Analysing the effects of extreme precipitation for municipalities and waterboards

Do they need to connect their sewer and surface water models?

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https://frieschdagblad.nl/2018/8/7/niet-de-droogte-maar-extreem-weer-is-het-probleem

Analysing the effects of extreme precipitation for municipalities and waterboards

Do they need to connect their sewer and surface water models?

by

G. Hoogmoet

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Monday June 17, 2019 at 4:00 PM.

Student number:	4227697	
Project duration:	October 1, 2018 – June 17, 2019	
Thesis committee:	Dr. ir. F. v.d. Ven	TU Delft
	Ir R. Velner	Sweco
	Dr. ir. O. Hoes	TU Delft
	Dr. ir. J. Bricker	TU Delft

An electronic version of this thesis is available at http://repository.tudelft.nl

Abstract

The world's climate is changing. In the Netherlands one of the consequences is that water boards and municipalities are preparing for an increase in extreme precipitation. To evaluate the consequences in case of extreme precipitation all Dutch municipalities and water boards have to perform a stress test. In these stress tests the response of the water system is evaluated during extreme precipitation events which are much larger than the events used to design the water system. It is analysed which places are vulnerable to flooding and what risk (probability x potential damage) is involved. In the Netherlands the responsibility of different parts of the water system are with different government authorities. The municipality is responsible for the sewer system and the waterboard is responsible the surface water system. As a result both municipalities and waterboards often perform separate climate stress tests. Most of the time the municipality will not take the surface water into account or does it in a very simplified manner, for the waterboards this is vice versa. However, these systems do influence and hinder each other. This may result in an underestimation of the actual flooding, and corresponding damage.

The aim of this research is to investigate to what extent the urban drainage system and the rural surface water system influence each other during extreme precipitation. In this research the case study area of Schijndel with the surrounding catchment area of the Schijndelse loop is analysed. The research must clarify if flooding caused by extreme precipitation is underestimated if the urban drainage system and the rural surface water system of Schijndel are analysed separately instead of combined.

For this research a hydrodynamic model of the area is constructed in the hydrodynamic software package Infoworks ICM. The hydrodynamic model was used to investigate the difference between a coupled and separate model setup.

The results show that the modelled flood locations correspond to known flood reports, but also that the difficult to determine infiltration rate, grid size and surface roughness significantly influence the model response. Nonetheless, the hydrodynamic model can be used to compare the response for short precipitation events between a coupled and separate sewer surface water model. The results show that flooding is underestimated if the sewer system and the surface water system are put to the test separately instead of combined. However, the differences are location and event specific and occur mainly just upstream and downstream of the combined sewer overflow locations in the study area. Here, the results show an increase in flood depth, flood duration, flood extent and the amount of houses flooded when the system is modelled coupled instead of separate.

For future stress test studies it is recommended to schematize both the urban sewer system and surface water system together in one model, as this gives a better representation of the flow dynamics which occur in reality.

Preface

This master thesis report is the result of my educational journey at Delft University of Technology. During the last three years I had the opportunity to discover different topics within the field of water management. I have always experienced this with joy because of the close connection between students and staf within the department of water management. This master thesis has given me more insight in the effects of extreme precipitation in urban and rural areas and how to model this. Besides this the thesis process has been a journey with ups and downs of which I have learned a lot.

This research is at first for the University, but also useful for employees working at municipalities, water boards and engineering companies who are engaged in studies concerning the consequences of extreme precipitation in water systems where sewer system and surface water might hinder each other.

This thesis wouldn't have been possible without the support and guidance of many people. I want to thank Frans van de Ven for being my daily supervisor at TU Delft and always giving me useful reviews which greatly improved the final results. Further I want to thank Roel Velner for being my daily supervisor at Sweco and helping me with brainstorming and data pre-processing. The input of Olivier Hoes and Jeremy Bricker from TU Delft helped me to better shape my report and process my results. I finally want to thank Jan van der Meulen from Sweco for the great help with Infoworks ICM and Jan Willem Bronkhorst for being there for my questions at the Sweco office in Eindhoven.

Valkenswaard, juni 2019
Gijs Hoogmoet

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1 Introduction

1.1 Background

The world is confronted with the consequences of climate change in the coming decades. For the Netherlands, one of the consequences is an increase of extreme precipitation events (KNMI, 2015; STOWA, 2018). Together with urbanisation, densification and soil subsidence this increases the chance of flooding in both urban and surrounding rural areas.

To map the consequences of climate change all Dutch municipalities, waterboards, and the Dutch ministry of public works must perform a so called 'stress test' on how their infrastructure responds to extreme precipitation, heat, droughts and floods before the end of 2019. These stress tests should include both urban and rural areas and must be repeated every six years. The different government authorities must co-operate during these stress tests. This is stated in the Delta program 2018 of the Dutch government (Rijksoverheid, 2017, p.128), see the Dutch text box below. As part of the stress test municipalities analyse their sewer water systems, identify places vulnerable to rainfall induced flooding and determine the risk involved (probability x potential damage). All Dutch waterboards also perform similar stress tests on all surface water systems for which they are responsible (STOWA, 2011).

> "Hoe raken extreme neerslag, hitte, droogte en eventuele overstromingen onze steden en dorpen en het landelijk gebied? Inzicht in de kwetsbaarheid voor weersextremen is de basis van ruimtelijke adaptatie. Daarom brengen alle gemeenten, waterschappen, provincies en het Rijk (waaronder RWS) uiterlijk in 2019 samen met de betrokkenen in hun gebied de kwetsbaarheid in beeld met een stresstest, voor zover dat nog niet is gebeurd. De stresstesten worden vervolgens iedere zes jaar herhaald. Gemeenten, waterschappen, provincies en het Rijk maken regionale afspraken over samenwerking bij deze analyse, om de uniformiteit te waarborgen en de beschikbare deskundigheid te benutten. Deze afspraken leggen ze vast in hun beleid; in de toekomst gebeurt dat in de Omgevingsvisies en Omgevingsplannen." (Rijksoverheid, 2017, p. 128)

For these stress tests and the identification of possible measures hydrodynamic computer models are being used. It is important that the underlying calculations and model structure of these models is well-founded and accurate. The possibilities of these type of hydrodynamic models increased in recent years because of new model setups, solving techniques and an ever increasing computer power. However, there is still room for improvement.

In the Netherlands the above mentioned different authorities – municipalities, water boards and the ministry of public works – are responsible for different parts of the water system. Zoomed in on extreme precipitation the water boards are responsible for the drainage of excess rainwater via the surface water system and the municipalities for drainage of waste water and excess rain via the sewer system. The ministry of Public Works is responsible for the drainage of excess water from high ways and the main water system. For an integral analysis of the water system the municipalities, waterboard and the ministry of public works must work together in order to couple the knowledge about all water systems. This co-operation turns out to be difficult in reality which can be because of different reasons. Because municipalities, water boards and the ministry are different government authorities and responsible for different parts of the water system data and knowledge about the systems is often split between them. The different government authorities may also have different interests in areas which may or may not be flooded as other parties are involved. Co-operation can also lead to new insights which may complicate the situation for one of the parties involved so sometimes it can be more convenient not to know. Each government authority also has its own budgets which can complicate the co-operation process. The above mentioned possible obstructions to co-operation are amplified by the fact that there are numerous municipalities within the area of a single water board and the possibilities of a municipality to lie within the area of multiple waterboards. This can increases the number of parties involved and results in a large amount of co-operation processes for the water boards with all the different municipalities. This separation of organizations, responsibilities, budgets, knowledge and data often leads to separate stress tests performed by municipalities, waterboards and the ministry. These separate stress tests often don't take the influences of the other water system into account or do so in a very simplified manner. Because of this, a lot of the times separate hydrodynamic models are constructed for the surface water systems and the sewer systems, often in different hydrodynamic software packages. However, if we look at the Delta program 2018 it is stated that all parties involved in a certain area must cooperate during these stress test analysis. This means that municipalities and water boards must share data and knowledge about the functioning of the two systems and maybe even perform integral stress tests for sewer and surface water systems, even though this co-operation might be challenging.

In reality urban sewer systems and the surface water systems do in fact interact with each other at multiple locations, especially during extreme rainfall events. For example, the rural surface water system receives water from the urban area at sewer overflow locations or directly as surface runoff. If the surface water system overflows, water could flow into the urban area. It might also be possible that sewer overflows cannot discharge their water freely because of high water levels in the receiving surface water body. The sewer system fills which can lead to more flooding in urban areas. This interaction is also acknowledged in reports about standardisation of stress tests and water system analysis of regional water systems (STOWA, 2011; Werkgroep standaardisatie stresstest wateroverlast, 2018). The total sewer-surface water system actually functions as one system, and separating it into different models for different analysis might lead to an underestimation of the actual flooding and damage. Some separate sewer and surface water models do apply inputs or boundary conditions from the other system. Think of a constant water level downstream of a sewer overflow as a boundary condition or sewer overflows as point inputs in the surface water system. However, this won't represent the real flow dynamics and interaction between the sewer and surface water system during extreme precipitation as in reality.

In this research the interaction between the urban sewer system and the regional surface water system of Schijndel will be analysed during extreme precipitation events. The objective is to investigate how severe flooding caused by extreme precipitation is underestimated when the urban drainage system and rural surface water system are analysed separately instead of coupled. For this research an integral hydrodynamic sewer-surface water model will be constructed for the study area of Schijndel. The hydrodynamic model build-up is based on the state of the art in hydrodynamic modelling and builds on knowledge gained from a selection of recent studies.

1.2 Research questions

The research objective has resulted in multiple research questions which must be answered during this research.

The main research question is:

Is flooding caused by extreme precipitation underestimated for Schijndel with the current separate analysis of the sewer and surface water systems when compared to an integral analysis of the sewer-surface water system?

Sub-questions:

1. Which analysis must be performed on the hydrodynamic model of the Schijndel in order to be able to analyse the interaction between the sewer and surface water system during extreme precipitation?
2. In what way can the urban area be linked to the surrounding catchment in a hydrodynamic model to investigate the interaction between the sewer and surface water system?
    - What is the state of the art in hydrodynamic modelling and what challenges arise when modelling a combined sewer-surface water system
    - What are the most sensitive parameters to take into account while modelling a combined sewer-surface water system?
    - What are the requirements set to the hydrodynamic model for the study area of Schijndel?
    - Which processes, mathematical equations and parameters must a hydrodynamic mode contain to be able to link flooding problems in both sewer and channel systems?
    - Does the hydrodynamic software package Infoworks ICM offer sufficient modelling capabilities to model the desired model concept and what are the possible shortcomings?
3. How does the case study area of Schijndel react to extreme precipitation?
    - Is flooding caused by extreme precipitation under-/overestimated when the sewer and surface water systems of Schijndel are modelled separately instead of combined?
    - How does the sewer-surface water system of Schijndel react to different intensities of precipitation events?
    - How does the hydrodynamic model of Schijndel respond to a change in sensitive model parameters and how can this knowledge be used for possible future calibration?
    - Does a coupled sewer-channel model have added value relative to a separate sewer-channel model for the study area of Schijndel?

1.3 Readers guide

In chapter two recent literature on the developments in the field of hydrologic calculations and hydrodynamic modelling is discussed. This results in an overview of important model components and sensitive model parameters. Chapter three is the methods section. At first the research build-up is discussed which is followed by a description of the analysis which will be performed and the hydrodynamic configuration. The analysis will be with a hydrodynamic model which is constructed for the case study area of Schijndel. The model is constructed in Infoworks ICM. The case study and the corresponding model are discussed in chapter four. A description of the study area, data used, and model built-up in Infoworks ICM is given. The results of the analysis for the case study of Schijndel are shown in chapter five. In chapter six the research is discussed and in chapter seven the conclusions and recommendations are given.

1.4 Delineation

This study will not include water quality aspects and sediment transport. The model will not be calibrated because of data and time constraints. Instead, different model configurations and precipitation inputs will be compared and analysed in order to investigate the functioning of a combined sewer and channel network. This includes an analysis about the sensitivity of the results with respect to choices of model setups and parameters.

