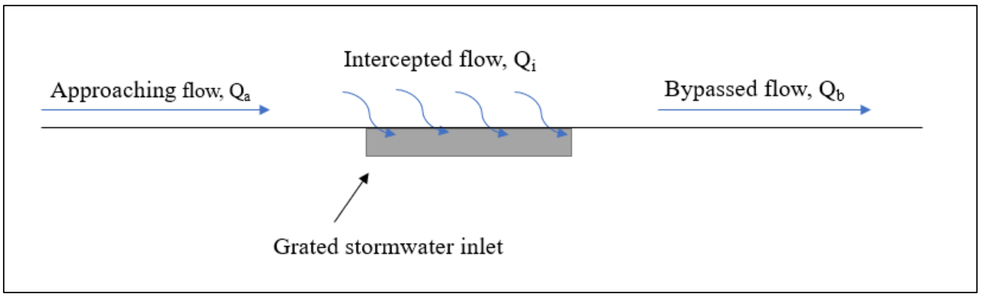

Figure 3. Illustration of the associated flows for hydraulic performance of a grated stormwater inlet. The Figure is inspired from Zaman et al. (2021) and made by the authors.

The sum of the flows Q_i and Q_b equals the flow Q_a (Zaman et al., 2021), Equation 5. For grated inlets located on a slope, Q_i generally corresponds to Q_a for low values of Q_a and hence no flow bypasses the inlet. A higher value of Q_a generally entails that the inlet is bypassed by a certain flow and hence that Q_a do not correspond to Q_i.

$$Q_a = Q_i + Q_b \qquad (5)$$

The interception capacity and the hydraulic efficiency are two common ways of describing the performance of a grated stormwater inlet (Zaman et al., 2021). The intercepted flow of a grated inlet which function as an orifice can be described with Equation 6 (Zaman et al., 2021). In the equation, *C* is an orifice constant equal to 0.67, *A* is the available opening area, *g* is the gravity of Earth and *D* is the water depth at the inlet.

$$Q_i = CA\sqrt{2gD} \qquad (6)$$

The hydraulic efficiency of a stormwater inlet (*E*) can be described as the ratio of the intercepted flow (Q_i) and the approaching flow (Q_a) (Gómez et al., 2013; Zaman et al., 2021), Equation 7. The efficiency of a stormwater inlet is dependent on the slope of the street (Salomonsson et al., 2017). The capacity of inlets located on streets with a high slope is smaller than the capacity of inlets located on streets with a low slope. The reason is that the stormwater tends to bypass the inlet and continue in the direction of the slope if the gradient is high.

$$E = \frac{Q_i}{Q_a} \tag{7}$$

The clogging phenomena can be considered by introducing a reduction factor (Gómez et al., 2013; Palla et al., 2018). The reduction factor (c_0) can be described as the ratio in Equation 8 where the hydraulic efficiency of a clean inlet is denoted as (E_{clean}) and the hydraulic efficiency of a clogged inlet is denoted as ($E_{clogged}$) (Gómez et al., 2013).

$$c_0 = \frac{E_{clean} - E_{clogged}}{E_{clean}} = \frac{\Delta E}{E} \tag{8}$$

If the clogging phenomena is considered, the hydraulic efficiency of a clogged inlet can be described by Equation 9 (Gómez et al., 2013).

$$E_{clogged} = (1 - c_0)E_{clean} \tag{9}$$

A c_0 of 1 represents a completely clogged inlet while a c_0 of 0 represents a completely clean inlet (Gómez et al., 2013). The reduction factor c_0 is often assigned a constant value of 0.5 regardless of the type of inlet when the actual hydraulic efficiency is expressed. In the study performed by Gómez et al. (2013) reduction factors were experimentally investigated for two of the inlet types identified in the Riera Blanca basin in Barcelona. Reduction factors were suggested for the different clogging patterns C1, C2 and C3 (see section 2.4.2). For the two analysed inlet types Embo and Impu the authors found c_0 to be within the range 0.265-0.667, which is both lower and higher than the standard value of 0.5. The results by Gómez et al. (2013) showed experimental determined values of c_0 are presented in Table 3. The table shows that the suggested values of c_0 differs considerable for the different patterns and inlet types. The values are based on a rain considering intensities of 60 mm/h. For this rain the values of c_0 showed to be almost constant (Gómez et al., 2013).

Table 3. Values of c_0 for two types of grated inlets. The values are experimental determined by Gómez et al. (2013) based on a rain considering an intensity of 60 mm/h.

	Clogging pattern C1	**Clogging pattern C2**	**Clogging pattern C3**
c_0 for inlet type Embro	0.451	0.502	0.674
c_0 for inlet type Impu	0.265	0.400	0.667

In Italy, clogging of stormwater inlets is suggested to be taking into consideration by reducing the hydraulic efficiency of inlets with 25% (Artina et al,. 2001, referred to in Gómez et al., 2013). In USA, it is stated in the Denver Urban Storm Drainage Criteria Manual that it is a common practice to consider the hydraulic efficiency of a single grated inlet reduced by 50% due to clogging (UDFCD, 2016). The manual also states that the risk for completely clogging should be assessed for all inlets placed in low points.

2.4.4 Modelling stormwater inlets

According to Bertsch et al. (2017) stormwater inlets are generally not included in 1D-2D hydrodynamic stormwater model. The exchange flow between the surface and the collection system is instead symbolized with exchange flow in the manholes. The reason to not including stormwater inlets in the model is usually due to lack of information about the location of the inlets.

Even though the actual hydraulic efficiency of the stormwater inlet can differ from the theoretical hydraulic efficiency, inlets to the collection system are generally assessed not to be clogged in urban stormwater models (Leitão et al., 2017; Salomonsson et al., 2017). The general ignorance of potentially clogged stormwater inlets when modelling is also stated by Salomonsson et al. (2017) in a report published by Svenskt Vatten Utveckling (SVU). Since efficiency can have a major impact on the model result, clogged inlets can be an important uncertainty (Leitão et al., 2017). Palla et al. (2018) claims that this is a large uncertainty that cannot be avoided even though the inlets have the correct dimension and location since clogging is unpredictable. If the assessment of the capacity of the collection system is based on theoretical efficiency of the inlets the assessment should only be considered as an indication (Salomonsson et al., 2017). Salomonsson et al. (2017) highlights the importance of making highly conservative assumptions about the efficiency of the collection system. To make an urban pluvial flood model (see section 2.5) assimilate the reality to a greater extent, variation in efficiency of the stormwater inlets should be considered (Leitão et al., 2017; Palla et al., 2018).

2.5 Analysis and modelling of pluvial flooding in urban areas

The aim of a model simulating pluvial flooding in urban areas is to present the extent of a potential flood and its location (MSB, 2017). A model can give information about flow direction, surface runoff, and water depth for a simulated rain. Models can be designed to include different information based on the purpose of the model (Blomquist et al., 2016). A model is a simplification of the reality, and the received result is never better than the quality of the data used to build the model.

There are several software programs developed to model pluvial flooding, one example of software is the MIKE-series (Salomonsson et al., 2017). MIKE+ is associated with different dfs-file formats (DHI, 2022a) which can be created, processed, and converted by the MIKE Zero Toolbox (DHI, 2020). MIKE+ is the software mainly used in the current study and is hence explained further in section 2.6. Another example of software that can be used to model pluvial flooding is SCALGO Live (SCALGO Live, n.d.). SCALGO Live enables the user to get an overview of the flood risk for a certain area, study dynamic watersheds for a certain point, and to inspect the terrain and basin volumes. The program can be used within the fields urban planning, emergency management, climate adaption, pluvial flooding, and watercourse flooding. Geographical Information Systems (GIS) can also be used in the purpose of modelling pluvial floodings (Blomquist et al., 2016). GIS manage and analyses geographically referenced data and can be applied within multiple fields (Auerbach, 2019). GIS can for example include toolboxes for conversion of data, data management, and spatial analyst (Esri, 2020). To convert data between different file formats, clip data, and interpolate data are a few examples of how the toolboxes makes it possible to process and analyse data. With input information like land use, topography, and soil type a pluvial flood model can be created in GIS (Vieux, 2015). There are two types of data associated with GIS: vector data and raster data (Auerbach, 2019). Vector data includes polygons, lines, and points and is a geometric shape. Raster data consists of rectangular cells organized in a grid with columns and rows (Lim, 2015). The size of the cells describes the resolution of the data. Each cell in the raster is assigned a value, for example describing bathymetry or soil type. The cell values can be either floating (continuous values) or integers. GIS also enables data exchange with ASCII-files which are files based on binary data format (Aggett & McColl, 2015). Furthermore, GIS is compatible to MIKE Zero Toolbox which for example enables the user to convert shape and raster-files into files associated with the MIKE-series and vice versa (DHI, 2020). Additionally, MIKE Zero Toolbox can be used to convert shape-files into xyz-files which are files containing columns for coordinates (x, y) and z-value. There are several available GIS software (Auerbach, 2019), two examples are ArcGIS (Maguire, 2015) and QGIS (Hugentobler, 2015).

In terms of pluvial flooding, a model can have one or two dimensions, and hence be a 1D or a 2D model (Blomquist et al., 2016). A 1D model describes the flow in one dimension. In terms of stormwater modelling 1D aims at the direction of the flow in a pipe or in a ditch. The results of 1D modelling are commonly the level of water pressure in pipes and nodes (Blomquist et al., 2016). The results can be presented as profiles or on a map showing the collection system. The 1D models simulate the collection system but do not simulate flooding of a node (Rangari et al., 2015). To also consider the flooding of the node a 2D model or coupled 1D 2D model is used. According to Blomquist et al. (2016) a 1D model is appropriate to use when for example designing new collection systems, designing measures of an existing collection system and analysis of potential flooding of basements.

A 2D model describes the flow in two dimensions and aims to describe the extent of a potential flood on the surface. By coupling a 1D model of the pipe network with a 2D model of the model area the interaction between the surface runoff and the pipe network can be modeled (MSB, 2017).

The boundary of the defined model area is described by boundary conditions (Blomquist et al., 2016). The boundary condition can for example describe precipitation, flow in and out of the model, water levels over time, and evaporation. The boundary condition can either be expressed as constant values or as values varying with time. It can also be necessary to assign initial conditions that yields before the simulation starts. Initial conditions can be assigned for both the 1D and the 2D model. Examples of parameters that can be assigned initial conditions are water levels, groundwater levels, and flow.

With no calibration Blomquist et al. (2016) claims that the model only is theoretical. A calibrated model means that the theoretical model has been adjusted to assimilate measured data over the model area which results in a model that to a greater extent describes the reality (Blomquist et al., 2016; MSB, 2017). For a 1D model of the collection system, measured data can include flow measurements in the collection system (Blomquist et al., 2016). For most cases it is suitable to calibrate the model to a similar scenario that the model aims to describe (MSB, 2017). However, a calibrated model is not always possible to achieve due to lack of data (Blomquist et al., 2016; MSB, 2017). In many cases measured water depths caused by cloudbursts are missing due to the seldom occurrence of extreme precipitation events and difficulties in measuring the water depths during the events (MSB, 2017). Hence, calibration of a model simulating cloudbursts is often associated with lack of data of the water depth. An optional method for calibrating models when no water depths are available is to compare the model result to markings on building etc caused by the water. This option requires information about the rain events distribution in time and space.

According to Leitão et al. (2017) modelling of collection systems within urban areas has been an active topic of research for decades. The research regarding modelling of collection systems has mostly focused on so called first sources of uncertainty, for example uncertainties regarding the model parameters, input/output data and the setup of the model (Leitão et al., 2017). Research regarding uncertainties about the operational conditions of the collection system, for example capacity of stormwater inlets has historically not been widely studied.

To evaluate uncertainties regarding, model parameters, the performance of sensitivity analyses have been applied in several studies (Kanso et al., 2003, Thorndahl et al., 2008, Dotto et al., 2009). The results of the sensitivity analyses have in several cases been used to generate probability distributions clarifying how the uncertainty of the evaluated model parameter affects the output result (Marshall et al., 2004, Dotto et al., 2010, McCarthy et al., 2010).

Regarding calibration of models of the collection system, the research has historically mainly focused on the effectiveness of process of calibration and verification (Deletic et al., 2012). Methods regarding how to divide data into calibration datasets and verification data sets has been an active topic of research (McCarthy, 1976, Klemes, 1986, Vaze and Chiew, 2003, Wagener et al., 2004). The research regarding calibration of model has clearly shown that there are uncertainties within the data used for calibration that affects the uncertainty of the calibration process (Deletic et al., 2012).

The impact of the uncertainties regarding the input data is not as well understood as the impact of the calibration (Deletic et al., 2012). Within the field of input data, Kleidorfer et al. (2009) and Freni et al. (2010) has evaluated how the uncertainties of the input data impact model parameters in order to evaluate the interaction between input data and model parameters.

The detail and advancement of the model should correspond to the purpose of the model (Blomquist et al., 2016). Blomquist et al. (2016) describes three different levels (level I-level III) of details for analysis and models which aims to identify flooding. All three levels require a Digital Elevation Model (DEM) (Blomquist et al., 2016) which is a model over the terrain containing elevations of the surface (McGlone, 2015).

2.5.1 Level I: Analysis of low points and flow paths

Level I aims to identify low points and flow paths by analysing a DEM (Blomquist et al., 2016). No specific precipitation is connected to the analysis and no modelling of the collection system is included. The analysis hence counts as relatively simple and is suitable for a first indication of areas that risk pluvial flooding and need more advanced analysis. Since the collection system is not included the analysis can represent a scenario where the capacity of the collection system has been reached. The analysis can be performed by using a Geographical Information Systems (GIS) software.

2.5.2 Level II: Modelling of surface runoff without consideration of the collection system

As for level I, level II aims to identify low points and flow paths (Blomquist et al., 2016). The difference between level I and level II are that level II considers a specific precipitation with certain properties like duration, intensity and return period. Generally, level II also includes the properties of the soil and hence consider infiltration and how the water flows on the surface. As for level I the collection system is not included and can therefore represent a scenario where the capacity of the collection system has been reached. Alternatively, the simulated precipitation can be reduced in the same magnitude as the capacity of the collection system. Blomquist et al. (2016) highlights that reducing the magnitude of the precipitation entails uncertainties. One reason for this is that the capacity of older collection systems does not always correspond to the capacity of which it was designed for. It can therefore be difficult to estimate how much the precipitation should be reduced. Another reason is that the surface runoff may not have time to reach the collection system in terms of intensive precipitation. If that is the case, the function of the collection system is limited.

2.5.3 Level III: Modelling of surface runoff and the collection system

In level III, a model of the surface runoff (2D) is coupled with a model of the collection system (1D) (Blomquist et al., 2016). In a coupled model the stormwater can flow between the two models and hence the exchange flow between the 2D and 1D model is obtained. For level III, the water level in the collection system is obtained in relation to the ground level. If the water level exceeds the ground level the model indicates that the water will flow from the collection system towards the surface. The exchange of flows between the two models can be intercepted through inlets to collection system. As for level II the flow paths and the extent of flooding on the surface is obtained.

The simulated precipitation can be applied either in the 1D or in the 2D model (Blomqvist et al., 2016). If the 1D model of the network is calibrated Blomquist et al. (2016) recommends that the precipitation is applied in this model. A consequence of this method is that the model result will not indicate flooding of surfaces that is not coupled to the 1D model. If the precipitation is applied in the 2D model reduction factors like infiltration should be considered carefully.

2.6 Modelling in MIKE+

MIKE+ is the latest software developed by the Danish Hydrological Institute (DHI) (DHI, 2022). MIKE+ consists of several features and modules and can hence be used for several purposes such as modelling of collection systems for stormwater and wastewater, modelling of water distribution networks and modelling of 2D surfaces.

MIKE+ consist of the three model types: ‘rivers, collection system and overland flows’, ‘SWMM5 collection system’ and ‘water distribution’ (DHI, 2021a). In this thesis the model type ‘rivers, collection system and overland flow’ will be used and is therefore explained further. Within the model type ‘rivers, collection system and overland flows’ the features catchments, collection system network, river network and 2D overland can be modelled (DHI, 2022b, 2022c): As mentioned above MIKE+ consists of several modules. For the model type ‘rivers, collection system and overland flows’ the modules rainfall runoff (RR), hydrodynamic (HD), transport, water quality and sediment transport are available (DHI, 2022b, 2022c).

Figure 4 provides a conceptual scheme of the features and modules associated with the model type ‘rivers, collection system and overland flow’. Within this project the features catchments, collection system network, and 2D overland are considered. Considered modules within the project are rainfall runoff (RR) and hydrodynamic (HD). In Figure 4, black boxes symbolise features and modules that this project includes. These features and modules are explained in more details.

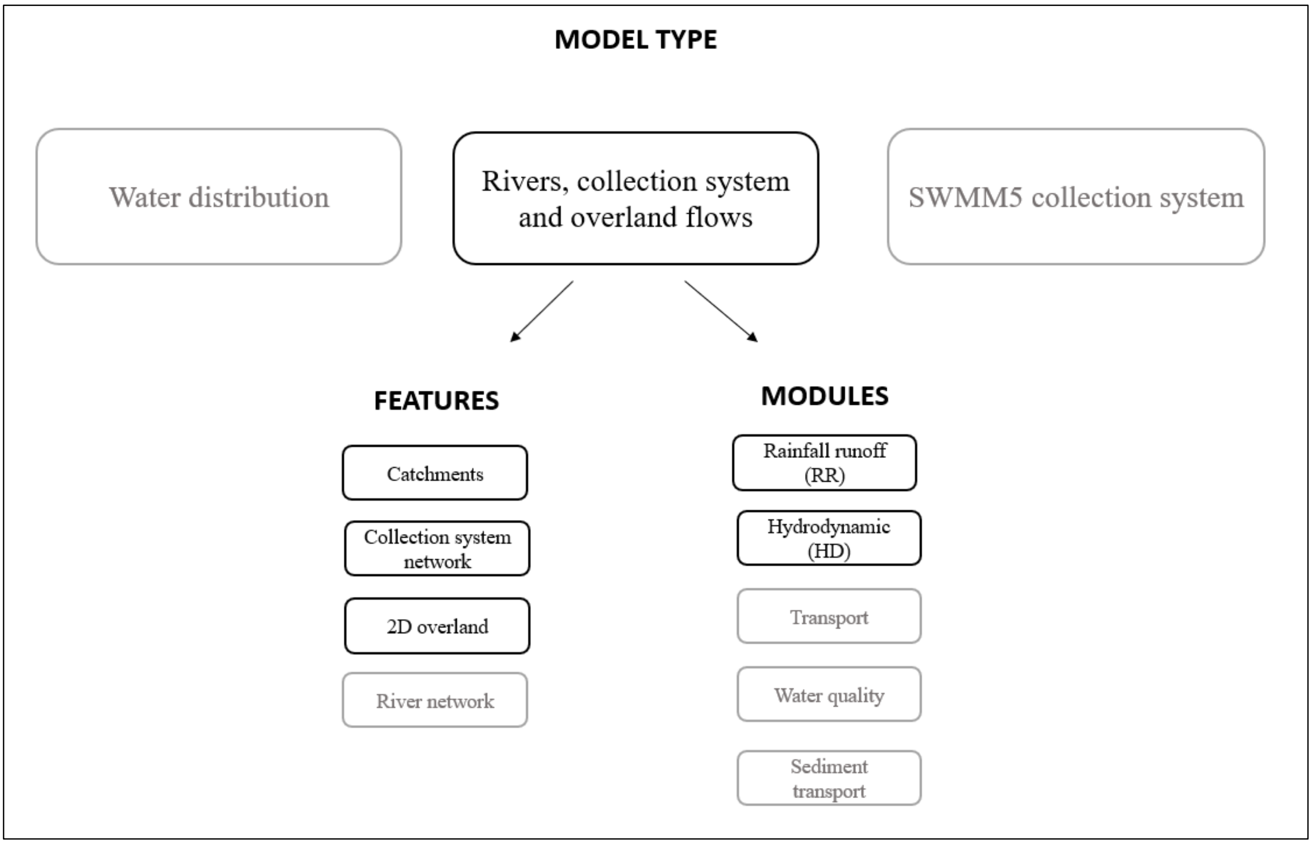

Figure 4. Conceptual scheme of features and modules associated with the model type rivers, collection system and overland flow in MIKE+. The thesis concerns boxes marked in black. Shaded boxes are not concerned in this thesis and will not be explained further.

2.6.1 1D modelling of collection systems

When modelling a collection system within MIKE+ a MIKE 1D network is defined (DHI, 2022b). Simulation of the defined network can be made to present water level and flow. The defined network is built with the following elements: nodes and structures, pipes and canals, weirs, orifices, curb inlets, pumps, and valves.

The different elements in the hydraulic model are assigned different properties (DHI, 2022b). For collection systems the nodes are often defined as circular manholes but can also be of the types basins, soakaway or outlets. Each node is assigned an ID and position. For nodes different properties like geometry, the type of cover (for a manhole), flow regulation, head loss, effective area and pressure can be assigned. Different properties should be assigned to different node types. A link in MIKE+ is defined as a conduit between two nodes. As for a node a link is assigned an ID and position. All links in the 1D model should be assigned a diameter and information about the roughness. The roughness of the link is dependent on the material of the pipe and can be expressed with either the Manning friction coefficient, the Colebrook White coefficient, or the Hazen-Williams coefficient. Another example of property that should be provided for a link is the upstream and downstream invert level.

The model area is divided into catchments which consists of polygons (DHI, 2022b). Each catchment is considered as one hydrological unit. The spatial discretization of the model is therefore dependent on the catchments. In MIKE+ catchments are created with the tool catchment delineation which provides three options for the type of catchments created (DHI, 2022a). The first option is to create catchments based on a point layer. Secondly, catchments can be created based on a line layer. Both the first and the second option creates catchments as Thiessen polygons, also called Voronoi cells. Thiessen polygons implies a triangulated irregular network with polygons where one polygon includes either one point feature or one layer feature depending on if the Thiessen polygons are created based on a point layer or a line layer. The third option is to create catchments based on the DEM in combination with nodes. This implies that the slope described in the DEM defines the catchments around the inlet nodes. The outlet of the catchment is linked to the collection system by a catchment connection (DHI, 2022b).

The module hydrodynamic (HD) enables simulations of flow in the defined 1D network (DHI, 2022b). All nodes in the defined network are assigned one computational point for which the water level is computed for each one of the defined time steps. A link has several computational points and hence calculations are performed for different parts of the same link. The computational points for links are organised in an alternating sequence of points which calculate either the water level or the discharge. The pattern is always ordered with a computational point calculating the water level located closest to a node.

As for most time dependent numerical models initial conditions need to be defined for the collection system in the 1D model in MIKE+ (DHI, 2022b). Examples of initial conditions are water level, water depth, and discharge of flow. The initial conditions can be defined in two ways, either with user defined values or with a hotstart file. The user defined values can be applied for either the whole collection system or as local values for parts of the collection system. A hotstart file is a file containing result from a previous simulation. For parts of the collection system where no initial conditions are provided MIKE+ applies default values.

Boundary conditions can be applied to the 1D model (DHI, 2022b). Examples of boundary conditions that can be applied are inflow to link, inflow to node, rainfall, and outlet water level. The boundary conditions can have different spatial extent as well as temporal variation.

2.6.2 2D Overland Modelling

Overland hydraulic modelling is available within the module hydrodynamic (HD) (DHI, 2022c). In terms of 2D overland modelling MIKE+ provides functions for both surface flows as well as pluvial/fluvial overland flooding and costal phenomena.

For 2D overland modelling a mesh or a grid for the 2D model area bathymetry needs to be defined (DHI, 2022c). The definition is managed under the 2D domain editor. The 2D domain constitutes the computational grid for the 2D modelling. The domain type can be either rectangular or flexible. The topographic of the 2D domain is based on scatter data which has been interpolated. The domain type rectangular is further explained since it is the domain type used in this thesis. A rectangular grid is built up with grid points placed uniformly and orthogonal (DHI, 2022c). When defining the rectangular grid, the size of the cells in both x- and y-directions need to be assigned as well as the extent of the grid.

The boundaries of the 2D domain can either be closed or opened (DHI, 2022c). A closed boundary does not allow any flow across the border of the domain. For a closed boundary MIKE+ raises the cells elevation at the border to the defined threshold for inactive cells. A closed boundary is the default setting for a rectangular grid in MIKE+. In opposite to closed boundaries, open boundaries allow flow across the border of the 2D domain. For open boundaries the elevations at the permit of the 2D domain are lowered. Computations for these cells are then performed.

Dry and flooded areas are in the 2D overland model defined by threshold values for drying and wetting depth (DHI, 2022c). Based on the threshold values cells are defined as dry, partially dry, or wet. The definition for a certain cell depends on the surrounding cells water depth in relation to the threshold values. Depending on if the cell is defined as dry, partially dry or wet different calculation methods are assigned to the cell for each time step.

