1D/2D modeling of the open stormwater system of Augustenborg using MIKE FLOOD by DHI

by

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Summary

Precipitation extremes are predicted to increase in magnitude and frequency due to the impact of climate change. This poses a challenge to the urban drainage systems, as they will have to be able to cope with increased stormwater volumes in the future. (Zhou, 2014). This project focus on the area of Augustenborg in Malmö in southern Sweden, where an open stormwater system has been constructed to improve the areas capacity to handle heavy rainfall events.

In this project, the hydraulic modeling software MIKE FLOOD by DHI will be used to develop a coupled 1D-2D model of the Augustenborg stormwater system. Flow in the pipe network, flow in the drainage channels and runoff from effective impervious surfaces is modeled in the 1D model. Overland flow and infiltration on previous surfaces is modeled in the 2D model. The two models are dynamically coupled, allowing for flow flow to be exchanged between the two models throughout the simulation. The model is calibrated against flow measurements from the Augustenborg area. The model could be calibrated in 3 out of 4 measurement points. The results show that runoff is accumulating on surfaces intended to be flooded. The model can thus reproduce flow in the drainage network as well as overland flow, and can produce pedagogical inundation maps. The developed model can be used for future studies of the Augustenborg area.

Contents

1 Introduction

Climate change is predicted to lead to increased frequency of extreme rainfall events. Coupled with increased urbanization and associated land use change this could cause an increase in the frequency and magnitude of urban flooding events. (Zhou, 2014). Improving the urban drainage systems to cope with the potential effects of a changing climate is a challenge for designers and engineers that needs to be addressed (Arisz and Burrell, 2006). In recent years much focus has been directed towards so called sustainable urban drainage systems (SUDS) that make use of a wide range of techniques to handle the urban runoff. By implementing structures that can detain or slow down the surface runoff, such as green roofs, infiltration trenches, and swales, the overall load on the traditional drainage pipe network can be reduced. (Zhou, 2014).

One example of an area where sustainable urban drainage techniques have been implemented is the area of Augustenborg, located in the city of Malmö in southern Sweden. Much of the stormwater in Augustenborg is handled locally by the the open stormwater system of the area. The area contains several ponds, green roofs and open drainage canals. (Stahre, 2008). According SMHI yearly rainfall as well as extreme rainfall events is likely to increase in Skåne due to climate change. Yearly rainfall is predicted to increase with 15-25%, and maximum daily rainfall is expected to increase with approximately 20%. (Asp et al., 2015). On the 31st of August 2014 Malmö experienced a rainfall event with a return period estimated to over 100 years (SMHI, 2014). During this event the efficiency of the stormwater system of Augustenborg was demonstrated, as the area proved to handle the extreme rainfall very well with only few basement floodings reported (MKB, 2014).

Hydraulic models can be powerful tools when investigating the consequences of extreme rainfall events in urban areas. Through hydraulic modeling surface runoff patterns can be predicted and flood prone areas can be identified. This provides valuable insight to city planners, and can assist in the development of sustainable urban areas. (Leandro, 2008). This project will focus on hydraulic modeling of SUDS. A model of the Augustenborg area will be set up and used to study the capacity of the stormwater system.

1.1 Aims and objectives

The overall aim with this project is to develop a coupled 1D-2D model of the stormwater system of Augustenborg using the hydraulic modeling software MIKE FLOOD by DHI, and to investigate how the system responds to rainfall events.

The following questions will be addressed:

- How are the different components of the Augustenborg stormwater system best modeled using the coupled 1D/2D-modeling approach?
- What are the advantages and disadvantages of using a coupled 1D/2D-model compared to a pure 1D-model?
- How well can the model reproduce measured flows and water levels?

2 Previous studies and literature review

There is a large variety of methods being used to model hydrological processes in urban environments, ranging from simple conceptual models to complex integrated models aiming at modeling the entire hydrological cycle. This review aims at identifying the various types of models that are being used to give an introduction to the field of urban drainage modeling. Also, a couple of modeling studies evaluating sustainable urban drainage systems (SUDS) and low impact development structures (LID) are presented, as well as two previous models of the Augustenborg area.

2.1 Urban drainage modeling

The most commonly used urban drainage models are 1D sewer network models. These models are limited in terms of predicting flood extent. (Chang et al., 2015). So called dual-drainage models adress this problem by recognizing the need to model both the pipe network, the overland flow paths, and the interaction between the two, to accurately represent the dynamics of urban storm drainage. In dual-drainage models the overland flow paths, such as streets and open parts of the drainage network, can be represented either as 1-dimensional cross sections (1D/1D-modelling), as in the models developed by Djordjević et al. (2005) and Mark et al. (2004), or by a 2-dimensional terrain model (1D/2D-modelling). These two types of modeling approaches have proved to perform equally well in highly urbanized areas with small surface slopes (Leandro, 2008). In highly irregular terrain the limitation of 1D-models are difficult to overcome, and 1D/2D-models provide more accurate results (Vojinovic and Tutulic, 2008).

Another approach to model urban surface flooding is through 2-dimensional overland flow models, were rainfall is applied on a 2D grid and the flood propagation is modeled by numerical solution of shallow water equations. An example of such a model is the MIKE 21 model developed in the master thesis by Filipova (2012). In a study by Chang et al. (2015) a new approach for modeling the interaction between overland flow and the sewer system using coupled 1D-2D modeling was developed. A 2D overland flow model was coupled to a 1D sewer network model using different modeling techniques depending on the type of land cover, applying the rainfall boundary condition either to the 1D model or the 2D model. Roads, pavements and plazas were assigned rainfall in the 2D-model, the 2D areas were coupled to the sewer network in coupling nodes. Runoff from buildings that were connected to the sewer network through drainage pipes was modelled directly in the 1D model, computing the surface runoff using the unit hydrograph method. Green areas were assigned rainfall in the 2D-model, with a reduction factor applied to take the effect of infiltration into account. The authors compared the accuracy of the flood extent prediction of their model with the results from five other models. The results from the comparison showed that the modeling approach developed by the authors provided more accurate results in terms of flood extent.

A recent review of hydrological modeling of urbanized catchments by Salvadore et al. (2015) highlights the complexity of the urban hydrological cycle and the fine temporal and spatial scales associated with urban flooding events. The processes of the complete urban hydrological cycle, comprising precipitation, infiltration, groundwater flow, surface runoff, river flow, and flow in the drainage network, are mutually integrated and operate at varying spatial and temporal scales. Modeling the urban hydrological cycle is therefore complex, inducing many sources of uncertainties.

The interaction between hydrology and hydraulics is a field that has been explored in studies by Sto. Domingo et al. (2010) and Kidmose et al. (2015), where integrated MOUSE and MIKE SHE models were devloped. Sto. Domingo et. al. developed an integrated model were a 1D drainage network model was coupled to a distributed hydrological model to represent the complex urban hydrological cycle and the interaction between its different elements. The authors investigate the impact of hydrological processes such as evaporation, infiltration, and groundwater flow on urban surface flooding.The conclusion is that in mixed urban areas hydrological processes could have a large impact on surface flooding, and that integrated hydrological-hydraulic modeling is required in these types of areas. Kidmose et. al. developed a similar type of model using the same modeling software. The authors also investigated the impact of three different planning scenarios where the surface runoff from impervious areas where to be redirected to infiltration facilities.

Modeling of sustainable urban drainage systems and low-impact development structures is something that has been adressed in many modeling studies. A study by Palla and Gnecco (2015), focus on modeling the impact of implementing green roofs and permeable pavements. The structures were represented in the model as a reduction of the imperviousness fraction for the catchments.The authors found that the implementation of such techniques reduced peak runoff with up to 45%. In a study by De Vleeschauwer et al. (2014) the stormwater modeling system EPA-SWMM was used to study the impact of implementing different types of stormwater management strategies. The effect of implementing source-control blue green structures was compared to the effects of other types of stormwater management structures such as large retention basins and end-of-the pipe solutions. In the model the various types of control structures were represented as storage volumes added to an existing 1-dimensional model. The result of the modeling study showed that implementing blue-green structures in the city to control the water at the source reduced both peak and total discharge from the catchment. Both the above-mentioned studies were performed using 1D-modeling tools. An example where 2D models has been used to model SUDS is the master thesis by Gunnarsson (2015), where an infiltration swale was modeled in 2D using the MIKE 21 modeling software with a infiltration and leakage module.

The uncertainties associated with urban drainage modeling is discussed by Salvadore et al. (2015). The authors propose extensive and spatially distributed calibration and validation, high temporal and spatial model resolution, and physically based model parameters as strategies to reduce model uncertainties. The uncertainty of urban drainage models is also adressed in a thesis by Kleidorfer (2009), focusing on the calibration of urban drainage models. The author identifies different sources of model uncertainties, such as uncertain input data, calibration data, and uncertainties related to modeling approach and structure. The need for temporally and spatially distributed calibration data is once again highlighted, case studies made by the author showed that even though a model could be successfully calibrated it could fail when modeling scenarios outside of the calibration period. One of the authors' conclusions was that the impact of model structure on the performance was not significant, given that the model could be successfully calibrated. This implies that model parameters are somewhat able to compensate for uncertainties in model structure, and can therefor not be transferred between different models.

2.2 Previous models of the Augustenborg area

Attempts have been made previously to model the Augustenborg system. A model of the hydraulic network was developed by Shukri (2010) using the MIKE Urban software. The performance of the stormwater system was evaluated by comparing the results from the model with the results from a model were the open part of the stormwater system had been replaced with a closed pipe system. The model developed by Shukri was used and updated in this project.

A model of the hydrological system of the Augustenborg area using the MIKE SHE software was developed by Kibringe and Tan (2013), with the aim to model the groundwater and overland flow in the area. The closed drainage system was not represented in the MIKE SHE model. However, certain parts of the open draiange system, such as wetlands and swales where water is allowed to infiltrate, were included in the model.

No model similar to the one developed in this project, considering both the hydraulic network and the overland flow, have been made.

3 Study area

The residential area of Augustenborg is located in the south east part of Malmö, Sweden. The area was constructed by the housing company MKB in the 1950's, and covers approximately 30 ha. The area is home to approximately 3000 inhabitants.

During the decades following the construction the social status of the Augustenborg area started to decay, and the residents started moving out of the area. In 1998 the city of Malmö and MKB launched the project "Eco-city Augustenborg", a project aiming at renewing the Augustenborg area and transforming it into a sustainable urban settlement. The transformation focused on social and economical as well as ecological sustainability, and involving the inhabitants was an important aspect of the transformation of the area (Stahre, 2008). In 2010 the Augustenborg area won the UN World Habitat Award. (Scandinavian Green Roof Institute, 2016).

One of the major components in the transformation of the Augustenborg area was the implementation of the new stormwater drainage system. Prior to the reconstruction the area was drained with a combined sewer network, and the area was prone to basement flooding (Scandinavian Green Roof Institute, 2016). In the following section the stormwater system of the area is described more in detail.

3.1 The stormwater system of Augustenborg

The stormwater system is constructed in a way so that most of the stormwater is handled locally on the surface. By detaining and slowing down the runoff, water is allowed to infiltrate and evaporate. The open part of the stormwater system makes use of varying types of techniques for handling the stormwater. The basic principles that the system is based on are local infiltration, flow detention, and slow transport.

The system can be divided in three parts, the northern, the southern and the separate system. All water from the area drains to the combined sewer system, but in the northern and the southern system the water is handled at the surface and detained before finally discharging to the combined pipe network. In the separate system, water is drained through gully pots to the pipe network in a conventional manner. The image below shows an overview of the Augustenborg area and the stormwater system.

Figure 1: Overview of the Augustenborg area. Area A: The northern system. Area B: The separate system. Area C: The southern system. Source: Green Landscaping AB, modified.

The northern system In the northern system, between Augustenborgsgatan and Lönngatan (area A in figure 1) runoff from roofs and yards are collected through small gullies into a grass canal along Lönngatan. In some parts of the canal the cross section expands and forms sinks in the terrain intended to slow down and detain the runoff. The downstream part of the northern canal is built of concrete. Along the canal there are two larger detention ponds that are permanently filled with water. (Stahre, 2008).