2 Hydrologic calculations and hydrodynamic modelling

In order to analyse the interaction between the urban sewer system and the rural surface water system of Schijndel a hydrodynamic model must be created. In this chapter literature on the history of hydrologic calculations and current day hydrodynamic models is discussed. It gives an overview of the developments in this field which have led to current day hydrodynamic models. The state of the art in hydrodynamic modelling is discussed based recent studies which gives an overview of important model components and possible challenges while modelling a combined sewer-surface water model. There are multiple parameters within a hydrodynamic model which determine the model outcome. An overview of sensitive model parameters discussed in recent literature is given. The chapter ends with an overview of lessons learned from previous studies.

2.1 History

Rainfall runoff calculations have evolved over the years. It started with hydrologic calculations to determine peak discharges and runoff hydrographs. This developed into computer based hydrodynamic models which are based on runoff hydrographs and physical equations which determine flow in the drainage system.

2.1.1 Hydrologic calculations

Hydrologic calculations have a long history with ongoing developments. According to Goyen (2000) the first hydrologic calculations were based on the rational method which was first proposed for agricultural land in 1850 by Mulvaney, later on Kuichlling (1889) and Lloyd-Davies(1906) used this method on urbanized catchments. The rational method, Q=C*I*A, was used to determine the peak discharge of a catchment (Q) and is based on the extreme design rainfall intensity (I) as a function of the time of concentration , the catchment area (A) and a catchment specific coefficient (C). Until today this method is still very popular.

Goyen (2000) states in the beginning of the 20th century the first literature on hydrograph methods emerged. The hydrograph methods were developed to estimate the peak discharges as well as the total runoff hydrograph. Ross (1921) and Hawken (1921) were one of the firsts to develop these hydrograph methods in specific the idea of time-area routing. Later on Sherman developed the unit hydrograph (1932). The unit hydrograph resembles the watershed response in terms of volume and timing to an input of rainfall. Further developments with hydrograph methods include the work that routes rainfall through one or multiple storage reservoirs. By routing inflow through these reservoirs, a catchment output hydrograph can be constructed. This started with Clark (1945) who routed rainfall excess through a single linear reservoir. The hydrograph model of Nash (1960) resembles the catchment with multiple identical linear storage reservoirs is series. Laurenson (1964) continued with the idea of storage reservoirs in series but used non-linear reservoirs instead. The preceding work focussed primarily on large rural catchments.

2.1.2 Hydrodynamic modelling

Further developments, in combination with the rise of computers, led to the first computer-based hydrodynamic models for urban areas. One of the first widely used models was the Storm Water Management Model (SWMM) which was released in 1971 (Goyen, 2000; Rui Daniel Pina et al., 2016; Wilbrink, 2010). The model was used to analyse combined sewer overflows. The model build up comprised the integration of a runoff routing model with a onedimensional (1D) sewer flow model. The above ground surface was divided in so-called sub-catchments for which runoff hydrographs are constructed based on a single non-linear reservoir. A sub-catchment is an area that drains to a specific point in the sewer network. Based on these runoff hydrographs flow is routed to the drainage network. Inside the drainage system the water is routed based on physical momentum and continuity equations. If water overflows the drainage system at a certain drainage node it is stored above this node in virtual, for example cone-shaped, features. Once part of the sewer capacity is available again the water drains back into the sewer system. The SWMM was further developed over the years which made it able to model the flow in open channels as well as conduits.

The idea of sub-catchments, which by 1971 were typical for pipe drainage models, changed the way total catchments were modelled. Goyen and Aitken developed the Regional Storm Water Model (RSWM) in 1976 (Goyen, 2000). The total catchment was divided in sub-catchments which were linked together by a series of pipes and channels, this was similar to urban drainage schemes at that time. Between sub-catchments and links, storage reservoirs could be present which allowed the representation of reservoirs or lakes. Hydrographs for the sub-catchments were created in the same way as was previously done for the catchment as a whole.

A few years later the need to model both sewer/channel flow as well as surface flow paths was acknowledged. Gray (2008) and Rui Daniel Pina and colleagues (2016) state that the first attempts to do this were conducted by Ellis (1982) and Kassem (1982). The concept of dual-drainage was introduced which meant the coupling of an overland model with a sewer model. A 1D overland flow model was coupled to a 1D sewer model. At this points the overland flow paths still had to be defined by the modeler in advance. During the 1980s and 1990s a lot of improvements were made on these so called 1D1D models.

The concept of 1D1D models was further developed into 1D2D models with the introduction of a 2D overland flow model in the early part of the 1990s. A 2D surface grid with height differences is constructed based and the topography of the landscape. One of the advantages of the 2D overland model was the fact that surface flow paths didn't have to be pre-assigned because flow is routed based on the topography and corresponding height variations in the 2D grid. Another advantage, if water overflows from the sewer or surface water system it can flow on the 2D surface grid and show nuisance locations on the surface instead of being kept in a 'virtual' cone above the drainage node. The wide spread use of the 2D model only came with the introduction of the Geographical Information System (GIS) and the increase in computer power during the late 1990s and the early 2000s (Gray, 2008; Rui Daniel Pina et al., 2016; Sto. Domingo, Refsgaard, Mark, & Paludan, 2010; Wilbrink, 2010). The 1D2D modelling concept is considered the state of the art in hydrodynamic modelling and recent studies each try to improve the concept.

2.2 State of the art in hydrodynamic modelling

In the recent years the state of the art in hydrodynamic modelling are coupled 1D pipe/channel and 2D overland flow models. These models are capable of calculating flow through the sewer/channel network, runoff and flooding on the surface as well as the dynamic exchange of water in between (Sto. Domingo et al., 2010). Within 1D2D models a distinction can be made between models were rainfall is applied to sub-catchments Figure 1(A) and models were rainfall is applied directly onto the 2D grid Figure 1(B).

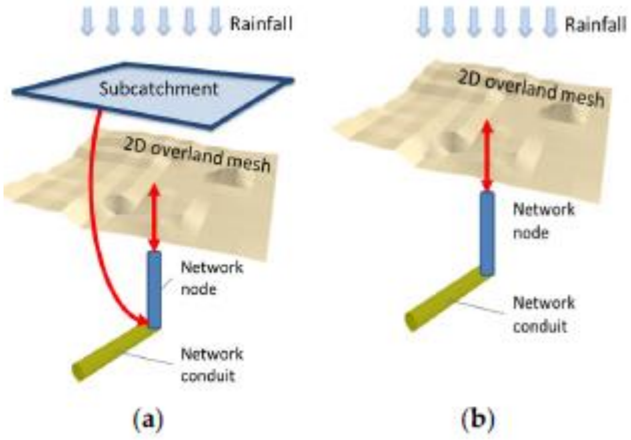

Figure 1: Rainfall routing – Sub-catchments (Left) – 2D grid (Right) – (R.D. Pina et al., 2016)

For the models where rainfall is applied to the sub-catchment the total catchment is first divided in these sub-catchments. Each sub-catchment is connected to a given discharge point, this may be a node, channel or even another sub-catchment. An outflow hydrograph is created for every sub-catchment based on land use and routing parameters. The runoff routing functions can be based on physical, empirical or conceptual methods. When the drainage system is overloaded flooding originates from the drainage system outwards. The latest type of 1D2D models is based on the 2D surface layer. Rainfall is applied directly to each 2D grid element and is routed, based on physical equations, via the 2D surface to the nearest drainage inlet. Hydrologic processes like infiltration and evaporation may be added to the 2D grid depending on the possibilities of the calculation tool and the modelers choices (Rui Daniel Pina et al., 2016). Over the recent years these 1D2D models have evolved where each study intended to improve the 1D2D hydrodynamic model concept. A brief overview of recent studies will be given below:

In (2016) Rui Daniel Pina and colleagues compared the two 1D2D model setups. The first one where precipitation was applied to sub-catchments and the second one where precipitation was applied directly to the 2D grid. With the exception of roofs which are modelled as sub-catchments so they can drain directly to the sewer. They conclude that physically based models where precipitation is applied directly to the 2D grid have the potential to be more realistic than models where rainfall is applied to sub-catchments. The reason for this is that by applying rainfall directly to the 2D grid simplifications and spatial data aggregation of the routing processes are minimized. This includes detailed representation of surface ponding (initial losses) and continuing infiltration (continuing losses) in depressions even after the end of a precipitation event. It also gives a detailed representation of surface water on its way to the nearest drain. There is also the difference in the runoff routing. This isn't possible with the sub-catchments method. The sub-catchments method uses a rainfall-runoff module to translate rainfall into catchment runoff hydrographs. This may simplify the actual runoff dynamics. If rainfall is applied directly to the 2D surface a more detailed representation of the runoff process is possible.

Gray (2008) tested the use of a 1D2D model, where rainfall excess was applied to a 2D grid and routed with the diffusive wave equations, on a well gauged catchment. The roofs were connected directly to the sewer. Gray did not use hydrological parameters like infiltration, or groundwater flow but used a loss map that applied a constant loss to the rainfall excess based on land use and the event modelled. Gray concludes that the model is able to reproduce gauged flows without the need for variation of model parameters other than proportional losses applied. He further states: "A real step forward would be the integration of an infiltration model that not only gave a reasonable estimate of the antecedent condition but that also allowed for a varying level of infiltration during the event including total saturation"(Gray, 2008, p. 99). As example the Horton infiltration method is stated.

Wilbrink (2010) tested the applicability of 1D2D models for flood prediction in urban areas. In order to verify the calculations of the 1D2D model Wilbrink compared the simulation results with hand calculations and a 1D1D model for several common profiles like streets and intersections. He concludes that the 1D2D model gives similar results as the 1D1D model and hand calculations. Wilbrink also performs analysis on a 1D2D sub-catchment based model where surface flow was routed based on the shallow water equations (SWE). The choice for a sub-catchment approach instead of applying precipitation directly on the 2D grid is based on the fact that the calculation tool could not incorporate infiltration and evaporation directly in the 2D grid, which is desirable. It is concluded that the accuracy of the results from 2D overland flow depends on the level of detail of the ground data digital elevation map (DEM) which is used a data source for the 2D grid and the size of the 2D grid elements. Wilbrink notes that the 1D2D connection must be made at the location of gully pots instead of manholes because they are the lowest points in the street.

In the study of Sto. Domingo and colleagues (2010) a hydrologic model is dynamically linked with a 1D2D pipe flow model in order to simulate the full water cycle for flood modelling in a catchment that consists of impervious and pervious areas. According to them, the state of the art 1D2D models perform well for highly paved urban areas but lack precision for pervious areas where hydrological processes are important. In the newly proposed 1D2D hydrologic-hydraulic model, rainfall that falls on the impervious areas is routed to the sewer system based on the sub-catchment approach. Rainfall over pervious surfaces is taken into account in the hydrologic model which considers overland flow based on the diffusive wave equation, evapotranspiration, infiltration, groundwater flow and abstractions. The hydrologic model interacts with the pipe model at manholes, channels and pipes. The newly proposed 1D2D hydrologic-hydraulic model is compared to a traditional existing 1D2D sewer model and tested on a new catchment and gauged data. The results show that the runoff from the pervious areas in the upper catchment influences the flooding in the lower urban catchment. It was therefore concluded that it is important to include pervious areas with hydrological processes like infiltration, evaporation and groundwater flows in hydrodynamic models.

Fernández-pato and colleague (2016) investigated if the two empirical infiltration laws of Horton and Green-Ampt could be used to estimate infiltration in a watershed in combination with a distributed physically based model which used the 2D SWE. This study did not include a sewer system. It is stated that when the focus is on overland flow the empirical infiltration methods of Horton and Green-Ampt are considered to work best for rainfall-runoff calculations in real basins. According to them this technique offers the capability to assign local and time-dependent infiltration to each computational grid cell based on available water, soil type and vegetation. They point out that infiltration parameters ideally must be calibrated and that the calibration is sensible to topography, initial conditions and rainfall patterns. The study points out the need for spatially distributed infiltration models instead of lumped models. In spatially distributed infiltration models water can flow to the lowest point in a catchment and keep infiltrating even when the rainfall stops. This will not happen in lumped models. According to this study an infiltration map which considers different soil types significantly improves the agreement between numerical and experimental hydrographs in both infiltration models.