The 2D initial conditions can express the 2D domain as either dry, with a uniform water level or varying in domain (DHI, 2022c). With a dry initial condition, the water depth and flow velocity will be equal to zero for the whole domain at the start of the simulation period. If the initial condition is described with a uniform water level at the start of the simulation period, areas can be initially dry or wet depending on the defined water level in relation to the topography. An initial condition that varies in domain can be defined with either a layer or a file describing the water level or water depth and the flow velocity at the start of the simulation.

The roughness of the 2D domain can be expressed as Manning's number (M) (DHI, 2022c). Each cell in the 2D domain is assigned a value of roughness. The roughness can be either uniform, varying in domain, varying in domain and type, or varying in domain and flow. The roughness of the model used in this thesis is expressed as varying in domain. This alternative enables the 2D roughness to vary across the 2D domain. Input data needed for this alternative is either a MIKE+ layer, a background layer or an existing dfs2 grid file.

Infiltration input to the 2D overland model is described with boundary conditions (DHI, 2022c). The infiltration input can for example be varying in domain and be described with a dfs2-file. Input information about leakage rate, infiltration zone depth, porosity and initial water percentage can be specified.

2.6.3 1D-2D couplings

In order to make the 1D and the 2D model interact with each other the outlet of the catchment need to be connected to the collection system (DHI, 2022b). The connection is done by couplings. In MIKE+ catchments can be coupled to the collection system through both nodes and links. The software supports couplings of one or several catchments to the same node as well as couplings of one catchment to several nodes

When creating couplings between the collection system and the 2D domain different settings are available (DHI, 2021a). It is for example possible to couple the 2D domain to manholes, outlets, and soakaways. Each coupling is represented with a unique ID number and it is possible to assign different settings to each ID (DHI, 2021a). For instance, it is possible to limit the flow between the 1D and the 2D model by applying a maximal flow for the couplings.

By default, the location of the coupling in the 2D domain is a point (DHI, 2022c). When coupling to a single point the coupling will be applied to the cell of the point during the simulation. Alternatively, couplings can be applied to a bigger area, then the flow will be distributed to a polygon including more than one single cell. The size of the polygon is determined by the square width setting. To couple more than one 2D cell is beneficial regarding computational stability and is recommended by DHI (2022c) when simulating high flows.

Four different methods to compute the exchange flow within the couplings are available (DHI, 2022c). These are the orifice equation, the weir equation, the exponential function, and the curb inlet function. In the received model the weir equation and the orifice equations are applied, therefore the parameters of these computational methods are further explained. There are two parameters associated with the weir equation, these are discharge coefficient and crest width. The discharge coefficient affects the scale of the flow and gets by default a value close to 1, the coefficient is non-dimensional. The crest width symbolises the circumference of the manhole cover. As for the weir equation, there are two parameters associated with the orifice equation. These parameters are the discharge coefficient which work the same way as for the weir equation and the inlet area. The inlet area represents the area of the manhole cover and is by default calculated based on the defined diameter of the node.

2.6.4 Precipitation

Precipitation can be applied in the 1D model with the module Rainfall runoff (RR) (DHI, 2022b). Several tools and computational models are available within the RR module. Two main classes of hydrological models are available in MIKE+: surface runoff models and continuous hydrological models. The surface runoff model is the most common class in terms of urban runoff analysis and is suitable to use when single events are simulated and when the urban area is relatively dense. For the surface runoff model MIKE+ provides four different calculation methods: the Time-Area method, the kinematic wave method, the linear reservoir method and the unit hydrograph method. All four methods can be used in combination with rainfall dependent infiltration (RDI) which is a modelling method that considers the four storage categories of precipitation: snow, groundwater, surface, and the unsaturated zone. MIKE+ provides default values for RDI. It is also possible to assign different calculation methods to different catchments.

In this thesis the Time-Area method is used for catchment runoff, the method is therefore explained further. Characteristics for the method is that it requires little input, is simple (DHI, 2022b), and that only impervious areas generates runoff in the 1D model (DHI, 2017). The impervious areas is defined by a shapefile (DHI, 2021a) and calculated as a percentage of the catchment. The percentage symbolises the amount of area that contribute to runoff (DHI, 2017). The method also requires several input hydrological parameters, one of which is initial loss. The initial loss controls when the surface runoff is activated by defining the required depth of precipitation. The default value of the initial loss is 6×10^{-4} m. Another hydrological parameter associated with the Time-Area method is the hydrological reduction which aims to account for reductions for example caused by evapotranspiration. The shape of the catchment controls which Time-Area curve that MIKE+ assigns the catchment. Curves representing rectangular, divergent, and convergent catchments are available. It is also possible for the user to specify different Time-Area curves to the catchments. Additionally input to the Time-Area method is the concentration time of the catchments. The concentration time describes the maximum time required for the flow within the catchment to reach the point defined as outflow.

Applying precipitation to the 1D model can be done as a rainfall catchments load (DHI, 2022b). Figure 5 provides an illustration of precipitation applied as catchment load in a 1D-2D hydrodynamic model. The precipitation applied as a catchment load is by the catchment connection connected to the collection system (DHI, 2022b). As illustrated in Figure 5 the precipitation can be diverted to the surface (DHI, 2021a). The diverted runoff can then enter the collection system by 1D-2D model couplings (DHI, 2022c). The catchment load can have varying spatial extent (DHI, 2021a). The spatial extent can for example be described with a list of catchments, individual catchments or with coordinates through the setting data source location. If several rainfall catchments load with coordinates are applied, MIKE+ assigns the catchments near a certain coordinate its load. Which catchment that has been assigned a certain catchment load can be viewed in the MIKE 1D computation engine summary after a simulation. The temporal extent of a catchment load can be either constant, cyclic, or defined with a time series dfs0-file. A time series dfs0-file can be of different data types, for example instantaneous or mean step accumulated (DHI, 2017). Instantaneous time series contain values only valid for a precise time. In opposite to instantaneous time series, mean step accumulated time series contain average values valid in between two time steps.

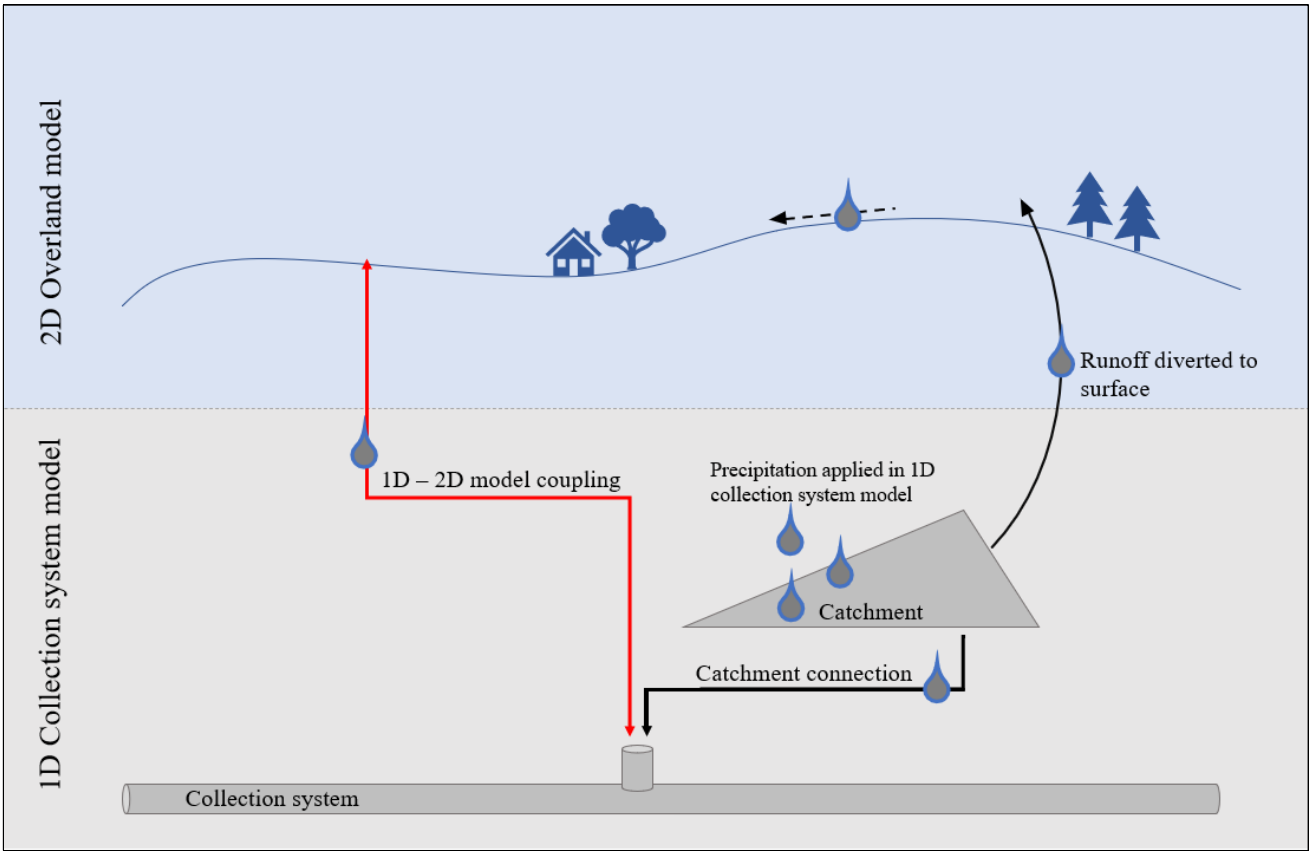

Figure 5. Illustration of precipitation applied in the 1D collection system model as a catchment load. Illustration made by the authors.

Precipitation can also be applied in the 2D overland model (DHI, 2022c). The precipitation applied in the 2D model can be expressed as either none, constant, varying in time or varying in domain (DHI, 2022c). If the precipitation is set to vary in time and domain, the precipitation data is read from a dfs2-file which needs to cover the 2D domain and the simulation time. When applying precipitation in the 2D overland model all cells in the computational domain contribute to runoff (DHI, 2022d), hence no difference is made regarding impervious/permeable areas. The precipitation in the 2D overland model is applied as a boundary condition (DHI, 2022c). Figure 6 provides an illustration of precipitation applied in the 2D overland model in a 1D-2D hydrodynamic model. The precipitation is connected to the collection system by the 1D-2D model couplings.

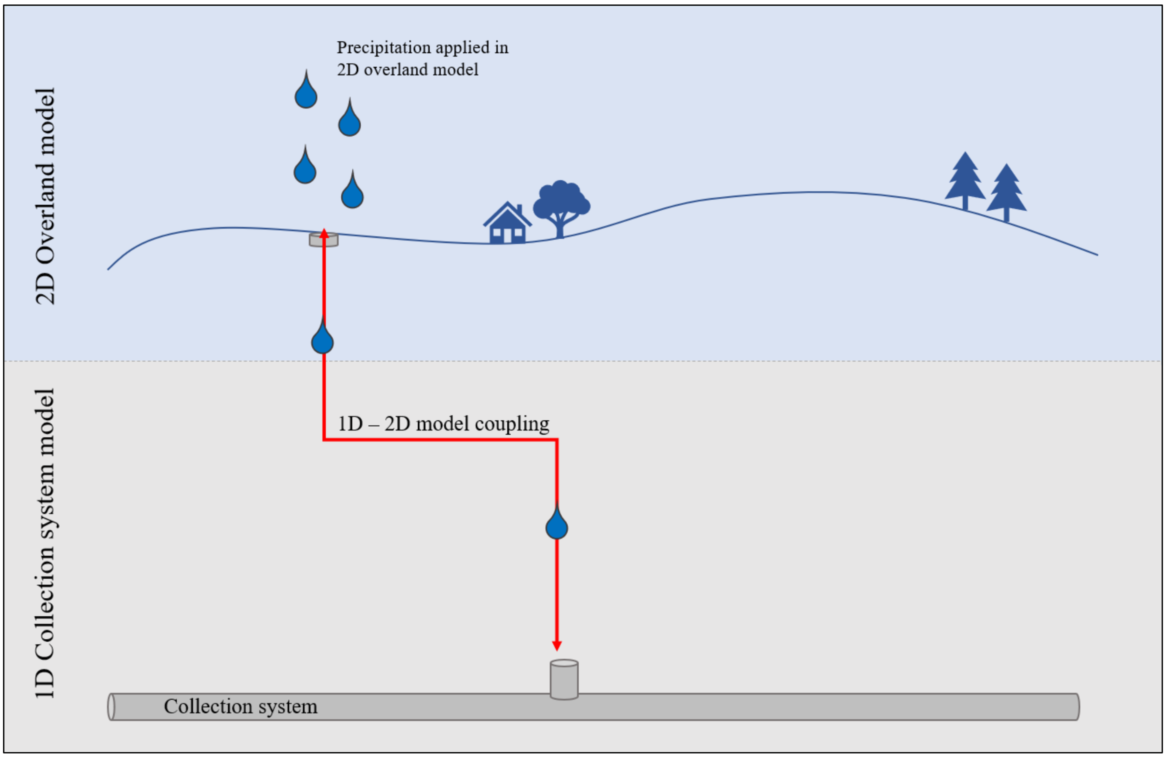

Figure 6. Illustration of precipitation applied in the 2D overland model. Illustration made by the authors.

A third method of application of precipitation is to combine the two methods described above. The precipitation is than applied both the 1D and the 2D model (DHI, 2021a), see Figure 7 for an illustration.

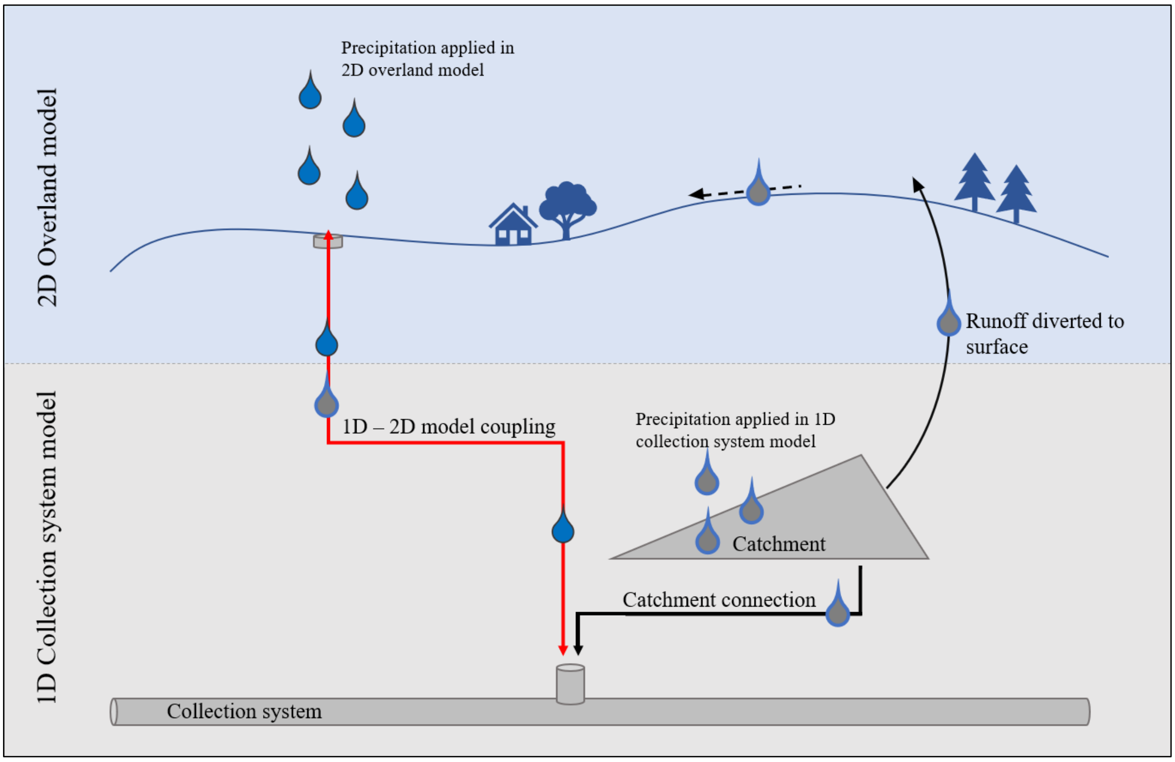

Figure 7. Illustration of precipitation applied in both in the 1D collection system model as a catchment load and in the 2D overland model. Illustration made by the authors.

3 Case study: Uppsala

This thesis builds on an existing 1D-2D hydrodynamic stormwater model of Uppsala (Sweden). The model was developed by DHI in the software MIKE+. This chapter will provide information about the city Uppsala and the rain event that occurred in Uppsala 2018. This chapter will also provide a description of the original model built by DHI.

3.1 Uppsala and the rain event 2018

Uppsala is located in eastern Sweden north of the capital Stockholm, see Figure 8. The municipality has approximately 240 000 inhabitants and is the fourth biggest municipality in Sweden with respect to the number of inhabitants (SCB, 2021a). The population density of Uppsala is approximately 110 inhabitants/km^2 (SCB, 2021b). The recipient of large parts of the city area is the watercourse Fyrisån (Fyrisåns vattenförbund, 2022) which flows through Uppsala and divides the city in one western and one eastern part. The location of Fyrisån is marked in Figure 8.

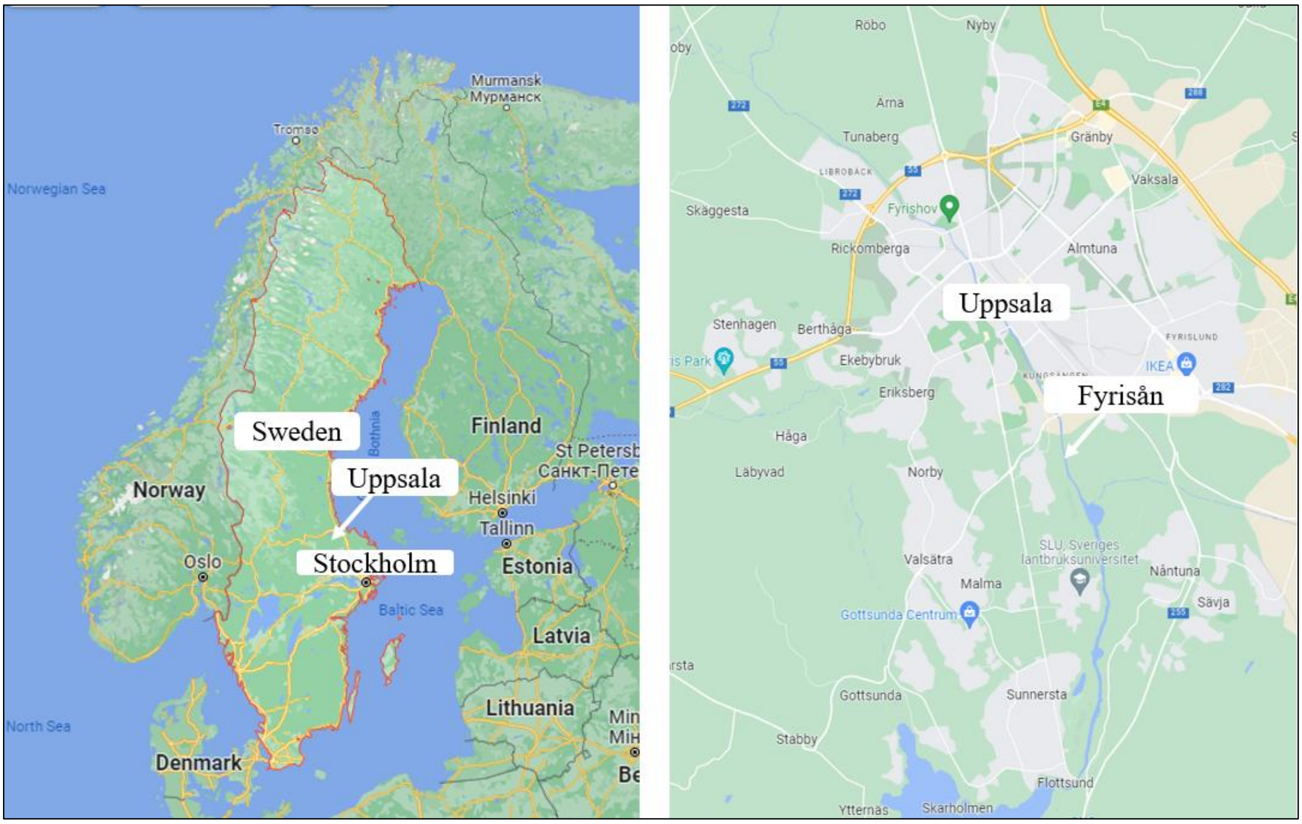

Figure 8. (a) Location of Uppsala and Stockholm. Annotated map data from Google Maps (2022) ©2022 GeoBasis-DE/BKG (©2009). (b) Uppsala and the location of Fyrisån. Annotated map data from Google Maps (2022) ©2022 GeoBasis-DE/BKG (©2009).

The 29th of July 2018 a rain event occurred in Uppsala. At the time of the rain event several measurement stations were collecting data of the precipitation. The majority of the stations measured a cloudburst according to the definition of a cloudburst stated by SMHI (2011).

3.2 Original model by DHI: Model setup

The original 1D-2D hydrodynamic model used in this thesis has been provided by Uppsala Vatten and has been built in MIKE+ by the consult company DHI. The model covers the eastern part of the city of Uppsala, Sweden. The area covered by the original model is presented in Figure 9. The original model includes both a 2D model of the surface and a 1D model of the collection system. The 1D and the 2D model are coupled to each other enabling interaction between the surface and the collection system.

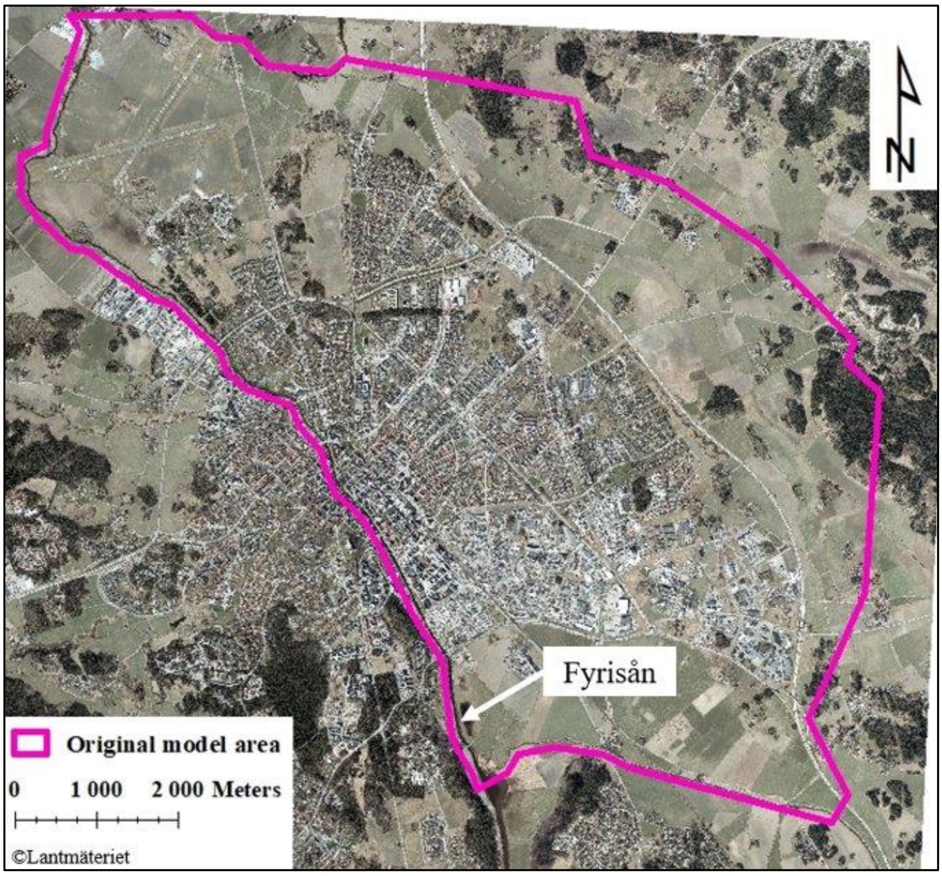

Figure 9. The original model area and the location of Fyrisån. Aerial photo from SCALGO Live (n.d) ©Lantmäteriet.

3.2.1 Bathymetry

Figure 10 presents the bathymetry of the original model area. The figure does not present any bathymetry of buildings and roads, these are shown in white as undefined values. The topography of the eastern part of Uppsala is relatively flat with the highest elevations in the northern part of the original model area, see Figure 10.