The southern system The southern system (area C in figure 1) consists of the botanical roof gardens in the south east part of the area, the residential buildings in the centre of the area, the Augustenborg school and the Augustenborg park in the south-west part of the area. The botanical roof gardens are located in the upstream part of the system. Runoff from the green roofs and the surrounding pavements is detained in a small pond. Further downstream the water is collected to a concrete canal, and detained in a pond called the "double-ponds". From the double ponds water is led through a concrete canal out to a grass lined canal meandering through the Augustenborg park. The grass canal leads to a detention pond in the west end of the park called the Delta pond (see figure 3 left), from which excess water is discharged to the combined sewer system. (Stahre, 2008), (VA SYD, 2008).

Local infiltration The local infiltration occurs on green roofs, yards and other green areas. The green roofs can be divided in two categories, intensive and extensive green roofs. The extensive green roofs are covered by a thinner layer of soil, usually around 4 cm thick, with a type of vegetation that is not sensitive to drought and does not require a high level of maintenance. The intensive green roofs has a thicker soil layer and are usually covered by other types of plants that require more care. In the botanical roof gardens there are both extensive and intensive green roofs, and a few experimental roofs where different types of green roof solutions are tested out. In the residential area several smaller buildings are covered by extensive green roofs. The image below shows the green roofs of the Augustenborg botanical roof gardens.

Figure 2: The botanical roof gardens of Augustenborg

Flow detention There are several ponds within the Augustenborg area intended to detain runoff. There are also many areas that are intended to be flooded during heavy rainfall events, to allow for a controlled flooding that does not risk damaging nearby structures. Examples of such areas are the green areas adjacent to the ”double-ponds”, and the entire Augustenborg park. The images below shows two of the ponds in the area.

Figure 3: Left: The Delta Pond at the outlet of the southern system. Right: The pond at the outlet of the northern system

Slow transport The many open canals and gutters within the area are designed to allow for slow water transport. Many of the canals are grass canals with wide cross sections. The canals made of concrete have structures at the bottom allowing for varying flow. (Stahre, 2008).

Figure 4: Left: The concrete canal along Lönngatan. Right: A small gutter with structured bottom allowing for a varying flow.

3.2 Available data

Measurements of flow, water level and precipitation were performed by Ph.D. student Salar Haghighatafshar at the Department of Chemical Engineering, Lund University. In total 8 gauges were installed in the Augustenborg area, the image below shows the location of the different flow and water level meters.

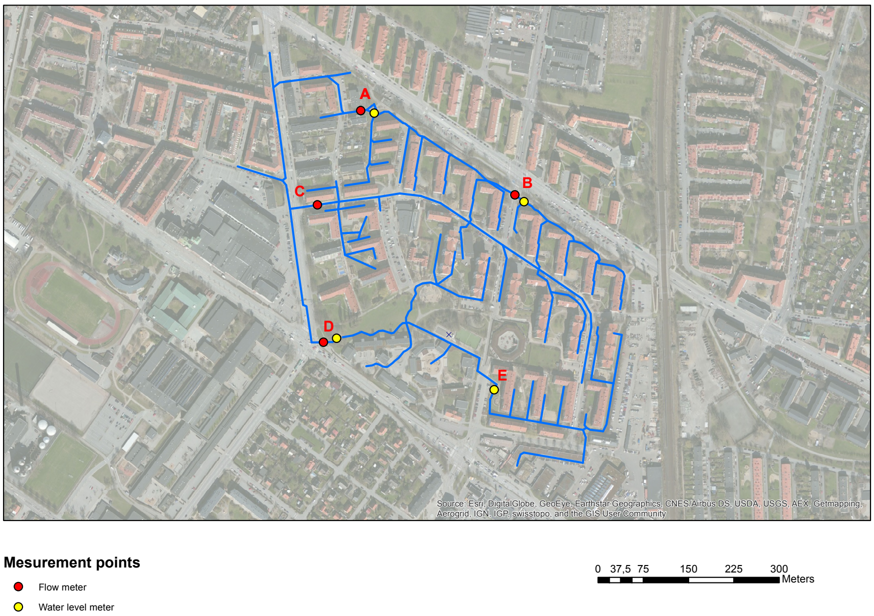

Figure 5: Location of the measurement stations in Augustenborg. A. Enegången, B. Norra Grängesbergsgatan, C. Augustenborgsgatan, D. Ystadvägen, E. Södra Grängesbersgatan.

Flow and water level data has been collected since since June 2015, and are still being carried out at the time of writing. During this period 6 larger rainfall events has occurred. Rainfall gauging has also been conducted at a measurement station in the east part of the catchment. The largest rainfall event that occurred during the measurement period occurred on the 29th of June 2016 and had a total volume of 22.8 mm. The return period of this event was estimated to 1.87 years using the Dahlström formula (Svenskt Vatten, 2011).

Flow measurements Flow measurements were conducted at four points in the area, see figure 5. Measurement point A is located at Enegången, the final outlet from the northern system. When the water level in this pond is sufficiently high the water is led through three small pipes to a dry pond a few meters away. If the water level in the wet pond continues to rise it reaches the crest level of a second drain pipe that leads the water directly to the separate system. The flow in the pipe where the flow meter is located is the outflow from both the wet and the connected dry pond. Measurement point B is an intermediate point in the northern system located at the outlet from the pond at Norra Grängensbergsgatan. When the water level in the ponds rises water will discharge into connected underground pipes. It will then rise up into a dry pond on the other side of the street, to thereafter be transported further downstream through the drain canal. Point C, located at Augustenborgsgatan, is the outlet point from the separate storm water system. Measurement point D, located at Ystadvägen, is placed at the outlet from the stormwater pond in the southern system, and is thereby the outlet from the southern system.

Water level measurements Measurements of water level were conducted at three of the ponds in the system, see figure 5. The water level measurements at point A, B and D are located at the ponds at Enegången, Norra Grängesbergsgatan and Ystadvägen, from which the outflow discharges are also measured. Measurement point E is located at the "double-ponds" in the southern system.

Precipitation measurements A rainfall gauge i located in the Augustenborg catchment. The gauge is a tipping-bucket that records the time interval between every 0.2 mm of accumulated rainfall. An individual rainfall event i defined as a rainfall event preceded by at least 8 hours of dry weather. The return period of individual rainfall events is calculated using the Dahlström formula. (Svenskt Vatten, 2011).

4 Theoretical background

This section gives a brief introduction to the equations governing open channel flow, flow in pressurized pipes, and shallow water flow. These equations make up the base for many hydraulic modeling tools, including the ones used in this project.

4.1 Open channel flow

The discharge in an open channel or a non-pressurized pipe can be described by the 1 D St. Venants equations. The St Venants equations are a set of coupled partial differential equations describing the continuity and momentum balance. The equations are based on the assumption that the pressure distribution is hydrostatic, and that the flow varies gradually. In 1D, the continutity equation can be expressed as below:

$$\frac{\delta A}{\delta t} + \frac{\delta Q}{\delta x} = 0 \tag{1}$$

Where Q is the flow in the x-direction and A is the area of the channel cross section.

The momentum equation can be expressed as:

$$\frac{1}{A}\frac{\delta Q}{\delta t} + \frac{1}{A}\frac{\delta}{\delta x}\left(\frac{Q^2}{A}\right) + g\frac{\delta h}{\delta x} = g(S - J) \tag{2}$$

Where h is the water depth, g is the gravitational acceleration, S is the bed slope and J is the friction slope. (Leandro, 2008). The MIKE Urban tool solves the 1D St. Venants equations to model flow in pipes and open cross section. (DHI, 2014).

4.2 Pressurized Pipe flow

When water flows in a pressurized pipe the assumptions for the St. Venants equations are no longer valid. The 1D continuity equation for a pressurized pipe takes the following form:

$$\frac{\delta H}{\delta t} + \frac{c^2}{gA}\frac{\delta Q}{\delta x} = 0 \tag{3}$$

Where H is the piezometric head in the pipe and c is the celerity of the pressure waves.

The momentum balance in a pressurized pipe takes is given by:

$$\frac{1}{A}\frac{\delta Q}{\delta t} + \frac{1}{A}\frac{\delta}{\delta x}\left(\frac{Q^2}{A}\right) + g\frac{\delta H}{\delta x} = g(S - J) \tag{4}$$

Since pressurized and non-pressurized are governed by different sets of equations with different dependent variables, the transition from non-pressurized to pressurized flow is challenging to model.(Leandro, 2008) The method used in MIKE Urban tool is to introduce a fictitious slot at the top of the pipe, and thereby generalizing the St Venants equations so that they are applicable for the pressurized pipes. (DHI, 2014).

4.3 Overland flow

Free surface overland flow can be described by the 2D St. Venants equations. The two equations governing the flow are the mass and momentum equations. 2D mass balance equation can be written as:

$$\frac{\delta h}{\delta t} + \frac{\delta hU}{\delta x} + \frac{\delta hV}{\delta y} = 0 \tag{5}$$

Where U is the velocity in the x-direction and V is the velocity in the y-direction.

The momentum equations in the x- and y-direction can be written as:

$$\frac{\delta hU}{\delta t} + \frac{\delta}{\delta x}(hU^2 + 0.5gh^2) + \frac{\delta}{\delta y}(hUV) = g(S_x - J_x) \tag{6}$$

$$\frac{\delta hV}{\delta t} + \frac{\delta}{\delta y}(hV^2 + 0.5gh^2) + \frac{\delta}{\delta x}(hUV) = g(S_y - J_y) \tag{7}$$

Many modeling tools uses the St. Venants equations to model free surface overland flow (Leandro, 2008). The MIKE 21 tool has the option to include coriolis and wind forcing, which gives a more complex formulation of the momentum balance. (DHI, 2016a).

5 1D-2D Hydrodynamic modeling with MIKE FLOOD

MIKE FLOOD is a tool developed by DHI that enables coupling between the 1D modeling tools MIKE Urban, MIKE 11, and MIKE Hydro River, and the 2D hydrodynamic modeling tool MIKE 21 (DHI, 2016c). In this project MIKE FLOOD is used to couple the MIKE Urban and the MIKE 21 models of the Augustenborg area. This section gives a brief introduction to these two modeling tools and the coupling between them.

5.1 MIKE Urban

MIKE Urban and the MOUSE engine is a tool developed by DHI for modeling urban collection and water distribution systems. It consists of two sub-models, the rainfall runoff model and the hydraulic network model. The rainfall-runoff model transforms input rainfall to runoff hydrographs. The output from the rainfall-runoff model is used as input to the hydraulic network model.

5.1.1 Rainfall-Runoff model

The rainfall-runoff model consists of catchment areas that are connected to the hydraulic network through so called catchment connections. The rainfall-runoff model computes runoff hydrographs from input precipitation time series. The model provides several computation methods for calculating the surface runoff. For Augustenborg model the Time-Area method is used. Other hydrological models that can be used are Kinematic Wave method, Linear reservoir method, Rainfall Dependant Infiltration model and Unit Hydrograph model.

The Time-Area method is a conceptual model to compute runoff, where the area contributing to surface runoff increases with time following a specified Time-Area curve. A number of parameters needs to be specified for each of the model catchments, these are impervious area, time of concentration, time-area curve, hydrological reduction factor and initial loss. The impervious area parameter defines the fraction of imperviousness for the model catchments. Only impervious parts of the catchments are considered to contribute to surface runoff. The time of concentration describes the time it takes for a water particle to travel from the most distant part of the catchment to the catchment outlet. The Time-Area curve describes how the fraction of the catchment area contributing surface runoff increases with time. The hydrological reduction factor describes how large a fraction of the input precipitation that will be transformed to runoff. The initial loss is the volume of water required to initiate surface runoff. (DHI, 2016d)

5.1.2 Hydraulic network model

The hydraulic network model and the MOUSE engine is a tool for simulating unsteady flow in 1D. The engine solves the 1D Saint Venant's equations presented in section 4.1 by using a finite difference numerical solution scheme. The network model consists of nodes that are connected through links.

The network simulation is done using the output from the rainfall-runoff simulation as a network load when computing the flow in the drainage network. (DHI, 2014)

Links A MIKE Urban link describes a pipe or a canal in the collection system. A link is characterized by its up- and down level nodes, material and size. The up- and down level nodes will determine the length and slope of the link. The choice of material will specify the friction in the link. The size of a pipe is given by the pipe diameter. For open channels a cross section describing how the width varies with the depth has to be defined. (DHI, 2014)

Nodes and structures The model links are connected in nodes. Manholes, basins, weirs, pumps and other structures are described as nodes in the MIKE Urban model.

The manholes of the closed storm water system as well as the junctions of the open system are modelled as manholes in the Augustenborg model. Manholes are characterized by their ground level, bottom level and diameter. The head loss in the manholes can be calculated using the Engelund formula, or can be assumed to be zero using the "No cross section changes" option.