There are multiple hydrodynamic software packages available which can be used to build hydrodynamic models that are used for stress tests. Because all Dutch municipalities and water boards have to perform these stress tests STOWA released a benchmark in which they compared the capabilities of hydrodynamic software packages commonly used in the Netherlands (STOWA, 2017). In the benchmark these hydrodynamic software packages were submitted to seven test cases, which often occur in reality to test the accuracy of the calculations. In 2017 they conclude that the hydrodynamic software packages Infoworks ICM, SOBEK2, 3DI and in the near future D-hydro are the most suitable for integral calculations on sewer-surface water system (STOWA, 2017). They note that the accuracy of flood calculations is much more dependent on the quality of the modeller and the available data than on the software package that is used. They further note that most hydrodynamic software packages use the Shallow water equation (SWE) for surface flow calculations and the 1D Saint Venant equations for calculations in the sewer and surface water system. Some packages use more simplified forms of the SWE like the diffusive or kinematic wave equations. The only packages reviewed not using the SWE are WOLK and Tygron.

2.3 Parameter sensitivity in hydrodynamic models

When using hydrodynamic models there are a couple of important parameters that influence the model response. Choosing these parameters with care is of great importance. An overview of sensitive model parameters as described in recent literature is given.

Adeogun, Darmola & Pathirana (2015) investigated the influence of modelling parameters on a 1D2D hydrodynamic inundation model for case study and a virtual environment. This model did not incorporate hydrological processes like infiltration. They performed a sensitivity analysis to provide insight into the influence of certain input parameters on the model performance. They conclude that input parameters, such as DEM resolution, grid size and roughness can significantly influence the performance of the model. Changing these parameters influences flooding characteristics such as the inundation extent, flow depth and velocity across the model domain.

The 2D surface grid used for hydrodynamic models is based on a DEM. The elevation of the grid elements is taken from the underlying DEM. A detailed DEM layer is required if a detailed 2D surface grid is to be constructed. The study tested different resolution input DEMs while keeping the grid size constant. The results show that the inundated area was constant for a DEM resolution of 1-5 m^2, it increased significant with a DEM resolution of 6 m^2 and then largely decreased for a DEM resolution of 10 m^2. The results for a DEM larger than 5 m^2 were deemed unacceptable because the topography of the area isn't represented correctly.

A variety of grid sizes from 7 m^2 to 200 m^2 were compared in this research. For the grid resolution they concluded that a better representation of the flood map was achieved with smaller grid elements at the cost of longer calculation times. A larger grid size reduced the computational time but compromised the representation of the inundated area. The results show that the total inundated area decreases with a larger grid size. The reason for this is that the topography and flow pats within an area are not represented correctly with a larger grid size. The elevation is averaged over larger grid elements which may no longer constitutes a good representation of the depressions in the landscape.

In order to investigate the sensitivity of the friction factor a variety of friction values from the physically plausible range were tested for different grid sizes. These were manning's n parameters in the range of 0.02-0.05 [$s/m^{1/3}$] and grid sizes varying between 5-100 m^2. The friction factor has an influence on the flood as it propagates across the floodplain which they described in the Manning formula below:

$$V = \frac{1}{n} \times R^{\frac{2}{3}} \times S^{\frac{1}{2}}$$

Where V is the cross-sectional average flow velocity (m/s), R is the hydraulic radius (m), n is the Manning friction parameter ($s/m^{1/3}$) and S is the slope (m/m). As can be seen in the above equation the friction parameter is inversely proportional to the flow velocity. Increased flood plain resistance will decrease the flow velocity and eventually reduce the area covered by the flood. The results show that the effect the roughness value has on the flooding extent increases with a finer grid resolution of $5m^2$. The flood extent decreases with a larger roughness value for these small grid elements because the water flows slower. It is stated that it is advised to analyse the response to several combinations of roughness values for every urban flood modelling study instead of relying on a single parameter set.

Another sensitive mode parameter which is not included in the study of Adeogun and colleageus (2015) is the infiltration capacity. Hydrodynamic models that incorporate permeable surfaces often use infiltration methods to account for this infiltration. The infiltration capacity is of great importance for the catchment runoff and has a high spatial and temporal variability because of the heterogeneity of the soil and vegetation. The input parameters for the infiltration methods therefore have a great impact on the model results. Beek (2019) measured the infiltration rate for different unpaved surface in urban areas. Beek found a great variability in infiltration capacity for the different unpaved surfaces in the urban area. He concluded that the compaction of the soil was of most influence for the infiltration rates in urban areas where other factors like, initial soil saturation, soil type and vegetation were also of influence.

2.4 Lessons learned from previous studies

The hydrodynamic model concept which will be used for the analysis of the sewer-surface water system of Schijndel should closely connect to the state of the art in hydrodynamic modelling. The model setup will be based on the lessons learned from previous studies and will incorporate the important model components stated in different studies. An overview of the most important lessons learned is given in this paragraph.

In order to calculate surface flow different equations can be used. For the surface flow calculations the state of the art in hydrodynamic modelling are shallow water equations (SWE), also called the dynamic wave equations for 2D surface flow calculations. The 2D SWE represent a complete mathematical description of the physical phenomena related to surface water flow (Fernández-Pato et al., 2016; STOWA, 2017; Wilbrink, 2010). The SWE are derived from depth-integrating the Navier-Stokes equations for viscous fluid motion and consist of mass and momentum equations. Some studies also use more simplified forms of the 2D shallow water equations, the diffusive and kinematic wave equations(Gray, 2008; Sto. Domingo et al., 2010). The most commonly used equations for flow in the 1D sewer/channel network are the 1D De Saint-Venant equations. The 1D De Saint-Venant equations are the shallow water equations in unidirectional form. The 1D De Saint-Venant equations have a much shorter calculation time when compared to the SWE because only flow in the length direction of conduits/channels is calculated (STOWA, 2017).

Recent studies show there have been a lot of developments since the implementation of the first 1D2D hydrodynamic models. Physically based models, where precipitation is directly applied to the 2D grid, are increasingly being used as they are potentially more realistic than models based on the sub-catchment method (R.D. Pina et al., 2016). Therefore it is preferred to apply rainfall directly onto the 2D grid in hydrodynamic models. Except for roofs as these should directly drain to the sewer system as mentioned by R.D. Pina and colleageus (2016).

According to Sto. Domingo and colleageus (2010) 1D2D models are already widely used for calculations on impervious urban catchments but need improvement for the catchments with a lot of pervious areas. This is also stated in recent review articles on urban catchment hydrology (Fletcher, Andrieu, & Hamel, 2013; Salvadore, Bronders, & Batelaan, 2015). Current models lack hydrological processes like infiltration, evaporation and flow exchange between surface and groundwater or use very simplified forms of these processes. This makes it hard to predict multiple peak flows which are likely to occur in areas consisting of both pervious and impervious surfaces. This is also supported by Gray (2008) who notes that the integration of a time varying infiltration to his model would be a great step forward. Fernández-Pato et al., (2016) further note that the infiltration should vary not only in time but also in space. Infiltration and a groundwater component must ideally be included in future models.

As can be seen in recent studies the models are getting ever more spatially distributed using specific parameters and flow calculations per 2D surface grid cell. Recent review articles on urban (catchment) hydrology acknowledge this trend to more spatially distributed simulation models (Fletcher et al., 2013; Salvadore et al., 2015). This trend is the result of the ever increasing knowledge of natural phenomena, data availability and computer power. The increase in computer power allows for more detailed calculations on ever larger systems. As described before models that only calculate in 1D with the 1D De Saint-Venant equations have a smaller calculation time than models that use the SWE for 2D surface flow calculations. The increase in computer power allowed the modellers to switch to models that calculate surface flow on a 2D surface grid with the SWE. As data of the surface layer, elevation and land use maps, get more detailed it is possible to use smaller grid cells for the 2D surface grid. This trend to more spatially distributed models will continue in the future and in time will allow for even more detail or extra components to be added to the models.

Most of the previous studies that used 1D2D hydrodynamic models focussed on the sewer system and corresponding flooding in urban areas (Gray, 2008; Rui Daniel Pina et al., 2016; Wilbrink, 2010). In these models there is no connection between the sewer system and the channel system surrounding the urban area. The study of Sto. Domingo and colleagues (2010) did included a surface water system of the rural area in the 1D2D model. They conclude that runoff from the rural upper catchment causes extra inflow into the lower urban catchment and they must therefore be connected. However, it is unclear in what way the sewer and surface water network are connected in their study. In publications on the standardisation of water system analyses and stress tests this interaction between the urban sewer system and the rural surface water system is acknowledged. It is advised to make integral analysis with both system which is not common practice in the Netherlands. (STOWA, 2011; Werkgroep standaardisatie stresstest wateroverlast, 2018).

The parameters used in the hydrodynamic must be chosen with care. As shown in recent literature of Adeogun and colleagues (2015) and Beek (2019) parameters like grid size, roughness, resolution input DEM and the infiltration capacity affect the model outcome.

3 Method

In this chapter the research method is presented. First a general overview of the research is discussed to get an understanding of the steps taken followed by an explanation of the analyses that need to be performed in order to answer the research questions. This leads to a hydrodynamic model setup which is the basis for the case study of Schijndel.

3.1 Research setup

In this research the interaction between the urban drainage and the rural surface water system of Schijndel is investigated. In the Netherlands these systems are often analysed separately instead of combined. This is because the responsibility lies with different government authorities either municipalities or waterboards. This may lead to an underestimation of the actual flooding and possible damage. In this research it is investigated how the two, the urban drainage and the rural surface water system, interact and function during extreme precipitation. Understanding the total system will eventually help to plan an effective strategy against rainfall induced flooding.

Because extreme rainfall events do not occur very often and most of the time there are no clear measurements of the actual extent of the flooding a tool is needed that can predict this flooding. In this study an integral 1D2D hydrodynamic model is constructed for the urban drainage system of Schijndel and the surface water system in the surrounding catchment area "The Schijndelse loop". Schijndel has been chosen because its an upstream catchment and therefore has no inflow from upstream which makes it an isolated catchment to analyse. This 1D2D hydrodynamic model is used to investigate the interaction of the urban drainage system and the rural surface water system.

A 1D2D hydrodynamic model configuration is set up based on the analyses that are to be performed, model outcome requirements and the lessons learned from previous studies. This model configuration must closely connect to the state of the art in hydrodynamic modelling. As shown above, STOWA concluded in their benchmark of different hydrodynamic software packages that Infoworks ICM, 3Di, SOBEK2 and in the near future (D-hydro) are all suitable for integral calculations on the sewer and surface water system. In this study the model concept will be translated into a working model for the case study of Schijndel in the hydrodynamic software package Infoworks ICM because this is the package Sweco often uses for these studies. This allowed for guidance during the modelling process.

This resulting integral sewer-surface water model of Schijndel is used to perform the pre-defined analyses and answer the research questions. Because of a lack of detailed discharge and precipitation data the model will not be calibrated, but different model configurations will be tested and compared. Together the results of these analyses should give insight in the overall functioning of the system, the interaction between urban and rural, and the sensitivity of some of the model parameters.

3.2 Analyses

In order to investigate the interaction between the urban drainage system and the rural surface water system a couple of analyses are performed. In this paragraph a more detailed explanation of the different analyses is given. The model outcome will be compared with known flood reports from the municipality of Schijndel. Two model setups will be compared with multiple precipitation events in order to investigate the differences in response. The first one where the sewer and surface water system are modelled separately, the second one where they are coupled. Finally, a sensitivity analysis will be performed on model parameters that are known from literature to be critical/sensitive. This helps to better understand the model response and evaluate the sensitivity of the parameters for a possible future calibration process.

3.2.1 Analysis 1: Check against flood reports

If the model cannot be calibrated because of a lack of detailed discharge and precipitation data it is still possible to compare the model outcome with known flood reports. This is a first check to see if the model outcomes correspond with reality. There is a list of known nuisance locations from the BRP (Basic sewer plan) report of Schijndel (Grontmij, 2009). In appendix A an overview of the flood reports is plotted on a map. This list will be compared with model outcomes for an event that occurs approximately once every five years ("*bui 9*") to see if the model response corresponds to reality, see Figure 2. This event is commonly used in the Netherlands to design urban drainage systems which has a return period of five years (DHV, Grontmij, 2004).