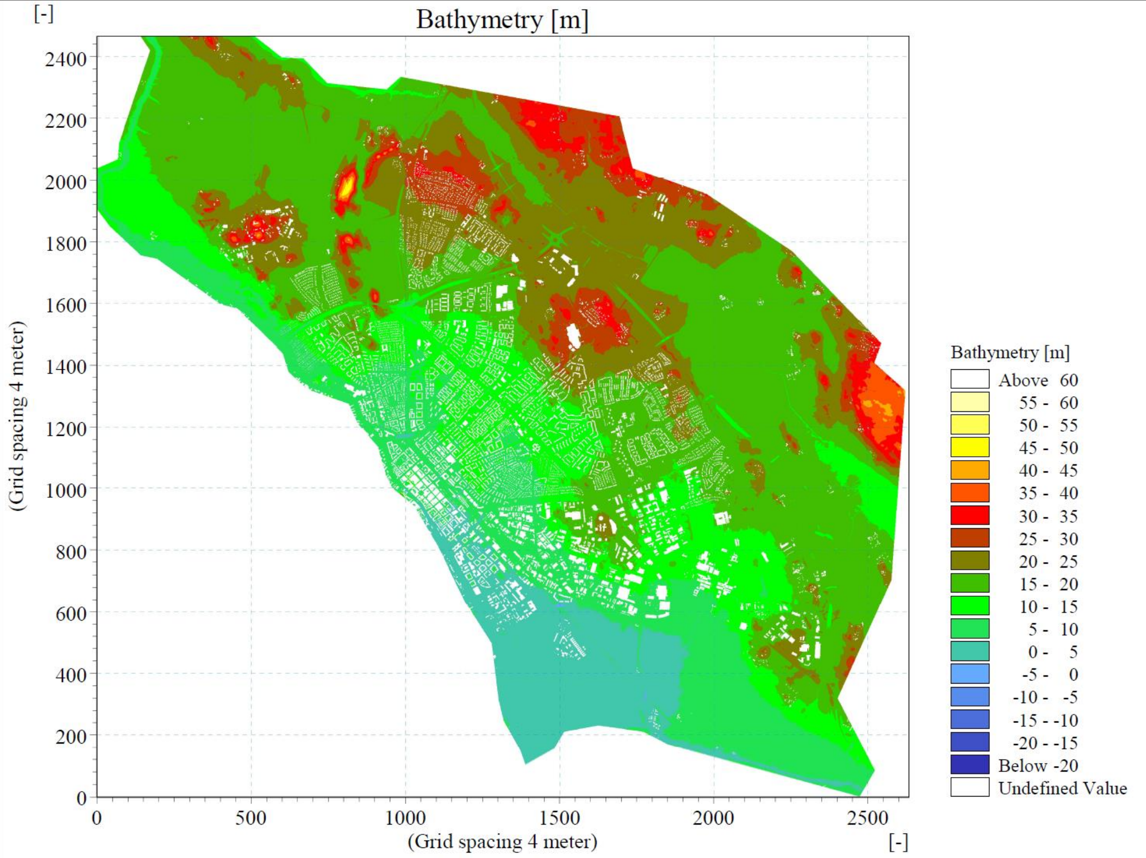

Figure 10. The bathymetry of the original model area (DHI, 2021c).

3.2.2 Original model: General settings

The model is of the model type 'rivers, collection system and overland flows' and the modules included are rainfall-runoff (RR) and hydrodynamic (HD). Simulated features are catchments, collection system network and 2D overland. The projection coordinate system of the model is SWEREF99 18 00.

The simulation date is the 29th of July 2018, and the simulation period is approximately 8 hours. The simulation starts at 12.15 and ends 20.00. The simulation time steps for catchments, network system and 2D overland vary between 0.01-60 s. The time steps are presented in Table 4.

Table 4. Time steps for catchments, the network system and the 2D overland.

	Catchments [s]	**Network system [s]**	**2D overland [s]**
Time step	60	0.1	Minimum: 0.01 Maximum: 0.1

3.2.3 Collection system

The collection system in the model consists of nodes, pipes, and pumps. Among the nodes the elements manholes, basins and outlets occur. Elements described as manholes in the model represent several different physical elements, for example manholes and inspection wells. The diameter of the nodes varies between 0.6 m and 4.0 m with most of the nodes having a diameter of 1 m. The diameter of the pipes is in the span 0.073-2.6 m. Only main wells are included in the model. Hence, no grated inlets or pipes to grated inlets are defined. The collection system includes a few pumps, all with a constant flow in the range 0.25-1.0 m^3/s. The model includes several outlets to Fyrisån which all have applied boundary conditions with a constant water level.

3.2.4 2D overland

The domain type is rectangular and consists of a grid with a grid spacing of 4x4 m. In the grid, all buildings have been assigned a bathymetry value, referred to as a z-value, of 200 m. By assigning a high z-value for the buildings, flow over the building areas is avoided. The boundary of the domain is set to be closed resulting in a z-value of 200 m at the boundaries of the model area preventing any flow over the boundary.

The surface roughness is set to vary in domain and is read from a dfs2-file. The surface roughness is described with Manning's number, (*M*). The values of *M* are set to vary between 2 $m^{(1/3)}/s$ and 30 $m^{(1/3)}/s$, the values are presented in Table 5. No dikes, culverts or weirs are included in the 2D overland model. The drying depth is set to 8 mm and the wetting depth is set to 10 mm.

Table 5. Manning's number, infiltration zone depth, and porosity for different surfaces (DHI, 2021c).

	Buildings	**Impervious surfaces**	**Water surfaces**	**Other surfaces**	**Railway**	**Primary rock**
Manning's number [$m^{(1/3)}/s$]	30	50	40	2	2	-
Infiltration zone depth [m]	0	0	0	0.3	2	0.1
Porosity [-]	0	0	0	0.4	0.4	0.4

Infiltration is included in the model. The bottom level of the infiltration zone is defined from the depth below ground level and the initial water volume in the infiltration zone is defined from the percentage of the capacity. The input to the infiltration is given by a dfs2-file containing information about infiltration rate [mm/h], leakage rate [mm/h], initial water percentage [%], infiltration zone depth [m] and porosity [-]. Infiltration and leakage rate as well as initial water percentage is in the model based on the soil type, used values are presented in Table 6. Values for infiltration zone depth and porosity is based on the type of surface. These values are presented in Table 5.

Table 6. Infiltration and leakage rate for different soil types (DHI, 2021c).

	Impervious surfaces and buildings	**Primary rock**	**Glacial deposit**	**Till**	**Peat**	**Clay**	**Water**
Infiltration rate [mm/h]	0	Varying	180	36	18	3.6	300
Leakage rate [mm/h]	0	0.036	18	3.6	1.8	0.36	300
Initial water percentage [%]	0	45	28	38	48	53	0

3.2.5 1D-2D couplings

The nodes coupled to the 2D domain are all of the type manholes or outlets. The weir equation yields for the manhole couplings. The crest width for the weir couplings is set to be 3.14 m and the discharge coefficient is 0.98. A maximum flow of 0.5 m^3/s has been assigned for all manhole couplings. The couplings between outlets and the 2D domain follows the orifice equation with a discharge coefficient of 0.98 and an inlet area of 0.79 m^2. The square width of all couplings is set to 0 m.

3.2.6 Catchments

The catchments are assigned the hydrological model Time-Area. The time of concentration for the catchments are within the range 10-31 min, the initial loss is 0.6 mm, and the reduction factor equals 1. For some catchments, the Time-Area method is combined with default values for RDI. The type of delineation for the catchments is

Thiessen polygons. The catchments are coupled to nodes and not to links. The share of impervious area is calculated for each catchment.

3.2.7 Precipitation

Precipitation applied in the received model describes the rain event that occurred in Uppsala 2018 and is based on precipitation data from measurement stations. The simulated precipitation is applied both in the 1D network model and in the 2D overland model. The precipitation applied in the 1D network model has a maximum intensity of approximately 41.7 mm/h corresponding to a block rain with a return period of 10 years and a duration of 30 min. presents an example of how the precipitation is applied both in 1D and 2D model. Since the hydrological model is set to follow the Time-Area method only impervious areas contribute to rainfall load in the 1D network model. At impervious areas where the intensity exceeds 41.7 mm/h the remaining precipitation load is applied in the 2D overland model (DHI, 2021c). At impervious areas where the precipitation does not exceed 41.7 mm/h no precipitation is applied in the 2D overland model.

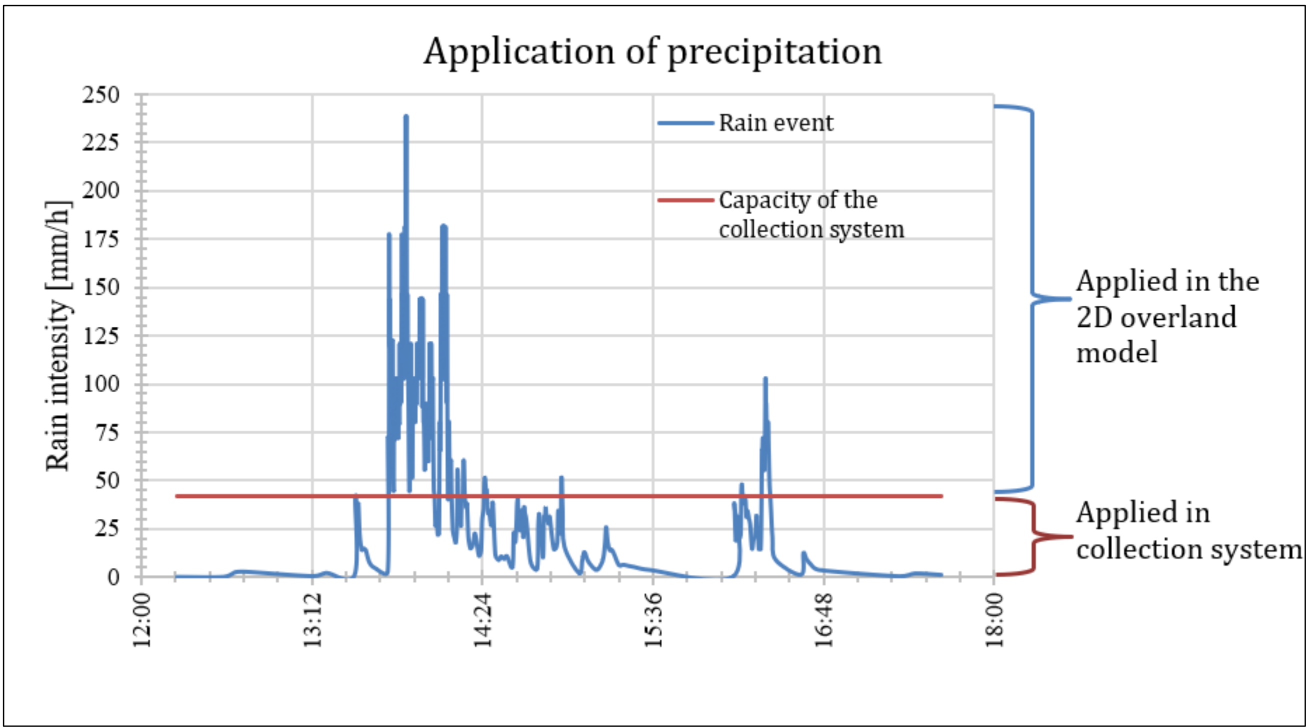

Figure 11. An example of which parts of a rain event that is applied in the 2D overland model and in the collection system, respectively.

Precipitation applied in the 1D network model is applied as a catchment load with data source locations corresponding to the coordinates of the measurement stations. In the 1D model, precipitation is applied as a time series dfs0-file containing rainfall intensity for every six minutes. In the 2D model precipitation has been applied as a dfs2-file interpolated in both time and space. The file is spatially interpolated with the inverse distance weighted interpolation method and includes one timesteps for every six minutes (DHI, 2021c).

The rain event that occurred before the main rain event 2018 is by DHI (2021c) assessed to be smaller than the capacity of both the collection system and the storage capacity of the soil and is therefore not included in the rain files. The rain is instead considered by a reduction of the infiltration zone depth and adjustments in the initial water percentage (DHI, 2021c).

3.2.8 Initial conditions

There are no local values used as initial conditions in the model and the network is set to be initially empty. The initial water level in the 2D model is set to 0 m.

3.3 Original model by DHI: Validation

The original model is validated by DHI based on precipitation data from measurement stations and pictures from the rainfall event 2018 (DHI, 2021c). Information about when the pictures were taken was missing and no information about the water depth was available. Hence, DHI have based the validation on the flood distribution and not depth. By comparing the model result with pictures DHI (2021c) has assessed the credibility of the model as generally very good.

The very good credibility of the model is by DHI (2021c) explained by several reasons. Firstly, the model includes surface runoff, runoff in the collection system and couplings between the surface model and the collection system. The model also includes infiltration. Secondly, precipitation data from several measurement stations were available during the rain event 2018 enabling detailed data of the rain distribution. Thirdly, the used bathymetry is from 2020 and considered as up to date. Lastly, most pictures used for the validation is from the urban parts of Uppsala with a lot of impervious surfaces. Since the surfaces are impervious uncertainties about the parameters regarding the infiltration is of less importance.

4 Methodology

The methodology chapter presents the methodology used to answer the research questions. It presents the method of the literature study, the survey, the simulated scenarios, identification of the research area and processing of data and the model.

4.1 Literature study

The master thesis started with a literature study to get knowledge and information about analysis and modelling of pluvial flooding. The literature study included the field of modelling stormwater inlets and if the hydraulic efficiency of these should be considered to be reduced due to clogging. Information about precipitation, stormwater and stormwater collection system was also included in the literature study. The literature study was based on scientific papers available through the search-engines Scopus and Google Scholar. Keywords associated with the thesis were considered in the beginning of the literature review in order to find relevant information. Some keywords used are *manhole AND clogged*, *stormwater AND inlet AND capacity, Chicago AND design AND storm,* and *GIS.* Primary sources were referenced to as far as possible to ensure a reliable result. Information was also gathered from institutes and authorities as well as from DHI who developed the software MIKE+.

4.2 Survey

To answer RQ 1 a survey was done. The survey's main question was if the respondent considers clogged wells when modelling rain events and in that case how. If the respondent did not consider clogged wells the survey asked if it is something that the respondents are interested in considering. The survey also covered how the respondents think the consideration would affect the results of 1D-2D hydrodynamic stormwater modelling. The questions that were asked in presented in Appendix A.

The target group for the survey was individuals working at consultant companies in Sweden that work with 1D-2D hydrodynamic stormwater modelling. The selection of consultant companies was based on the authors knowledge and by using Google to find consultant companies marketing that they are working within the field of 1D-2D hydrodynamic stormwater modelling. The survey was sent to the eight consultant companies AFRY, Atkins, DHI, NAWE, Norconsult, Ramboll, Sweco, Tyréns and WSP.

Consultants are often the ones who work with 1D-2D hydrodynamic stormwater modelling, and a consultant can have been involved in multiple models that have are geographically widespread during his/her professional career. Therefore, consultants were chosen as the target group, and it can be seen as more interesting than for example municipalities since municipalities mainly work within their geographical area.

The survey was based on the methods described in Questions and answers – question design in self-administered- and interview questionnaires (Persson, 2016a). A web based survey was chosen since it is one of the four most established methods to collect data (Persson, 2016b). The other three methods are interview in person or on phone, or a survey in paper form. The survey was made in Google Forms and Persson (2016b) write that web based surveys also give the respondent the possibility to answer it when time is available which increases the quality of the data.

According to Fjelkegård and Persson (2016), the length of the survey affects the number of respondents completing the survey and the quality of the data. Therefore, the survey was kept short and consisted of 8-14 questions. The estimated time to take the survey was about five minutes.

The questions were divided into different parts. The parts consisted of filter questions that lead the respondent to the next part. A schematic figure of the parts and its filtration is presented in Figure 12. The parts included follow-up questions and related questions, which were dependent on the respondent's previous answer. By using filter questions it is possible to ask questions that are relevant for this specific respondent (Hartwig & Person, 2016). This was used to for example divide the respondents that have considered clogged stormwater inlets and those who have not in a 1D-2D hydrodynamic stormwater model. The filtration question in Part 1, see Figure 12, of the survey was included to filter out the respondents that were not included in the target group.

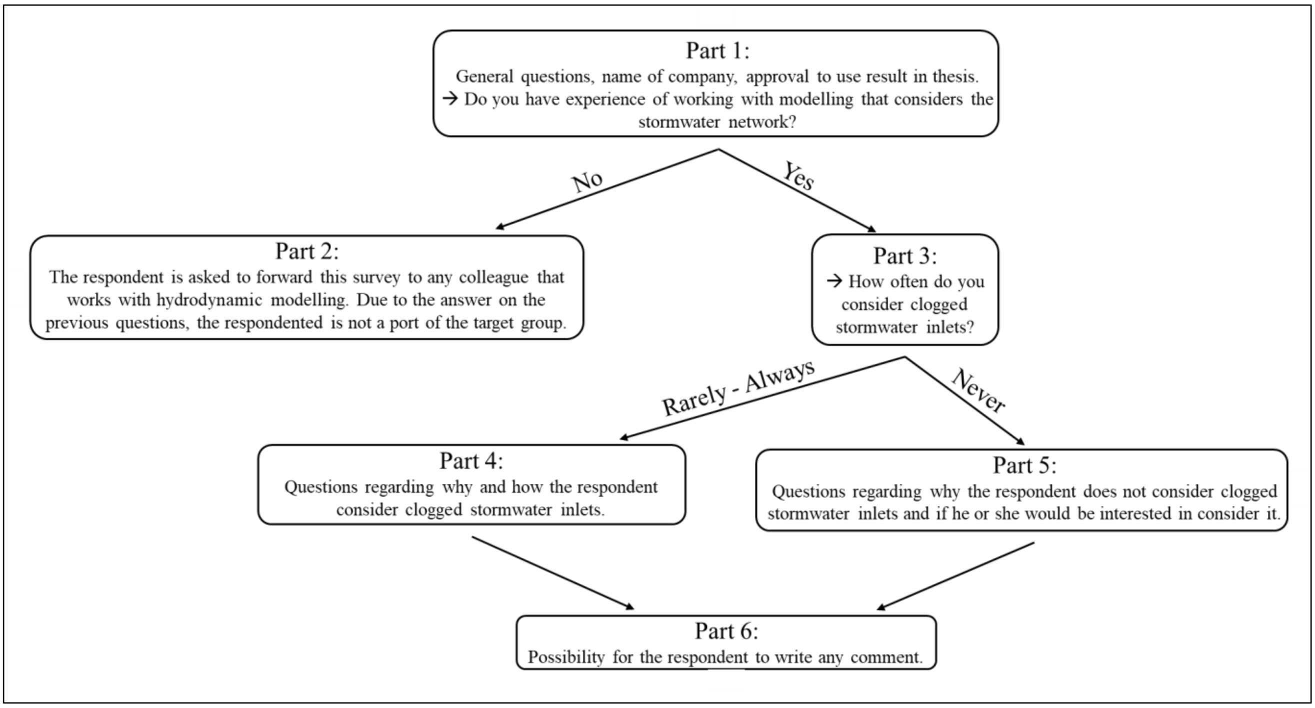

Figure 12. The parts of the survey and the filtering questions. The arrows in the part boxes represent filtering questions.

The questions in the survey were built with the funnel principle (Fjelkegård & Persson, 2016), from general to detailed questions. There were questions of behaviour and attitude regarding clogged stormwater inlets. The way to answer the question differed between Yes or No, text answer or multiple choice. There were no questions collecting personal information about the respondent, therefore, the survey was anonymous.

The survey was sent to the respondents as a link in an email. Since the survey was self-administered, the email also included a missive (Fjelkegård & Persson, 2016). The missive informed the respondent about the purpose of the survey, how the data were to be used and presented, together with some practical information, for example the estimated time length of the survey. In the missive the respondent could also read about how and where this study will be available when completed. The missive also asked the respondent to forward the email to colleagues that work with 1D-2D hydrodynamic stormwater modelling.

The consultant companies or its employees were contacted the 2nd of February 2022. Some email addresses to individuals on the companies were found on the internet and to these consultants the survey was sent. Some of the consultant companies were initially contacted on a general email to the company, an information email, before personal email addresses were received that the survey could be sent to. Therefore, the response period varied for the respondents and was 6-13 office days. The last day to answer the survey was 18th of February 2022. Table 7 presents when the survey was sent to the consultant companies and the last day to answer.

Fjelkegård and Persson (2016) write that reminder is necessary when using web based surveys. The reminder was only sent to the consultant companies who had not answered the survey. The reminder was a forwarded message of the original email with the missive and included a question about if they had received the previous email. A reminder was only sent to WSP 7 office days after the initial survey was sent, see Table 7, but the reminder could not be delivered to the email address due to suspected phishing. Email addresses to other employees at WSP were found and the survey was sent to them, see Table 7.

Table 7: The dates of when the survey and reminder were sent to the respondent, and the last day to answer the survey.

Consultant company	Survey sent out	Reminder sent out	Last day to answer
AFRY	7th of February 2022	-	18th of February 2022
Atkins	2nd of February 2022	-	18th of February 2022
DHI	2nd of February 2022	-	18th of February 2022
NAWE	2nd of February 2022	-	18th of February 2022
Norconsult	2nd of February 2022	-	18th of February 2022
Ramboll	4th of February 2022	-	18th of February 2022
Sweco	2nd of February 2022	-	18th of February 2022
Tyréns	2nd of February 2022	-	18th of February 2022
WSP	2nd of February 2022 11th of February 2022 *	11th of February 2022	18th of February 2022

* Survey sent to other employees at WSP due to suspected phishing.

4.3 Defining smaller research and model area within the original model area

To answer RQ 2 a sensitivity analysis evaluating different clogging factors affecting the flow capacity in the 1D-2D model couplings has been conducted. A smaller research and model area within the original model (see chapter 3) has been used in this thesis. The reason for only evaluating a smaller research and model area was to limit the simulation time. How the research area and the corresponding model area were determined are presented in this section. The identification of the areas, the cutting of model area and grid data are described.

The research area was determined from the original model that was received from Uppsala Vatten. The original model was simulated without any changes to control that all necessary data were available, the simulation of the original model is further denoted as simulation ID A.

4.3.1 Identification of model and research area

The research area was determined by considering topography, area, collection system, flooding, watershed and surface runoff. The extent of the research area was aimed to be reduced to decrease the simulation time and the topography was considered by following water dividers when it was possible due to existence. The research area aimed to include flooding close to nodes due to the purpose of this thesis. Where flooding occurred was seen in the results from the original model, simulation ID A. To determine the research area's model area the surface runoff, the upstream watershed and downstream flow path was analysed with SCALGO Live. In SCALGO Live the tool watershed was used, and a rain event of 78 mm was analysed, since 78 mm was the largest volume of the precipitation event that occurred in Uppsala 2018. The model area includes the research area and its watershed. The research area is about 210 ha and is presented in Figure 13 together with the watershed and model area.