Ponds, wetlands, swales and other storage elements are modeled as basins in MIKE Urban. A basin is defines by its bottom level, ground level and the basin geometry. The basin geometry describes how the storage volume in the basin increases with the water level.

Weirs are modelled as connections between two nodes. Weir overflow can be computed using the weir formula or by a user-defined table specifying the overflow discharge for a series of water levels above the weir crest. (DHI, 2014)

5.2 MIKE 21 Hydrodynamic Module

MIKE 21 is a numerical modeling tool developed by DHI used to simulate water level and flow in 2D. It was originally developed mainly for marine and coastal applications, but it can also be used to model overland flow. The governing equations are the conservation of mass and momentum presented in section 4.3. The momentum equation takes various sources of forcing into account, such as gravity, bed resistance, eddy viscosity, Coriolis forcing and wind stress. (DHI, 2016a) When modeling overland flow, not all of these types of forcing are of interest, and they can be chosen to be turned off.

The governing equations are integrated in space and time and solved numerically using a difference approximation. MIKE 21 uses a double sweep algorithm where the equations are solved in one dimension, altering between the x- and y-direction. (DHI, 2016a)

Bathymetry The bathymetry describes the elevation data and boundary conditions for the model (DHI, 2016b). MIKE 21 can model open boundaries, for which surface elevation and/or flux density must be specified (DHI, 2016a).When modeling inland flow in a catchment area there are no open boundaries, and hence no such boundary conditions must be specified. However, the model area must be constrained to only involve the cells within the catchment in the computation. This is done by specifying so called "land boundaries". This is done by, in the bathymetry file, assigning what is called "land values" to cells outside the modeled catchment. All cells that are assigned land values will be considered as permanently dry, and will thereby be excluded from the calculation. (DHI, 2016b)

Flooding and drying When modeling overland flow, the computational cells are regarded as either wet or dry, depending on the water depth in the cell. Wet cells are included in the calculations and dry cells are taken out. The two thresholds flooding and drying depth determines when a cell should be checked for flooding or drying.

A cell can be flooded either due to accumulation of water from external sources or due to high water levels in a neighboring cells. When the water is accumulated in a cell due to for example precipitation, the cell will be flooded when the water level exceeds the flooding depth. A cell can also be flooded when bathymetry in the cell plus the flooding depth is lower than the water surface elevation in any of the neighboring cells. The drying depth is the threshold below which a cell will be checked for drying. If the water level in the cell is below the drying depth, and the water surface elevation in the neighboring cells does not exceed the bathymetry plus the flooding depth in the cell, the cell is dried.

Initially all cells contain a small amount of water, corresponding to the minimal water depth of 0.0002 m. If the water level in a cell falls below this minimum water depth it will be artificially adjusted and reset to this level. This causes artificial water to be generated. The total amount of artificially generated water is summarized in the volume balance of the simulation as the "Total water level correction". (DHI, 2016a)

Precipitation Precipitation can be added to the MIKE 21 model as an external water source. It can be added as a constant value, a time series (DHI .dfs0 file extension) or as a spatially varied time series (DHI .dfs2 file extension) covering the extent of the bathymetry.

When coupling the MIKE 21 model with a MIKE Urban model, the rainfall can be divided between the two models by using spatially varied precipitation time series. Impervious areas within the catchment that are assumed to be directly connected to the drainage system can be modelled in MIKE Urban, where the rainfall-runoff transformation is calculated using one of the methods described in section 5.1.1. Surrounding areas, where the water is assumed to flow overland to the nearest network node, is assigned rainfall in the MIKE 21 model. The rainfall input to MIKE 21 will be a temporally and spatially varied file, where the rainfall intensity is assumed to be zero on all impermeable surfaces connected to the drainage network.

Infiltration and leakage Since MIKE 21 is a 2D modeling tool it does not model any flow in the vertical direction. Infiltration is treated as sink where water is lost from the surface, infiltrated water cannot reenter the model. The infiltration calculation is performed after the hydrodynamic computations have been carried out.

MIKE 21 can model infiltration as a net infiltration rate or as a constant loss with a specified capacity. The first option assumes a constant infiltration over the entire bathymetry. When using the second option, the infiltration is assumed to occur at a constant rate until the infiltration layer is filled with water. When modeling infiltration with a constant infiltration rate and capacity the unsaturated zone is modeled as an infiltration layer with a specified storage capacity. The input file consists of 5 items describing how the infiltration parameters varies spatially over the model domain. These parameters are infiltration rate, porosity, initial fill, leakage rate, and depth. The infiltration rate is the rate at which water infiltrates from the soil surface to the infiltration layer. The leakage rate describes the rate at which the water is lost from the infiltration layer, and can be considered to reflect the flow from the unsaturated zone to the groundwater. The porosity, depth and initial fill parameters together determine the capacity of the infiltration zone. The porosity specifies the percentage of pore volume in the infiltration zone, and can be seen as a representation to the effective porosity of the soil. The initial fill describes to what percentage the pores are filled with water in the beginning of the simulation period. The depth describes how deep the infiltration layer is. These three parameters together determine how much water that can be stored in the infiltration zone. (Gunnarsson, 2015). (DHI, 2016a).

The volume of water that infiltrates in a cell during a given time step is given by:

$$V_{infiltration} = min(Q_{infiltration} * \Delta x * \Delta y * \Delta t, SC - V_i, H * \Delta x * \Delta y) \tag{8}$$

Where $Q_{infiltration}$ is the infiltration rate, $\Delta x * \Delta y$ is the cell size, SC is the storage capacity, V_i is the water volume in the storage zone, and H is the water depth in a cell. Hence, when the water depth in the cell is smaller than the potential infiltration, all water in the cell is infiltrated.

The leakage from the storage zone is calculated by:

$$V_{leakage} = min(Q_{leakage} * \Delta x * \Delta y * \Delta t, V_i) \tag{9}$$

When the leakage potential exceeds the volume of water in the infiltration zone, all water in the storage zone is removed through leakage. (DHI, 2016a)

Bed resistance The bed resistance can be represented as a constant value or as a spatially varied value specified over the entire bathymetry. The bed resistance layer consist of the Mannning or Chezy number for the different areas of the model domain. Impermeable surfaces are usually hydrologically smoother that natural terrain, and are therefore assigned a higher Manning number than the permeable surfaces. (DHI, 2016b)

5.3 Model Coupling

The MIKE FLOOD tool enables coupling between the MIKE Urban and the MIKE 21 model through coupling links. Linkages between a MIKE Urban manhole and one or more MIKE 21 grid cells are called urban links. An urban link is designed to model the interaction between the hydraulic network and the overland flow, and allows for transfer of water between the two models. For instance, when a manhole is overtopped, water is transferred from the MIKE Urban to the MIKE 21 model, and when a cell linked to a manhole is flooded water will be transferred from the MIKE 21 to the MIKE Urban model. Figure 6 below shows the general principle of the urban link. (DHI, 2016c)

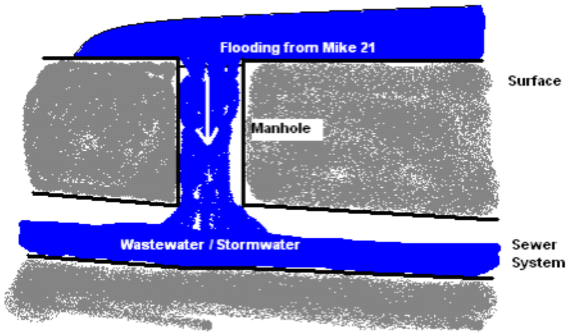

Figure 6: The principle of the urban link. Source: (DHI, 2016c)

The linkage between the overland model and a manhole or a basin in the network is described with a so called M21 to inlet link. This is the only type of link that is used in the Augustenborg model. The M21 to inlet link can calculate the exchange of water between the two models in four different ways, using the orifice equation, the weir equation, an exponential function or using a curb inlet function. In the Augustenborg model all the coupling links are modeled using the weir equation. The exchange of water between the two models is calculated using equation (10) below:

$$Q_{UM21} = C(H_U - H_M 21)W\sqrt{2g \mid H_U - H_{M21} \mid}\frac{\mid H_U - H_{M21} \mid}{max(H_{M21}, H_U) - H_g} \tag{10}$$

Where Q is the flow between the two models, W is the weir crest width, H_U is the water level in the node, and H_{M21} is the water level in the overland cell. The weir crest width is usually defined as the manhole circumference.

Linkages between MIKE Urban and MIKE 21 can only be made through the urban links, which couples the overland model with nodes in the hydraulic network model. No lateral linkages can be made. The interaction between the terrain model and the open drainage system is hence modeled in the same way as the interaction with the separate pipe system. A network node can be coupled to one or more 2D cells. When a node is coupled to more than one cell the H_{M21} water level is calculated as the average water level in the coupled cells.

When modeling a scenario where the difference in water levels between the MIKE Urban nodes and the coupled overland cells is very small there is a risk of oscillating flow between the two models. This can be resolved by applying a suppression factor to the exchange flow when the difference in water level is small. When the difference in water depth is smaller than the user-defined depth Q_{dh}, equation 10 will multiplied with a factor ranging from 0-1. The suppression factor is given by the equation: (DHI, 2016c)

$$Suppressionfactor = 1 - ((Q_{dh} - dh)/Q_{dh})^2 \tag{11}$$

Where Q_{dh} is a user-specified depth and dh is the difference in water level between the MIKE Urban and the MIKE 21 model.

6 Model set-up

This section describes how the two sub-models were set-up and how the coupling between the two models was made. The interaction between the two models and the associated challenges are also presented.

6.1 Modelling the different components of the Augustenborg system

As described earlier, the stormwater system of Augustenborg consists mainly of open channels and ponds. The terrain contains many designated flooding areas and sinks intended to store runoff before it discharges to the pipe system. This presents a challenge when creating a coupled 1D-2D model of the area. The used software is designed to model the interaction between a pipe system and the overland flow. In the Augustenborg area most of the water is handled at the surface, which makes it difficult to clearly distinguish between overland flow and flow in the network. Different modelling approaches were chosen for different parts of the Augustenborg area, this will be described more in detail below.

6.1.1 Pipe network

The pipe network was modelled in the MIKE Urban model as links connected in nodes. All manholes within the catchment area where coupled to the 2D surface model to allow for exchange between the two models when manholes are overtopped or when surface runoff reaches a manhole.

6.1.2 Open channels

The open channels in the Augustenborg area area of varying size and material, ranging from small gutters around 10 cm wide to large grass channels.

Some of the larger channels are visible in the 2 m x 2m terrain model, which indicates that flow in these channels can to some extent be captured in the 2D model. However, the cross section of the channels are in the same order of magnitude as the resolution of the terrain model, indicating that the resolution of the terrain model is too coarse to capture the small scale variations in the channel cross sections. Therefore, a pure 2D representation of the larger open channels would not model the flow situation sufficiently accurate. Modelling the larger channels in 1D also has drawbacks. The 1D channel cannot be laterally coupled to the overland, which only allows for water to be exchanged in the nodes. The chosen approach was to represent the larger open channels as 1D links with nodes coupled to the 2D terrain model. The nodes where placed short-distance apart to reduce the inaccuracy caused by the the lack of lateral linkages. The cross sections of the channels where defined to capture the flow on the sub-grid scale. The ground level of the 1D channel is adjusted so that it coincides with the ground level in the terrain model to allow for exchange between the models when the water level in the 1D channel is sufficiently high. The image below shows the concept of how larger open channels are represented in the coupled 1D/2D model.

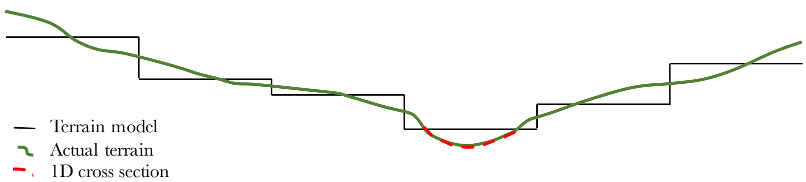

Figure 7: Conceptual image of how large open channels are represented in the coupled 1D/2D model

The majority of the open channels and drains are too small to be visual in the terrain model. The entire cross sections of these channels are modelled in 1D, and the links are coupled to the overland in a similar manner as the larger channels.