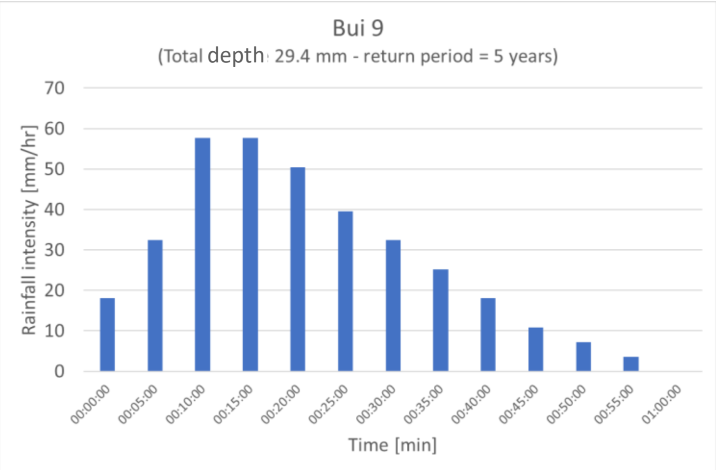

Figure 2: Precipitation event with a return period of five years (DHV, Grontmij, 2004)

3.2.2 Analysis 2: Separate vs coupled model setup

The interaction between the urban drainage system and the rural surface water system is investigated based on two model setups that are subjected to multiple precipitation events. The response of the two model setups will be compared. The results must clarify if current day separate urban drainage and rural surface water model setups potentially under- or overestimate the actual flooding and damage when compared to the integral model setup.

<u>Model setup 1</u>

In the first model setup, the sewer system and the surface water system are not connected at the locations of sewer overflows. The sewer system has free outflow at the location of these sewer overflows and the surface water system does not receive water from the sewer system at the location of sewer overflows.

Model setup 2

In the second model setup the two systems are connected and a dynamic exchange of water at the sewer overflow locations is possible during the duration of the calculations.

The model setups are analysed during multiple rainfall events, short and long duration and multiple intensities. The rainfall events are based on standardised precipitation events for stress-tests as described by a workgroup that is commissioned by the Dutch ministry of I&W, STOWA and RIONED (Werkgroep standaardisatie stresstest wateroverlast, 2018). The workgroup is commissioned to standardise the process of stress-tests. One of the components to standardise was the input of precipitation. They conclude that standardised events should have a **constant spatial and temporal intensity** over the study area. In addition, historic events can be tested according to the workgroup. The events that are used are based on a short and long duration precipitation event that have a return period of 100 years (T=100) in 2050. These events are:

- Short duration (T=100): 70 mm in 1 hour
- Long duration (T=100): 120 mm in 48 hours

The short duration events will most likely occur in summer, during which the soil will be unsaturated so dry initial conditions will be used for that. The longer duration event may also occur in autumn and spring when the groundwater table may be high and the soil partly saturated. For the longer duration events the saturation of the soil over time plays an important role on the model outcome. For this reason two conditions for the infiltration will be modelled and compared for the long duration event. This first one with an initial soil saturation of 80% and the Horton infiltration method in order to mimic a high initial soil water content which can occur during spring or autumn. This will results in a final constant infiltration rate which is reached after a certain amount of time. The second one with no infiltration at all. This should help to analyse the influence infiltration and possible total saturation have on the model outcome for long duration precipitation events.

To get a better understanding of the functioning of the system during different rainfall intensities the two model setups will be submitted to extra precipitation events. These are based on the short duration event but with different intensities. These events also have a constant spatial and temporal intensity. The additional events used are:

- Short duration (T=10) 30 mm in 1 hour
- Short duration (T=40) 50 mm in 1 hour
- Short duration (T=500) 90 mm in 1 hour

The response of the two model setups can be analysed based on multiple parameters. Think of the difference in flood extent, flood duration, flood depth, combined sewer overflow response, and buildings flooded. The variety of parameters which can be analysed already illustrates the complexity in the way the system can respond. Besides that, the influence the urban drainage system and the rural surface water system have on each other will be probably location specific because the interaction between the two systems takes place where the two systems meet. For this reason the results will zoom in on an area of interest after an overview of the entire area is given for the events with a return period of 100 years. The area of interest will be chosen based on the results. The focus in the results will be on the difference in flood depth, flood extent, flood duration and houses flooded. Building are considered flooded when the water depth surrounding the building is larger than 10 cm.

3.2.3 Analysis 3: Sensitivity analysis

In the literature some sensitive model parameters were discussed. Because at this point the model cannot be calibrated properly but might in the future a pe-calibration sensitivity analysis is conducted for the sensitive parameters. This analysis will yield the parameters that are of most influence on the outcome of the model and should therefore be studied in detail during a possible future calibration process. The parameters that will be tested during this sensitivity analysis area the grid size, roughness and initial infiltration rate of the unpaved surface. The results are compared based on flooding extent and the catchment outflow hydrograph. The parameters will be tested for the coupled model setup during the short duration 70 mm in 1hr precipitation event because this is the event that is commonly used in the Netherlands during stress-tests.

For the grid size three alternative are compared ranging from small to large, differentiating between urban and rural areas and based on the parameters used for the case study. This in order to analyse the difference in response for a detailed a less detailed representation of the surface layer. For the roughness four constant roughness values for the whole study area are compared. These manning values are based on the literature and range from 0.02-0.05 [$s/m^{1/3}$] (Adeogun et al., 2015). For the infiltration on the unpaved surfaces also four alternative initial infiltration parameters are compared ranging from a small to large initial infiltration rate based on the parameters used in the case study.

3.3 Hydrodynamic model setup

The hydrodynamic model that is used for this study must be able to perform the analysis previously defined. In order to do this, certain requirements with respect to the model outcome must be met. Based on these requirements and the lessons learned from previous studies a hydrodynamic model configuration is described. This model configuration closely relates to the state of the art in hydrodynamic modelling and is the basis for the hydrodynamic model of the case study. As described in the literature the reliability of the model outcome is closely related to the parameters that are used. The parameter requirements are discussed which are used to determine the input parameters of the case study.

3.3.1 Model outcome requirements

In order to analyse the integrated water system the model outcomes must represent all parts of the urban drainage system and the rural surface water system. The discharge and head must be calculated in the surface water system, the sewer system, the locations where they interact and the land and street surface once the surface water system and sewer system get overloaded.

The dynamic exchange of water at the location of combined sewer overflows must be modelled throughout the duration of a precipitation event. This helps to give a representation of possible bottlenecks and locations with a backwater effect. This is needed to investigate the interaction between the urban drainage system and the rural surface water system.

This research doesn't include a calibration process because of data and time constraints. However, for a possible future calibration process the model must be able the deliver discharges at the locations of combined sewer overflows and in the surface water system over the duration of the event.

A surcharge of the sewer system and the surface water system doesn't automatically lead to nuisance and damage. This depends on the location and the magnitude of the flooding event. It is therefore desired to represent surface flooding in space and time. This includes the representation of depth, flooding extent, flow direction and flow speed. The flooding locations can be compared to known nuisance locations in order to verify the model outcome.

The model must be suitable for water system analysis. Once flooded locations are identified location specific interventions can be planned based on calculated flow paths and flooding extent. It is important that the model is able to represent the flooding at small time steps in the order of minutes. This way the system response can be analysed over the course of the extreme precipitation event which often take place within a short period of time.

This concludes the following outcome requirements for the hydrodynamic model:

- Representation of discharge and head in all parts of the sewer and surface water system in space and time
- Representation of surface flood extent, flow paths and flow velocity in space and time
- Representation of results with a time step in the order of minutes because short duration events will be analysed

3.3.2 Model configuration based on literature

The model configuration should closely connect to the state of the art in hydrodynamic modelling and must be able to deliver the desired model outcomes. It must include certain model components and apply the lessons learned from literature. In Figure 3 an example of a coupled (combined) sewer and surface water system can be seen. The atmosphere controls the precipitation inputs and the evaporative outputs. The precipitation falls on the surface layer which consists of roofs, unpaved surfaces and paved surfaces. The water infiltrates to the groundwater or continues as surface runoff and finds its way to the nearest drainage point in the sewer-surface water system. During extreme precipitation the sewer and surface water interact at the location of sewer overflows. The combined sewer surface water system is divided in four groups: the atmosphere, the surface layer, the sewer-surface water system and groundwater. Based on these groups the model configuration is described.

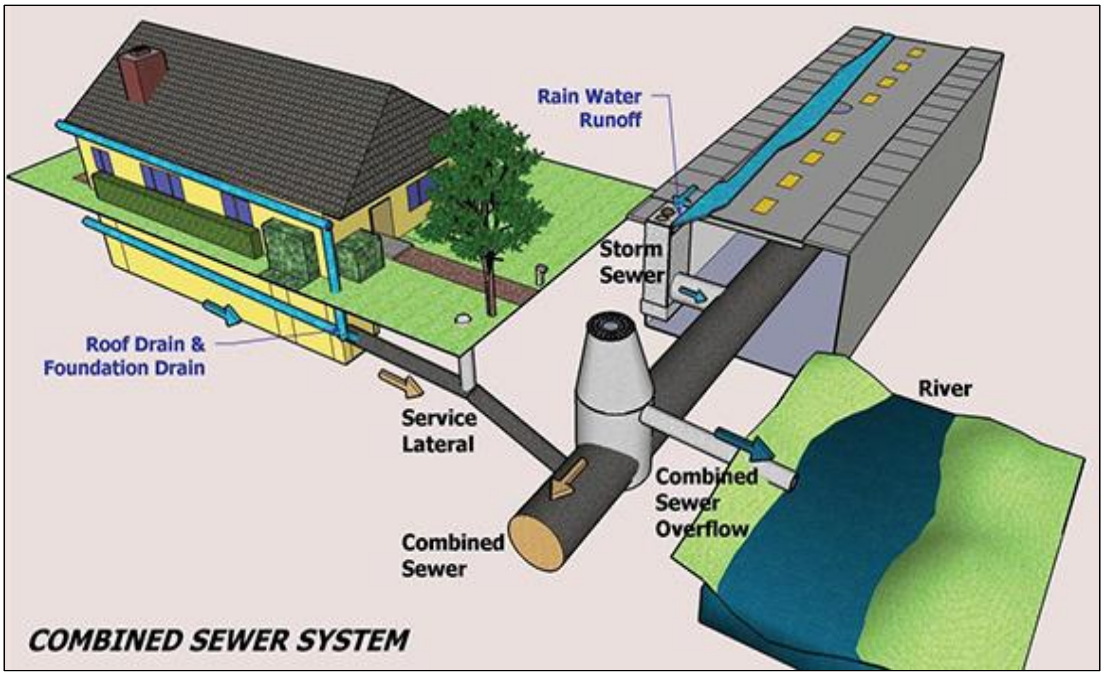

Figure 3: Example of a coupled (combined) sewer – surface water system, source: https://therouge.org/combined-sewers/

Atmosphere

It must be possible to included atmospheric inputs/outputs like precipitation and evaporation. This study does not aim to calibrate the model but instead compared different model configurations and precipitation inputs. As described before the precipitation inputs used for this study have a constant spatial and temporal intensity. The event that is used to check the model against known flooding locations is spatially constant but time variable. If the model is to be calibrated in the future is might be desired to include spatially and time variable rainfall. It must thus be possible to add precipitation which varies in time and space. Evaporation may be neglected for the short duration rainfall events but might be of influence for the long duration precipitation events. It must be possible to include time varying evaporation values.

Surface layer

As can be seen in Figure 3 the surface layer consists of both pervious and impervious surfaces that determine the runoff process. The model must be able to predict runoff and flooding on both impervious and pervious surfaces. It must therefore include the infiltration and roughness of the area.

The infiltration and roughness must have a spatial and temporal variability based on land use, soil characteristics and initial conditions. (Fernández-Pato et al., 2016; Gray, 2008; Sto. Domingo et al., 2010). The empirical infiltration methods of Horton and Green-Ampt are the most common mentioned in the literature. The infiltration loss is the most important hydrologic water loss in a catchment as stated by Fernández-Pato (2016). Within this model the focus is on overland flow and flooding. Fernández-Pato (2016) states that when the focus is on overland flow, infiltration participates as water volume loss and can be best be formulated using empirical laws like Horton and Green-Ampt (Adeogun et al., 2015; Gray, 2008). The study area should be divided in areas of different infiltration rates based on land use and soil properties to get the best results. This way the infiltration can be computed spatially and temporally. In the work of Fernández-Pato and colleagues (2016) infiltration was seen as a loss and excluded from further calculations. This may however not always be a valid assumption. Part of the infiltrated water will normaly percolate to the deep ground water from where it may contribute to the channel system as base flow.