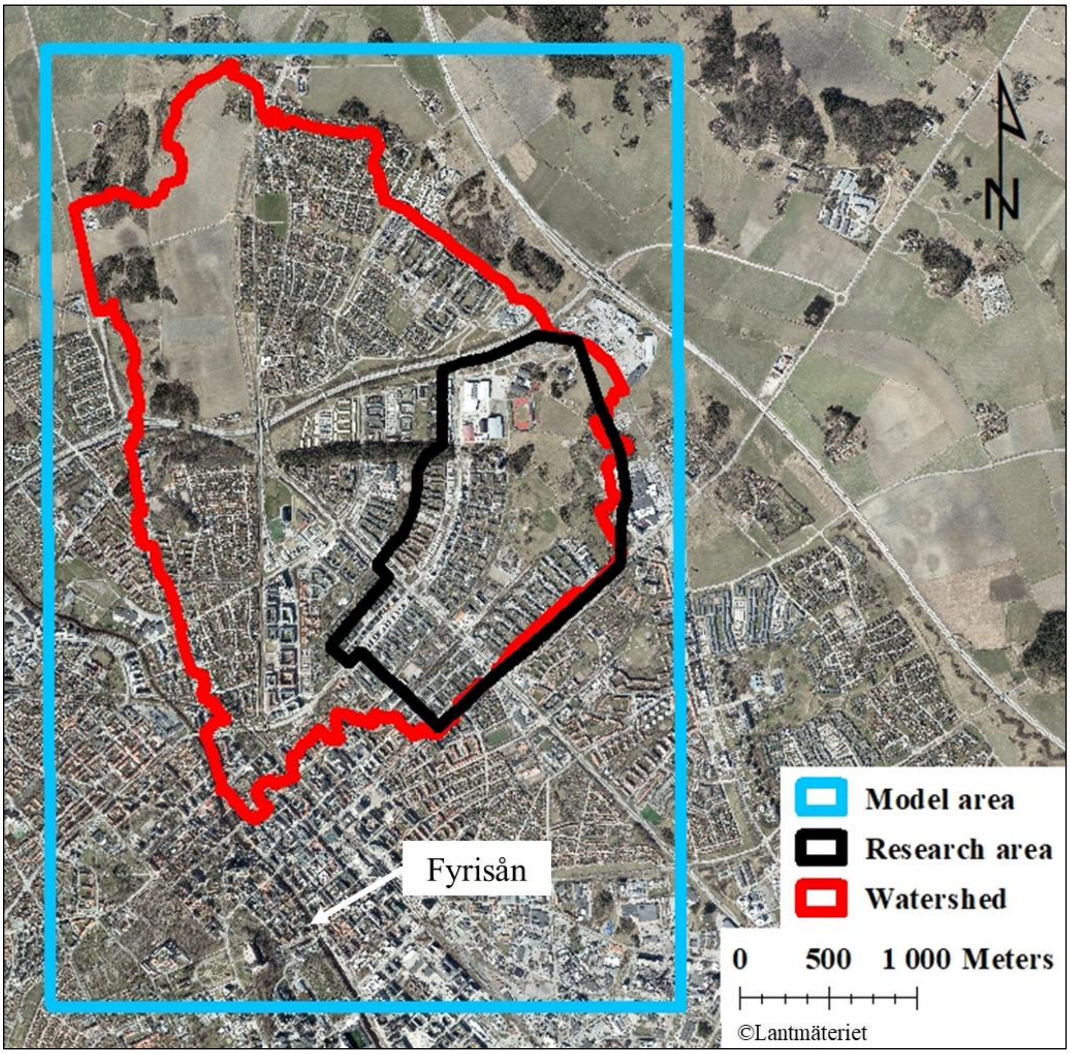

Figure 13. Location of the model area, research area and watershed. Aerial photo from SCALGO Live (n.d) ©Lantmäteriet.

4.3.2 Cutting of model area

The model area includes the research area and upstream watershed area. It also includes the areas that has a collection system connected to the collection system inside the research area. A rectangular polygon corresponding to the new model area was created in ArcGIS, see Figure 13.

Independent parts of the collection system outside the research area and its upstream watershed, considering the collection system and topography, were assessed to not have any impact on the research area and were therefore deleted. Collection system downstream the research area was not deleted due to the possibility affecting upstream collection system. Isolated and smaller collection systems downstream the research area was also deleted. All remaining elements of the collection system maintained their original dimensions. At two nodes the collection system was cut. The collection system was cut at these two nodes to reduce the simulation time. The two nodes connected a collection system of an upstream area to the collection system in the research area. The upstream area was separated from the research area considering topography due to a larger road. In the data presenting the bathymetry it could be seen that the road was on lower levels than the upstream area and research area. The difference in elevation differed along the road but was around 6 m. Due to this difference the stormwater surface runoff was assumed to not be able to flow from the upstream area to the research area, if not through these two nodes. Therefore, the collection system was cut and the flow in the collection system was instead described with a boundary condition in each node. The methodology for the two boundary conditions is described in section 4.4.1. All model couplings in the model area were deleted, and then new ones were generated, see section 4.3.4 These were deleted since a new research and model area were created, and that some parts of the collection system had been deleted.

4.3.3 Processing of input grid data

The grid data describing the infiltration, *M* and bathymetry were processed by limiting their spatial extent. Initially, the grid data was geographically compared to each other. It was concluded that the grid data of *M* and bathymetry, respectively, were not located at the same position. The two data sets were compared to the collection system in the model and to a file presenting the impervious areas received from Uppsala Vatten. When comparing the bathymetry data with the collection system it could be seen that nodes of the collection system was located inside buildings, which was not a problem when comparing the collection system with the file describing *M*. It could also be seen that the file presenting buildings corresponded better with the file describing *M* than the file describing the bathymetry. Therefore, the geographical position of the file describing *M* was assumed to be correct. All other grid data files were adjusted to align with the file describing *M*. The position was adjusted by moving the origin of the file with the adjustments presented in Table 8.

Table 8. The adjustments of the grid data's origin.

	Original position [m]	Adjusted position [m]	Adjustment [m]
X-position	125518.00012	125519.54620	1.54608
Y-position	6634440.00013	6634441.68235	1.68221

The grid files were received as dfs2-files and by using the MIKE Zero Toolbox and the tool Mike2Grd the files were converted to the format of ASCII. The ASCII-files were then imported to ArcGIS and converted to raster using the tool ASCII to raster. To limit and decrease the spatial extent the data management tool Clip raster was used. The grid data files were cut aligned with the polygon representing the model area. The new raster files were exported to ASCII-files and opened in Excel. By using MIKE Zero new dfs2-files were created for each file respectively, and the data opened in Excel were pasted in the new dfs2-files.

The edges of the bathymetry data were processed to represent closed boundaries when modelling. The first and last row and column, respectively, were changed to the value 200 m manually in MIKE Zero.

4.3.4 Model couplings

New model couplings were generated in MIKE+ with the 1D-2D Coupling tool called Create couplings. The couplings were created with the same settings as the original model. The couplings were created between the manholes in the 1D model and the 2D overland model, the square width was set to 0 m. Due to error six of the couplings were excluded. The error indicated that the couplings were located outside of the computational domain. The location of the nodes coupled to the 2D overland model were investigated and the nodes were inside the domain although the error message. Five of the six couplings were excluded in the original model from DHI and a common parameter for all five couplings was a 2D domain of the value 200 m. The sixth coupling was also excluded since it had the same 2D domain.

4.3.5 Original model and validation

The original model received from Uppsala Vatten was validated compared to pictures from the rain event 2018 by DHI, see section 3.3 Initially, the original model was simulated (ID A) with the original input files presenting the Manning's number (*M*), properties of infiltration and bathymetry were used. The original files created by DHI presenting the precipitation in the collection system and in the 2D overland model were used. No settings in the model were changed before the simulation.

To validate the new model of the research area the model was validated by running a simulation ID B with the same data and settings as in the original model. The results were then compared with the results from the original simulation ID A to validate the new smaller model. The simulations of validation are presented in Figure 14.

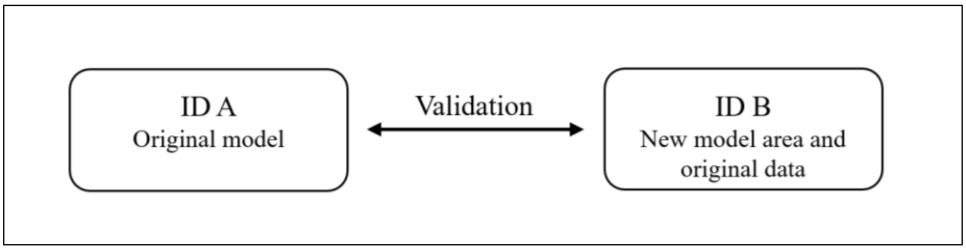

Figure 14. The simulations used to validate the model of the research area.

4.4 Boundary conditions

The following sections presents new boundary conditions of the model and adjusted boundary conditions from the original model. The method for the boundary condition of inflow to nodes and outlets at Fyrisån are presented in section 4.4.

4.4.1 Inflow to nodes

Two boundary conditions with the type Inflow to node were made to describe the inflow from upstream collection system into the nodes where the collection system was cut. The boundary conditions were applied to the corresponding node, and it temporally varied based on a time series. The time series used was the result from simulation ID A of the original model and described the discharge [m^3/sec] for each minute between 12.15–20.00. A new dfs0-file was made where the discharge for both nodes was imported in one item each. The time series was applied as boundary conditions for the scenarios that are simulated in the sensitivity analysis.

4.4.2 Outlets at Fyrisån

In the received original model boundary conditions were applied at all outlets to Fyrisån. The boundary conditions were constant outlet water levels. The outlets applied to a specific boundary condition were defined with a selection list with the same name as the boundary condition ID.

It could be identified that one selection list name was not the same as the boundary condition ID and the constant outlet level, see the first part in Table 9. The chosen selection list was also applied to another boundary which had the same boundary condition ID and the constant outlet level, see the second part in Table 9. It was questioned if something was wrong with these two boundary conditions since two outlet level cannot be applied at the same time to the same nodes.

Initially, a selection list with the name O_BC_+6_60 was identified, and this list was not applied for any boundary condition. Secondly, the outlets included in this selection list were identified in the model. The boundary conditions upstream and downstream theses outlets were analysed, and it could be seen that these were close to 6.6 m and far from 1.1 m. Thirdly, the outlets in the selection list O_BC_+1_10 were identified, and the downstream outlet had a constant outlet value of 1.2 m applied.

The outlet levels at the nodes in selection list O_BC_+6_60 were analysed from simulation ID A. The results of simulation ID A showed an outlet level slightly below 6.6 m. Therefore, the lack of boundary condition applied to the selection list was assessed to have an insignificant effect on the results of simulation ID A.

Since two boundary conditions were applied to selection list O_BC_+1_10 (see Table 9) the water level in the outlets were analysed in the results from simulation ID A. The results showed that the outlets of the selection list were equal to 1.1 m. Therefore, the outlets in selection O_BC_+1_10 were assumed to have the correct boundary condition applied and did not have to be adjusted.

The initial boundaries were assumed to be wrong, and the boundary conditions were adjusted. The adjusted boundary conditions can be seen in the second part of Table 9. The selection list O_BC_+6_60 was applied to the constant outlet value 6.6 m instead of the selection list O_BC_+1_10.

Table 9. The initial and adjusted boundary conditions for two selections of outlets.

Boundary condition ID	**Selection list**	**Constant outlet level [m]**
	Initial	
O_BC_+6_60	O_BC_+1_10	6.6
O_BC_+1_10	O_BC_+1_10	1.1
	Adjusted	
O_BC_+6_60	O_BC_+6_60	6.6
O_BC_+1_10	O_BC_+1_10	1.1

4.5 Simulated scenarios

To answer RQ 2 a sensitivity analysis evaluating different clogging factors affecting the flow capacity in the 1D-2D model couplings has been conducted. Simulations evaluating different clogging factors are denoted as simulation ID's and are presented in Figure 15. Simulation ID 0 represents a scenario where no consideration of potentially clogged stormwater inlets was taken and hence the clogging factor was 0. Simulation ID 0 represents a base scenario and was compared with simulation ID 1-ID 3 which represents scenarios considering clogged stormwater inlets in different magnitudes. The clogging factors were based on the reviewed literature as well as the survey.

As reported by the literature in section 2.4.1 stormwater inlets in low points and close to vegetation are more likely to be clogged that other stormwater inlets. The literature also reports that it is hard to predict which stormwater inlets that risk clogging and that all inlets can be subjected to the clogging phenomena. Therefore, in simulation ID 1-ID 3 all the stormwater inlets have been considered clogged. Clogging all stormwater inlets is supported by the survey where concrete suggestions of the share of clogged inlets in a model was either 0% or 100%. To choose to clog only a certain share of the inlets would entail in uncertainties about which inlets that are clogged or not as well as the method of choosing those inlets. Another aspect that has been important through the process of this thesis is that the evaluated scenarios should be applicable in the industry. Therefore, the method should not be time consuming.

Based on the literature and the survey it was not evident to what extent the inlets in simulation ID 1-ID 3 should be clogged. One respondent of the survey expressed that it would be interesting to conduct a sensitivity analysis with clogging factors of 0.10, 0.20 and, 0.30. A second respondent expressed interest in a sensitivity analysis including the factors 0.25, 0.50 and 0.75. There are some uncertainties regarding if the factors given by the second respondent aims at capacity reduction of the inlet (clogging factor) or to reduce the area of the inlet cover. Since the questions in the survey was designed with regards to capacity reduction it was interpreted that the respondent aimed at capacity reduction. Therefore, based on the survey it is valid to evaluate clogging factors in the range of 0.10 to 0.75. Unfortunately, no respondent reported a clogging factor that they generally use when modelling pluvial flooding. Moreover, as declared in section 2.4.3, Gómez et al. (2013) determined different clogging factors for the two inlets types Embro and Impu which are used in Barcelona. Gómez et al. (2013) reported values of clogging factors in the range of 0.27-0.67 for the clogging patterns C1, C2 and C3. Taking the accumulated frequency of the clogging pattern for each inlet type into account an average clogging factor of 0.43 was calculated.

With the literature and the survey in mind, simulations with clogging factors of 0.20 (ID 1), 0.40 (ID 2), and 0.60 (ID 3) were determined to be evaluated. The clogging factors in simulation ID 1-ID 3 are all included in the common range of clogging factors suggested by the two respondents in the survey. Furthermore, a clogging factor of 0.20 as in simulation ID 1 is a bit lower than the range of clogging factors determined by Gómez et al.

(2013) but is assessed to be reasonable since all of the stormwater inlets in this thesis will be clogged in opposite to the study by Gómez et al. (2013). The clogging factors of 0.40 and 0.60 as in simulation ID 2 and ID 3 are both in the range of clogging factors determined by Gómez et al. (2013). Furthermore, a clogging factor of 0.40 as in simulation ID 2 is close to the average clogging factor of 0.43 in the study by Gómez et al. (2013).

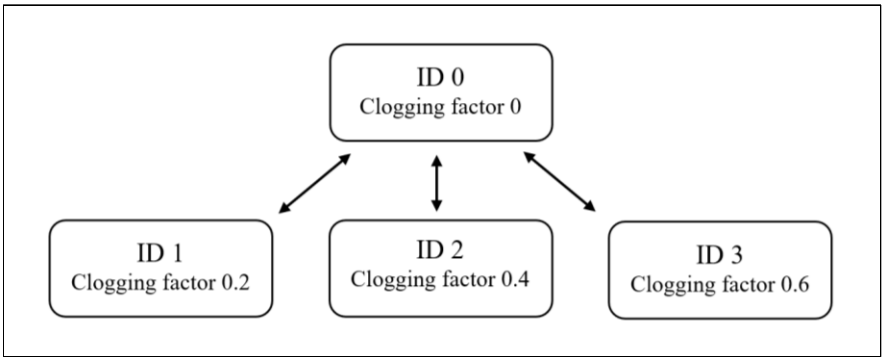

Figure 15. The four simulations, its clogging factor, and comparison.

In MIKE+ the clogging factors in simulation ID 1-ID 3 has been applied by adjusting the discharge coefficient of the 1D-2D coupling. Since the default value of the discharge coefficient is close to 1 (see section 2.6.3) and a discharge coefficient of 0 do not allow any flow in the coupling the discharge coefficient works in the opposite way than the clogging factors. Hence, a clogging factor of 0.20 as in simulation ID 1 corresponds to a discharge coefficient of 0.80. With the same methodology discharge coefficients of 0.60 and 0.40 has been applied for simulation ID 2 and ID 3, respectively. No other parameters than the discharge coefficient was changed to represent different clogging factors.

4.6 Processing of precipitation data

For the sensitivity analysis, a CDS-rain has been used instead of the precipitation data of the rain event that occurred in Uppsala 2018. Therefore, the precipitation data has been processed. Measured precipitation data of the rain event that occurred in Uppsala 2018 have been received from the department of Earth Science at Uppsala University and Uppsala Vatten. The historical precipitation data has been processed to represent a CDS-rain. MSB (2017) states that the design storm CDS is preferable when a cloudburst is modelled. To consider local variances of precipitation the applied CDS-rains has been generated to correspond to the measured data from 2018. Based on the generated CDS-rains, a temporally and spatially interpolated rain intensity file has been created. The following sections explains the processing of the measured precipitation data, the generation of CDS-rains and the method for creating the rainfall intensity file.

4.6.1 Measured precipitation data and identification of rain events

Measured data for ten different stations have been provided by Uppsala Vatten. Measured data for one additionally station has been provided by Uppsala University. Totally, precipitation data for 11 different measurement stations has been received. Two of the stations (Järlåsa and Almunge) have been assessed to be located too far from the model area to be relevant and were therefore excluded from the analysis. According to Uppsala Vatten (personal communication, December 14, 2021) uncertainties about the registered volume in the data yields for a third station (Sunnersta). DHI (2021c) states that additionally one station (Sävja) was out of order at the time of the rain event. Out of the 11 stations, data from seven stations has been assessed to be processed to generate the interpolated CDS-file for the sensitivity analysis. The locations of the seven stations are presented in Figure 16.

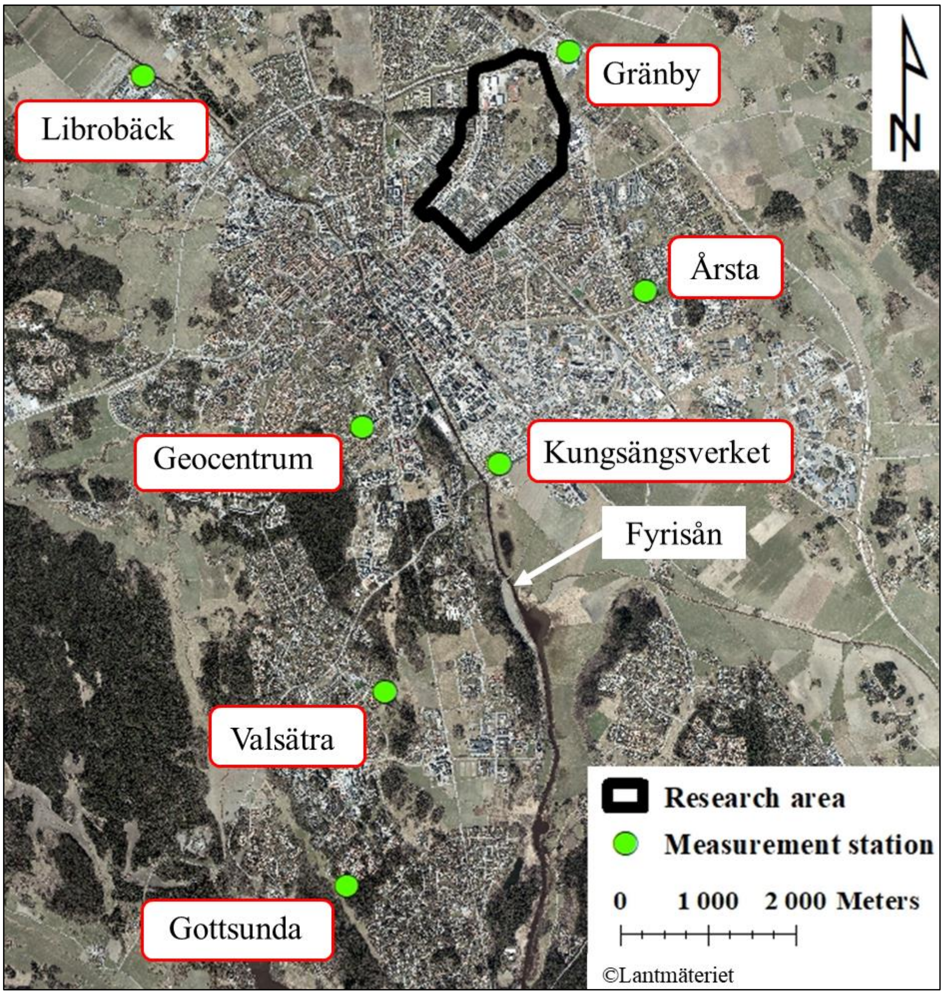

Figure 16. Locations of measurement stations used. Aerial photo from SCALGO Live (n.d) ©Lantmäteriet.

All stations are of the type tipping-bucket. The data sets for all stations except Geocentrum were raw data, describing the time when the bucket tipped. The volume of the tipping-bucket is either 0.1 or 0.2 mm. The received data set of Geocentrum from Uppsala University, was accumulated volumes of precipitation for each 10 min.

The received rain data from the rain event 2018 were analysed and processed. Initially, rain events were defined for each data set and measurement station. Based on the literature study the rain events were identified according to the break between two persistent periods of precipitation. If the break between the two periods was equal to or above 0.5 h a rain event was identified. The identified events for a data set were compared to each other to identify a main rain event and its starting point. The main event was the event with largest volume of precipitation. The rain events that occurred before the main event were not considered in the precipitation data. The rain events that occurred after the main event have for some datasets been included in the main event. If the rain event has been included depends on its volume, the event was considered to have an impact on the main event if the volume was equal to or larger than 5 mm. If it was considered to have an impact on the main rain event the volume and duration was included in the main event. To maintain a distinct peak of rain intensity when determining the CDS-rain, rain events with small volumes were not considered since it would increase the duration without contributing to the precipitation volume.

The volume and duration for the determined main rain events were used to calculate the average rain intensity and return period. The rain intensity was calculated with Equation 1 (section 2.1) and the return period was calculated with Equation 2 (section 2.1.2). The calculated duration, volume and return period, together with the events' starting point is presented in Table 10.

Table 10. The calculated duration, volume and return period, and the starting point of the rains.

	Calculated parameters of historical data			
Measurement station	**Duration [min]**	**Volume [mm]**	**Return period [years]**	**Starting point [time]**
Geocentrum	280	78	93	12.20
Gottsunda	136	77	149	13.15
Gränby	219	55	38	13.14
Kungsängsverket	303	78	87	12.35
Libroback	186	60	54	13.29
Valsätra	180	75	112	13.08
Årsta	218	66	67	13.09

4.6.2 Application of precipitation

The precipitation applied in the original model was divided into two separate input files and applied in both the 1D and the 2D model, see section 3.2.7. In the sensitivity analysis the precipitation was only applied in the 2D overland model instead of dividing it between the 1D collection system and the 2D overland model. The discharge coefficient that was adjusted to represent clogged stormwater inlets (see section 4.5) do only affect the water that flow through the 1D-2D model couplings, therefore, the precipitation was only applied in 2D.

4.6.2.1 Determination of CDS-rain

To determine the curves of the CDS-rain events a spreadsheet provided by Norconsult was used. The spreadsheet determined the CDS-rain event considering return period, duration, climate factor and skewness factor. It calculated the precipitation volume and a time series of the rain intensity as a CDS-rain. The spreadsheet determined the CDS-rain based on Dahlström's equation (Equation 2) and the method described by Swedish Water (2011).

The calculated duration was adjusted to the nearest predefined durations in the spreadsheet, the predefined durations were 30 min, 60 min, 120 min, 180 min, 240 min, 300 min and 360 min. The CDS-rain events were based on the adjusted durations and the return periods generating the volume closest to the calculated volume was determined. The calculated duration, volume and return period together with the adjusted duration, used volume and return period, is presented in Table 11. The skewness factor was assumed to be 0.37 and no factor of climate was considered since the CDS-rain events presents an actual rain event.

Table 11. The adjusted and used duration, volume and return period to determine CDS-rain events.

	Adjusted and used parameters for CDS-rain		
	Duration [min]	**Volume [mm]**	**Return period [years]**
Geocentrum	280	78	111
Gottsunda	120	77	163
Gränby	240	56	36
Kungsängsverket	300	78	110
Libroback	180	60	56
Valsätra	180	75	112
Årsta	240	66	62

4.6.2.2 Application of precipitation in the 2D overland model

The determined time series of CDS-rain were spatially and temporally interpolated to be applicable as precipitation in the 2D overland model. Initially, the determined time series of the rain event were imported to a new dfs0-files for each station. The new dfs0-files were created in the Time series editor in MIKE Zero and had the temporal extent of 12.15-21.15 to make it possible to run the model within this period. The dfs0-files were mean step accumulated, and the item type was precipitation rate [mm/hr]. The time series were imported from the starting point of the defined rain event and forward.

4.6.2.3 Temporal interpolation

Each dfs0-file was then temporally interpolated using the MIKE Zero Toolbox and the tool Interpolate Time Series. The interpolation was linear, and the time step was 6 min. This generated a dfs0-file for each data set with mean step accumulated precipitation rate.

4.6.2.4 Spatial interpolation

To spatially interpolate the accumulated time series the tool Preprocessing Temporal Data in the MIKE Zero Toolbox was used. Initially, a new dfs0-file was created for the rain event and the accumulated time series for the seven different measurement stations were pasted in the file as different items. The items had the type precipitation rate [mm/hr] and were mean step accumulated. To use the tool the measurement station's location needed to be defined by a xyz-file. A shapefile with points representing the stations was made in ArcGIS and information about the stations' locations were received from Uppsala Vatten and Uppsala University. A tool, Shape2xyz, in the MIKE Zero Toolbox was the used to convert the shapefile to a xyz-file.

The dfs0-file and the xyz-file were used as input to the tool Preprocessing Temporal Data. The tool was used with a power factor of 2 and covered the time period 12.15-21.15. The generated file consisted of grid data of spatially interpolated precipitation rate. The file contained 91 time steps of 6 min each, the grid spacing was 4x4 m and the geographical extent was based on the bathymetry file. The generated file presents the temporally and spatially interpolated rain-file. Figure 16 presents the interpolated CDS-rain for time step 23, at the time 14.33. The approximate location for the research area is presented as a black line.