6.1.3 Roofs and pavements

Runoff from the roofs of the residential buildings are collected and drained through drain pipes. The drain pipes discharge to gutters or pipes. The majority of the asphalt roads and paved areas are directly connected to the separate pipe network through manholes. The drainage network is assumed to be capable of handling runoff from a 10-year return period storm, for rainfall events smaller than this, all runoff from the roofs and pavements is assumed to be directly drained through the drainage pipes. The runoff from these areas are therefore modelled directly in the MIKE Urban 1D model using the Time-Area method.

6.1.4 Green roofs

The runoff from the green roofs is collected and discharged in the same way as the runoff from the tile roofs. The runoff from these roofs is also modelled in 1D, with modified parameters to take the effect of infiltration and delayed runoff into account. The green roof catchments are assigned a reduced runoff coefficient and an increased time of concentration. A runoff coefficient of 50 % is chosen for the two calibration rainfall events. However, when modeling larger rainfall events a higher value should be chosen to compensate for the fact that the runoff coefficient of green roofs in general increases with increasing storm magnitude (Stovin et al., 2012).

6.1.5 Yards and parks

Surface runoff on green areas such as yards and parks are modeled in the 2D model. Water can infiltrate or flow overland depending on the level of saturation of the soil. Since many of the green areas within Augustenborg are intended to be flooded during heavy rainfall events, it is important to accurately model the overland flow patterns and infiltration in these areas. This can only be done in the 2D model representation.

6.1.6 Modeling storage volumes

The Augustenborg area contains many areas that are designated to be flooded and act as detention ponds during heavy rainfall events. These storage areas are an important part of the stormwater management. By detaining and slowing down the water and thereby allowing for infiltration and evaporation to occur, they contribute to decreasing the load to the pipe network.

In MIKE Urban a storage area is always described as a basin with a specified depth-volume curve, (see section 5.1.2). When the water level in the basin reaches the level of connecting downstream pipe, the water will discharge. In the MIKE 21 terrain model the storage areas are not explicitly defined, but only present as sinks in the terrain where water will naturally be collected and stored. In a coupled 1D-2D the storage volume must be represented either as a basin in the 1D models or as a sink in the 2D terrain model, or as a combination of both. If the full storage volume is represented in both the 1D and the 2D model, the volume will be counted twice.

Intended flood areas and sinks In the original 1D model of the area all intended storage areas were modeled as basins. When the 1D model was coupled to a terrain model, many of these basins were visible as sinks in the terrain, indicating that these areas should rather be modeled in 2D. However, the resolution of the terrain model is too coarse for it to capture small scale variations in topography, such as smaller drains and canals. The amphitheater in the schoolyard is one good example of an intended storage area that poses some difficulties in the modeling procedure.

The image below shows the terrain model zoomed in around the Augustenborg school area, with the location of the amphitheater circled. Runoff from the schoolyard and the roofs of the school buildings is collected in the the amphitheater. When the water level is sufficiently high, water will discharge to the outlet canal and continue to the grass canal in the Augustenborg park.

Figure 8: The terrain around the Augustenborg school.

As seen in the figure, the sink in the terrain is clearly visible, indicating that water in the 2D model will accumulate here. However, the small drain leading water to and from the amphitheater can only barely be distinguished. The drain is hence modeled in the 1D model, to more accurately mimic the flow that occurs. The amphitheater itself however cannot be modeled in the 1D model, since the storage volume associated with it is already captured in the 2D model. To allow for water accumulating in the amphitheater to discharge through the drain canal when the water level is sufficiently high, a node is placed at the sink and all cells covering the amphitheater sink are coupled to this node.

All storage areas that are not normally water filled are modeled in the same way as the amphitheater. Some of the storage areas that where modeled as basins in the original model where not large enough to be clearly visible in the terrain model. However, arguing that the detention capacity of these sinks is relatively small, they where still modeled as nodes in the 1D model.

Ponds There are seven ponds in the area that are permanently filled with water. These ponds are modeled as basins in the pure 1D model. In the 2D model, the ponds are visible as small sinks in the terrain model. Due to the ponds being permanently water filled, the terrain model does not capture the actual ground level at the location of the ponds, but rather the elevation of the water surface at the time the elevation data was collected. The small sink in the terrain model can thus be regarded as the additional water detention capacity of the ponds. To model the water filled ponds as physically accurate as possible, they are modeled as 1D basins coupled to several 2D cells covering the extent of the ponds. The ground elevation of the 1D basins where set to the elevation of the adjacent 2D cells. This way, the part of the pond volume that is not captured in the 2D model is represented in the 1D basin. When the 1D basin is overtopped, water will flow to the 2D model. The figure below shows the concept of modeling ponds in the coupled 1D/2D model.

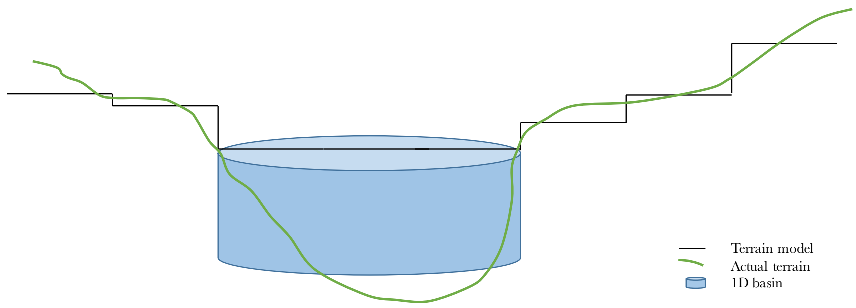

Figure 9: A conceptual image of how ponds are modeled in the coupled 1D/2D model.

When modeling a pond in 1D the initial water level is set to the water level of the lowest connecting link. In reality, the water level in the pond will change due to evaporation and infiltration. The initial water level effects the storage capacity of the pond, wherefore it is important to specify a correct initial water level in the model. In the model, the initial water level is set to the normal water depth given in the blueprints, or, if no blueprints are available, as the elevation in the 2D model. However, the actual initial water level in the ponds will be different for every rainfall event. This can not be compensated for in the model without altering the network connections before every simulation.

6.2 Dividing rainfall between the two models

The rainfall was divided between the 1D and the 2D model. To determine whether or not an area should be assigned rainfall in the 1D or the 2D model, the runoff from that surface had to be characterised. The areas that were considered as effective impervious areas, i.e. areas that where assumed to generate fast runoff and that drained directly to the drainage network (Palla and Gnecco, 2015), such as pavements and roofs with drainpipes, where loaded with rainfall in the 1D model. Areas where the runoff was assumed be slower and where surface flow and infiltration were assumed to be important were loaded with rainfall in the 2D model, these areas included the parks and yards.

Some areas, such as the schoolyard and the parking lots surrounding the Augustenborg botanical rooftop gardens, where not as straightforward to model. The runoff from these areas is likely to be fast due to the surface being smooth and impermeable. However, the areas are drained through the open drainage network, and therefor the surface flow routing could be important and interesting to study. It was decided to model the runoff routing on the schoolyard in the 2D model, since the surface runoff patterns are important in this part of the area. Furthermore, modeling the rainfall-runoff in 2D would clearly indicate on the result maps where the water accumulates. Due to the fact that not all parts of the parking lots around the rooftop gardens were part of the MIKE Urban model, it was decided to model all the runoff from these areas in the 1D model. Otherwise, the produced result maps would be confusing.

Figure 10 shows a schematic overview of the Augustenborg stormwater system, and what components of the system that are modeled in which sub-model.

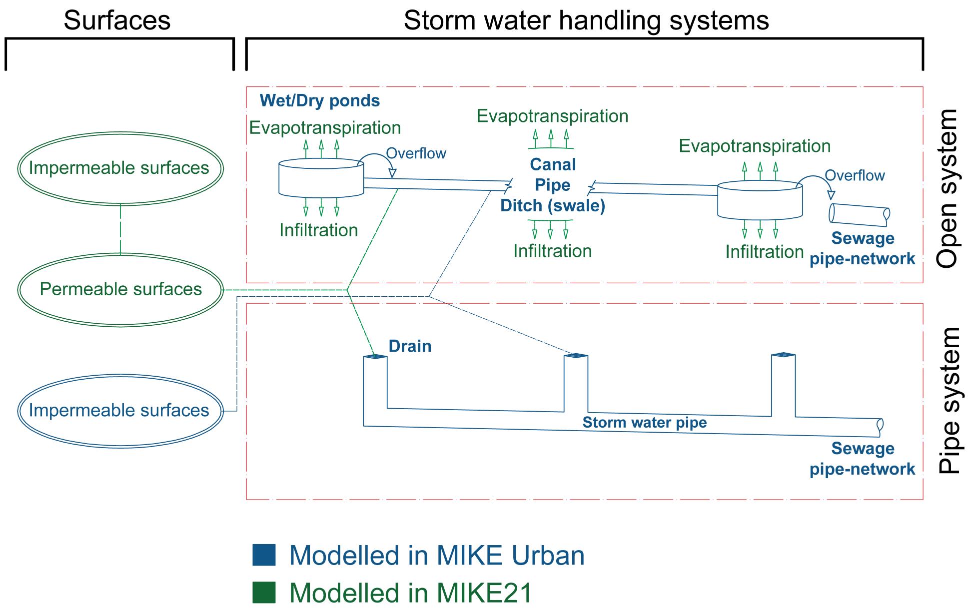

Figure 10: A schematic model of the Augustenborg stormwater system. Source: Salar Haghighatafshar

6.3 Adjusting the existing MIKE Urban model

The MIKE Urban model developed by Aza Shukri was used as a base for the model. The rainfall-runoff model consists of 173 catchment areas, the runoff is computed using the Time-Area method. The network model consists of pipes and open canals represented as model links. Ponds, swales wetlands, and other storage volumes were modeled as basins. The cross sections of the open channels and the geometries of the basins were determined based on maps or estimated during field visits to the area. For a detailed description on the development of the MIKE Urban model the reader is referred to the master thesis of Aza Shukri (Shukri, 2010).

The network model was updated with respect to basin geometries and elevation data. The storage volumes previously represented as 1D basins were modified according to the methodology presented in section 6.1.6, and some previously neglected elements were added to the model. A digital elevation model (DEM) of the study area was used as a base when updating the elevation of existing pipes and nodes in the model. Blueprints of some of the ponds in the area were available from MKB. These were used to update the basin geometries and the elevation of the basin outlets. For the parts of the system for which blueprints were not available, the existing basin volumes were validated by estimating the volume from satellite images of the area.

The model catchments and catchment connections were updated based on the findings during a field visit to the area. In the MIKE FLOOD model only impermeable areas directly connected to the drainage network were to be modelled in the rainfall-runoff simulation in MIKE Urban. These areas were identified during the surface inventory. The boundary conditions in the model were changed so that only these areas were loaded with precipitation.

6.4 Set up of MIKE 21 Model

The 2D hydrodynamic model of the Augustenborg catchment area was developed. The model consisted of a bathymetry and spatially varied bed resistance, with spatially and temporally varying rainfall as an external water source, and infiltration with constant rate and capacity as a sink.

6.4.1 Bathymetry and boundaries

The DEM used was a terrain model with resolution 2x2 meter. The terrain model only contained ground elevation. In order to avoid flooding on buildings or water crossing over buildings, the terrain model was modified so that all buildings were raised 2 meters above their original level. The terrain model was cropped to the extent of the catchment area. The cells outside the catchment area were assigned "land values" and thereby taken out of the calculations. Figure 11 shows the original terrain model and the modified terrain model that was used as bathymetry in the MIKE 21 model.