According to recent literature it is advised to use a detailed 2D surface model for the runoff routing where precipitation is applied directly to the 2D surface grid (R.D. Pina et al., 2016). The 2D surface model consists of grid elements each having their own land use characteristics and elevation (see Figure 4). For the land use characteristics a land use map is used an the elevation is taken from an underlaying DEM layer. This allows for a detailed representation of the topography of the area, depression storage and spatially different infiltration and roughness. The roofs however are often connected directly to the urban drainage system. In the model the buildings and corresponding roofs should therefore be connected to the sewer system and left out of the 2D surface model, an example can be seen in Figure 4. The discharge or roofs in normally represented with the sub-catchment approach. A sub-catchment in the drainage network represents the physical area from which a manhole or channel collects water, which may be a collection of roofs. Rainfall is routed for this area based on empirical or physically based methods and transformed into inflow hydrographs for the drainage system.

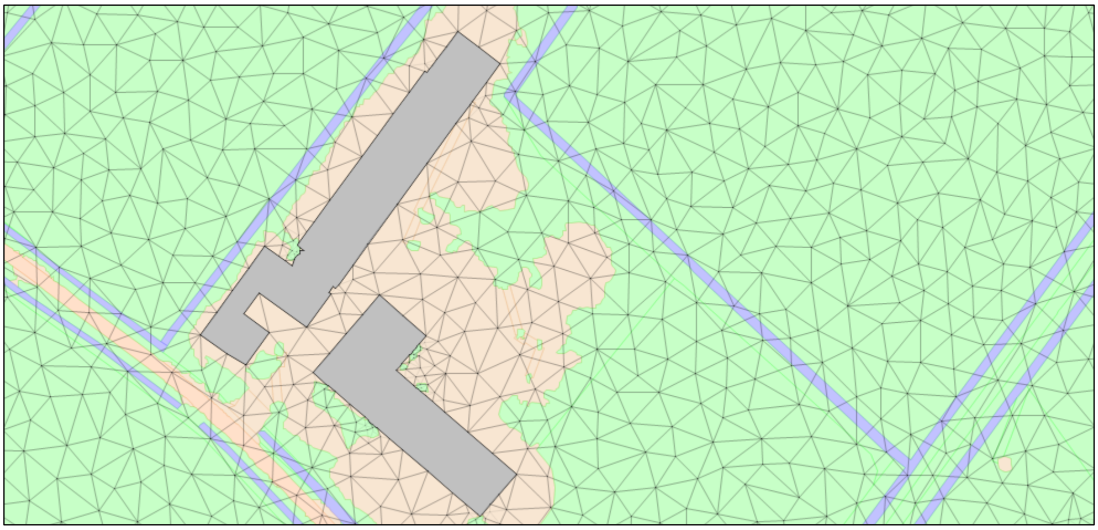

Figure 4: Example of a triangular surface grid

Because the model needs to deliver detailed flow calculations on the land surface it is important to use detailed physically based flow equations for this. As mentioned in chapter two the state of the arts in hydrodynamic modelling is the use of the shallow water equations (SWE). These SWE will be used for this study.

<u>Groundwater</u>

Part of the infiltrated water reaches the groundwater system. Part of the groundwater may contribute as base flow to the surface water system (Sto. Domingo et al., 2010). During extreme precipitation part of the infiltrated water may force extra baseflow to the surface water system. The magnitude of this effect is dependent on local conditions like the groundwater level, the composition of the soil, and the duration of the calculated event. The effect of this can be of different influence for polder areas with high groundwater table during longer precipitation time series versus highly permeable soils with a low groundwater table for short duration events. Ideally the baseflow to the channel system should be modelled based on groundwater level and infiltration as a results of a precipitation event.

Sewer and Surface water system

In order to calculate the flow through the sewer and surface water systems correctly these systems must be included with all hydraulic structures. This includes, weirs, pump, pipe dimension, channel cross sections etc. Flow through pumps should be based on head-discharge curves and flow over weir should be calculated based on the weir equations. The flow calculations must be based on the 1D Saint-Venant equations. These are the state of the art in hydrodynamic modelling (Gray, 2008; STOWA, 2017; Wilbrink, 2010). The sewer system must be connected to the surface layer at the location of gully pots and roofs should directly drain to the sewer system. The interaction between channels and the surface layer must take place over the entire length of the channels.

This results in the following requirements for the model configuration:

- Atmospheric inputs
  - Spatial and time variable precipitation
  - Time variable evaporation
- Surface layer
  - Rainfall applied to the 2D grid and routed via the surface grid
  - Roofs drain directly to the sewer system
  - Surface flow calculations based in 2D shallow water equations
  - Spatial and time variable infiltration base on empirical equations of Horton or Green-Ampt
  - Spatially variable roughness
- Sewer and surface water system
  - Flow calculation based on 1D Saint-Venant equations
  - Connected to the surface model at gully pots
  - Connected to the surface model along channel lengths
- Groundwater system
  - Base flow to the channels based on infiltration and ground water table

3.3.3 Parameter requirements

A hydrodynamic model is as strong as the parameters that are put into it. It is of great importance to define these with care. For the sewer systems this means the correct dimensions and parameters of **all** hydraulic structures, including roughness, the pump capacities etc. In the 1D surface water model it is important to include all of the channels and ditches for which reliable data is available. Don't include elements with questionable data. Check it or find another way to represent the features. The rest of the waterways and ditches should be represented in the 2D surface grid as depressions based on elevation data from the DEM. Hydraulic structures like weirs, bridges and culverts must be included in the 1D surface water model with their correct dimensions and parameters.

The runoff of a catchment is based on the land use within that catchments. When rainfall is applied directly to the 2D surface each grid cell has a certain land use assigned to it. Based on that land use it is determined if water infiltrates or runs off and which roughness is assigned. Roofs for example directly drain to the sewer system, water on permeable surfaces can infiltrate and water on impermeable surfaces will flow to the lowest nearby point. It is therefore of utmost importance to use a detailed land use map as input for the hydrodynamic model.

The size of the grid cells and the DEM that is used as data layer for the elevation also determine the model outcome. Adeogun et al. (2015) describe in their study that input DEM with a resolution of 1-5 m^2 gave similar results but a DEM with a resolution of $10m^2$ gave unacceptable results. Because the grid cells take their elevation from the DEM the resolutions of the DEM should be smaller than the average area of the grid cells. Otherwise multiple grid cells get their elevation from the same DEM tile. The DEM with the smallest resolutions which is available has to be used.

Adeogun et al. (2015) also describe that a better representation of the flood map is achieved with a smaller grid size, but with higher computational time. They conclude that the level of detail, and corresponding grid size, should be based on the area of interest. Is must be a balance between detailed required and desired calculation time. Small grid sizes must be used in the highly heterogeneous urban area whereas slightly larger grid sizes can be used for the more homogeneous rural area. A variety of grid sizes will be tested in order to investigate the influence on the model outcomes.

The roughness of the area is of influence on the flow speed of water and the propagation of the flood over the area. A higher roughness slows down the flood speed and eventually decreases the flooded area. Adeogun et al. (2015) found that the influence of roughness on the flooding extent is much higher for smaller grid sizes. The roughness depends on the land use in the area and is spatially variable over the catchment. It is therefore important to use roughness parameters based on land use, specifically for the small grid cells. In the sensitivity analysis (SA) multiple roughness values are tested to better understand the influence this value has on the system.

One of the most influential parameters is the infiltration capacity of the permeable surfaces. This determines what amount of the rainfall infiltrates to the groundwater or continues as surface runoff. In the research of Beek (2019) he investigates the spatial difference of infiltration for different unpaved surfaces in urban areas. He concluded that the infiltration capacity is highly spatially variable and depends on the compaction of the soil, soil composition and soil saturation. It is therefore of great importance to understand the impact of the infiltration parameters that are used as input for the model. The infiltration parameters have to be based on land use, soil composition and initial conditions. Multiple values for the infiltration parameter are tested for the unpaved areas to investigate the model response.

This concludes the following parameter requirements:

- Correct dimensions and parameters for all hydraulic structures in the sewer and surface water system
- Detailed land use map to determine the runoff routing
- Detailed DEM with a resolution no larger than $5m^2$
- Grid size base on the level of detail needed to represent the topography of the area.
- Infiltration parameters based on land use map, soil composition and initial conditions
- Roughness parameters based on land use map

4 Case study Schijndel

In the previous chapter three different analyses were explained which were needed to answer the research questions and to investigate the interaction between the urban drainage system and the rural surface water system. Based on these analysis and recent literature a model configuration with corresponding parameter requirements was discussed.

In this chapter a 1D2D hydrodynamic model is tested on the study area of Schijndel. This model is used to perform the analyses needed to answer the research questions. The 1D2D hydrodynamic model is based upon the model configuration discussed in the previous chapter. This model configuration is transformed into a working hydrodynamic model for the study area of Schijndel based on the available data and capabilities of the hydrodynamic software package Infoworks ICM. Possible limitation of Infoworks ICM are discussed. The model parameters are based upon the lessons learned from recent literature and correspond to the parameter requirements discussed in the previous chapter.

At first the layout of the study area and the different data sources will be discussed. This is followed by a detailed description of the model configuration and the way this is modelled within the Infoworks ICM model. This includes the theory, formulas and parameters that were used.

4.1 Study area

The study area for this research is the village of Schijndel and the surrounding catchment area “de Schijndelse loop”, see Figure 5. Schijndel and the surrounding catchment cover an area of approximately 2300 ha. This village is situated in centre of southern Netherlands in the province Noord-Brabant. The old urban core of Schijndel is positioned on a sand ridge between the stream valleys of the river Aa and the river Dommel. The cachment area of Schijndel has been chosen because it is upstream and therefore has no inflow from other catchments. The area is relatively flat with a minimum elevation of NAP + 6m, a maximum elevation of NAP + 11m and an average elevation of NAP + 8 (see Figure 5). The manhole cover levels vary between NAP + 7.10 and NAP + 10.70 meters. Surrounding the village are widespread agricultural areas with some forestation in the north-eastern corner.

The soil consists mainly of moderately coarse sands with local clay and loam sheets. The channels in the catchment area of “de Schijndelse loop” mainly flow from the south-east to the north-west where the water leaves the catchment area. The surface water system in the area consists of channels and ditches. Some of them are filled over the course of a year and other may be dry some time of the year. There are multiple weirs present in the study area as can be seen in Figure 5. The sewer system in the urban area of Schijndel which is connected to the surface water system in the Schijndelse loop consists of a combined sewer network. Within the combined sewer network there are 7 combined sewer overflows that discharge into the surface water system of the Schijndelse loop, these will be studies in this research. The combined sewer system that is connected to the Schijndelse loop is divided in different sewer districts that are connected to each other via internal weirs and pumps. An overview is given in Figure 6.