Since the geographical extent was based on the original bathymetry file the temporally and spatially interpolated rain file's location was later adjusted according to the adjustments presented in Table 8. This resulted in that the interpolated rain was not located at its correct location. This was assumed to have an insignificant impact on the model result since the adjustments were small compared to the grid spacing 4x4 m.

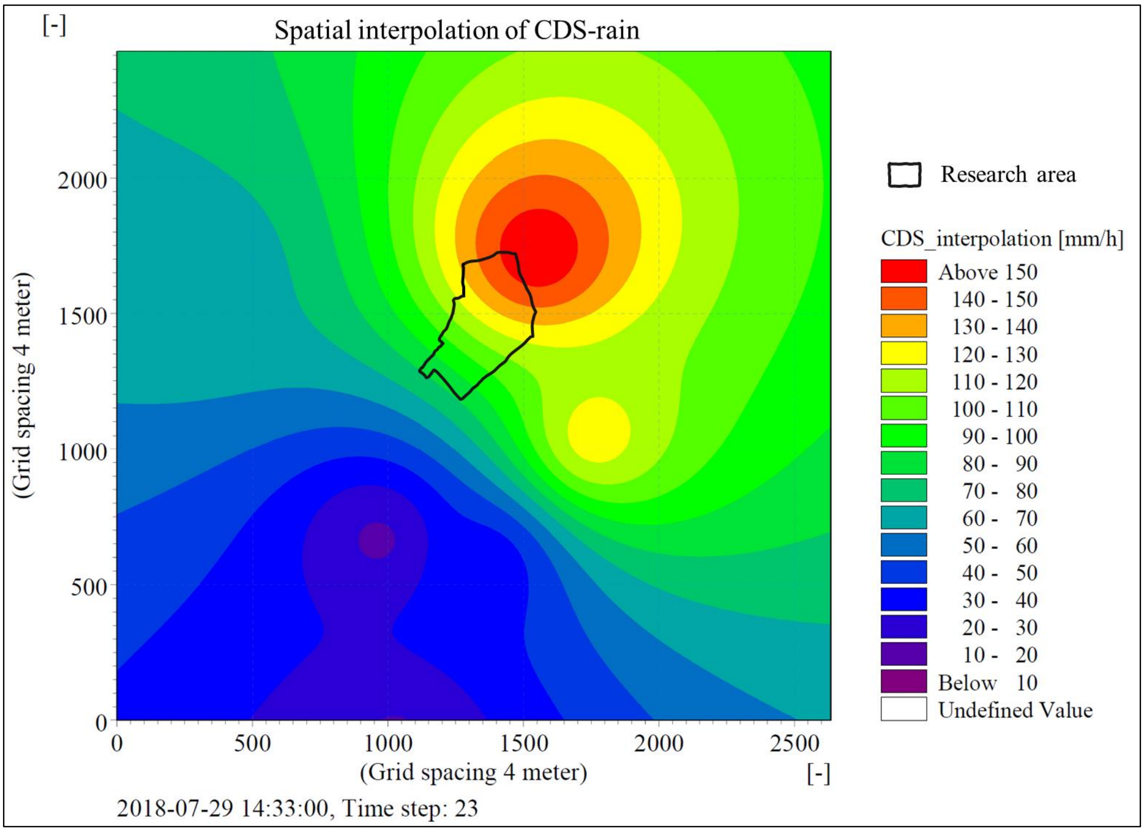

Figure 17. Temporally and spatially interpolated CDS-rain.

5 Results

In this chapter the results answering RQ 1 and RQ 2 are presented.

5.1 Results of the survey

The questions asked in the survey is presented in Appendix A. The survey was sent to different consultant companies that work with 1D-2D hydrodynamic stormwater modelling. Eight different consultant companies answered the survey and the survey totally got 18 responses. One of the respondents answered that he/she have never participated in a project of cloudburst modelling considering the stormwater network. This was a filtering question in Part 1 of the survey, see Figure 12, and therefore, this respondent did not continue the survey and the respondent will be excluded in the following results. Therefore, the following results will only consider 17 responses.

The 17 respondents are represented with letters between A and Q without any specific order. The result of the survey is presented in graphs and the text answers are summarised in this chapter. The sections below present the different questions of the survey and its responses.

In Figure 18 the different consultant companies that participated and the distribution of responses can be seen. Most of the responses were from Norconsult (23%) and Ramboll (23%) and the fewest responses were from NAWE (6%), DHI (6%) and Atkins (6%). It can also be seen that no responses are from WSP that also received the survey.

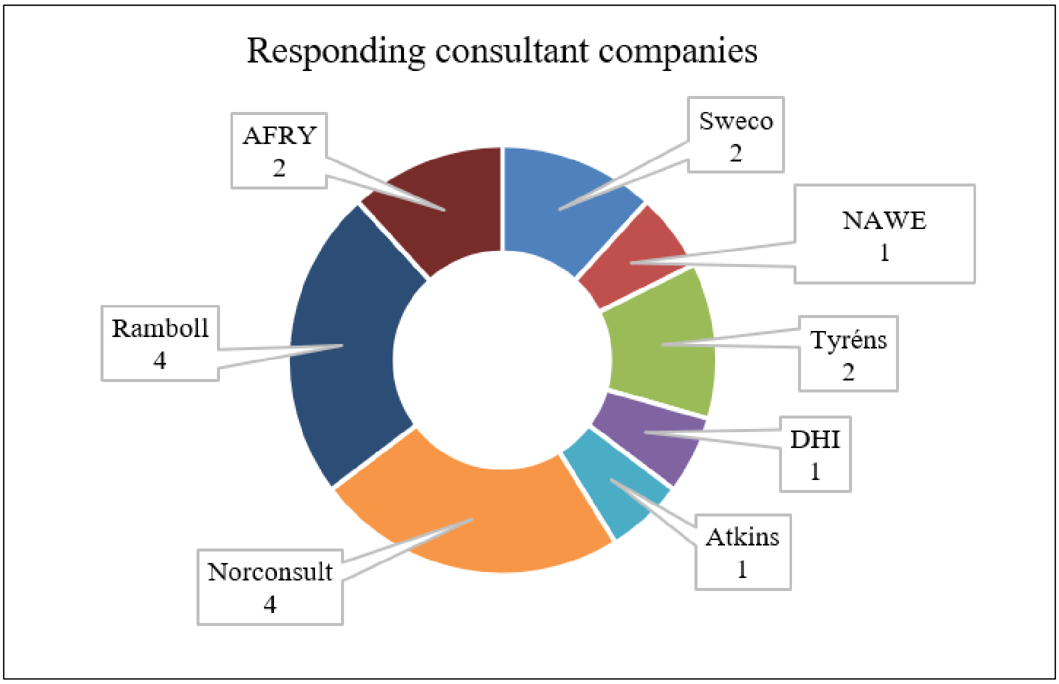

Figure 18. The consultant companies that have participated in the survey and the number of responses.

5.1.1 Frequency of considering clogged stormwater inlets

Figure 19 presents how often the respondents consider clogged stormwater inlets when modelling cloudbursts. Nine of the respondents (53%) never consider clogged stormwater inlets and totally eight respondents (47%) have at least considered it at some point. The respondents that had never considered clogged stormwater inlets were asked different questions than the respondents that had considered it, see Appendix A. The responses of the respondents that had never considered clogged stormwater inlets is presented in section 5.1.2 and the responses of the respondents that had considered it is presented in section 5.1.3.

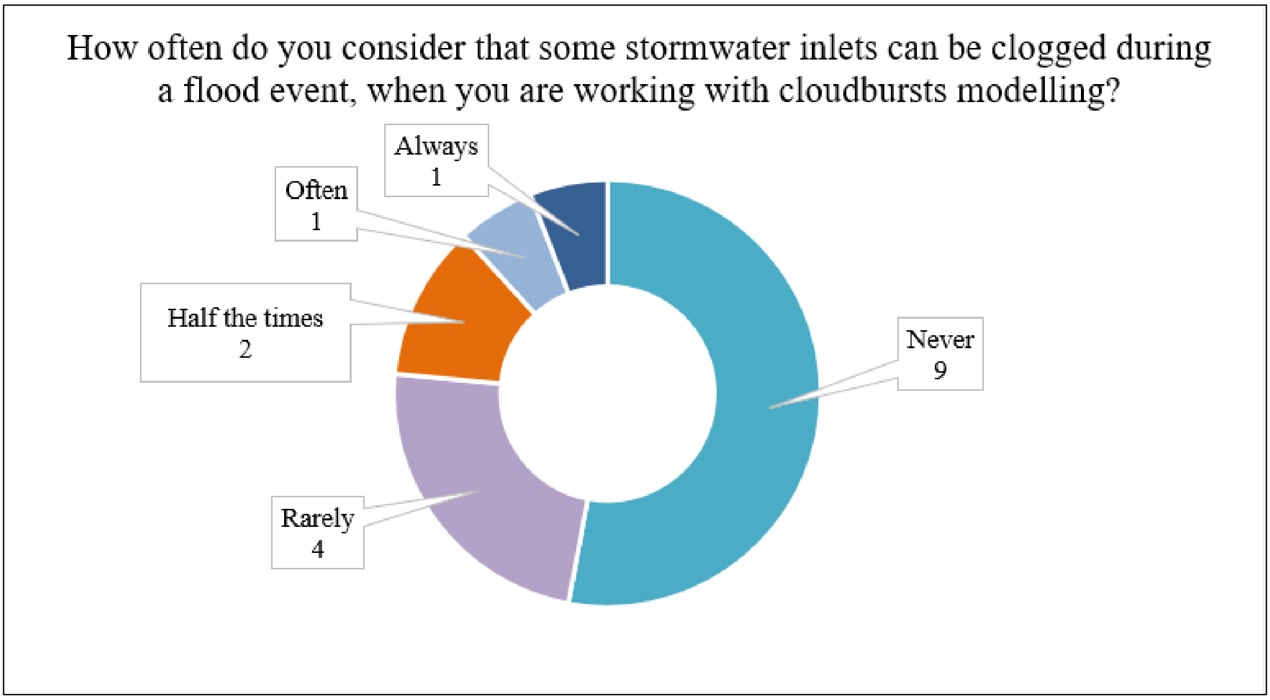

Figure 19. The frequency of how often clogged stormwater inlets are considered by the responding consultant when modelling cloudbursts.

5.1.2 Responses from respondents that have never considered clogged stormwater inlets

The respondents that have never considered clogged stormwater inlets are nine respondents (53%). The results presented in this section only consider responses from these nine respondents. The following section presents the results of the questions in Part 5, see Appendix A.

5.1.2.1 Reasons to not consider clogged stormwater inlets

Regarding why the respondents do not consider clogged inlets, respondent *A*, *E* and *F* highlighted that stormwater inlets as elements in the collection system is often not considered. *A* and *E* wrote that this is due to that it is time consuming. *E* also wrote that material presenting the stormwater inlets is usually not available for the whole catchment area and *A* wrote that it can be of bad quality. Instead of considering stormwater inlets, *A* wrote that it is more common to consider manholes than stormwater inlets in the models. According to *E* it could lead to more uncertainties if all stormwater inlets would be included in a model compared to a simpler model. For example, to include all stormwater inlets would lead to that many shorter pipes need to be included which can create instability in the collection system model (*E*).

Respondent *F* highlighted that it is not rare that the covers of the manholes get pushed away by the water pressure and therefore, the capacity of these have a larger impact than the capacity of the stormwater inlets. *F* also wrote that the collection system is not dimensioned to handle the stormwater during a cloudburst. According to *G*, the collection system is full during cloudburst and therefore *G* assumes that the result is not sensitive to clogged stormwater inlets but sometimes assume a certain value of the capacity of the inlet.

According to *F*, it is difficult to verify the clogging of stormwater inlets, but he/she also writes that it is indirectly considered when calibrating the model. *O* wrote that they do not have the knowledge of how clogged stormwater inlet can be considered. *M* wrote that he/she is unsure if the clogging has a large impact on the result of the model and to which extent the clogging should be considered. According to *O*, the extent of clogging varies with the maintenance of the stormwater inlets, and this is mentioned as a difficulty when predicting the extent. *N* wrote that a condition when modelling is that the stormwater inlets are maintained. If not, *N* wrote that many other parameters in the model can be questioned, but the respondent do not give any examples of other parameters.

5.1.2.2 The interest of considering clogged stormwater inlets when modelling cloudburst

Figure 20 presents how many of the nine respondents that have never considered clogged stormwater inlets that were interested in considering it. One respondent was not interest, four are interested and four did not know. The respondents had the possibility to comment this question.

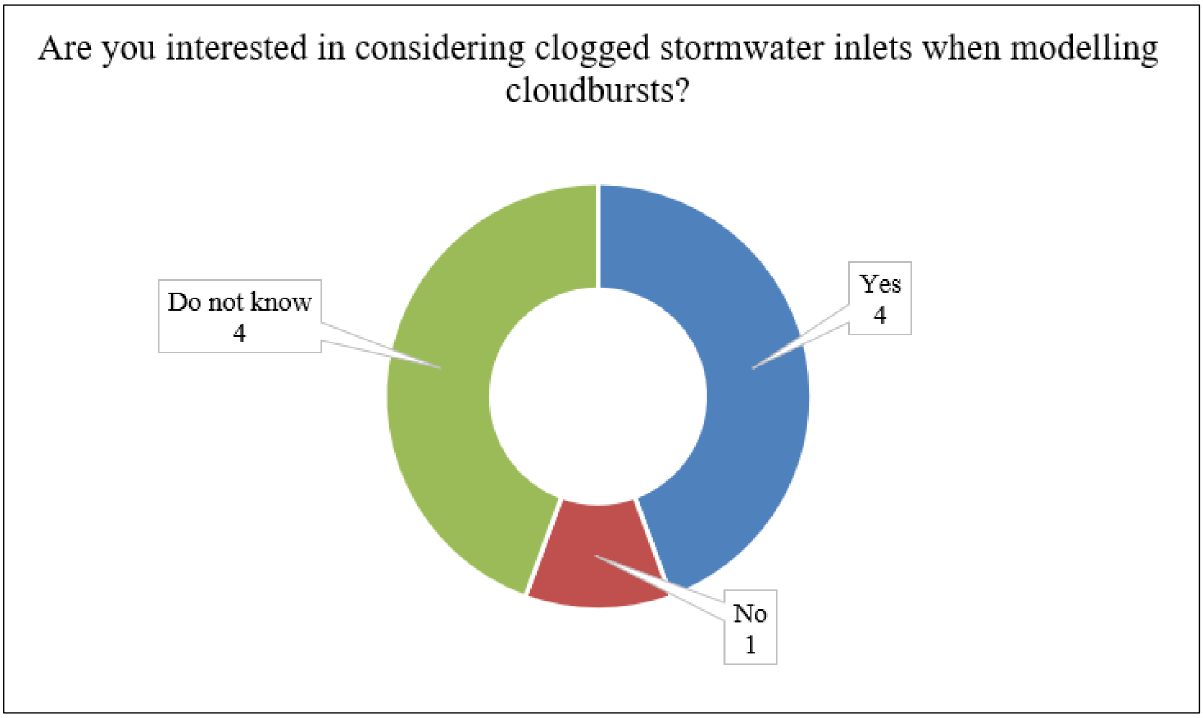

Figure 20. The results of if the responding consultants that have never considered clogged stormwater inlets are interested in considering it.

E commented that he/she is aware that the capacity in the stormwater inlets decreases when the inlets get clogged, and *E* highlighted that this also happens when it is raining with lower intensity than a cloudburst. *F* stated that the actor responsible for the maintenance of the inlets is responsible of the stormwater management when lower rain intensities. Therefore, *F* thought it would be interesting to look at clogged inlets when lower rain intensities, but respondent *F* did not define in his/her response what lower rain intensities are.

E wrote that it would be good to create a scenario when stormwater inlets are clogged but the inlets need to be carefully selected. According to *E*, the selected inlets should be in low points or in areas with vegetation. However, *E* highlighted that this would lead to more time consuming and therefore, more expensive which the costumer does not like. It would also lead to complicate descriptions and assumptions of the model, some examples given by respondent *E* are, which inlets should be clogged? For how long time should the inlets have its full capacity and how is the capacity affected by the precipitation?

A wrote that for some models they have adjusted the capacity of the manholes dependent on the number of stormwater inlets. *N* commented that all inlets cannot be assumed to be fully clogged. According to *N*, the precipitation can be applied only to the 2D overland model in that case, and not partly to the collection system.

N wrote that additional simulation could be done where more sensitive inlets due to flooding are located, for example in isolated areas.

5.1.2.3 Estimated effect of clogged stormwater inlets on the model results

Of the respondent that have never considered clogged wells, six out of nine thought that clogging of inlets would have an impact on the result, see Figure 21. One respondent did not know if consideration of clogged inlets would affect the results and two respondents did not think so.

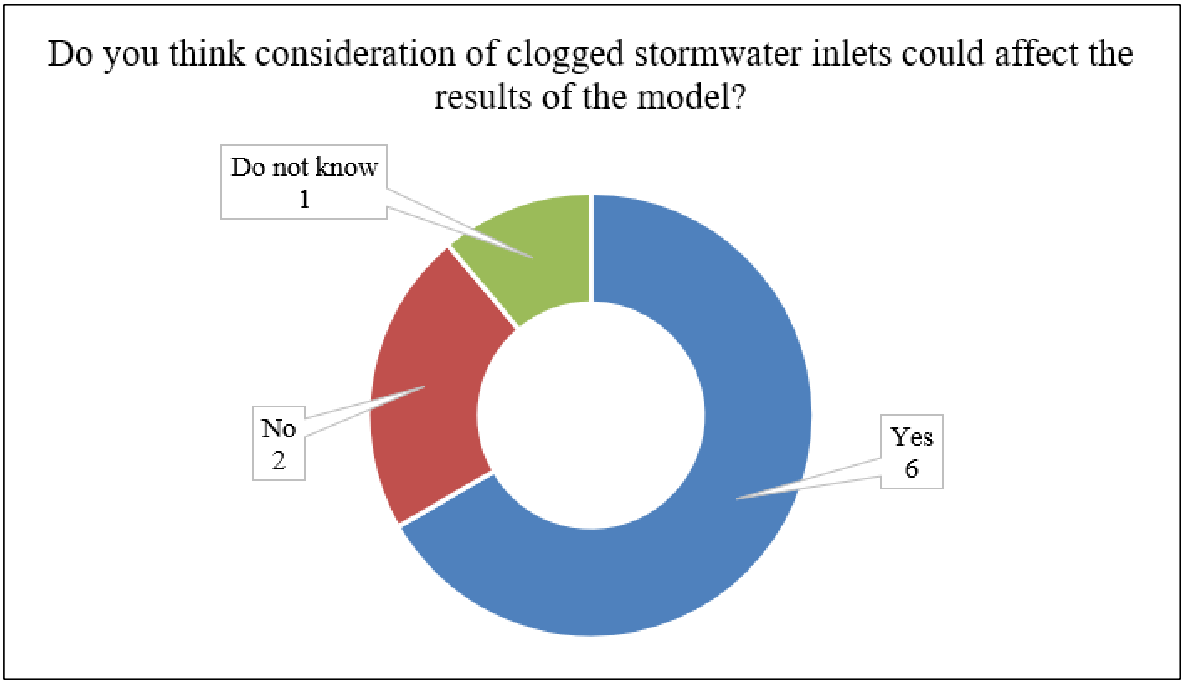

Figure 21. If the respondents that have never considered clogged stormwater inlets thinks it could affect the results of a model.

5.1.3 Responses from respondents that have considered clogged stormwater inlets

The eight respondents, totally 47% of the respondents, that have at least considered clogged inlets at some points have answered the questions presented in the following section. The following section presents the results of the questions in Part 4, see Appendix A.

5.1.3.1 Reasons to consider clogged stormwater inlets

Regarding why the respondent have considered clogged inlets has got different answers. *K* wrote that it is due to that it can affect the results of the calculation, *I* wrote that he/she have done it to study the effects when large portion of the precipitation stays on the surface. *P* wrote that due to own experience and logic clogged inlets happens quite often and he/she stated that rain events with higher intensity tend to flush items, not only debris, from areas where the rain events with lower rain intensity not flush which can clog the inlets.

B has considered clogged stormwater inlets due to the costumer’s request, for example if the costumer has had problem with clogged inlets before, or to do a sensitivity analysis of a cloudburst model. *Q* has considered it when simulating a pessimistic scenario of when the collection system does not function as it should. *Q* wrote that it depends on the purpose of the simulation, but the clogging can be used as a safety margin in a pessimistic scenario.

J wrote that the collection system has a theoretical function that is often similar for many collection systems, but the actual function of the system does vary between the systems due to different simulated rain intensities. It may be so that the inlets capacity cannot handle the rain intensity and therefore, *J* wrote that the reduction of capacity in the inlets are considered and not the clogging caused by debris. *L* highlighted that the capacity of the stormwater collection system is often exceeded when cloudbursts or the flow cannot enter the inlets fast enough to make a difference. *L* wrote that the clogging can be seen as a safety factor if the collection system cannot handle the flow.

5.1.3.2 How to consider clogged stormwater inlets when modelling cloudburst

The consultants were asked how they consider clogged stormwater inlets and respondent *J* highlighted that stormwater inlets are often not presented in the models, usually represented by manholes or inspection wells. *J* wrote that the collection system would be too complicated with all stormwater inlets and corresponding connected short pipes presented. *I*, *L* and *Q* responded that clogged inlets can be considered by changing the portion of precipitation that is applied on the 2D model and *I* also mentioned that the capacity through the inlets can be reduced. But how this is done is not described by the respondent. *Q* wrote that clogged inlets can be considered by reducing the number of manholes coupled to the collection system. *B* and *J* wrote that when using a coupled 1D and 2D model the manholes that is coupled to the 2D model can be adjusted. *B* also added that the max inflow and inlet area can be changed.

L and *P* wrote that a method to consider clogged inlets is by assuming that the collection system does not work. But *P* stated that this is only done to do a sensitivity analysis and simulate a worst-case scenario.

5.1.3.3 Portion of stormwater inlets considered clogged

Regarding which portion of the stormwater inlets that should be considered clogged, *I, L* and *P* wrote that 100% of the manholes representing the stormwater inlets are considered clogged. *B* has not done this type of assumption and *C* wrote that it depends on the slope and possible low points.

5.1.3.4 Reduction of capacity in clogged stormwater inlets

The consultants were asked how much they assume that the capacity of the clogged inlets is reduced. *B* and *I* did not have a specific factor for this, but *B* suggested clogging factors of 0.25, 0.50 or 0.75, and *I* suggested capacity reduction of 10%, 20% or 30%. Due to how respondent *B* wrote the answer there are uncertainties weather the respondent aims at capacity reduction of the inlet (clogging factor) or to reduce the area of the inlet cover. The question in the survey asked about the capacity reduction, therefore, it is assumed that respondent *B* aims at capacity reduction of the inlet (clogging factor). *L* and *P* wrote that they consider 100% reduction. *C* stated that it depends on the flow geometry. *B* mentioned that his/her company have determined hydrographs of how the capacity of an inlet vary dependent on the water depth above the inlet.

5.1.3.5 Location of the clogged stormwater inlets

Regarding where the clogged inlets are located respondents *B* and *P* wrote that they have not done that type of assumption. *J* highlighted that the location of the clogged inlets would be based on a lot of assumptions. *L* wrote that stormwater inlets that have been proved clogged can be considered clogged in the simulation when calibrating the model.

Q wrote that the clogged inlets are chosen randomly and with even distribution and *L* stated that all or no inlets are assumed clogged since this cannot be controlled or modelled uniformly. *I* wrote that all inlets are assumed to have reduced capacity.

5.1.3.6 Experienced effect of clogged stormwater inlets on the model results

Three of the eight respondents that had at some point considered clogged inlets thought that it has a significant impact on the results of the simulation and one thought that it has a large impact on the results, see Figure 22. Two respondents answered that he/she did not know, one that it does not affect the results and one responded that the impact is insignificant.