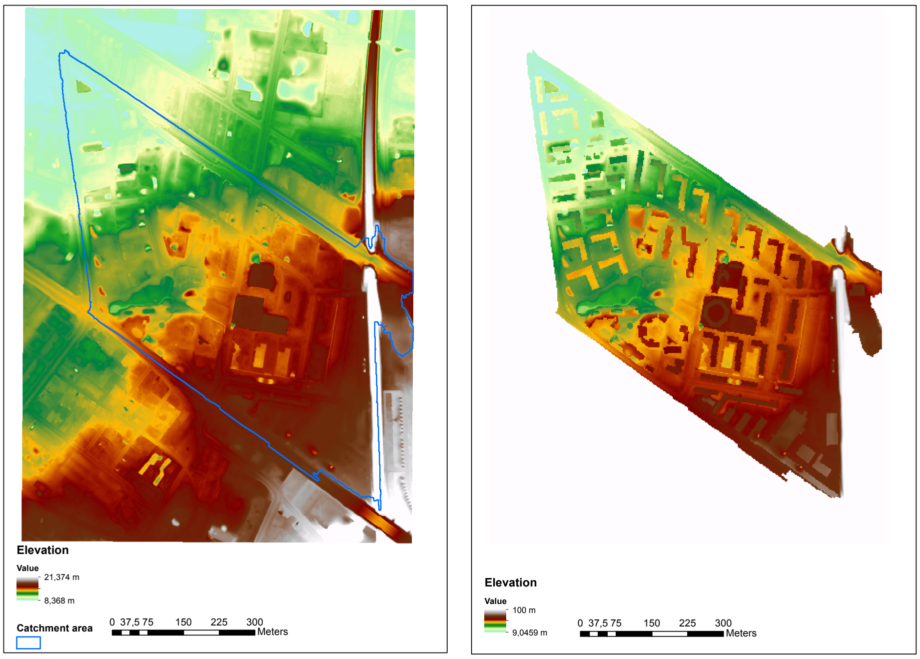

Figure 11: Left: The original terrain model and the extent of the catchment area, resolution 1x1 m. Right: The MIKE 21 bathymetry with elevated buildings and 2x2m resolution.

6.4.2 Flooding and drying

The flooding and drying depth was set to 0.002 and 0.001 m respectively, values that are in the same order of magnitude as those in the MIKE 21 models developed by Filipova (2012) and Gunnarsson (2015).

6.4.3 Land cover classification

The infiltration and bed resistance parameters in the MIKE 21 model were estimated based on the land use in the catchment area. A thorough investigation of the land use in Augustenborg catchment area was done using ArcGIS. For the classification the ESRI open basemap World Imagery and Google Earth was used. The land use classification was verified during a field visit to the area. The land use was divided into 9 categories, tile roofs, asphalt, water, gravel, sand, extensive and intensive green roofs, grass and railway. The image below shows the land use classification in the catchment area. The total and relative area of the different land use classes are summarized in table 1.

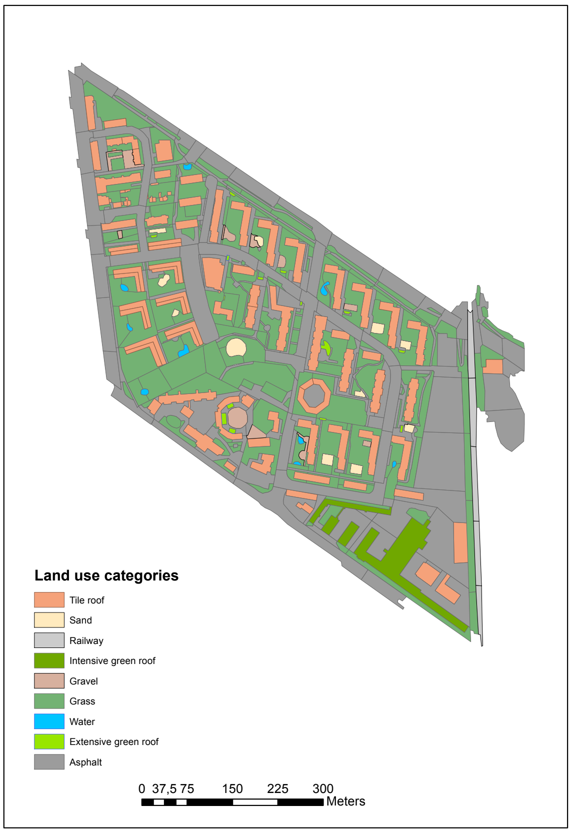

Figure 12: Landuse in the Augustenborg area

Table 1: Summary of land use within the Augustenborg catchment

Land use	Area (ha)	Relative area (%)
Tile roof	5.487	15.4
Sand	0.312	0.9
Railway	0.520	1.5
Intensive Green Roofs	0.997	2.8
Extensive Green Roofs	0.096	0.3
Gravel	0.390	1.1
Grass	11.760	33.1
Water	0.099	0.3
Asphalt	15.866	44.7
Total area	35.52	100

6.4.4 Bed resistance

The bed resistance in the 2D model was assumed to vary depending on the land cover. Impermeable surfaces such as asphalt roads and tile roofs usually has a lower bed resistance than permeable surfaces such as parks and sand covered playgrounds. The Manning coefficients for asphalt, grass covered areas, sand and gravel surfaces were assigned based on the the results from a study by Engman (Engman, 1986). Tile roofs and green roofs were not be assigned any rainfall in the MIKE 21 model, and therefor the Manning coefficient of these two types of surface cover would not have any effect on the model results. As an approximate estimate, the Manning coefficient for green roofs was set to the same value as for grass areas, and that of tile roofs was set to the same value as for asphalt.

6.4.5 Infiltration

Leakage rate The infiltration losses were modeled using the constant infiltration rate and capacity option. According to Swedish Geological Survey (SGU) the dominating soil type in the Augustenborg area is clay morain (Sveriges Geologiska Undersökning, 2016), which has a saturated hydraulic conductivity of approximately $10^{-8} - 10^{-10}$ m/s (Larsson, 2008). The leakage rate was set to 0.036 mm/hr for all permeable areas within the catchment.

Infiltration rate The infiltration rate was determined based on the land use classification. Tabulated values of constant infiltration rates are not available. The initial value of the infiltration rate was set to 36 mm/hr.

Layer depth No data on depth of the unsaturated soil was found. Therefor, the depth of the infiltration layer was assumed to be 0.3 m, and homogeneous over the permeable parts of the catchment. The capacity of the infiltration layer is determined by the depth, porosity and initial fill parameters togehter. The porosity will be altered in the calibration process, and will hence partly compensate for the lack of available soil depth data.

Porosity The porosity of the infiltration layer was estimated based on the land use classification. The effective porosity for the sand and gravel was set to 25 %, based on tabulated values from Sundberg (1991) and Espeby and Petter (1998). The porosity for the soil in the park areas was assumed to 30 %, based on estimates from Jim (1998).

Initial fill The initial volume in the storage zone was set to 100% for the areas covered by ponds, where the underlying soil can be assumed to be completely saturated. For the rest of the catchment the initial fill was assumed to be 50%. The initial fill parameter was considered to reflect the initial conditions of the soil depending on preceding weather conditions. The choice of 50% as the default value was made based on two considerations. Firstly, the larger of the two calibration events, the rainfall of 29th of June, was preceded by a rainfall of similar magnitude a few days earlier indicating that the soil is likely not to be completely dry. Secondly, a choice of 50% would allow for this parameter to be increased or decreased, allowing the user to change infiltration capacity of the soil without altering other infiltration parameters.

6.4.6 Precipitation

The precipitation in the MIKE 21 model was added as a spatially varying time series of rainfall intensity (given in mm/hr) with a 15 minute time step. As described in section 5.2 the areas that were directly connected to the drainage system were not assigned any rainfall at any time step in the MIKE 21 model. Precipitation data from the rain gauge in Augustenborg was converted into 15 min time step. The conversion was done by computing the average intensity for every 15 min time step, preserving the total rain volume.

6.5 Coupling parameters

The connection between the two models is created by defining coupling nodes, through which exchange of water between the two models is allowed. All basins and junctions in the open drainage system and all manholes in the separate storm water system were coupled to the 2D model.

Weir equation The weir equation was chosen as the method to calculate the exchange flow between the MIKE 21 and MIKE Urban model. The weir crest width parameter was set to the circumference of the coupled 1D manhole, and the weir inlet area parameter was set to the surface area of the connected 1D manhole. The 1D basins where coupled in the same way, the only difference being the larger values of the crest width and inlet area parameters.

Coupling cells All nodes in the 1D network model located within extent of the 2D model were coupled to the 2D model. Manholes where coupled to the closest cell in the 2D model. Nodes in larger canals in the open part of the network were coupled to several 2D cells in the proximity of the node in order to increase the stability of the coupling. When coupling the ponds to the 2D model a larger number of 2D cells where coupled to the 1D model, covering the entire extent of the pond surface area. This was done to more accurately represent the physical situation. When the average water level in all the cells exceeds the node water level water is transferred from the 2D model to the 1D model.

Q_{dh} **parameter** The Q_{dh}-parameter was initially set to 2 cm, meaning that when the difference in water level between the two models is less than 2 cm the flow will be reduced with the suppression factor according to equation 11. This value was chosen since it is in the same order of magnitude as the modeled rainfall events. Higher and lower values were tested, but the effect of a changed value on the modeled discharge was negligible. However, setting this parameter to zero induced oscillating flow in some of the coupling links and high water level correction in the coupled cells.

7 Sensitivity analysis

Due to the fact that the model was run with relatively small rainfall events (13.6-22.8 mm), the infiltration rate of the model exceeded the rainfall intensity. When the infiltration rate exceeds the precipitation rate in a cell, it is possible that all water from the cell is removed. This causes the model to automatically reset the water level to the minimum water depth of 0.0002 m, possibly giving rise to a mass balance error. A time step sensitivity analysis was conducted to investigate the impact of the time step on the mass balance. The time step sensitivity analysis was conducted to identify the largest possible calculation time step that would not allow the simulation to run without large numerical errors. A larger time step is preferable since it gives a shorter calculation time.

The table below show the different scenarios that were tested in the sensitivity analysis. The rainfall event of 4th of August 2015 was chosen for the sensitivity analysis simulations.

Table 2: Scenarios tested in the sensitivity analysis

	Time step (s)
Scenario 1	0.5
Scenario 2	0.25
Scenario 3	0.05

The general aim with a sensitivity analysis is to identify what parameters that has large impact on the model output and thereby reduce the number of parameters that are to be adjusted in the calibration process. Due to time limitation no separate sensitivity analyses of the individual 1D and 2D models were carried out. Instead, results from previous sensitivity analyses on similar models were used.

A sensitivity analysis of the original 1D MIKE Urban model was conducted in the master thesis by Shukri (2010). The sensitivity analysis indicated that the imperviousness fraction and hydrological reduction factor had large impact on the discharge volumes, and that the Manning friction coefficient had large impact on the lag time and discharge rate. The results from this sensitivity analysis were used and no further sensitivity analysis of the 1D model was carried out.

A sensitivity analysis of a MIKE 21 model with infiltration and leakage was carried out by Gunnarsson (2015). Since the storage capacity of the infiltration layer is determined by the porosity, initial fill, and depth parameter together, only one of these was modified in the sensitivity analysis by Gunnarson. The sensitivity analysis showed that the model results are sensitive to infiltration rate, roughness parameters and porosity.

8 Model calibration and validation

The model was calibrated against flow measurements from the 4 measurement stations showed in figure 5 following the two rainfall events of 4th August 2015 and 29th June 2016. The two rainfall events are shown in figure 13 and 14 below.