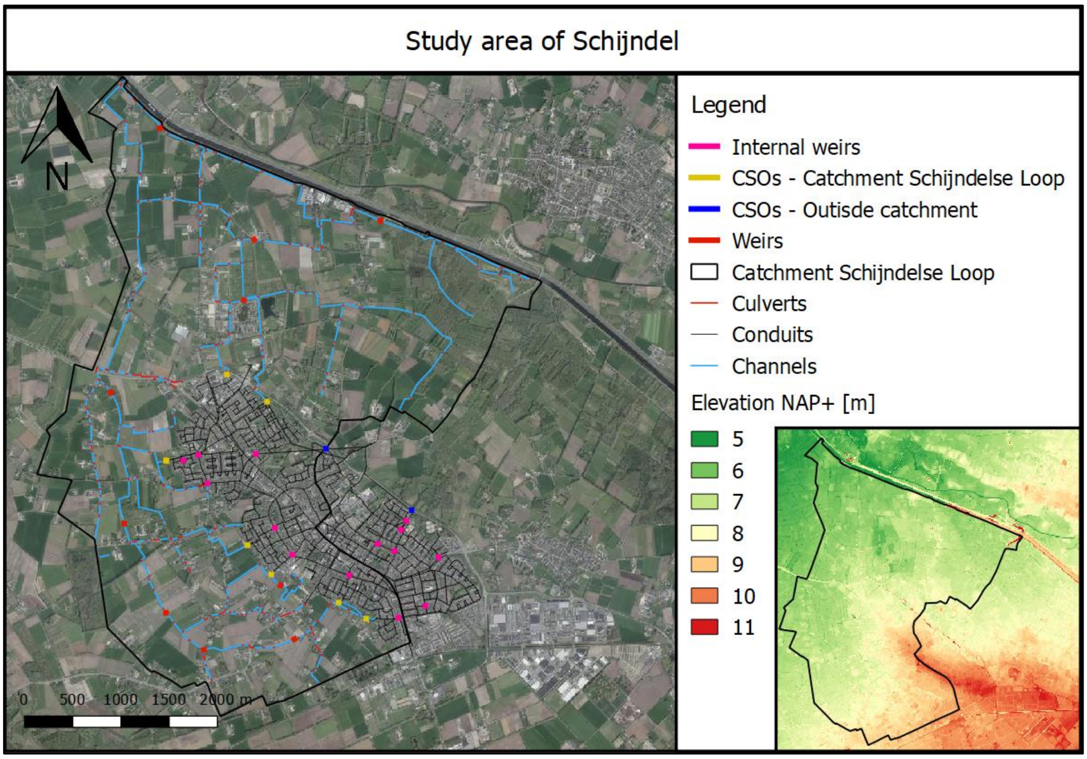

Figure 5: Study area of Schijndel

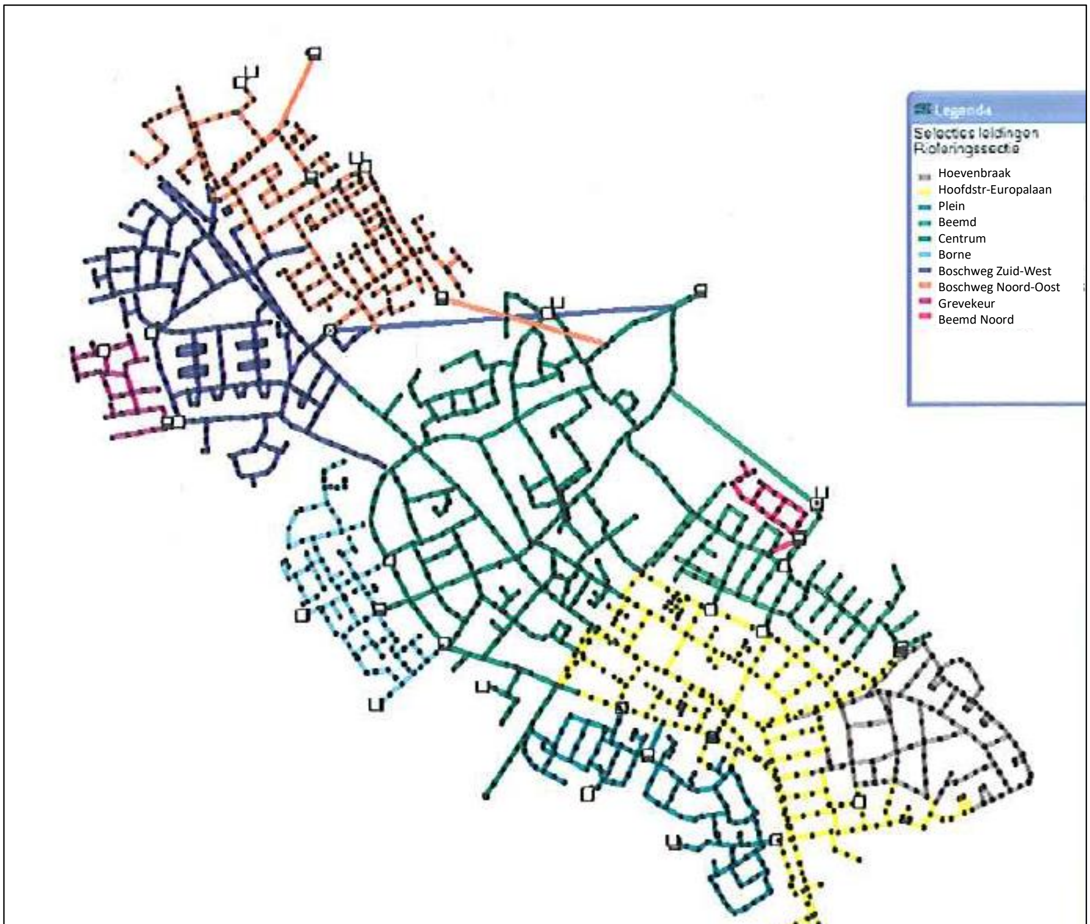

Figure 6: Sewer districts within the combined sewer network of Schijndel

4.2 Data

In order to build the actual hydrodynamic model for the study area of Schijndel multiple data sources were used. The different data sources are schematised in Figure 7. The left part represents the schematisation of the model based on big data. Source data is converted to data that can be used within Infoworks ICM with tools like Feature Manipulation Engine (FME) or Python. The input for the integral 1D2D hydrodynamic model consists of four components: the 1D sewer model, a DEM (digital elevation map), a land use map and a 1D channel model.

The right part represents the stress test or water system analysis. The integral model is combined with atmospheric inputs like precipitation and evaporation. Calculations are performed and impact analyses, which are part of stress tests, are conducted with the results. For the integral 1D2D model components 1D (sewer model, DEM, land use map and 1D channel model) and the precipitation evaporation data sources are discussed.

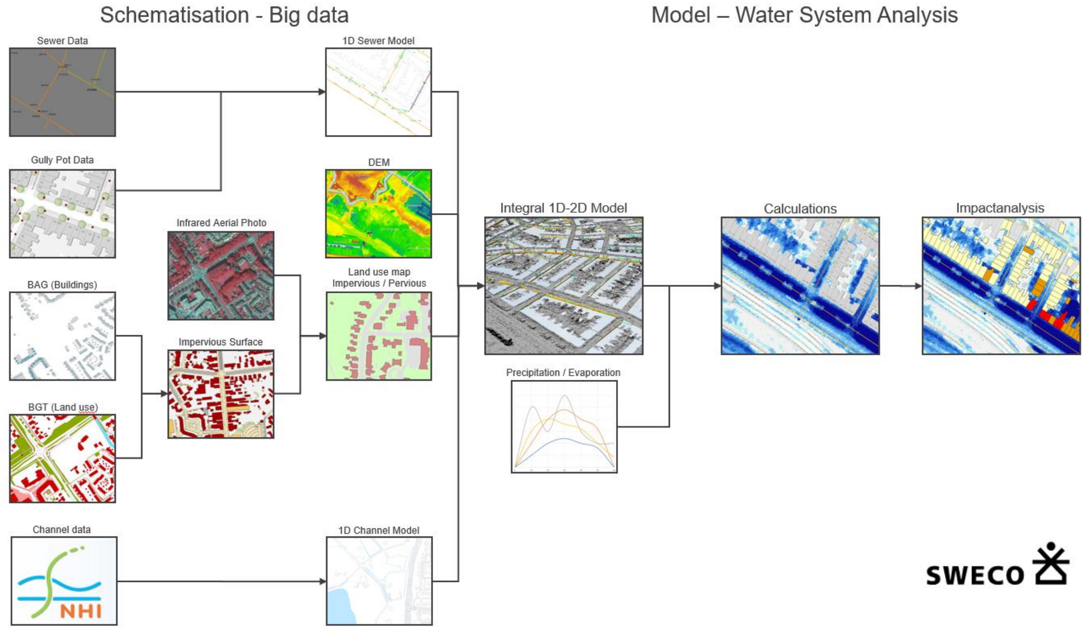

Figure 7: Flow chart of data sources and model inputs

The 1D sewer model data is a combination of existing sewer data and new gully pot data. The sewer data that is used for the model originates from an existing sewer model which was made for the sewer system analysis in 2009 (Grontmij, 2009). This included sewer pipes, manholes, internal weirs, pumps, external weirs (combined sewer overflows) and shield walls. Parameters like the dimensions, roughness, discharge coefficients etc were included in this model. Only the combined sewer network is included in the model data of 2009. This combined sewer network with corresponding parameters is used for this study because this is the network that overflows in the catchment area of the Schijndelse loop. The sewer system might have changed at a few points over the years because some combined systems have been separated and new areas have been built. However, for this study the combined sewer data from 2009 model was used as gathering the latest sewer data is outside the scope of this research. The sewer data is supplemented with gully pot data because this is the location where the sewer system and surface water system interact. The location data for the gully pots originates from the basisregistratie grootschalige gopografie (BGT).

The DEM (digital elevation map) that is used for the surface layer is the AHN3 (Algmeeen Hoogtebestand Nederland V3). The AHN is the elevation map commonly used in the Netherlands. This elevation map has a resolution of 0.5x0.5m and originates from the year 2018 for the study area of Schijndel. The AHN3 is the data source for all terrain elevations within the Infoworks ICM model.

The land use maps that are used for the surface layer and the unsaturated zone are produced using the BAG (Basisregistratie Adressen en Gebouwen), the BGT and infrared aerial photos. These three maps are used as input for a script that translates the rough data into a land use map that can be used as input for Infoworks ICM. This land use map is manually "cleaned up" in order to prevents errors while modelling. The map differentiates between flat roofs, sloping roofs, unpaved areas, closed paved areas, open paved areas and water. Because of the infrared image it is possible to determine the land use in peoples back gardens. It determines which areas are paved and unpaved. The land use map can be used to spatially differentiate between infiltration capacities and roughness. The land use map can also be used to identify roofs and surface water bodies.

The 1D channel model is constructed based on data from the NHI (Nederlands Hydrologisch Instrumentarium) data portal. This is a free open data portal where Dutch waterboard share their data regarding surface water and groundwater. For the channel network this includes data about channels, channel cross sections, weirs, pumps, culverts, bridges etc. The rough data is pre-processed with an FME script in order to produce input for Infoworks ICM. Because the NHI data portal is relatively new, it turned out that some data was missing including a few weirs in the north of the catchment area. Just as with the sewer data the available data has been used as for the purpose of this research this is sufficient.

The Precipitation and evaporation data used is based on two separate data sources. The integral 1D2D model can, in combination with a precipitation input, be used for water system analysis or so-called stress tests. As discussed before, the Dutch government and the knowledge centres STOWA and RIONED want to standardise different parts of the stress tests. The first part of this standardisation is the standardisation of the precipitation input that is used. This standardisation is discussed in the preliminary notation of a workgroup which is commissioned by the ministry of Infrastructure and Water, STOWA and RIONED (Werkgroep standaardisatie stresstest wateroverlast, 2018. This document is the basis for the precipitation events that are used as input for this study. Average daily evaporation which is common in the Netherlands is used in the model. This data originates from the guidelines for sewer calculations which is commonly in the Netherlands, the 'leidraad riolering' (DHV, Grontmij, 2004).

All together this data serves as input for the Integral 1D2D model for the catchment area of Schijndel. As mentioned before only the available data is used. Normally all data is checked and supplemented where necessary but this is outside the scope of this research. Enough data isavailable to build the model which can be used to analyse the interaction between the urban drainage system and the surrounding surface water system of Schijndel.

4.3 Model configuration in Infoworks ICM

The model configuration discussed in the previous paragraph is transformed into a working 1D2D hydrodynamic model for the study area of Schijndel. This is done with the hydrodynamic software package Infoworks ICM. In this paragraph the model is discussed divided in the model components atmosphere, surface layer, sewer/surface water and the groundwater as discussed in the methods chapter. This includes the theory, formulas and parameters used.

4.3.1 Atmosphere

The atmospheric governs the precipitation input and the evaporative output. First the precipitation input is discussed which is followed by a description of the evaporative output.

Precipitation

A differentiation is made between local (short duration) and regional (long duration) precipitation events. The workgroup notes that in order to analyse the vulnerability of a catchment that consist of both urban and rural characteristics it is important to analyse a water system with both short and long term precipitation events (Werkgroep standaardisatie stresstest wateroverlast, 2018). The short-term precipitation events are used to analyse the fast responding impervious urban area with the corresponding sewer system. The long term precipitation events are used to analyse the slower responding rural area with the channel system.