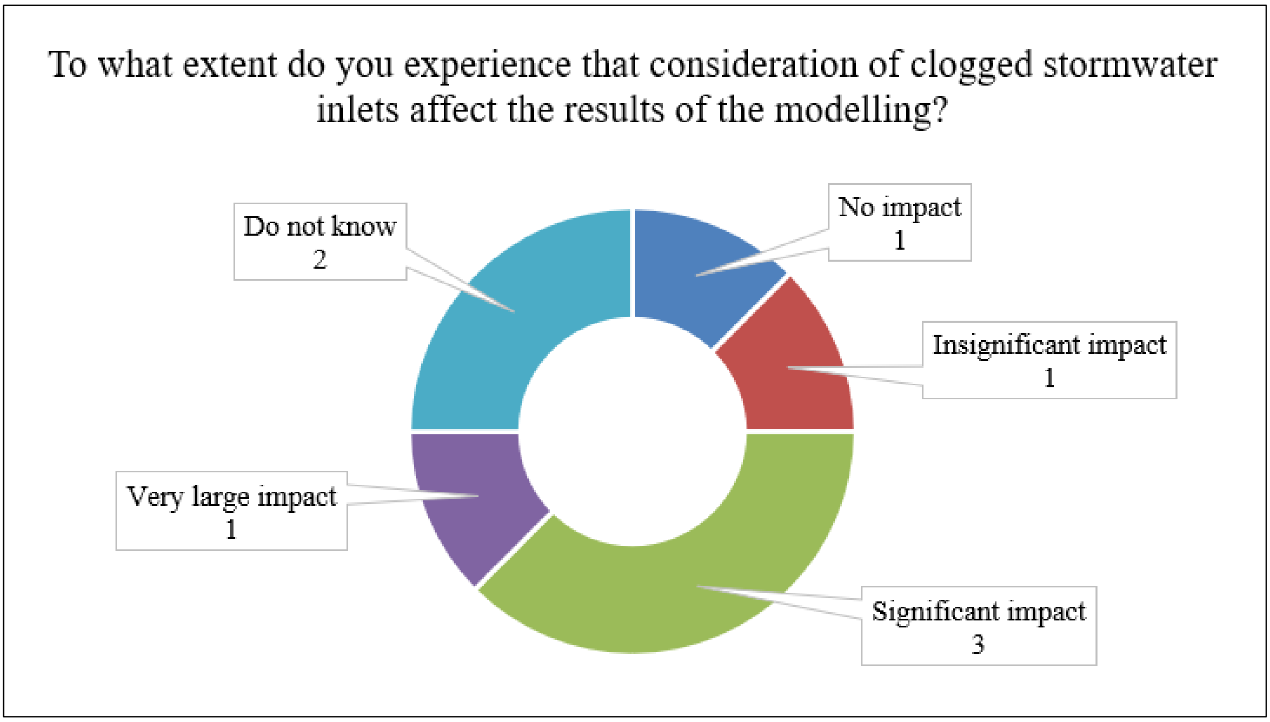

Figure 22. To which extent the respondents think consideration of clogged stormwater inlets affect the results.

Some of the respondents commented the question regarding the impact of clogged inlets. *L* commented that clogged stormwater inlets are varying in time and space and therefore it is better to not consider it. By not considering clogged stormwater inlets *L* stated that the results are more comparable. *P* wrote that the capacity of the collection system affects the impact of clogged inlets. If the capacity of the system is small, clogged inlets will not have a large impact but if the capacity is large the impact of clogged inlet is larger (*P*).

Q commented that clogged inlets are not considered to a large extent even though he/she knew that the impact can be significant. This can be due to that data is not available and that if too many "pessimistic" assumptions are made the results can be misleading if not a worst-case scenario of a sensitivity analysis is the purpose with the simulation (*Q*).

5.1.3.7 The extent of consideration to clogged stormwater inlets

Four of the eight respondents thought that clogged inlets should be considered to a larger extent, while three respondents did not think so and one did not know, see Figure 23.

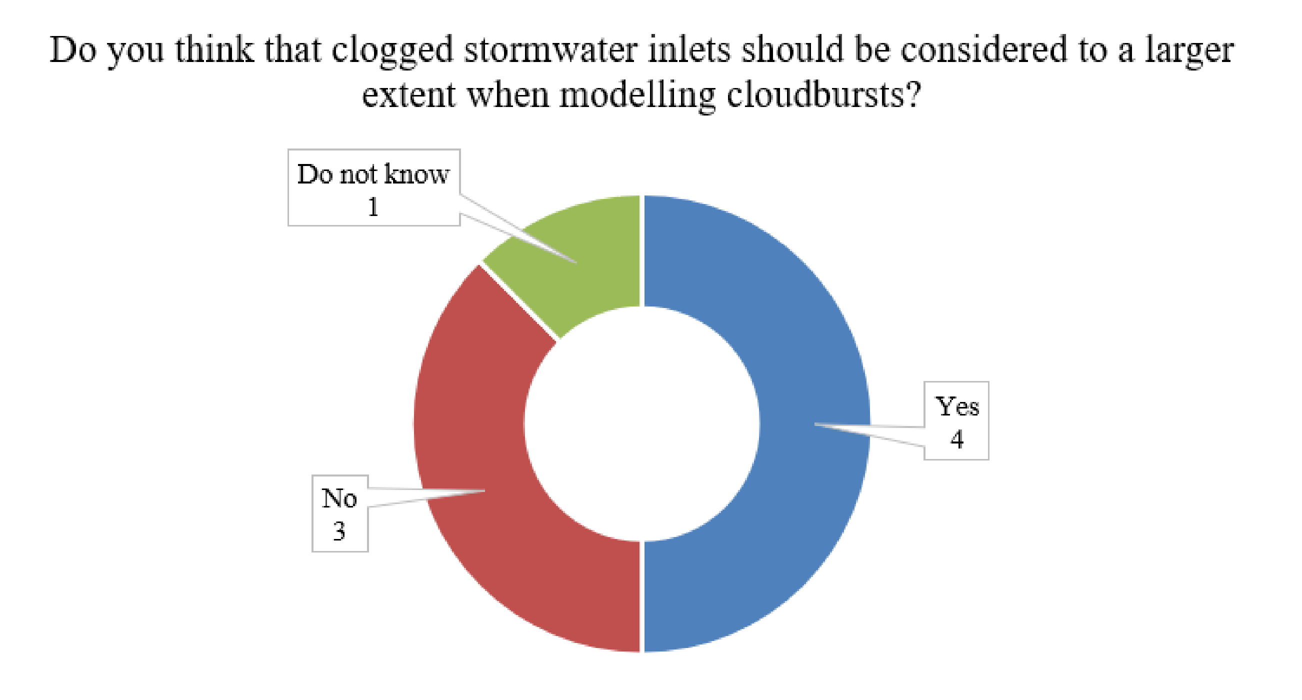

Figure 23. If the respondents think clogging should be considered to a larger extent.

I stated that consideration of clogged inlets would be a conservative assumption regarding the capacity of the collection system and the dynamic between the pipes and the surface. *Q* commented that consideration of clogged inlets is not motivated due to other pessimistic assumptions.

P wrote that reduced inflow to the manholes should be considered in a sensitivity analysis to analyse its affect. *P* also thought that scenarios when the capacity of large culverts are reduced should be simulated since these often can be clogged.

B commented that clogged inlets is only one of many uncertainties when modelling cloudbursts. Other examples given by *B* are the capacity of infiltration, distribution of precipitation between the collection system and 2D model, and the classification of Manning's number. According to *B*, data and statistics are often unavailable when calibrating models. Therefore, it is not sure that the calibrated model can be applied in other areas or with other rain events (*B*). If the time and budget allow, *B* wrote that sensitivity analysis should be sought even though uncertainties will remain.

5.2 Results of the sensitivity analysis

To answer RQ 2, results of interaction volumes between the 1D and the 2D model are presented. As are a comparison of maximum water depth as well as the discharge to the surface and water levels in nodes for respectively simulation.

5.2.1 Interaction volumes between the 1D and the 2D model

Table 12 presents the interaction volumes between the 1D and the 2D model for each simulation ID. The table also presents the difference in percentage for simulation ID 1-ID 3 in relation to simulation ID 0. As presented in the table, the interaction volume flowing from the 2D to the 1D model decreases with a reduced flow capacity in the 1D-2D model couplings. The same yields for the interaction volume flowing from the 1D to the 2D model. Also, the total volume from the 2D model to the 1D model decreases with a reduced flow capacity in the 1D-2D model couplings. The total volume accounts for the volume from the 2D to the 1D model and the volume from the 1D to the 2D model. The total volume also includes a correction flow which in simulation ID 0-ID 3 is minor.

With regard to percentage points the volume flowing from the 1D to the 2D model is more affected by a reduced flow capacity in the 1D-2D model couplings than the volume flowing from the 2D to the 1D model. The total volume from the 2D model to the 1D model is the volume with less change in percentage points.

Table 12. Interaction volumes between the 1D and the 2D model.

		Volume flowing from the 2D to the 1D model		**Volume flowing from the 1D to the 2D model**		**Total volume from the 2D to the 1D model.**	
Simulation ID	**Clogging factor [-]**	**Volume [m^3]**	**Difference in relation to simulation ID 0**	**Volume [m^3]**	**Difference in relation to simulation ID 0**	**Volume [m^3]**	**Difference in relation to simulation ID 0**
ID 0	0	110 134		29 857		80 264	
ID 1	0.2	109 283	-0.77%	29 185	-2.3%	80 086	-0.2%
ID 2	0.4	107 551	-2.35%	27 675	-7.3%	79 868	-0.5%
ID 3	0.6	104 736	-4.90%	25 516	-14.5%	79 218	-1.3%

5.2.2 Maximum water depth

The maximum water depth for simulation ID 0 in relation to the maximum water depth for simulation ID 1- ID 3, respectively, has been compared. Table 13 presents the portion of positive and negative cells received when subtracting the raster of the maximum water depth in simulation ID 1-ID 3, respectively, from the raster of the maximum water depth in simulation ID 0. Negative values indicates that the maximum water depth in simulation ID 0 is lower than in simulation ID 1-ID 3, respectively. Positive values indicates that the maximum water depth in simulation ID 0 is higher the compared simulation. The table also presents to portion of cells being equal to zero. Moreover, Table 13 also presents the mean values of the water depths for negative and positive cells.

In all three comparisons, the portion of negative cells increases with the reduction of flow capacity. The mean value of the negative cells decreases with the reduction of the flow capacity. Hence both the spatial extent (portion of cells) and maximum water depth increases with a reduction of flow capacity. The portion of positive cells for ID0 minus ID2 is lower than for the other two comparisons. The mean value of the positive cells increases with the reduction of flow capacity. Moreover, the portion of negative cells shows a bigger difference in percentage points for the three comparisons than the portion of positive cell values. The negative cells also show a bigger difference in mean value of the water depth than the positive cell values. The portion of cells being equal to zero decreases with the reduction of the flow capacity in the 1D-2D model coupling.

Table 13. The maximum water depth for simulation ID 0 in relation to the maximum water depth for simulation ID 1-ID 3, respectively. Negative and positive cells and their mean value for each mathematical operation is presented. As are the portion of cells being equal to zero.

Comparison	**Portion negative cells**	**Mean value of the negative cells [m]**	**Portion positive cells**	**Mean value of positive cells [m]**	**Portion of cells equal to zero**
ID0 minus ID1	22.5%	-0.77×10^{-3}	12.7%	0.86×10^{-3}	65.8%
ID0 minus ID2	24.1%	-1.7×10^{-3}	12.0%	1.5×10^{-3}	63.9%
ID0 minus ID3	25.2%	-3.2×10^{-3}	12.2%	2.1×10^{-3}	63.7%

Figure 24-Figure 26 presents the difference in maximum water depth for the three comparisons. Red and blue colours indicate negative differences, which is when the maximum water depth of simulation ID 0 is lower than in simulation ID 1-ID 3. Green values indicate the opposite, that the maximum water depth in simulation ID 0 is higher than in simulation ID 1-ID 3. Differences +/- 0.02 m has been assessed as negatable and is therefore presented as transparent in Figure 24-Figure 26. Where the extent of the difference is limited a more detailed

picture of the area is provided, see red markings in Figure 24-Figure 26. No markings are provided of areas where the differences affect less than five cells, the extent of these areas are assessed as negatable.

Figure 24 presents the difference in maximum water depth for simulation ID 0 minus simulation ID 1. The maximum difference are within the range 0.02-0.05 m and the minimum values are within the range (- 0.10 m)-(- 0.05 m).

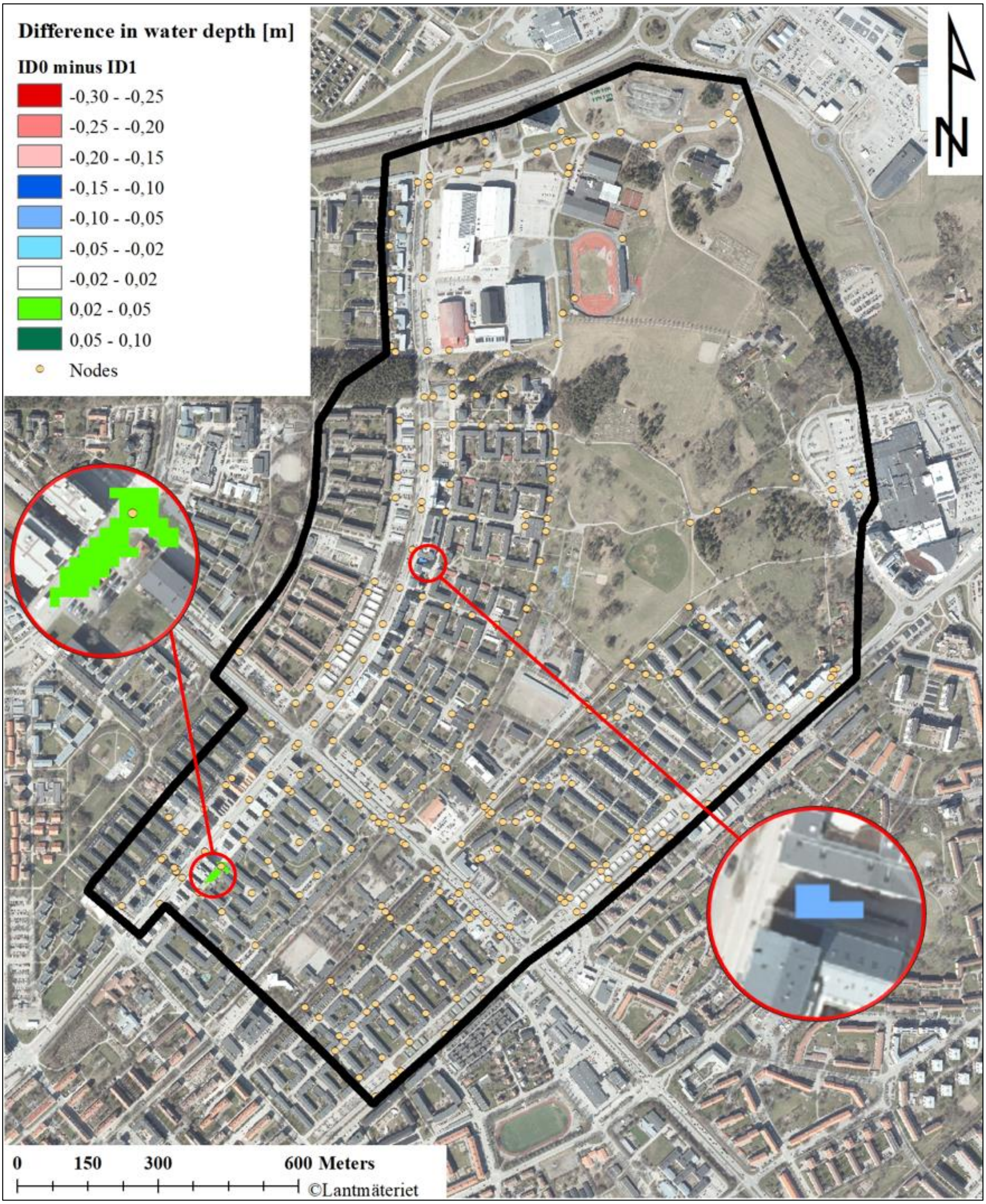

Figure 24. Difference in maximum water depth for simulation ID 0 minus simulation ID 1. Aerial photo from SCALGO Live (n.d) ©Lantmäteriet.

Figure 25 presents the difference in maximum water depth for simulation ID 0 minus simulation ID 2. The maximum difference are within the range 0.05-0.10 and the minimum value are within the range (- 0.20)-(- 0.15).

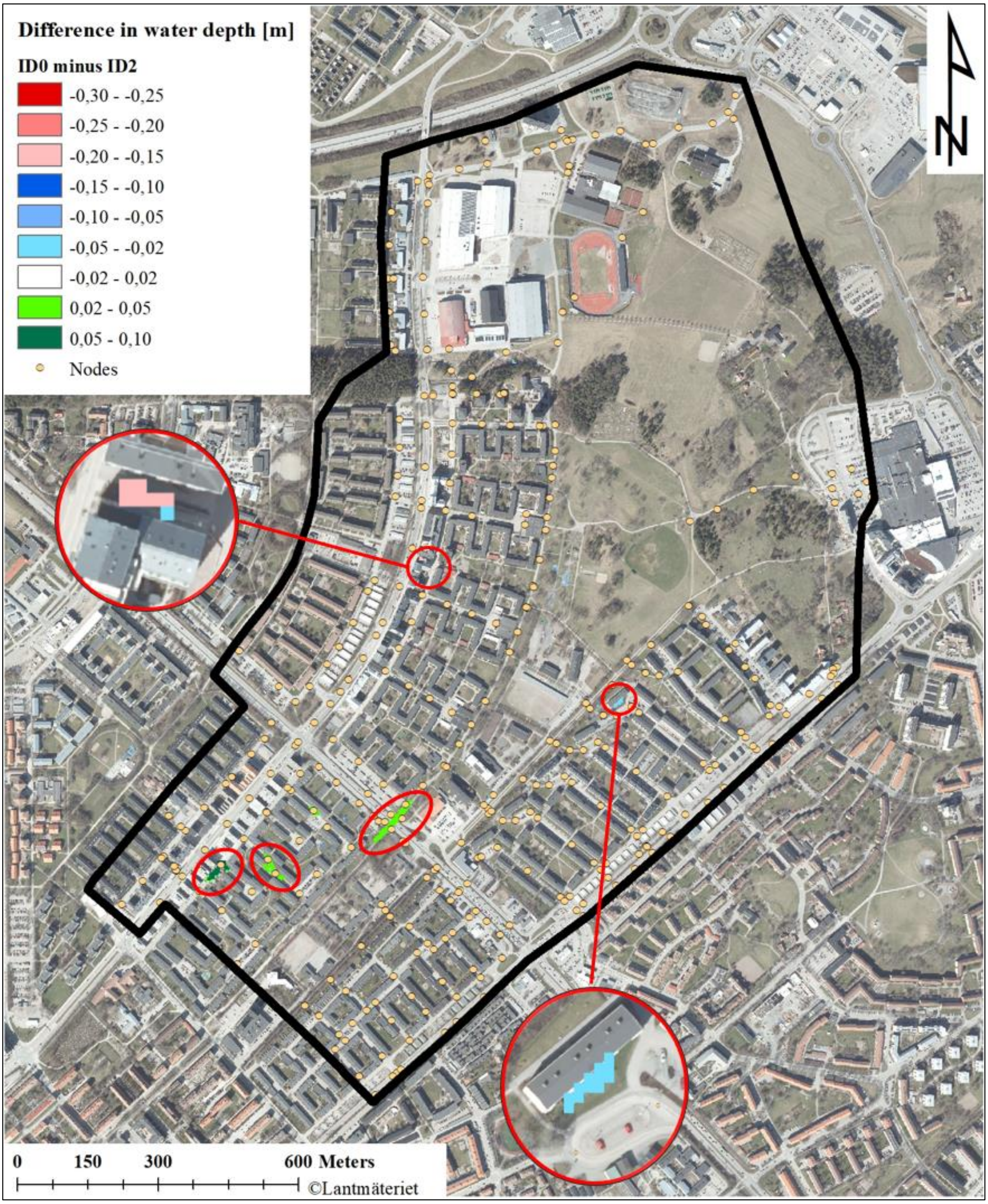

Figure 25. Difference in maximum water depth for simulation ID 0 minus simulation ID 2. Aerial photo from SCALGO Live (n.d) ©Lantmäteriet.

Figure 26 presents the difference in maximum water depth for simulation ID 0 minus simulation ID 3. The maximum difference are within the range 0.05-0.10 and the minimum value are within the range (- 0.30)-(- 0.25).

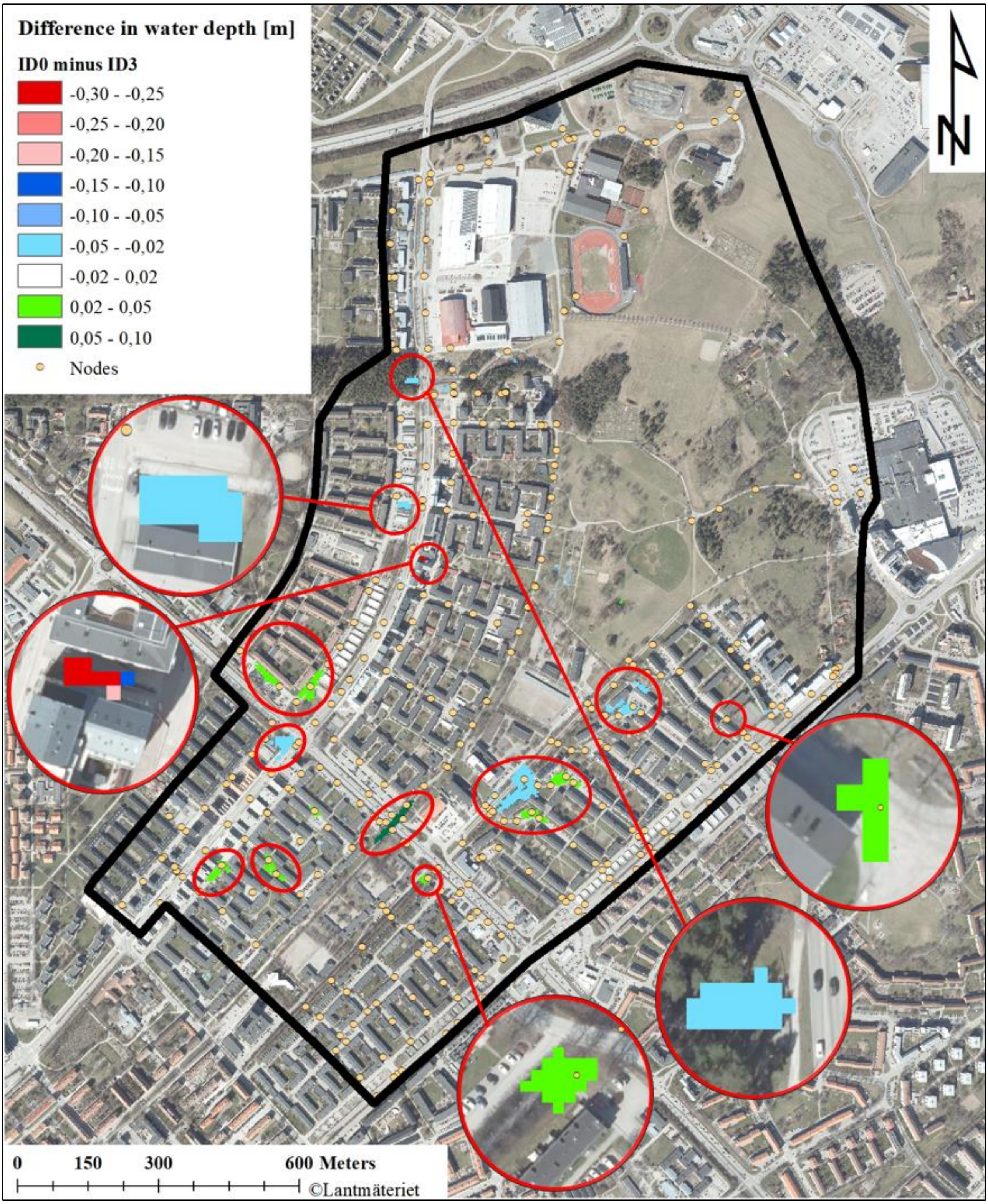

Figure 26. Difference in maximum water depth for simulation ID 0 minus simulation ID 3. Aerial photo from SCALGO Live (n.d) ©Lantmäteriet.

5.2.3 Discharge to surface and water level in nodes

The discharge to surface and the water level over time of three nodes of totally 341 nodes in the research area are presented in this section. The three nodes are presented in Figure 27. These three nodes are further analysed since they had flooding at the node and around the node in the simulations.