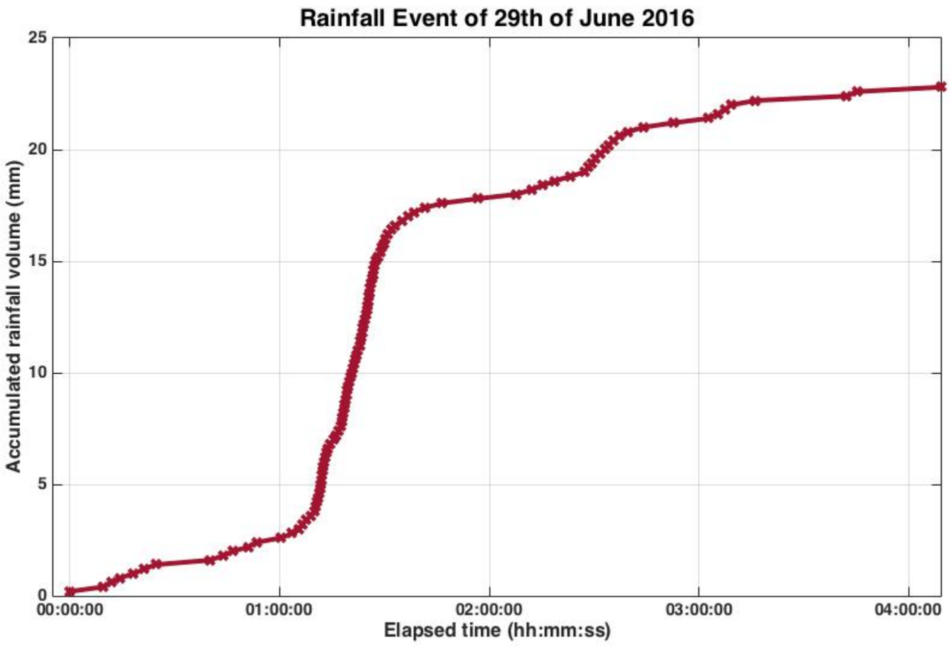

Figure 13: The rainfall event of 29th of June 2016 used for model calibration

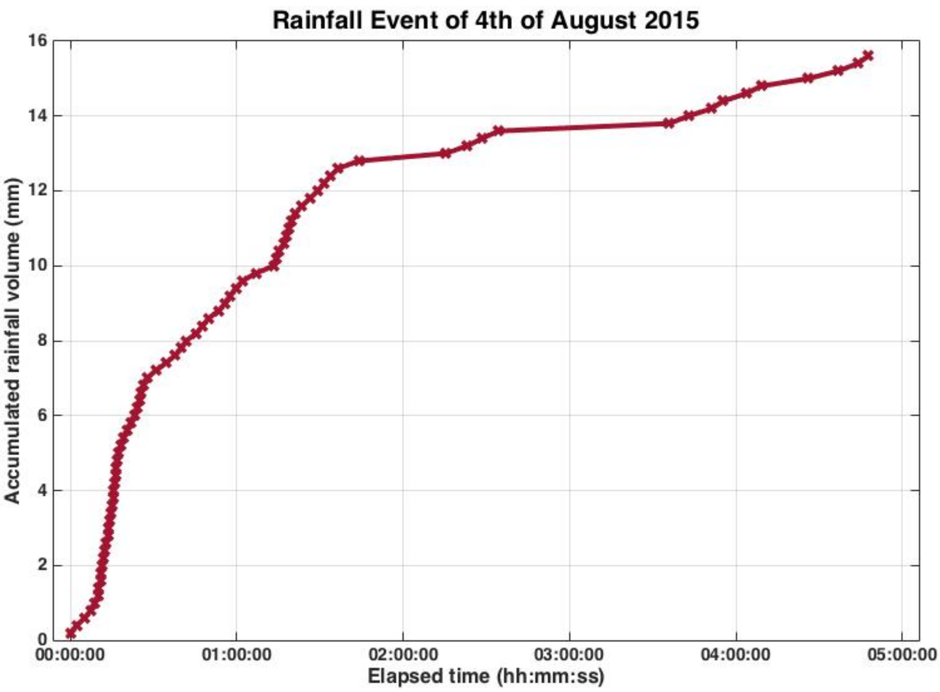

Figure 14: The rainfall event of 4th of August 2015 used for model calibration

These two event are chosen since they are two of the largest rainfall events that occurred during the data collection period. The rainfall event of 29th of June 2016 had a total volume of 22.8 mm, and the event of 4th of August 2015 had a total volume of 15.6 mm. There are several reasons for calibrating only against larger rainfall events. First of all, the model is intended to be used to evaluate the consequences of a large rainfall event, a model that is calibrated against a larger event would hopefully reproduce the effect of an extreme event more accurately. Second, the model tool is not well suited for modeling smaller flows due to the numerical solution scheme being used. The MIKE Urban model always assumes a minimum water level in the pipes, which could induce large mass balance errors when the modeling dry or low-flow periods. As explained in section 5.2, the MIKE 21 model always assumes a minimum water level in every computational cell, which can cause water to be artificially generated in a cell. A final argument for choosing the larger events for calibration is that during smaller events the flows are very small, sometimes as low as only a few liter per second. This makes calibration difficult since the relative errors become very large.

Calibration is performed by iterative adjustment of the parameters identified in the sensitivity analysis until a satisfying correlation between measured and simulated flows is achieved. The calibration mainly focused on obtaining a good correlation between measured and modeled peak flow, total flow volume and timing of peak flow. The available water level measurements where used to validate the modeled water levels, but no extensive calibration was conducted against the water level measurements. In the MIKE Urban model the imperviousness fraction of the pavements and tile roofs are modified, as well as the initial loss factor. In the MIKE 21 model the infiltration and leakage parameters and the Manning coefficients are modified.

When the model is successfully calibrated the model is validated by simulating another rainfall event using the obtained parameter settings. The event chosen for validation is a rainfall event that occurred the 11th of August 2015 (figure 15. This event was of the same magnitude as the rainfall from the 4th of August 2015, with a total volume of 13.6 mm.

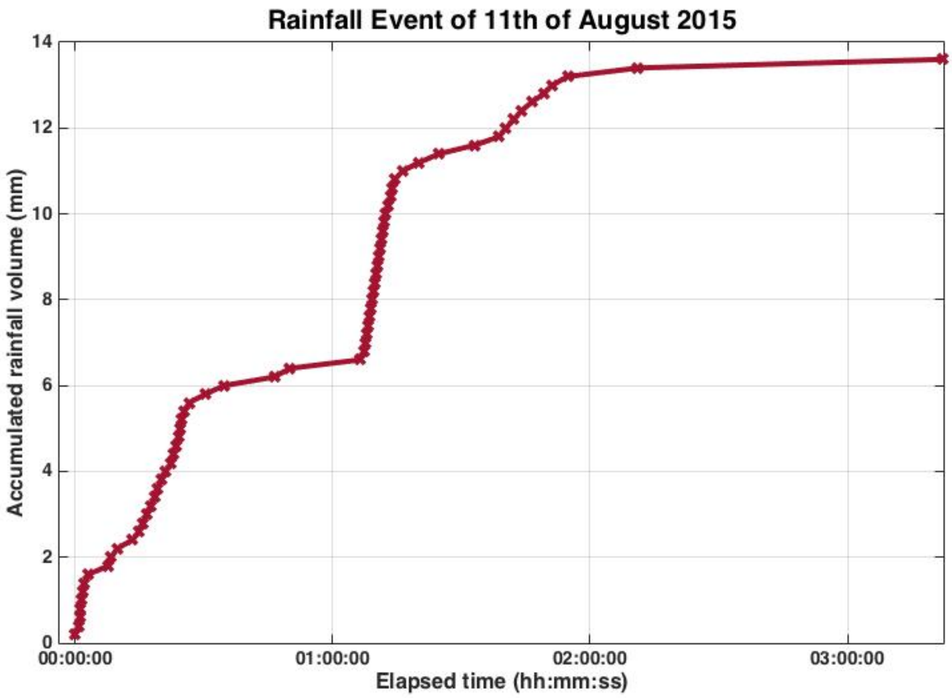

Figure 15: The rainfall event used for model validation, from 11th of August 2015.

9 Results

9.1 Results from time step sensitivity analysis

The results from the time step sensitivity analysis are presented in table 3 below. The computation time increased significantly with every reduction in time step. The water level correction was not significantly affected by the change in time step. Interestingly, the continuity balance error of the 1D simulation was larger with the smallest time step than with the largest one. The exchange of water between the two models was also affected by the choice of time step. Since no significant improvement in model result could be achieved through decreasing the model time step, the larger time step of 0.5 s was chosen for further simulations.

Table 3: Results from time step sensitivity analysis

Simulation time step	0.5 s	0.25 s	0.005s
M21 Water Level Correction (m^3)	351.35	351.15	354.28
M21 Continuity Balance (m^3)	-0.21	-0.21	-0.22
MU Continuity Balance (m^3)	71.5	97.3	277.7
Simulation time (hh:mm:ss)	1:17:13	2:36:37	14:06:37
Exchange MU to M21 (m^3)	161.59	149.5	179.61
Exchange M21 to MU (m^3)	161.72	164.2	166.01

9.2 Calibration and validation results

9.2.1 Calibration results

In general, peak flows are well estimated by the model, whereas the total outflow volume is much overestimated. The measurement point at Enegången could not be calibrated, the model persistently predicted a slower, less pronounced response. The relative volumetric error in the measurement point at Ystadvägen is very high for the 4th of August rain, however, the peak discharge flow is only overestimated with a few liter per second, the very low measured flow rates makes the relative difference very large. Table 4 summarizes the results from the calibration. Figures 16 and 17 show measured and modeled discharge in the 4 flow measurement stations.

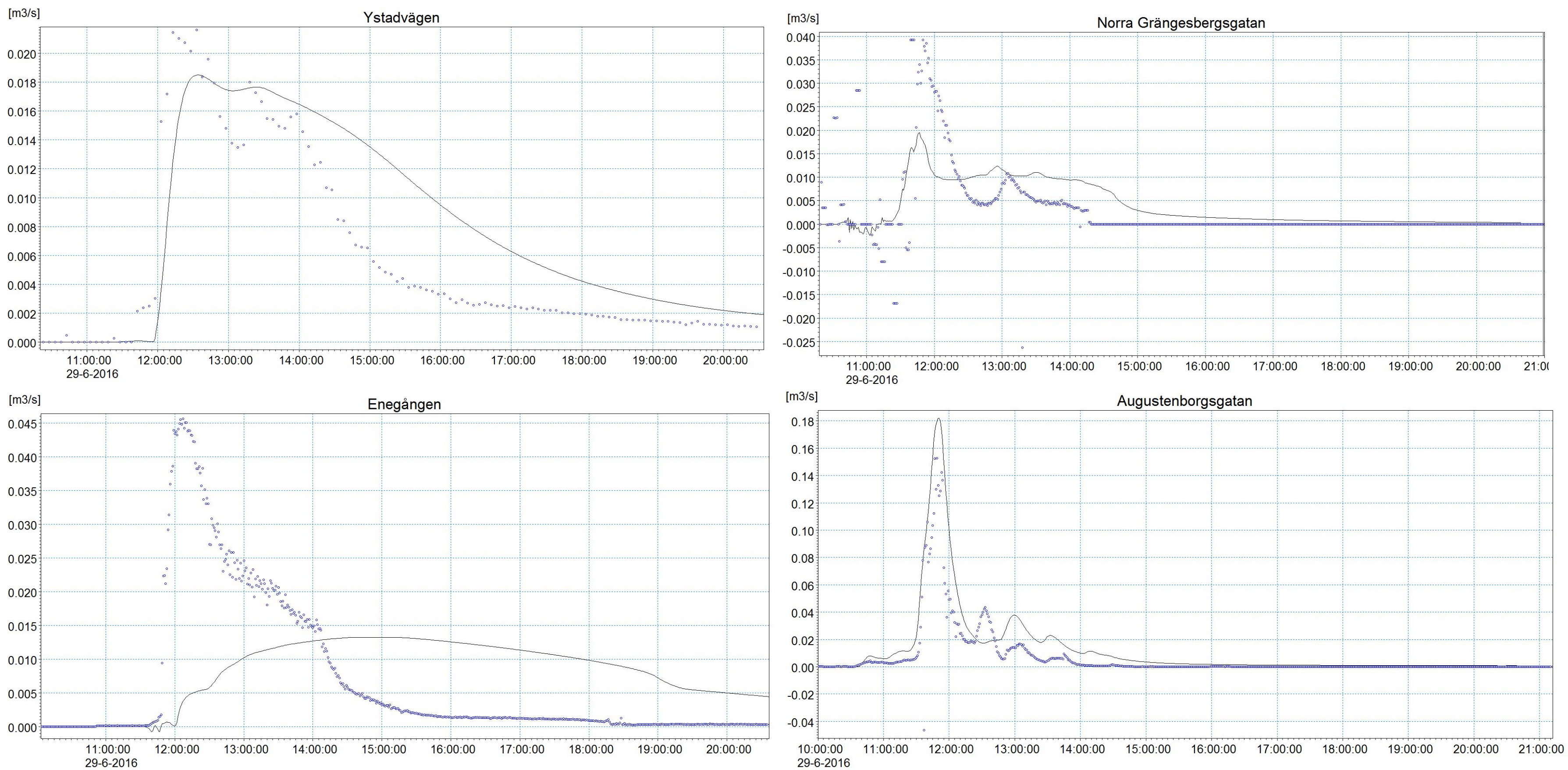

Figure 16: Measured (blue dots) and modeled (black lines) flows from the four measurement stations from the 29th of June 2016. Upper left: Ystadvägen Upper right: Norra Grängesbergsgatan. Lower left: Enegången , Lower right: Augustenborgsgatan.