For this study the precipitation events that have a return period of 100 years in 2050 will be used. These are local (1 hour) and regional (48 hours) as described in the analysis. The rainfall intensity is constant during the whole event and constant over the whole area as discussed by the workgroup. This is a simplification of reality but the workgroup choses for a clear and simple standardisation. For the purpose of this research these standardised precipitation events will suffice. However, if a model has to be calibrated/validated historic time series of rainfall stations or radar data should be used. For the regional precipitation event initial soil saturation should be included. These initial conditions will be applied for the surface layer is and discussed in more detail there. In addition extra intensities for the short duration local events are tested and "*bui 9*" as discussed in the chapter three. This results in the following precipitation events used in this study:

- Bui 9 29.4 mm in 1 hour (not a constant intensity)
- Short duration 30 mm in 1 hour
- Short duration 50 mm in 1 hour
- Short duration (T=100, 2050): 70 mm in 1 hour
- Short duration 90 mm in 1 hour
- Long duration (T=100, 2050): 120 mm in 48 hours.

Evaporation

Evaporation is coupled directly to the precipitation event in the input. Average daily evaporation which is common in the Netherlands can be seen in Table 1. The evaporation for the month June is used for the local short duration events because they are likely to occur in summer. The evaporation of September is used for the long duration regional precipitation events because these events can also occur in autumn and spring. The evaporation is almost negligible for the short events but may be of some influence for the longer duration rainfall events. For this reason it is included in the model.

Table 1: Average daily evaporation for the Netherlands (DHV, Grontmij, 2004)

Verdamping volgens Penman (mm.dag-1)			
Maand	**Maandsom (mm)**	**Aantal dagen (-)**	**Verdamping (mm dag -1)**
januari	5	31	0.16
februari	15	28	0.54
maart	40	31	1.29
april	70	30	2.33
mei	100	31	3.23
juni	120	30	4.00
juli	110	31	3.55
augustus	90	31	2.90
september	60	30	2.00
oktober	25	31	0.81
november	10	30	0.33
december	5	31	0.16

4.3.2 Surface layer

The surface layer is separated in three elements which will be discussed. First the rainfall routing process is discussed. This is followed by a description of the 2D surface grid and finally the 2D hydraulic theory which describes the surface flow is described.

Rainfall routing

In this study rainfall excess (precipitation – evaporation) is applied directly to the 2D surface grid and routed based on processes that take place at the surface layer, except for roofs which are modelled with the sub-catchment method. Buildings, including roofs are therefore not included in the 2D surface grid. Per 2D grid element water may, infiltrate or flow to neighbouring grid elements according to the 2D hydraulic theory, see Figure 8 (left).

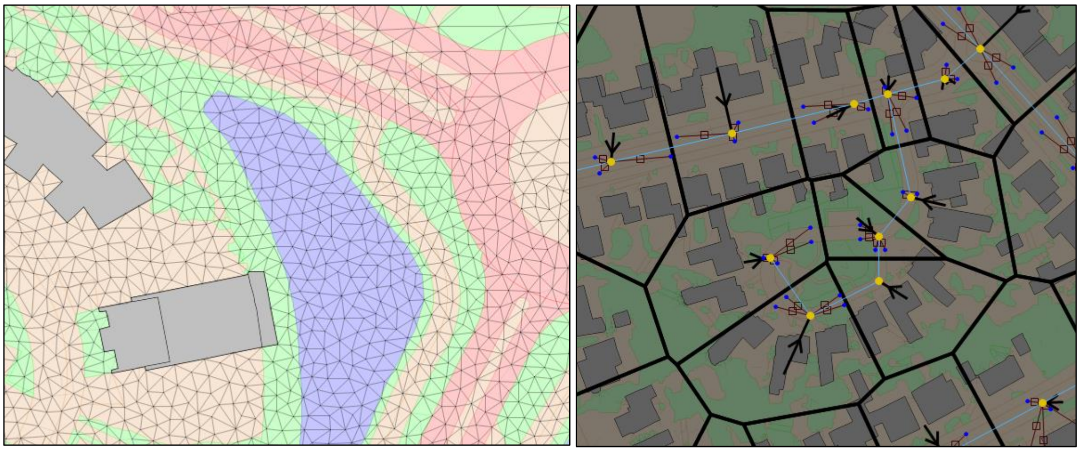

Figure 8: Example of the triangular surface grid (left) and sub-catchments (right)

The infiltration for the 2D grid elements is governed by the empirical equation of Horton which can be in Figure 9. The Horton equation determines the infiltration rate of the soil based on the initial infiltration rate f_0, the final infiltration rate f_c and the decay rate k_{decay}. Based on the land use map that is generated, spatially differentiation in infiltration parameters are assigned to each grid cell, see Table 2. Closed paved surfaces (Red), open paved surfaces (Orange), unpaved surface (Green), water (Blue) and roofs (Grey). An example of the infiltration rate in time for unpaved surfaces can be seen in Figure 10. Closed paved surfaces and water don't infiltrate at all. Roofs are not implemented in the 2D surface grid and are therefore represented by voids through which no water can flow in the 2D surface grid.

$$f = f_c + (f_0 - f_c)e^{-k_{decay}t}$$

where:

f is the potential infiltration rate (mm/hr)

f_0 is the initial infiltration rate (soil water content is zero) (mm/hr)

f_c is the final (limiting) infiltration rate (soil is saturated) (mm/hr)

k_{decay} is an exponent governing the rate of decay of the potential infiltration rate (1/hr)

t is equivalent infiltration time

Figure 9: Horton equation used in Infoworks ICM

Table 2: Horton infiltration parameters for the case study of Schijndel

	F_o [mm/hr]	F_c [mm/hr]	K_{decay} [1/hour]
Open paved surfaces (green)	40	10	3
Closed paved surfaces (red)	0	0	0
Unpaved surfaces (orange)	100	20	4
Water (blue)	0	0	0

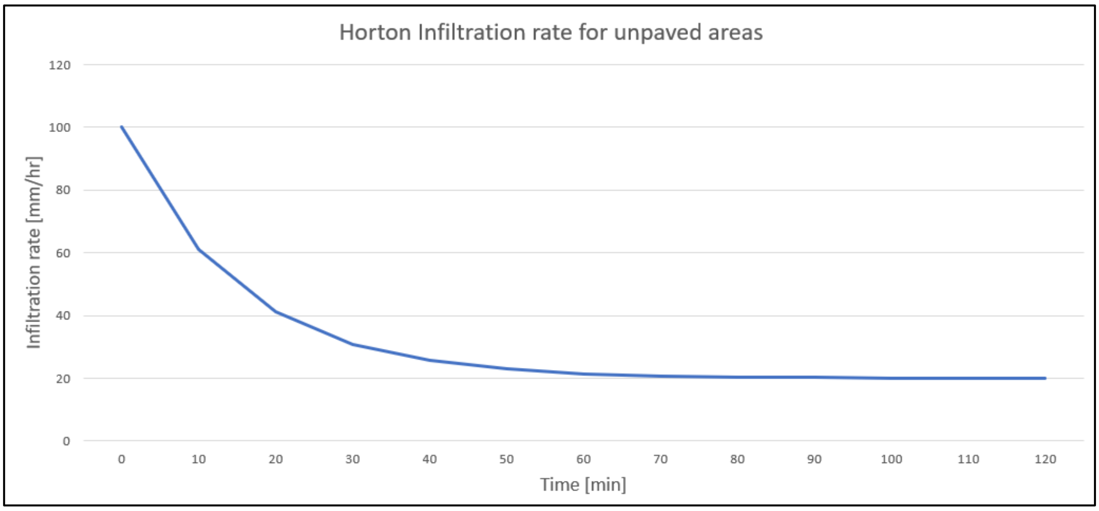

Figure 10: Example of the Horton infiltration rate for unpaved areas

It is possible to set an initial soil saturation percentage for the 2D zone. Soil water content values between 0 and 100 can be specified, where 0 represents dry initial condition, and 100 represents saturated initial conditions. The initial soil water content can be used to mimic high soil water contents in the model. For the first calculations of the long duration precipitation event with the separate and coupled model setups an initial soil saturation percentage of 80% is applied. This means at the start of the event the infiltration will be at 80% between the initial infiltration rate f_0 and the final infiltration rate f_c. Unpaved surfaces will have a final infiltration rate of 20 mm/hr as can be seen in Figure 10 and openly paved surfaces have a final infiltration of 10 mm/hr. For the the second calculations of the long duration precipitation event with the second and coupled model setups all infiltration will be set to 0. This will give insight in the response of the system when total saturation is possible, which will not happen with the Horton infiltration method.

Rainfall routing of roofs is slightly different. The sub-catchment method is used. A runoff hydrograph is constructed for all the roofs within a sub-catchment, differentiating between sloped and flat roofs. The runoff hydrographs are applied directly to the 1D network as inflow for each sub-catchment as can be seen Figure 8 (right). The roofs are the grey polygons, the sub-catchments the black polygons and the black arrows point out the nodes in the 1D sewer network to which the sub-catchments discharge their water.

<u>2D surface grid</u>
In Infoworks ICM the 2D surface layer is represented by a triangular grid. This triangular grid is generated using the Shewchuk Triangle meshing functionality that is integrated in Infoworks ICM. The elevation of the 2D grid cells is calculated based on a DEM, the AHN3 in this study. An example of the 2D grid for the study area can be seen in Figure 8. The construction of a 2D grid is based on a couple of input polygons. Based on these polygons Infoworks ICM generated the 2D surface grid. This enabled the modeller to add certain elements and details to the 2D grid, which are:

Voids: These are polygons into and through which no surface flow is allowed so no interaction with the 2D grid. In this study these are used to represent houses and channels. Voids are used at the locations of channels that are represented in the 1D channel model. This avoids double storage because the channels are also represented as depressions in the DEM.

Mesh zones: Polygons which are used to specify areas with deviating triangles areas. These are used to differentiate between the urban area and the rural surrounding catchment. In urban areas more detail is required because of the large heterogeneity and possible flow pathways. Based on the parameter requirements of chapter three the grid size in the urban is set to 2-5 m^2. The rural area is more homogeneous in nature and slightly larger grid sizes are applied, between 5-50 m^2. This grid size is a balance between modelling detail and calculation time.

Roughness zones: The roughness influences the runoff process as described in the chapter three. Roughness zones are used to assign spatially different roughness values based on the land use map. Roughness zones are polygons with a specific Manning's roughness coefficient in Infoworks ICM. The different manning's n roughness parameters that are used in this model are:

- Open paved surfaces: n = 0.0160 [s/$m^{1/3}$]
- Closed paved surfaces: n = 0.0160 [s/$m^{1/3}$]
- Unpaved surfaces: n = 0.0350 [s/$m^{1/3}$]
- Water: n = 0.0220 [s/$m^{1/3}$]

2D infiltration zone: Infiltration zones area polygons which are used to spatially differentiate between infiltration parameters. The land use map is used to assign these polygons in the area.

The 2D grid is created based on the different polygons which are described above. A minimum and maximum grid size is assigned as a starting point for the grid generation. Unfortunately, these minimum triangle sizes are overruled by the mesh generator at some locations. This often happened when infiltration zones intersect with the corner of a void. This may result in grid elements which are much smaller than the minimum element area as can be seen in Figure 11. This influences the calculation time as will be described in the 2D hydraulic theory.

It should be possible to fix this problem in the future with a different setup of the input land use map. For this study however this fix wasn't in time. This resulted in longer run times for the model.