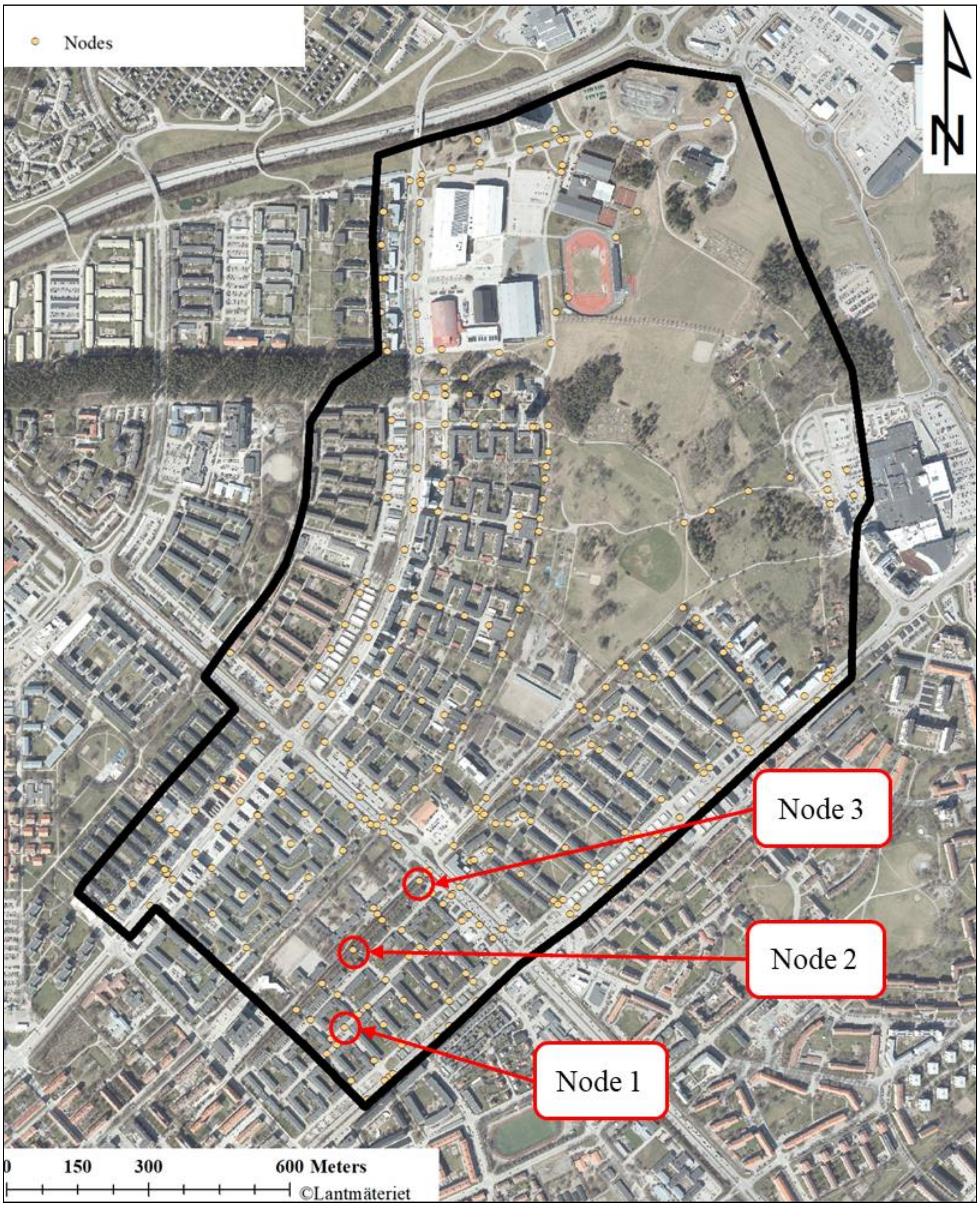

Figure 27. The three nodes analysed regarding discharge to surface and water level. Aerial photo from SCALGO Live (n.d) ©Lantmäteriet.

The discharge and the water level were calculated to moving average (MA) of every ten minute to better visualize the result. The original result is presented in Appendix B. In the three following graphs (Figure 28, Figure 29, Figure 30) the upper part of each graph presents the water level over time and the ground level of the node. When the water level is above the ground level flooding occur. The lower part of each graph presents the discharge in the node over time. Positive discharge represents a discharge from the 1D collection system to the 2D overland model, and a negative value represents a discharge from the 2D overland model to the 1D collection system. The time covered in the graphs is the simulation time 12:15-20:00.

5.2.3.1 Discharge to surface and water level over time: Node 1

In Figure 28 the four simulations generally follow the same pattern and are mostly ordered from ID 0-ID 3 or ID 3-ID 0 in Node 1. Initially there is discharge from the 2D overland model to the 1D collection system. From about 14:40 the simulations have discharge to surface (1D collection system to 2D overland model) during approximately 1 h and 15 min. The discharge of simulation ID 0 is the highest closely followed by simulation ID 1, thereafter simulation ID 2, and the discharge of simulation ID 3 is the lowest. Around 16:00 the four simulations are varying more, simulation ID 0 and ID 2 are varying more compared to simulation ID 1 and ID 3 which are relatively stable. All simulations do then have discharge from the 2D overland model to the 1D collection system.

The water level in Node 1 (Figure 28) increase from 14:00 and reaches the ground level at approximately14:30 for all simulations. The node is then flooded, and the water level starts to decrease at around 14:30. Around 17:00 the water level is under the ground level and the node is no longer flooded. The four simulations are about the same until approximately 17:00. Simulation ID 3 has the fastest decrease of water level, followed by simulation ID 2, ID 1 and ID 0 has the slowest decrease of water level.

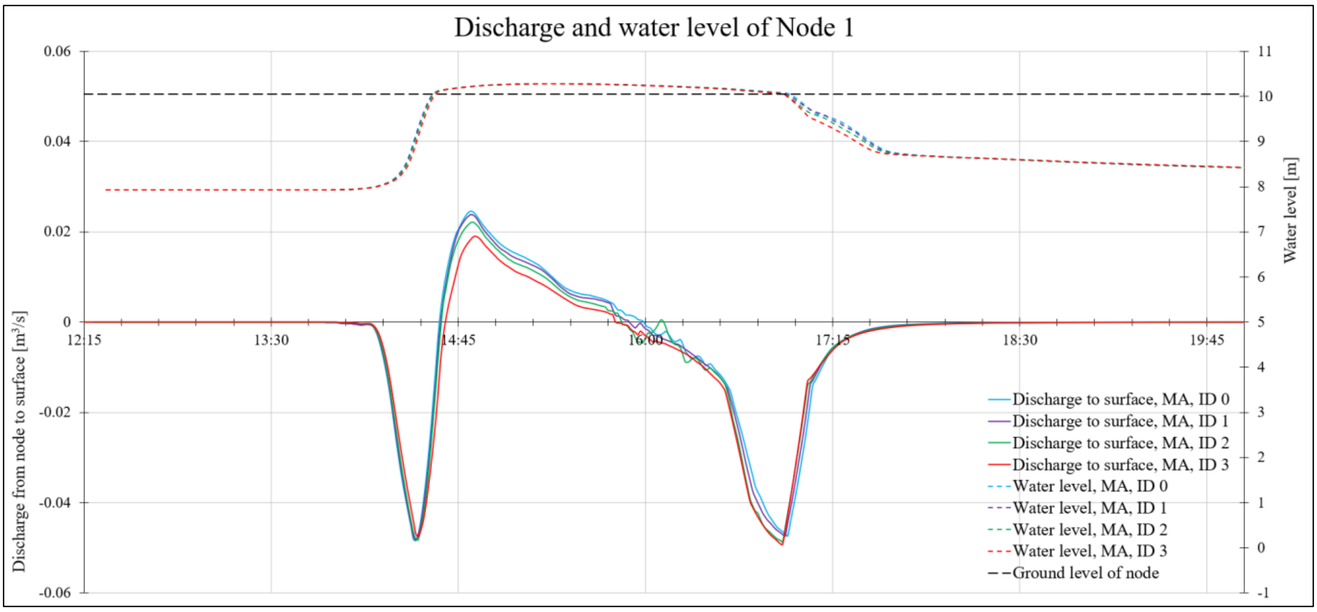

Figure 28. Discharge and water level of Node 1.

5.2.3.2 Discharge to surface and water level over time: Node 2

In general, the four simulations in Node 2 follow the same path, see Figure 29. Between around 14:45 to 15:10 the simulations have discharge from the 1D collection system to the 2D overland model. Then the simulations have discharge from the 2D overland model to the 1D collection system. All four simulations are varying a lot from approximately 14:45 to 17:15. Each simulation is varying, as are the difference between the simulations. The order of the simulations also differs during the simulation.

The water level increases from approximately 14:00 to 14:45, then the water level reach the ground level, and the node is flooded (Figure 29). The node is flooded until about 17:00. There are some displacements between the simulations regarding how long the node is flooded. Simulation ID 0 is flooded the longest followed by simulation ID 1, simulation ID 2, and simulation ID 3 is flooded the shortest.

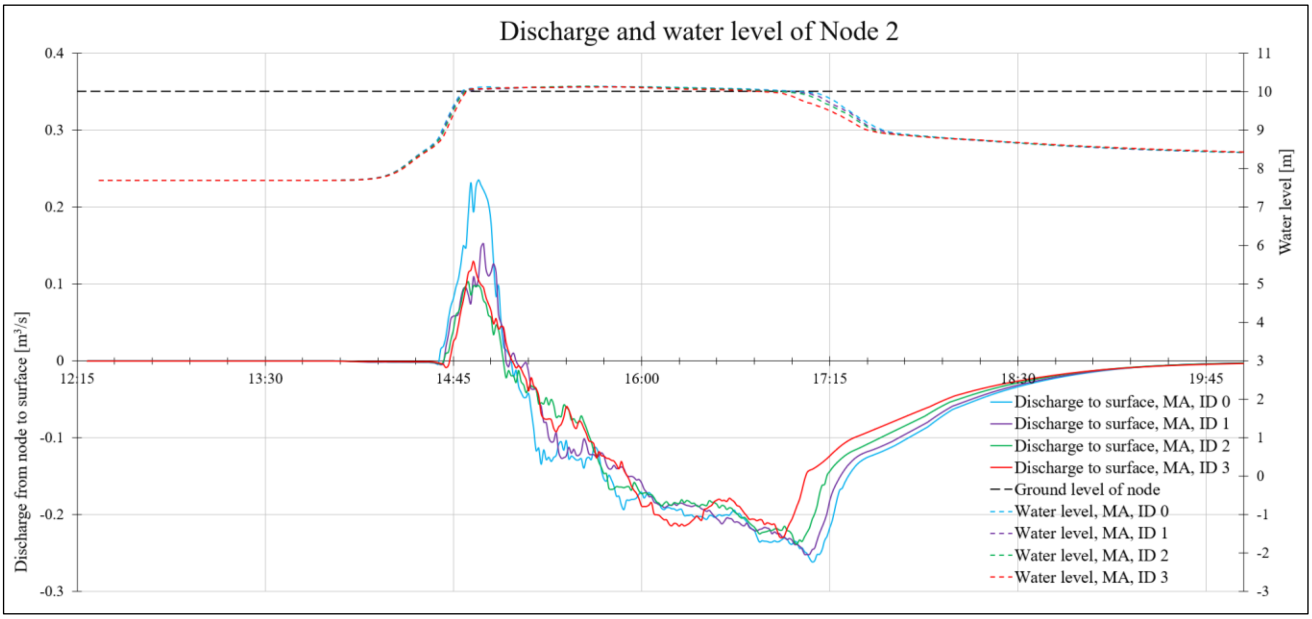

Figure 29. Discharge and water level of Node 2.

5.2.3.3 Discharge to surface and water level over time: Node 3

The four simulations vary a lot in Node 3 (Figure 30). The four simulations do mainly have discharge to the surface except for simulation ID 2 that have some discharge to the 1D collection system at approximately 16:15. Simulation ID 3 have smaller variations than the other three simulations. Around 17:00, simulation ID 3 have a decreasing discharge while simulation ID 0 have a more quick and abrupt decrease of the discharge at around 17:15.

From about 14:00 the water level increase and at approximately 14:45 the water level reaches the ground level and the node is flooded (Figure 30). The flooding ends at around 17:00 with some displacements between the four simulations. Simulation ID 3 has the shortest flooding, followed by ID 2, ID 1 and ID 0 has the longest.

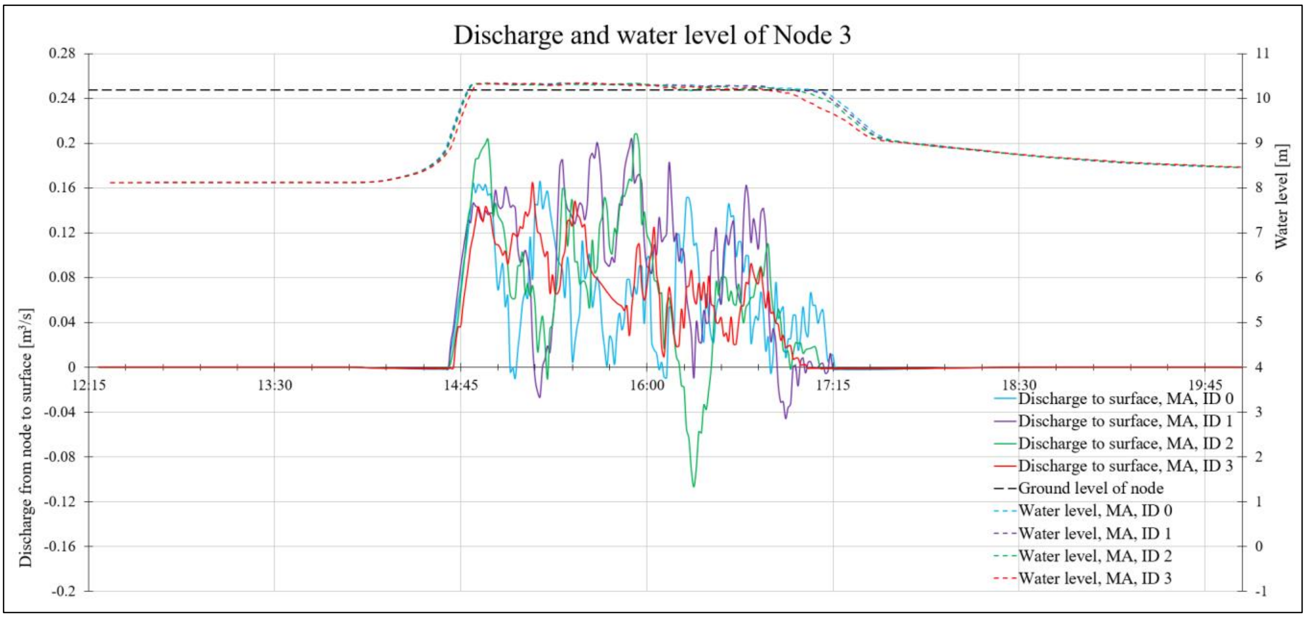

Figure 30. Discharge and water level of Node 3.

6 Discussion

This chapter discusses the findings of the survey (RQ 1) and the sensitivity analysis (RQ 2).

6.1 Discussion of the survey

The responses regarding if clogged stormwater inlets should or should not be considered in a 1D-2D hydrodynamic stormwater model differed. Hence, it can be concluded that no united opinion or reason exists regarding if clogged stormwater inlets should be considered clogged or not within the group of consultants that have responded to the survey. One respondent stated that consideration of clogged stormwater inlets is a conservative assumption of the collection system’s capacity and the dynamic between the surface and collection system. The same argument was stated by Salomonsson et al. (2017). Another respondent wrote that clogged stormwater inlets can be used as a safety margin in a pessimistic simulation. On the other hand, one respondent wrote that the consideration is not motivated due to other pessimistic assumptions. Respondents wrote that clogged stormwater inlets are one of many uncertainties when modelling cloudbursts and that there is lack of knowledge regarding how clogged stormwater inlets can be considered. The lack of knowledge indicated by the respondents can be one reason to the relatively high percentage of respondents that answered “do not know” at several questions. For example, four of the nine respondents that have never considered clogged stormwater inlets have answered “do not know” at the question regarding if they are interested in considering it.

Regarding where the clogged stormwater inlets are located the responses differ too. One respondent that have never considered clogged stormwater inlets wrote that the clogged inlets should be carefully selected and the ones to be selected should be in low points and close to vegetation. A respondent that has considered clogged stormwater inlets also wrote that the low points should be considered. The surface runoff flow towards low points (Salomonsson et al., 2017) and vegetation that releases leaves are a reason to clogged stormwater inlets (Gómez et al., 2013; Leitão et al., 2017; Palla et al., 2018).

The likelihood of clogging is affected by the maintenance (Gómez et al., 2013; Leitão et al., 2017; Palla et al., 2018) and Salomonsson et al. (2017) highlight the importance of maintaining the stormwater collection systems. Aligned with the literature two respondents wrote that the maintenance affect to what extent the clogging should be considered, and one respondent assume that the stormwater inlets are maintained when modelling.

One of the eight respondents that have considered clogged stormwater inlets answered that it has a large impact on the results and three answered that it has a significant impact which Leitão et al. (2017) also wrote that the reduced capacity can have.

6.1.1 Uncertainties with the survey

The survey totally got 17 responses which is a limited number of responses. The number of consultants working with 1D-2D hydrodynamic stormwater modelling in Sweden is not known, but is assumed to be more than 17 consultants. Therefore, the discussion and conclusion of this study regarding RQ 1 cannot be seen as general for Sweden.

Since the survey was web based it is not possible to know how the respondents have answered the survey. The missive told that the survey was individual, but it is not possible to control weather it was answered by one consultant or if multiple consultants answered it together. It is also possible that the consultants can have discussed the questions in advance. The survey was anonymous and therefore it is not possible to know if all responses from a consultant company were from the same office or department, or if it was from different offices in Sweden. This can lead to uncertainties regarding the number of respondents and regarding if a respondent’s answer was affected by other respondents.

A survey as a form gives the respondent the possibility to interpret the questions. Since the survey was web based and the respondent answered it when it was possible for him/her there were no opportunity for the respondent to ask for clarification regarding the questions and their interpretation. This can lead to uncertainties in the results since the questions can have been interpreted differently by the respondents. Multiple questions were text answers, and the responses of these questions indicate that the interpretation can have differed between the respondents since the content varied a lot.

If interviews would have been done instead the uncertainties due to interpretation could have been smaller. But interviews would have been more time consuming. Therefore, interviews with larger quality but smaller quantity could have been an option.

One uncertainty with the survey is that it consequently asks regarding to stormwater inlets. As can be seen in the received responses of the survey and according to Bertsch et al. (2017) stormwater inlets are rarely considered when modelling stormwater, instead manholes are considered. This can lead to that the respondents consider this simplification differently when answering the questions. For example, some respondents may reason that clogged stormwater inlets are never considered since the actual stormwater inlets are rarely presented in the model, while other may reason that the stormwater inlets can be considered since they are represented with the manholes which can consider it. This can have a large impact on the received answers of the survey.

6.2 Discussion of the sensitivity analysis

Within this chapter the interaction volumes between the 1D and the 2D model as well as maximum water depth are discussed. As are the discharge to the surface and water levels in nodes as well as uncertainties conducted by the method.

6.2.1 Interaction volumes between the 1D and the 2D model

By the interaction volumes between the 1D and the 2D model presented in Table 12 it is apparent that a reduced capacity in the 1D-2D model coupling affects the volume flowing from the 1D to the 2D model more than the volume flowing from the 2D to the 1D model. It is also apparent that the total interaction volume during the simulation is not affected significantly. With a reduced flow capacity of the 1D-2D model couplings with 60% the total interaction volume is affected with 1.3%.

6.2.2 Maximum water depth

The maximum water depth of the cells is affected by a reduced flow capacity in the 1D-2D model coupling, Table 13 (section 5.2.2). Although, the difference in maximum water depth between the scenarios is small. The results also demonstrates that the effect of the reduced capacity in the 1D-2D model coupling is limited to relatively small areas of the research area, Table 13 and Figure 24-Figure 26 (section 5.2.2).

For maximum water depth, Table 13, the portion of negative cells increases with a reduced flow capacity in the 1D-2D model couplings. The same relation is not evident for the portion of positive cells. Here the portion for simulation ID0 minus simulation ID2 is lower than the portion for simulation ID0 minus simulation ID1 and the portion for simulation ID0 minus simulation ID3.The portion positive cells for simulation ID0 minus simulation ID2 are 0.2 percentage points higher than the portion for simulation ID0 minus simulation ID3. Since the portion of cells being equal to zero decreases with a reduced flow capacity in the 1D-2D model couplings the difference of 0.2 percentage points can be explained by a redistribution between negative cells and cells being equal to zero.

As presented both in Table 13 and Figure 24-Figure 26 (section 5.2.2) the reduction of flow capacity in the model coupling affects both the portion of positive and negative cells, i.e. a reduced flow capacity in the model couplings resulted in both higher and lower maximum water depth. Hence, it is not evident that a reduction of the flow capacity will be a more conservative approach of the capacity of the collection system as suggested by Salomonsson et al. (2017). 1D-2D couplings in areas sensitive to flooding can therefore be simulated both with and without a reduction of the capacity for a more conservative analysis.

6.2.3 Discharge to surface and water level in nodes

The water level of Node 1 presented in Figure 28 initially increases when the discharge to the 1D collection system increases. Few minutes after the water level have reached the ground level the discharge to the 2D overland model starts due to flooding. From about 15:50 the discharge to 1D collection system continues and the water level decreases slowly. Around 17:00 the discharge to 1D collection system decreases and therefore the water level could recover and decrease under the ground level and the flooding stops.

The water level in Node 2 (Figure 29) increased before there was any discharge in the node and the initial discharge in the node was from the 1D collection system to the 2D overland model. The increasing water level and the flooding of the node at about 14:50 can therefore be caused by increasing water level due to discharge to the 1D collection system in other surrounding nodes. From around 15:10 there was discharge into the 1D collection system, but the water level remains almost the same until around 16:00. This can be due to that there was surface runoff that flowed to the node on the surface and counteracted that the water level could decreased.

Similar to Node 2, Node 3 (Figure 30) have increasing water level and then initial discharge from 1D collection system model to 2D overland model. Which can be due to discharge in the collection system from surrounding nodes and therefore increased water level.

During the discharge to 2D overland between around 14:40-15:50 in Node 1 (Figure 28) the smallest discharge was for simulation ID 3 and the discharge to the 2D model increased with decreasing clogging factor. This can be due to the reduced capacity in the coupling, for example simulation ID 3 has the largest clogging factor, therefore lowest capacity which results in lowest discharge to the 2D overland model. On the other hand, the water level was similar for all four simulations during this period. This indicates that there are more surface runoff flowing to the node in simulation ID 3 than in for example simulation ID 0 since the water level was still the same.

From about 15:50 when the discharge started to flow from the 2D model to the 1D model in Node 1 there were some displacements. Simulation ID 3 and ID 2 started earlier than simulation ID 1 and even earlier than simulation ID 0. From 15:50 to about 17:00 the water level was the same in all four simulations. Since the displacement of discharge did not show in the water level, this means that another flow counteracts the different decrease of water level for simulation ID 3 and ID 2. The counteracting flow can for example be surface runoff.

In Node 3 (Figure 30) all four simulations were varying a lot and differed from each other. The fluctuation of simulation ID 3 was the smallest which can be due to that this simulation had the largest clogging factor and therefore lowest capacity. Lower capacity decreases the susceptibility of quick changes.

When comparing the peaks and low points of the simulations in Node 1 and Node 2, respectively, the peaks have larger spread of discharge between the simulations than the low points. This indicates that the discharge from 1D collection system model to 2D overland model vary more between the four simulations that the discharge from 2D to 1D. This agrees with the results of the interacted volumes in Table 12. Interaction volumes between the 1D and the 2D model. The interacted volumes present that the difference between simulation ID 0 and ID 1-ID 3, respectively, is larger for the volumes that flow from 1D collection system to 2D overland.

When the water level recovered there was some displacements in all three nodes. Simulation ID 3 recovered first, followed by ID 2, ID 1, and last ID 0. Which indicates that largest clogging factor recover first, followed by the second largest, and last the simulation with no clogging factor. Simulation ID 3 is the simulation with largest clogging factor, and it was therefore expected that this simulation would be the slowest to recover, followed by ID 2, ID 1 and ID 0 the fastest.

The maximum water level of the four simulations in the three nodes, respectively, are approximately the same. Some difference can be seen in Node 3 where simulation ID 3 have the highest maximum water level. The results of the maximum water depth (section 5.2.2) presents that the difference between the simulations were small. The difference in the maximum water depth of Node 3 cannot be seen in simulation ID0 minus simulation ID1 or in simulation ID0 minus simulation ID2, in simulation ID0 minus simulation ID3 the difference is 0.02-0.05 m, see Figure 30. This indicates that the clogging factor do not have a large impact on the maximum water level.

In the results of the four simulations in the three nodes the relation between the discharge, water level and flows like surface runoff and discharge in the collection system from other nodes is important. In all nodes there is some differences in discharge between the simulation, more differences in Node 3 than in Node 1, but the water level between the simulations are similar. It can also be seen that the recovery of the water level happens in the order from largest clogging factor to no clogging factor.