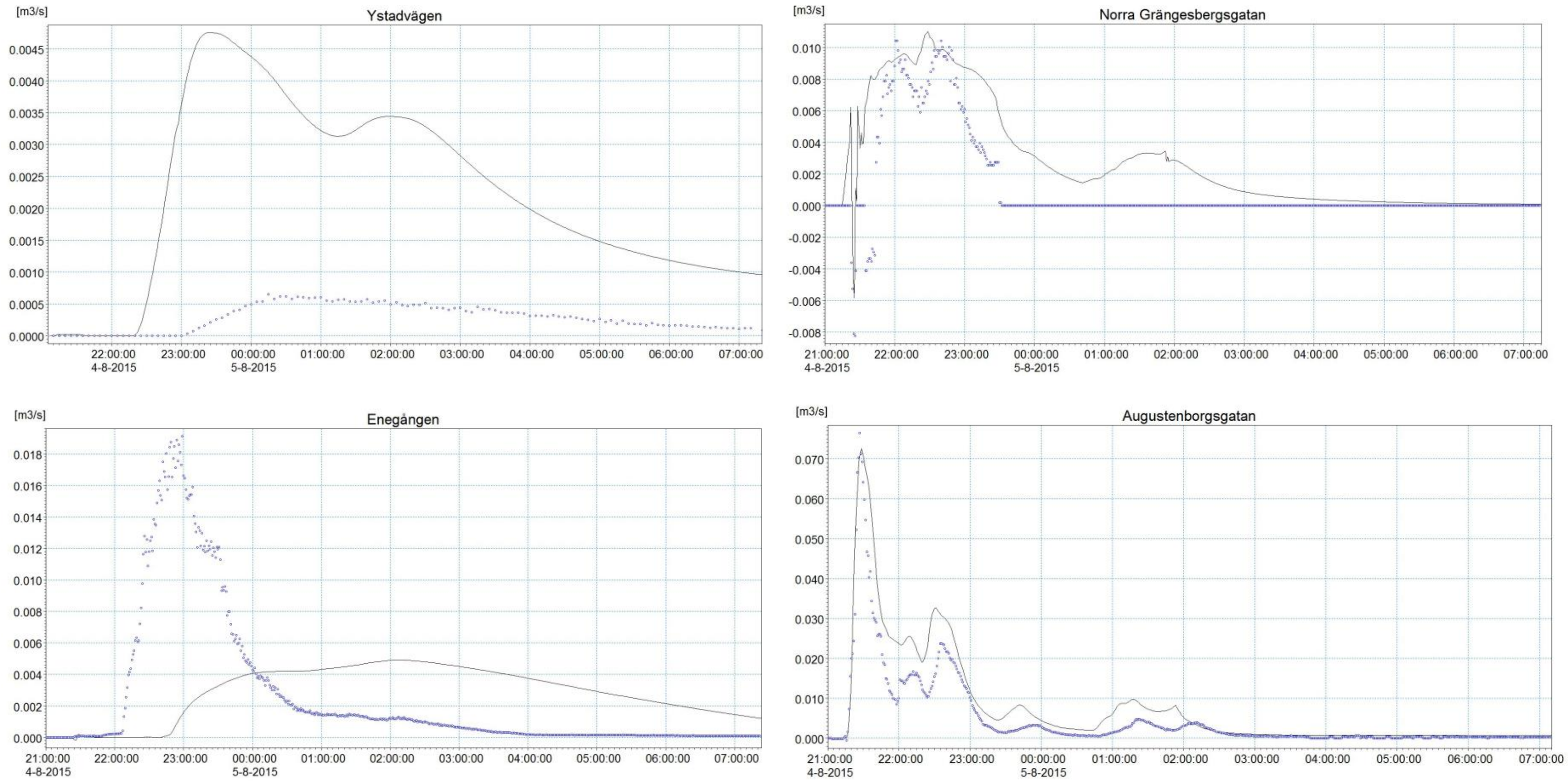

Figure 17: Measured (blue dots) and modeled(black line) flows from the four measurement station from the 4th of August 2015. Upper left: Ystadvägen Upper right: Norra Grängesbergsgatan. Lower left: Enegången , Lower right: Augustenborgsgatan.

Table 4: Volume error and peak discharge error between measured and modeled link discharge.

		Enegången	Norra Grängesbergs-gatan	Augustenborgs-gatan	Ystadvägen
2016-06-29	Volume error(%)	+19	+28	+81	+37
	Peak difference(l/s)	-33	-19	+29	-4
	Peak error(%)	-71	-50	+19	-14
2015-08-04	Volume error(%)	+10	+156	+57	+680
	Peak difference(l/s)	-14	+1	-3	+4
	Peak error(%)	-74	+6	-5	+629

Water level measurements were only available for the rainfall event of 29th of June 2016. Figure 18 shows the measured and modeled water levels in the 4 water level measurement points. The initial water level in the model ponds does not coincide with measured values. The peak water level in the Ystadvägen and Södra Grängesbersgatan ponds correspond well with measured values, whereas peak water level is underestimated in the Enegången and Norra Grängebergsgatan ponds.

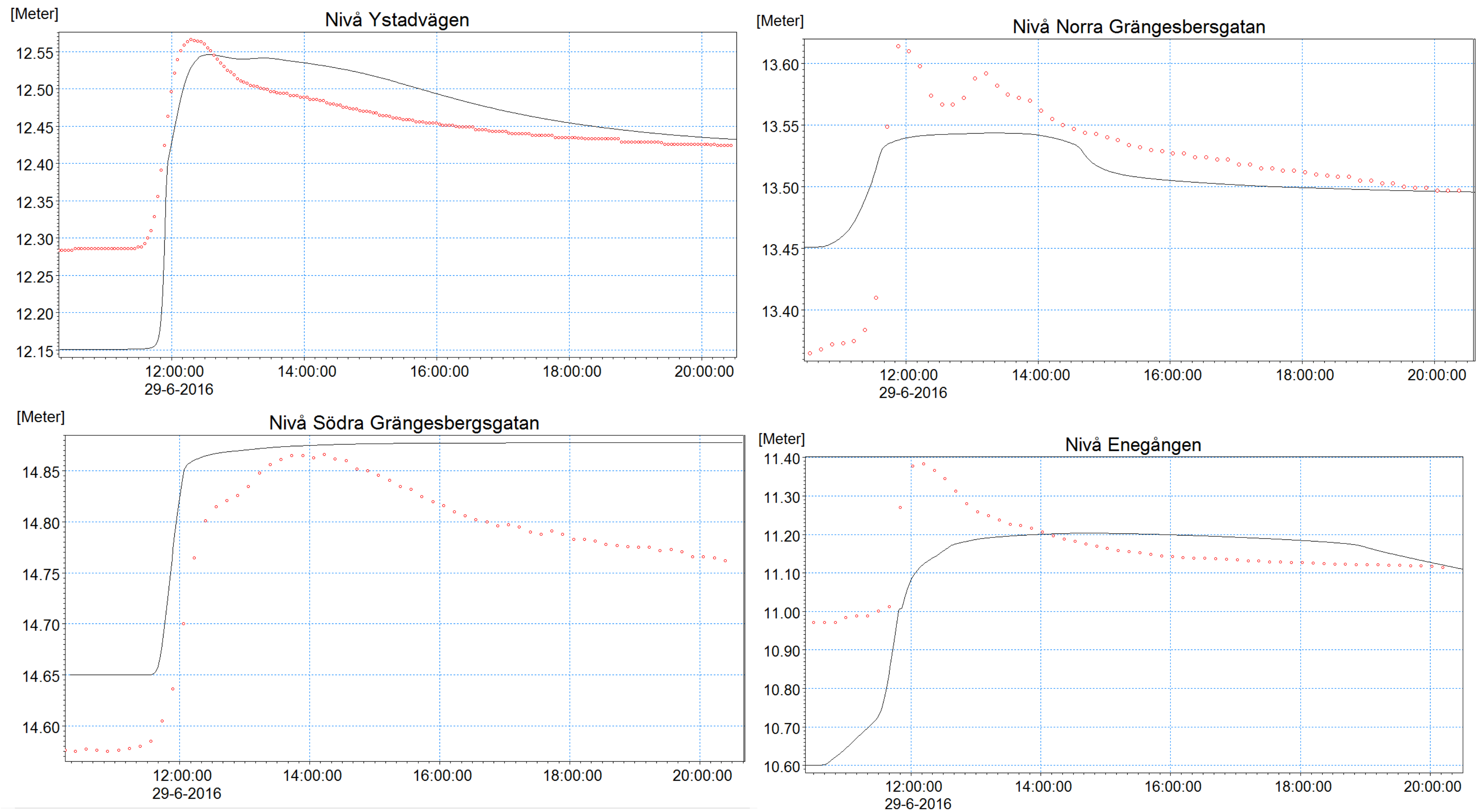

Figure 18: Measured (red dots) and modeled (black line) water levels in the four measurement points. Upper left: Ystadvägen Upper right: Norra Grängesbergsgatan. Lower left: Södra Grängesbersgatan. Lower right: Enegången.

Figures 19 and 20 hows the maximum inundation depth from the simulations of the rainfall events of 29th of June 2016 and 4th of August 2015 respectively. The map shows the maximum water depth from the entire simulation, and is not showing the water depths at any specific time step. For both rainfall events most of the surface runoff accumulates in the ponds, in the Augustenborg park, in the storage basin of the schoolyard and along the Lönngatan drainage canal. Some water also accumulates along the streets, especially in the north-west corner of the area.

Figure 19: Maximum water depth from the simulation of the 29th of June 2016 rainfall event.

Figure 20: Maximum water depth from the simulation of the 4th of August 2015 rainfall event.

The model was calibrated by adjusting the imperviousness and the time of concentration parameters in the 1D model and the infiltration and bed resistance parameters in the 2D model. Since only roofs and paved areas where loaded with rainfall in the 1D model, only these catchment area parameters where adjusted. The imperviousness was initially set to 100% for all impermeable catchments. This however gave rise to very large runoff volumes, and the parameter was reduced in the calibration process to values ranging from 70-90%. The runoff volumes where much overestimated when applying a runoff coefficient of 100%, even when running the standalone 1D model with rainfall only applied to impervious surfaces, thus disregarding the contribution of overland flow from other parts of the area.

In the 2D model the leakage rate, Manning coefficient and porosity for three of the land use classes were adjusted. The 2D model parameters for tile roofs, green roofs and railway were not adjusted since these areas are elevated from the terrain model and the runoff from these areas are modeled in 1D. Hence, these areas will not be part of the 2D model, and therefor their 2D parameters were not adjusted. Table 5 summarizes the resulting parameters for the 2D model.

Table 5: Parameter for the different land use classes after calibration.

Land use	Manning coefficient ($m^{1/3}/s$)	Infiltration rate (mm/hr)	Porosity ()
Grass	1.5	10	0.1
Sand and gravel	2	30	0.25
Asphalt	40	0	0

9.2.2 Validation results

The model was validated by simulating the rainfall event of 11th of August 2015. Figure 21 shows the modeled and measured flows from the four measurement stations for the simulation of this rainfall event. The results are summarized in table 6.

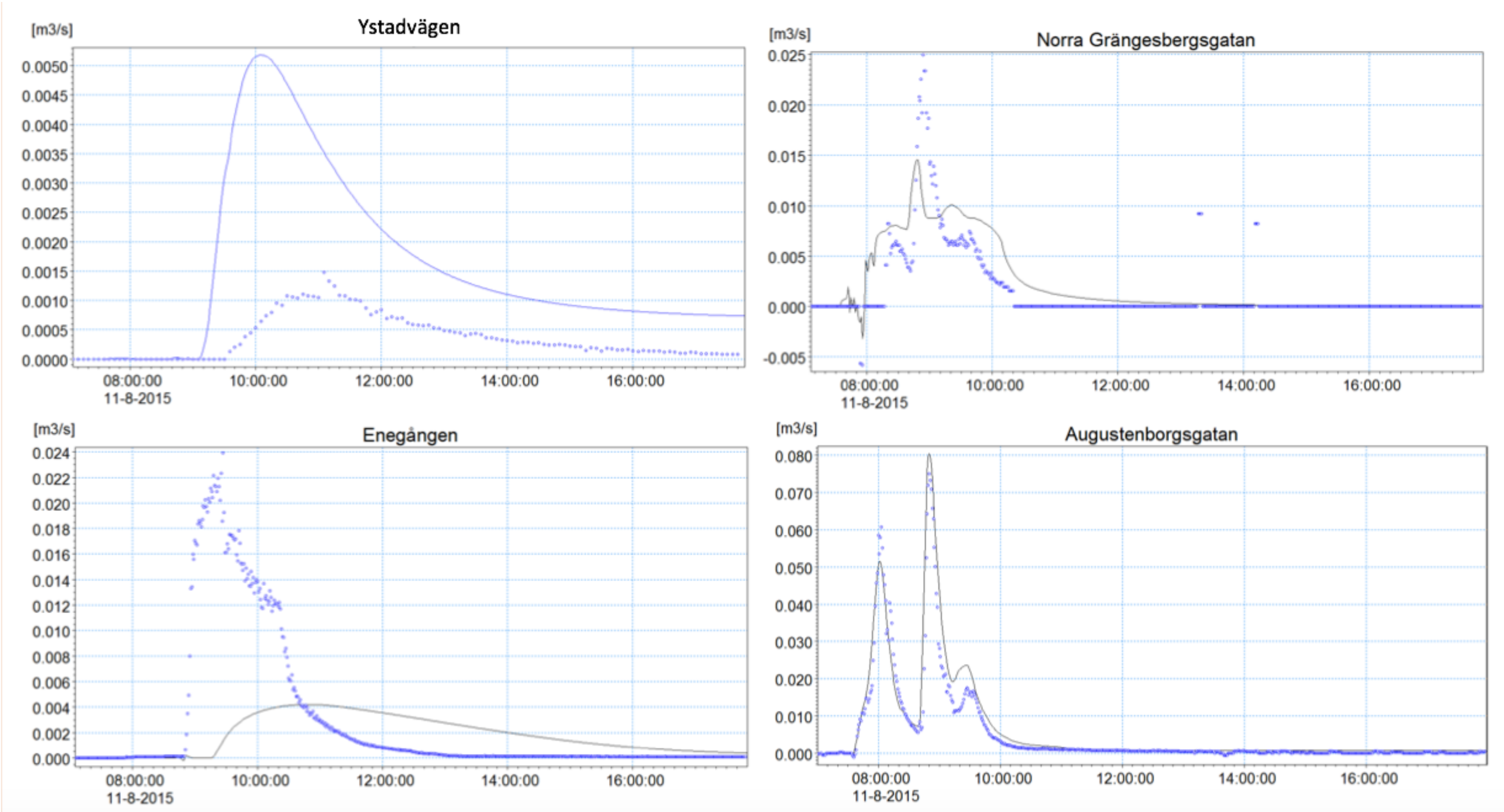

Figure 21: Measured (blue dots) and modeled (black line) flows from the four measurement stations for the 11th of August 2015 rainfall event. Upper left: Ystadvägen Upper right: Norra Grängesbergsgatan. Lower left: Enegången , Lower right: Augustenborgsgatan.

Table 6: Correlation coefficients, volume error and peak discharge error between measured and modeled link discharge for the validation simulation

		Enegången	Norra Gränges - bergsgatan	Augusten-borgsgatan	Ystadvägen
2015-08-11	Volume error (%)	-36.2	+45.2	+23.9	+336
	Peak difference (l/s)	-20	-10	+5	+4
	Peak error (%)	-84.4	-41.5	+7.2	+250

The image below shows a map of the maximum flood depth from the simulation of the 11th of August rainfall. Water is accumulating in the ponds, in the amphitheater, along the northern drainage canal and along the sides of the Augustenborg street. In the north-west corner there is some accumulation of water on the street.

Figure 22: Maximum water depth from the simulation of the 11th of August rainfall event.

10 Discussion

10.1 General model performance

In general, the model is capable of accurately reproducing the measured flows and water levels and produce credible inundation maps. The coupled 1D/2D approach allows overland flow, flow in the drainage network, and the exchange between the two to be modeled simultaneously. Thereby, the coupled model can provide more information compared to a pure 1D or a pure 2D model.

The result maps from the 2D model show that the water accumulates in the ponds, on some of the yards and in the intended sinks. There are some sinks in the terrain where the water levels become very high, these are most likely garage driveways. It might be a good idea to modify the terrain model and remove these sinks to more accurately model where water will accumulate in the system. In general, the 2D model results imply that runoff is detained where intended to.

The mass balance errors of the 2D model could not be overcome. Numerical instabilities are often related to the computational time step (DHI, 2016a), the MIKE 21 user guide recommends to use a time step sufficiently small to achieve a Courant number less than 1, which is the case for all the time steps tested in the sensitivity analysis. Further reducing the time step did not reduce the numerical errors in the 2D model, however, it increased the continuity balance errors of the 1D model. The most likely reason to why numerical water is added to the 2D model is that the model always assumes a minimum water level in every computational cell. When the water level fall beneath this level it is automatically reset, violating the continuity balance. The water level correction is not isolated to any specific point in the model, although in the beginning of the simulation the water level correction is higher in the areas covered by sand and gravel, where a higher infiltration rate was applied. In this project the Augustenborg model is run with relatively small rainfall events. In the beginning of each simulation the rainfall intensity is smaller than the infiltration rate, a high infiltration rate coupled with the hydrodynamic routing of the water causes the water level in many cells to fall below the minimum water level. One way to possibly overcome the problem with numerical water would be to apply a lower infiltration rate, however, this would not represent the actual physical conditions of the soil, and would probably lead to poorer results when running the model with a more intense rainfall event. Changing the minimum allowed water depth to a lower value could possibly reduce the mass balance errors, however, testing this consistently lead to model blow-ups.

Despite the mass balance issues related to modeling overland flow and infiltration with the 2D model, there are many advantages with this approach compared to a 1D rainfall-runoff model. Using 1D rainfall-runoff modeling the same runoff coefficient is applied regardless of the magnitude of the rainfall event. With the 2D model the infiltration capacity can be specified, and rainfall dependent infiltration and runoff patterns can be more accurately modeled. Since no simulation of extreme rainfall events were performed within the scope of this project, no conclusions could be drawn regarding the systems capacity to cope with such events. The model is calibrated against smaller rainfall events, and it is therefor difficult to determine whether it will perform equally well when heavier rainfall events are simulated. However, following the argumentation by Kleidorfer (2009), the 2D model is more likely to perform better outside of the calibration range compared to the previous 1D model, since the 2D infiltration parameters are physically based. In the previous pure 1D model of the area very low runoff coefficients had to be applied in order to obtain good calibration results, which would likely lead to an underestimation of the runoff volumes following extreme rainfall events.

As mentioned in section 6.1 it was challenging to represent the different components of the system using the coupled 1D/2D model, since it is difficult to distinguish between when the flow is overland and when the flow is in the network. It is possible that the exchange of water between the 1D and the 2D model is underestimated since exchange is only allowed in the nodes. Along the drainage canals in the northern and southern system the flow will naturally enter the canals laterally. No lateral linkages are allowed when coupling a MIKE Urban and a MIKE 21 model. To overcome this shortcoming additional nodes are added along the canals to enhance the exchange of water.

In general, it was challenging to model the storage volumes of the system with the coupled 1D/2D model. In low flow situations when the 1D node located in the storage zone is not over topped the water already present in canal continues further downstream in the model. In real-life, the water is probably detained in the storage, and not lead on, until the capacity of that storage volume if filled. In the coupled model almost all storage volumes are represented as a sinks in the 2D model. The low resolution of the 2D grid might underestimate the volume of the storage zones in the area.

For future studies of the area, more flow and water level measurements, preferably from more extreme rainfall events than the ones recorded during during the study period, would be useful for further model calibration. Furthermore, more effort needs to be put into modeling the Enegången pond. It would also be interesting to model the LID structures of the area using the features of the SWMM mode of MIKE Urban.

10.2 Results from model calibration and validation

The model could not be successfully calibrated against measurements from all stations. Peak flows were well estimated, but he total runoff volume was overestimated in all measurement points.

The three measurement points of Enegången, Norra Grängesbergsgatan and Ystadvägen are all located at the outlet from a pond. The flow out of the ponds are modeled as flow over a weir, with the weir crest level being determined from blueprints of measurements. The flow out of the pond is naturally determined by the water level in the pond. As explained in section 6.1.6, the initial water level in the ponds in the model is determined by the level of the lowest connected pipe. When comparing modeled water levels with water level measurements it can be seen that the water level in the ponds deviates depending preceding weather conditions (see figure 18). Since the available storage capacity of the ponds depend on the initial water level, this initial condition will have a big impact on the correlation between measured and modeled flows. The only way to compensate for this is to change the network model prior to every simulation, so that the elevation of the lowest connecting link corresponds to the measured water level. In this project, the network model was kept unchanged once it had been set up. Furthermore, water level measurements where not available for all of the simulated events. Initial conditions is therefore a big uncertainty that might contribute to the poor correlation between measured and modeled flow out of the ponds.

10.2.1 Augustenborgsgatan

The measurement point of Augustenborgsgatan is located in the closed system, which drains mainly impervious surfaces and a few yards. Calibration against flow measurements from 4th of August 2015 could be successfully conducted, but the model could not be successfully calibrated with regard to timing of peak discharge when simulating the rainfall of 29th of June 2016. However, when validating the model against the rainfall event of 11th of August 2015 the peak discharge timing was well captured. It was not possible to achieve a good correlation between measured and modeled flows while applying a imperviousness of 100% on the roofs and asphalt areas in this part of the catchment. When an imperviousness of 100% was applied the modeled runoff volumes became much higher than the measured. To determine if the excess runoff originated from the surfaces modeled in the 1D or the 2D model, the 1D model was run on its own, with rainfall only applied to the impervious areas. The runoff volumes where much overestimated also in this run. A good correlation could be achieved through reducing the imperviousness to approximately 70%. The fact that a good correlation could not be achieved using values around 100% indicate that the total surface area drained by this part of the network might be overestimated. Another possible explanation is that the drain pipes of the connected houses were overtopped, discharging water onto the grass surfaces. As argued by Kleidorfer (2009), the post-calibration parameter values can compensate for errors in the model structure, but the model might still fail to make accurate predictions when it is being run with events outside of the calibration period. Surface runoff from the 2D model also contributes significantly to the flow in this point, hence one possible source of uncertainty is the parameters chosen for the model coupling. The exchange flow is calculated using the weir formula, using the manhole circumference as the weir crest width. This might overestimate the exchange of flow between the two models, since this represents a situation where the manhole cover is completely removed.

10.2.2 Enegången

The model could not be calibrated against the flow measurements from the Enegången station. Changing the values of the parameters identified in the sensitivity analysis did not improve the correlation between measured and modeled flows in this point. Attempts to modify the structure of the model in this point were also made, without successful results. The flow in point is rather complex, as explained in section 3.2, making it difficult to distinguish what part of the system that is not accurately represented in the model. The measured flow in in this point rapidly increases when the pond water level is sufficiently high, to then decrease again quite rapidly. The modeled flows shows a very different pattern, the flow is slow with a low peak. When running the 1D model independently the modeled flow pattern better resembles the measured. A lot of water is exchanged between the 1D and the 2D model in this part of the area, since the water level in the nodes are similar to the water level in the 2D model. The storage volumes are represented in the 2D model, but the low resolution of the 2D grid might lead to an underestimate of the actual storage capacity in this area. Further effort must be put towards modeling this part of the system.

10.2.3 Norra Grängesbergsgatan

The correlation between modeled and recorded flow from the Norra Grängesbergsgatan station was not perfect, but peak flow timing and total runoff volume was quite well estimated by the model. The flow situation in this point is rather complex, making it difficult to model. During many simulations this part of the system became unstable and the modeled flows were oscillating. The total runoff volume in this point is overestimated, but the peak flow as well as the timing of the peak flow is captured by the model. The validation simulation showed a good correlation with regards to timing of peak flow, but the peak was underestimated by the model.

10.2.4 Ystadvägen

For the measurement station at Ystadvägen a relatively good correlation between measured and modeled flow could be achieved. When modeling the two smaller rainfall events of from August 2015, the model much overestimated the flow, the measured flows were less than 1 l/s, making the relative errors very large. There is a large exchange of water between the 1D and the 2D model in this point. All of the storage is represented in the 2D model, so when the flow in the 1D model reaches the node that represents the pond it is quickly overtopped and the water is transferred to the 2D model.

11 Conclusions

In this project a coupled 1D/2D model of the stormwater system of Augustenborg was developed using the MIKE FLOOD toolbox by DHI. Although some issues remain that needs to be addressed before the model can be considered to be fully calibrated, the general results produced by the model are credible.

- The model could be sucessfully calibrated against flow measurements in 3 out of 4 calibration points.
- The 2D model results indicate that the surface runoff accumulates where intended to.
- A coupled 1D/2D model can accurately reproduce flow in the drainage network as well as overland flow, which is beneficial when modeling open stormwater systems where a lot of runoff is handled locally on the surface.

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