The analysed results are moving average of every ten minute. If the analysis would be made on higher resolution data, for example for every one minute (see Appendix B), the results may be different. To be noted is also that this includes the results of three nodes out of totally 341 nodes in the research area.

6.2.4 Uncertainties with the sensitivity analysis

The aim of RQ 2 was to evaluate the effect of clogged stormwater inlets in a 1D-2D hydrodynamic stormwater model. To do this the flow capacity in the 1D-2D couplings were reduced with different factors. To represent the stormwater inlets with 1D-2D couplings could be discussed. Since the received model did not contain any stormwater inlets it could also be discussed whether the received model was suitable to use for a sensitivity analysis answering RQ 2. Based on the survey it is a general simplification to exclude the stormwater inlets in a 1D-2D hydrodynamic stormwater model based on lack of documentation of the inlets and disadvantages with a too advanced model. That stormwater inlets generally are explicated from 1D-2D hydrodynamic stormwater models are also reported by Bertsch et al. (2017) who describes that the exchange flow between the surface and the collection system in a model usually takes place in the manholes. It can also be argued that exclusion of stormwater inlets is one of many simplifications of the model. Other simplifications and assumptions like the cell size of the grid and the infiltration parameters may have a more significant impact on the result. Blomquist et al. (2016) states that the advancement of the model should correspond to the aim of the model. With the perspective of a municipality the aim may be to generally evaluate the risk of flooding for a large area and hence it may be difficult to have a too detailed model including stormwater inlets. Therefore, the 1D-2D couplings enables flow between the surface and the collection system and can physically correspond to stormwater inlets. To decrease the flow capacity in the 1D-2D couplings could hence physically correspond to decreased capacity in the stormwater inlets due to clogging.

To make all the rain flow through the 1D-2D couplings the rain was only applied in the 2D model. This is a difference compared to the original model setup of the received model that can be questioned. If the rain were to be applied both in the 1D and in the 2D model a different method to delimit the flow were to be found. One alternative method enabling precipitation both in the 1D and in the 2D model would be to delimit the area of the manholes. Since MIKE+ only calculates the water level and not any flow in the nodes (DHI, 2022b) this alternative would entail in adjustments of the manhole area and not the flow capacity. The survey was enunciated early in the process of the thesis and were based on questions regarding the capacity of stormwater inlets and not the portion of area being clogged. It was hence, according to us, a more direct relation between the survey and the sensitivity analysis if the analysis evaluated reduced flow capacity.

It was not obvious to use an interpolated CDS-rain in the sensitivity analysis to answer RQ 2. Two other considered alternatives were to use the measured historical data and to use a standard CDS-rain with a uniform intensity over the model area. Since it is suitable to use a CDS-rain when modelling cloudbursts (MSB, 2017) it was assessed as beneficial to use a CDS-rain for the sensitivity analysis. The used CDS-rain corresponded to the measured data of the historical rain event 2018 and was interpolated in the areas between the measurement stations. That way the CDS-rain was adjusted after local prerequisites. However, if the research area were larger the spatial differences in intensity and volume would be expected to be more comprehensive. Moreover, the historical rain event that occurred in Uppsala 2018 is defined as a cloudburst according to the definition of a cloudburst stated by (SMHI, 2011). Since collection systems in Sweden generally are dimensioned for a rain event with the return period of 10 years collection systems can be assumed to reach their capacity if the rain has a longer return period. Hence, it can be argued that the effect of clogged stormwater inlets would be more extensive for rain events with a return period of 10 years or less. It would therefore be interesting to investigate the effect of clogged stormwater inlets for rain events with a return period of 10 years or less.

The model used within this thesis consists of several uncertainties which models generally do (MSB, 2017). The uncertainties and the model setup of the used model may have an impact on the received results. One uncertainty is the grid size of the model. The grid size of 4x4 m conducts that only one value for grid-files is considered for every 4x4 m. For the bathymetry this can result in that not all the objects or all changes in the topography are considered (MSB, 2017). The gathering of bathymetry data also conducts uncertainties. The bathymetry data used in the model is based on laser scanning (DHI, 2021c). At flat permeable surfaces laser scanning generally conduct an average error of <0.1m in the z-direction (Lantmäteriet, 2022). The average error in the z-direction at surfaces adjacent to a different land use or topography can be higher. Hence, differences in the result <0.1 m should be carefully considered. Other uncertainties that can affect the results are the infiltration parameters and the capacity of the collection system (MSB, 2017). According to MSB (2017) these parameters generally affect the result more than the bathymetry data. Moreover, settings regarding the 1D-2D model couplings may have impacted the results. The model setup included a maximum flow of 0.5 m^3/s and the flow in the couplings were set to follow the weir equation. If the setup of the model would have been different, the received results may have been different.

The clogging factors used within the sensitivity analysis were partly based on literature. Since it has been hard to find literature reporting the frequency of clogged stormwater inlets and the extent of clogging the study performed by Gómez et al. (2013) has played a significant role for this thesis. However, a weakness with the study by Gómez et al. (2013) is that the results are based on only one case study. If Gómez et al. (2013) would have performed field visits in other case studies, it would be interesting to see if the results were the same. Moreover, since the case study was performed in Barcelona all the findings may not be applicable in Sweden due to different topography, maintenance routines, and inlet types (dimensions etc.). Hence, it is an uncertainty that not more literature regarding this topic were found. Most preferable, with regard to the aim of this thesis, would have been if Swedish studies evaluating the extent of clogged stormwater inlets would have been performed.

The reviewed literature within this thesis imply that clogged stormwater inlets have a significant impact on the capacity of the inlets. The findings from the literature review indicated larger differences in the result of the sensitivity analysis than obtained in this thesis. It has however been hard to compare the results of the sensitivity analysis with literature due to difficulties in finding equivalent studies as the performed sensitivity analysis. To not compare the received results of this thesis with other studies is an uncertainty.

6.3 Comparison of the survey and the sensitivity analysis

Half of the survey's respondents that have at some point considered clogged stormwater inlets answered that the impact of clogged stormwater inlets in a 1D-2D hydrodynamic stormwater model was significant or very large. The same cannot be said about the results of RQ 2 which indicated that simulation of clogged stormwater inlets do not impact the results in a major way. Regarding this point the answers of RQ 1 and RQ 2 do not agree. The disagreement can possible be explained by different model setup, model area, the simulated rain or other prerequisites that can impact the effect of clogged stormwater inlets. The disagreement can also be explained by different methods of simulating clogged stormwater inlets in a 1D-2D hydrodynamic stormwater model.

It can be questioned if the results of RQ 1 and RQ 2 are comparable due to the limitations of this thesis, the survey have limited number of respondents and the sensitivity analysis is only made in one research area. To make the two research questions more comparable the survey would need more responses and the sensitivity analysis would be made on multiple research areas with different characteristics.

It is according to us, in overall, important with general working methods regarding stormwater modelling. The municipalities that are responsible for assessing areas suitability for a certain land use can rely on dependent and resembling models independent of the involved consultant company. However, since the answer of this thesis indicates that simulations of clogged stormwater inlets in a 1D-2D hydrodynamic stormwater model do not impact the results in a major way a general working method specifically regarding clogged stormwater inlets may not be as important as a general working method regarding other uncertainties within a model. On the other hand, several respondents in RQ 1 answered that simulation of clogged stormwater inlets do have a significant or very large impact on the result. The disagreement between the results of RQ 1 and RQ 2 indicates that the effect of clogged stormwater inlets within a 1D-2D hydrodynamic stormwater model should be investigated further.

6.4 Ethical aspects

Consideration of clogged stormwater inlets can be discussed if it is necessary for the society. When rain events occur and lead to flooding it causes consequences for the society. For example, damage of buildings and infrastructure, health related consequences, disruption of traffic due to for example flooded roads (Hernebring & Mårtensson, 2013). The consequences affect both individuals and socially important functions. Therefore, preventing of flooding can be seen as necessary for the society.

On the other hand, the modelling of clogged stormwater inlets is dependent on multiple factors. The result of the survey and the literature review presents that necessary data is not always available to do this type of modelling, for example data of stormwater inlets. The respondents write that stormwater inlets are rarely used when modelling, instead manholes are used. The same method is described by Bertsch et al. (2017). To make data of stormwater inlets available would require more resources from the society. Therefore, to ethically assess the necessity of considering clogged stormwater inlets should be weighed against other improvements of the society that require resources.

7 Conclusion

This chapter presents the conclusions of RQ 1 and RQ 2 as well as suggestions of further research. The performed sensitivity analysis has indicated that clogged stormwater inlets did not show a major impact on the 1D-2D hydrodynamic model result which disagrees with the findings of the survey and the literature review. However, due to several limitations of this thesis and the fact that no general working method regarding clogged stormwater inlets exists, further research about simulation of clogged stormwater inlets in a 1D-2D hydrodynamic stormwater model is needed before recommendations can be made for consultants working in the field.

7.1 Conclusions of the survey

The general working method adapted by the consultants that participated in the survey regarding assumptions made about clogged stormwater inlets in a 1D-2D hydrodynamic stormwater are identified as follows:

- Most responding consultants do not consider potentially clogged stormwater inlets in a 1D-2D hydrodynamic model.

- A general adapted working method regarding clogged stormwater inlets in a 1D-2D hydrodynamic stormwater model does not exist.

- Half of the responding consultants that at any occasion have considered clogged stormwater inlets in a 1D-2D hydrodynamic stormwater model have experiences a very large or significant impact on the model results. The same number of responding consultants do also think that the phenomena should be considered to a larger extent.

7.2 Conclusions of the sensitivity analysis

Based on the conducted sensitivity analysis, consideration of clogged stormwater inlets in a 1D-2D hydrodynamic stormwater model by a reduction of capacity in the 1D-2D model couplings affects the result in the following way:

- Both the extent of the flooding and the maximum water depth are affected by a reduction of flow capacity in the 1D-2D model couplings. The impact is not major.

- A reduced flow capacity in the 1D-2D model couplings can result in both higher and lower maximum water depth.

- The volume flowing from the 1D collection system model to the 2D overland model is more affected by a reduction of the flow capacity in the 1D-2D model couplings than the volume flowing from the 2D model to the 1D model. The impact on the total volume flowing between the 1D and the 2D model is assessed as insignificant. The result is affected more if the flow capacity in the 1D-2D model couplings is reduced more.

- Water levels in nodes are not affected much by a reduced flow capacity in the 1D-2D model couplings.

- The node's discharge to surface is affected differently for different nodes when reducing the flow capacity in the 1D-2D model couplings.

7.3 Suggestions of further research

Two limitations within this thesis are that only one research area and one rain event have been evaluated. Therefore, it would be interesting to evaluate other research areas with different characteristics like topography. It would also be of interest to simulate the impact of clogged stormwater inlets in combination with a different rain. Since the flow to the collection system can be reduced by different methods it would also be interesting to evaluate which method that is most suitable to use. Further research about clogged stormwater inlets in a 1D-2D hydrodynamic stormwater model is also motivated by the responses in the conducted survey.

The conducted sensitivity analysis within this thesis has evaluated the effect of clogged stormwater inlets. In further research it would be interesting to also evaluate to which magnitude the flow should be reduced to correspond to a physical situation.

Further research regarding clogged stormwater inlets in a 1D-2D hydrodynamic stormwater model will hopefully fill the lack of knowledge within the field proven by the conducted survey within this thesis.

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Appendix A: Questions in the survey sent to consultants

This appendix presents the questions and content in the survey that were sent to consultants. The questions were asked in Swedish. Both the Swedish formulation of the questions and their translation into English are presented in this appendix. How the questions were determined is presented in section 4.2. The following sections presents the questions corresponding to the schematic Figure 12. The parts of the survey and the filtering questions. The arrows in the part boxes represent filtering questions. presented in section 4.2. If the question is a cross question the alternatives are presented in parentheses after the question. The other questions are questioning a text answer. Questions with an arrow is filtering questions that filter the respondents according to their answer.

Part 1: General questions

Namn på företaget
Name of the consultant company

Godkänner ni att vi bearbetar och använder svaren i denna enkät i samband med publicering av vårt examensarbete? Om ni inte godkänner det kan ni välja att avstå från deltagande i enkäten. (Ja)
Do you agree that we process and use the answers in this survey when publishing this master's thesis? If you do not agree you can choose to refrain participation in this survey. (Yes)

→Har ni varit delaktig i arbetet med någon skyfallsmodell som tar hänsyn till dagvattennätet? (Ja/Nej)
Have you participated in any project regarding cloudburst modelling that considers the stormwater network? (Yes/No)

Part 2: Message to respondents that have not considered the stormwater network

Eftersom ni svarade Nej på föregående fråga önskar vi att ni skickar vidare mailet med enkäten till en person inom ditt företag som arbetar med skyfallsmodellering som tar hänsyn till dagvattennätet. På så sätt hoppas vi få mer underlag till nulägesbeskrivningen i vårt examensarbete. Tack på förhand!
Since you answered No on the previous question, we wish that you forward the mail with this survey to a colleague within your company that work with cloudburst modelling that considers the stormwater network. By doing that, we hope to receive more support to our master's thesis. Thanks in advance!

Part 3: Filtering question regarding frequency

→Hur ofta brukar hänsyn tas till att vissa rännstensbrunnar kan vara igensatta vid översvämningstillfället när ni arbetar med skyfallsmodeller? (Aldrig/Sällan/Hälften av gångerna/Ofta/Alltid)
How often do you consider that some stormwater inlets can be clogged during a flood event, when you are working with cloudbursts modelling? (Never/Rarely/Half the times/Often/Always)

Part 4: Questions to respondents who have at some point considered clogged inlets

Varför tar ni hänsyn till igensatta rännstensbrunnar?
Why do you consider clogged stormwater inlets?

Hur tar ni hänsyn till igensatta brunnar vid skyfallsmodellering?
How do you consider clogged stormwater inlets when modelling cloudburst?

Hur stor andel av rännstensbrunnarna inom modellområdet brukar ni anta är igensatta?

How large portion of the stormwater inlets in the model area do you usually consider to be clogged?

Hur mycket brukar ni anta att brunnarnas kapacitet reduceras?
How much do you usually assume that the stormwater inlet's capacity is reduced?

Var är de igensatta brunnarna lokaliserade i modellen? Exempelvis slumpmässigt, vid lågpunkter, i närhet av vegetation eller i närhet till samhällsviktig verksamhet. Hur motiveras detta?
Where are the clogged stormwater inlets located in the model? For example, random, at low points, close to vegetation or close to socially important functions. How is this motivated?

I vilken utsträckning upplever ni att hänsyn till igensatta rännstensbrunnar påverkar modellresultatet? Om ni vill kommentera är det möjligt att göra i nästa fråga. (Ingen påverkan/Obetydlig påverkan/Betydlig påverkan/Mycket stor påverkan/Vet ej)
To what extent do you experience that consideration of clogged stormwater inlets affect the results of the modelling? If you want to comment, it is possible in the next question. (No impact/Insignificant impact/Significant impact/Very large impact/Do not know)

Här är det möjligt att kommentera föregående fråga om påverkan på resultatet.
Here you have the possibility to comment the previous question regarding affect on the results.

Tycker ni att igensättning av rännstensbrunnar borde tas större hänsyn till vid skyfallsmodellering? Om ni vill kommentera frågan kan ni göra det i nästa fråga. (Ja/Nej/Vet ej)
Do you think that clogged stormwater inlets should be considered to a larger extent when modelling cloudbursts? If you want to comment, it is possible in the next question. (Yes/No/Do not know)

Här är det möjligt att kommentera föregående fråga angående om större hänsyn borde tas till igensatta rännstensbrunnar.
Here you have the possibility to comment the previous question regarding if clogged stormwater inlets should be considered to a larger extent.

Part 5: Questions to respondents who have never considered clogged inlets

Varför brukar ni inte ta hänsyn till igensatta rännstensbrunnar vid skyfallsmodellering?
Why do you not consider clogged stormwater inlets when modelling cloudbursts?

Är ni intresserade av att inkludera igensatta rännstensbrunnar vid skyfallsmodellering? Om ni vill kommentera frågan kan ni göra det i nästa fråga. (Ja/Nej/Vet ej)
Are you interested in considering clogged stormwater inlets when modelling cloudbursts? If you want to comment, it is possible in the next question. (Yes/No/Do not know)

Här finns det möjlighet att kommentera föregående fråga angående intresse att inkludera igensatta brunnar vid skyfallsmodellering.
Here you have the possibility to comment the previous question regarding interest in considering clogged stormwater inlets when modelling cloudbursts.

Tror ni att hänsyn till igensatta brunnar vid skyfallsmodellering skulle påverka modellresultatet? (Ja/Nej/Vet ej)
Do you think consideration of clogged stormwater inlets could affect the results of the model? (Yes/No/Do not know)

Part 6: Final possibility to leave a comment

Om du har några övriga kommentarer angående hur hänsyn tas/bör tas till igensättning av rännstensbrunnar inom skyfallsmodellering får du gärna skriva dessa här.
If you have any additional comments regarding how clogged stormwater inlets is/could be considered, you are welcome to write these here.

Appendix B: Results of discharge to surface and water level in nodes

This appendix presents the original results of the discharge to surface and water level in three nodes, see Figure B1-Figure B3. The results used in this thesis are calculated as moving average of every ten minute, see section 5.2.3.

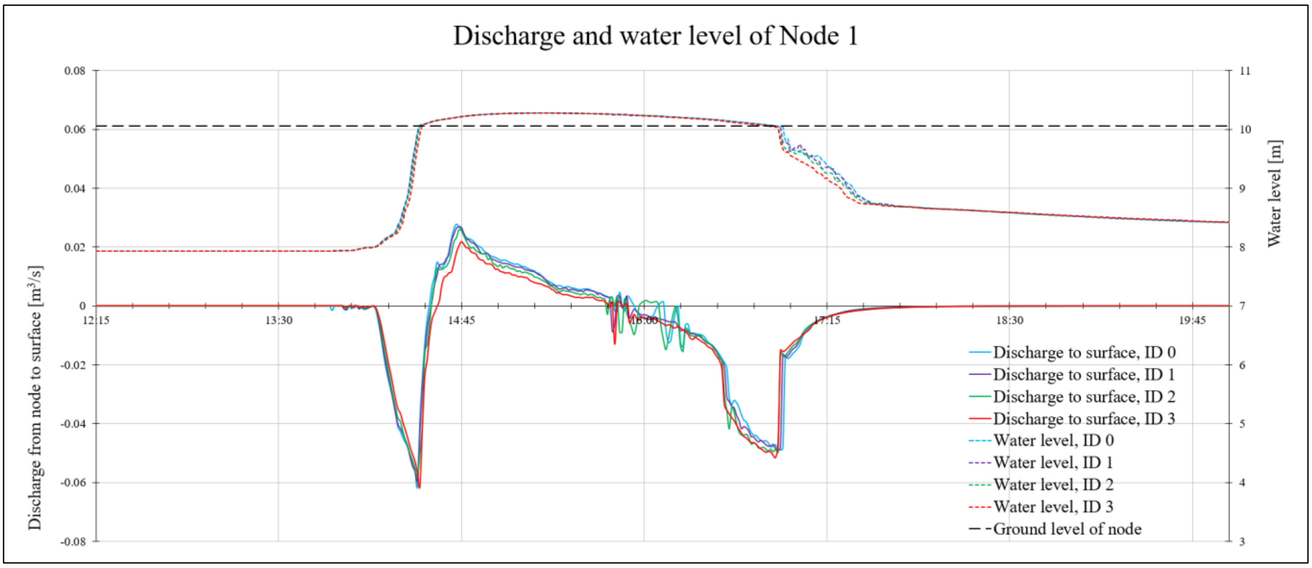

Figure B1. The figure presents the original result of discharge to surface and water level in Node 1.

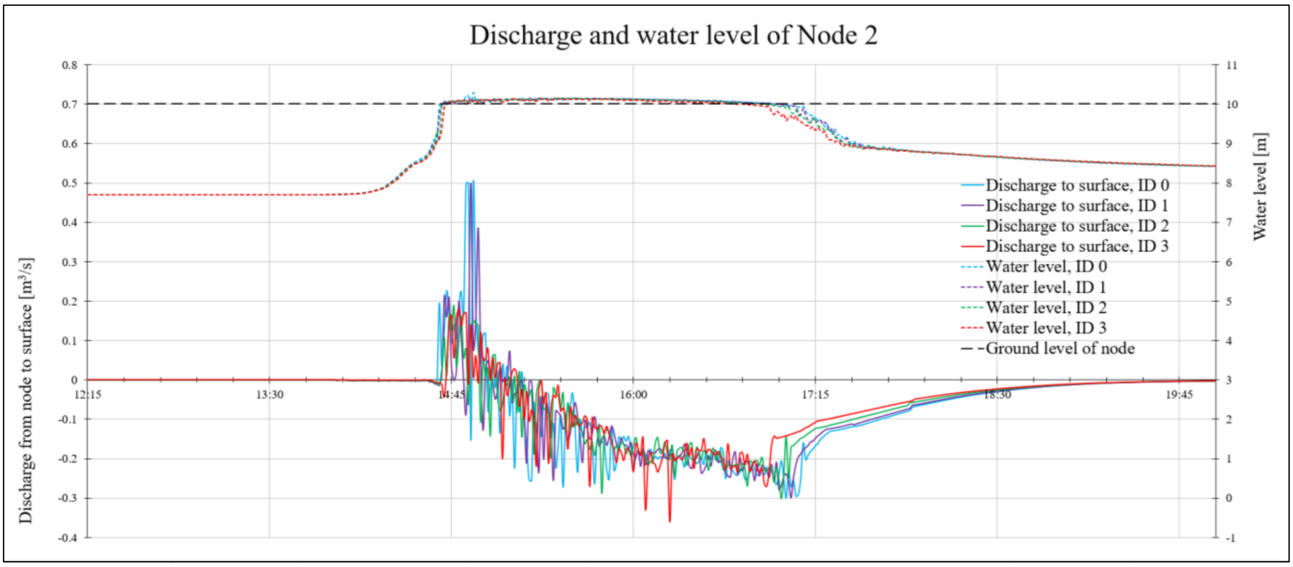

Figure B2. The figure presents the original result of discharge to surface and water level in Node 2.

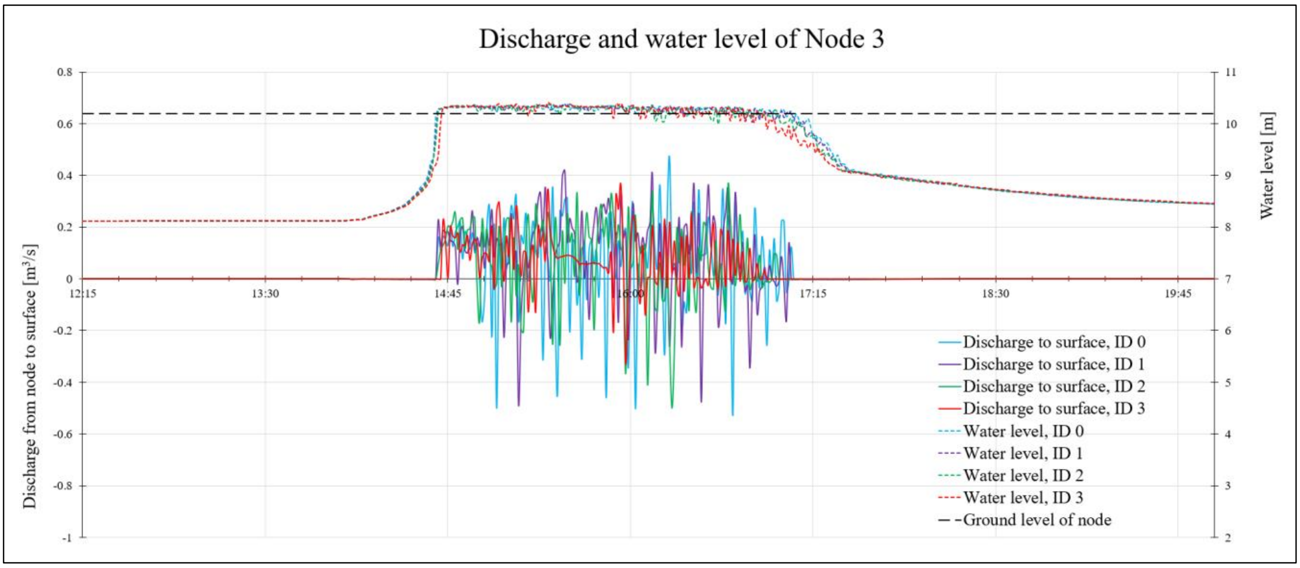

Figure B3. The figure presents the original result of discharge to surface and water level in Node 3.

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