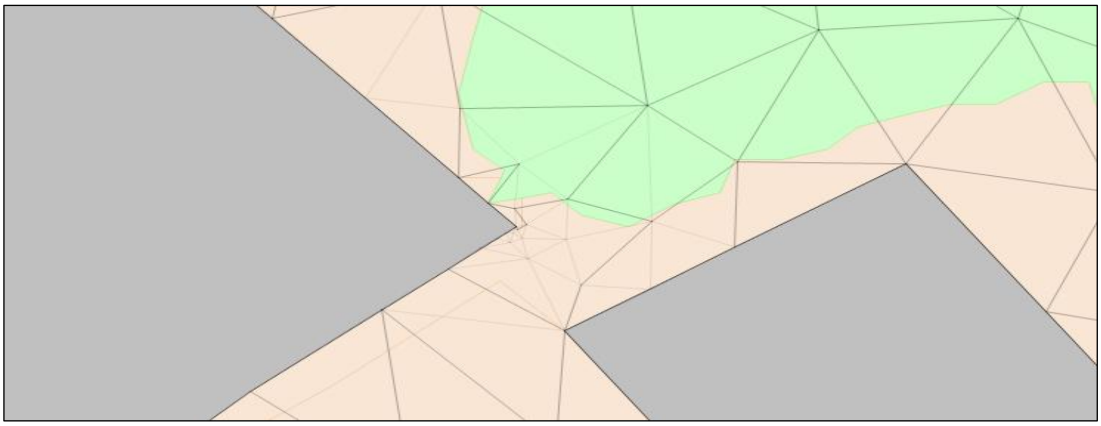

Figure 11: Example of small grid elements

<u>2D hydraulic theory</u>

In Infoworks ICM surface flow calculations are conducted by the 2D engine. The surface flow calculations are based upon the shallow water equations (SWE). These equations can be used if the flow is predominantly horizontal and the variation of the velocity over the vertical coordinate can be neglected. Think of a surface with a small layer of water on top of it. In Infoworks ICM the conservative formulation of the SWE is used, see Figure 12. The SWE equations are equations for the conservation of mass (eq. 1) and momentum (eq. 2/3). The roughness of the surface layer is incorporated in the friction slopes $S_{f,x}$ and $S_{f,y}$. As can be seen in the equation the friction slope has negative influence on the flow while the bed slope has a positive effect on the flow.

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = \sum_{i=1}^{n} q_i \quad (1)$$

$$\frac{\partial (hu)}{\partial t} + \frac{\partial}{\partial x}\left(hu^2 + \frac{gh^2}{2}\right) + \frac{\partial (huv)}{\partial y} - \frac{\partial}{\partial x}\left(\varepsilon h \frac{\partial u}{\partial x}\right) - \frac{\partial}{\partial y}\left(\varepsilon h \frac{\partial u}{\partial y}\right) = gh(S_{0,x} - S_{f,x}) + \sum_{i=1}^{n} q_i\, u_i \quad (2)$$

$$\frac{\partial (hv)}{\partial t} + \frac{\partial}{\partial y}\left(hv^2 + \frac{gh^2}{2}\right) + \frac{\partial (huv)}{\partial x} - \frac{\partial}{\partial x}\left(\varepsilon h \frac{\partial v}{\partial x}\right) - \frac{\partial}{\partial y}\left(\varepsilon h \frac{\partial v}{\partial y}\right) = gh(S_{0,y} - S_{f,y}) + \sum_{i=1}^{n} q_i\, v_i \quad (3)$$

where:
h is the water depth (m)
u and v are the velocities (m/s) in the x and y directions, respectively
q_i is the ith net source discharge per area (m/s)
u_i and v_i are the velocities (m/s) in the x and y directions of the ith net source discharge, respectively
g is gravity acceleration (m^2/s)
ε is eddy viscosity (m^2/s)
$S_{0,x}$ and $S_{0,y}$ are the bed slopes in the x and y directions, respectively
$S_{f,x}$ and $S_{f,y}$ are the friction slopes in the x and y directions, respectively
n is the number of source discharges

Figure 12: Shallow water equations used in Infoworks ICM

The conservative formulation of the SWE is needed to conserve the basic quantities of mass and momentum. The conservative SWE are discretised using a first-order finite volume explicit scheme. With finite volume methods the modelling domain is divided into geometric shapes over which the SWE are integrated to give equations in terms of fluxes through the control volume boundaries. These shapes are the triangular grid elements. As the scheme is an explicit solution it does not require iteration to achieve stability. Instead, for each element, the timestep required to achieve stability is calculated using the Courant-Friedrichs-Lewy condition, see Figure 13. From this equation you can see that the time step needed for stability decreases with a smaller grid size and corresponding characteristic mesh element length (Δx). The required time step is further dependent on the flow velocity and the wave celerity (c). An increase in flow velocity results in a smaller calculation time step. The smaller the calculation time step the longer the calculation time.

$$\Delta t \leq \frac{CFL\,\Delta x}{(\sqrt{u^2+v^2}+c)} \quad (4)$$

where:

CFL is a dimensionless Courant number (The Timestep Stability Control set in the 2D parameters. Default=0.95)

u is the velocity (m/s) in the x direction

v is the velocity (m/s) in the y direction

c is the flow celerity calculated as √gh (m/s)

Δt is the time step (s)

Δx is the characteristic mesh element length (m)

Figure 13: Courant-Friedrichs-Lewy condition used in Infoworks ICM

4.3.3 Sewer and Surface water system

The sewer and surface water system together form the 1D component of the 1D2D hydrodynamic model. In this 1D model the combined sewer network of Schijndel is incorporated. This includes data of sewer pipes, manholes, shield walls, internal weirs, external weirs and pumps. For the surface water system the channels of which data is available are incorporated in the 1D model, this includes cross-sections as in Figure 14. Smaller ditches and channels of which no data is available are represented as depressions in the 2D surface grid. Weirs and culverts are also represented in the 1D surface water model.

The 1D hydraulic theory for pipes and channels will be discussed first followed by a description of the weirs and pumps. Finally the interaction between the 1D sewer and surface water system and the 2D surface layer is discussed.

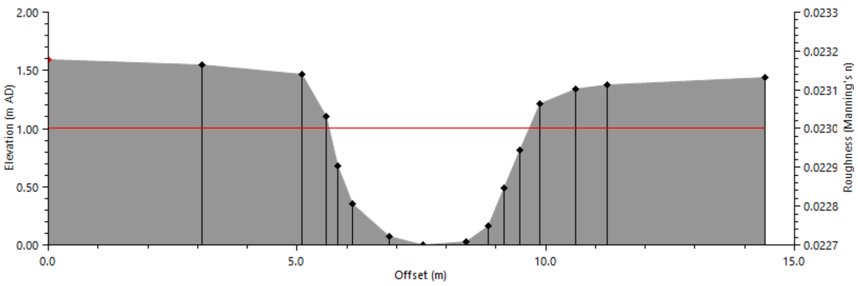

Figure 14: Example of a channel cross section

1D hydraulic theory

The flow through conduits is governed by the 1D Saint-Venant equations. These are the 1D variant of the shallow water quations. 1D means that only flow along the length direction of the conduit is calculated. The 1D Saint-Venant equations are a pair of conservation equations of mass (eq. 1) and momentum (eq. 2), see Figure 15 (left). The solution of the Saint-Venant equations may be retained in pressurised flow by introducing a suitably narrow slot, the Preissman slot, into the pipe soffit, see Figure 15 (right). The pipe or channel roughness is incorporated in the conveyance factor K. The conveyance factor K is calculated based on the manning roughness (n), the cross sectional area (A) and the hydraulic radius (R) in the following equation:

$$K = \frac{A \times R^{\frac{2}{3}}}{n}$$

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \quad (1)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\left(\cos\theta \frac{\partial y}{\partial x} - S_0 + \frac{Q|Q|}{K^2}\right) = 0 \quad (2)$$

where

Q - discharge (m^3/s)

A - cross-sectional area (m^2)

g - acceleration due to gravity (m/s^2)

θ - angle of bed to horizontal (degrees)

S_0 - bed slope

K - conveyance

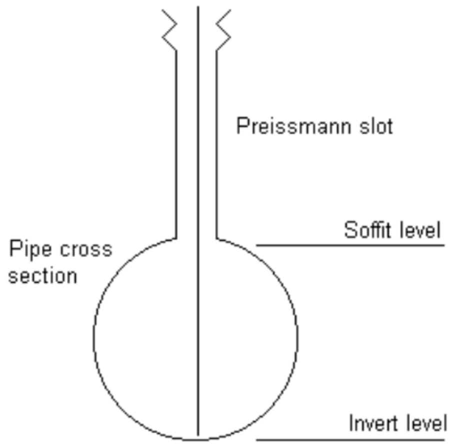

Figure 15: 1D Saint-Venant equations (left) - Preismann slot (right)

Weirs

In the sewer network weirs are used internally to divide/connect different sewer districts and externally at sewer overflow locations. In the channel system weirs are used to regulate the water level. In this model standard thin plate weirs have been used as can be seen in Figure 16. A weir can function under two different flow conditions:

- Free discharge: the depth of the water at the downstream end is below the weirs crest and doesn't influence the depth upstream of flow over the weir.
- Drowned discharge: the downstream depth of the water is above the weir crest and influences the discharge over the weir.

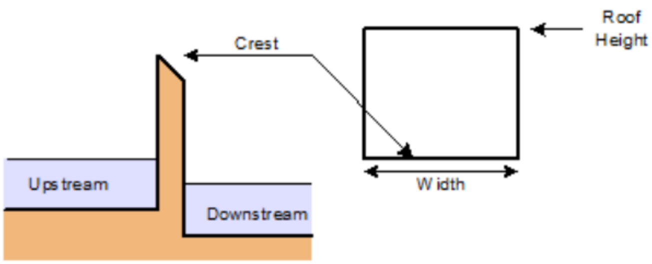

Figure 16: Example of a thin plate weir used in Infoworks ICM

Free discharge is calculated according to equation 1 in Figure 17 (left) and drowned charge is calculated based on eq. 2, Figure 17 (right). Drowned discharge is when the water level in the receiving surface water system is above the weir crest. The outfall discharged is decreased significantly when drowned discharged in compared to free discharge as can be seen in the formulas. A weir has a crest height, width and sometimes a roof height. The external weirs within the model, at the location of sewer overflows, have a roof height assigned to them based on data provided by the municipality.

$$Q_0 = C_d \sqrt{g}\, B\, D_u^{3/2} \quad (1)$$

where:

Q_o is the free outfall discharge

C_d is the discharge coefficient

g is the acceleration due to gravity

B is the width of the weir

D_u is the upstream depth with respect to the crest

$$Q = C_d\, B\, D_u \sqrt{g}\, (D_u - D_d)^{1/2} \quad (2)$$

where:

D_d is the downstream depth with respect to the crest

Figure 17: Weir equations, free discharge (left) - drowned discharge (right)

<u>Pumps</u>

The pumps within the sewer network are fixed discharge pumps which pump at a constant discharge. These are dry weather pumps pumping foul water from all the sewer districts to the central pumping station or to neighbouring sewer districts. These pumps switch on if the water level in the pumping chamber is above a certain threshold, the switch-on level. When the water is below the switch-off level the pumping is stopped.

<u>1D2D link</u>

The interaction between the 1D sewer network and the 2D surface layer takes place at the location of gully pots. The interaction is governed by a head discharge table according to Beng (2011) and can be seen in Figure 18.

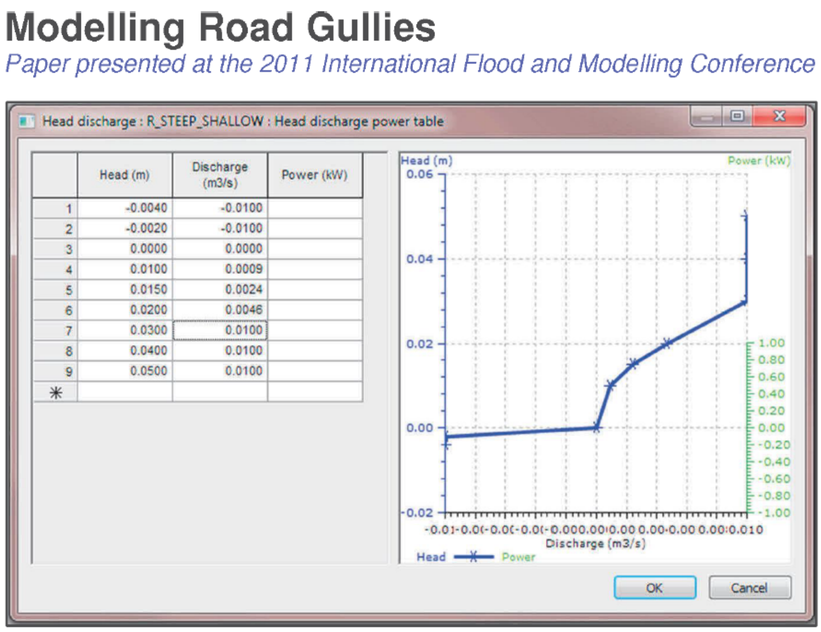

Figure 18: Head discharge relation for 1D2D linkage at the location of gully pots

The interaction between the 1D channel system and the 2D surface layer takes place along the lengths of the channels. In Figure 19 (Left) a channel schematisation in the 2D domain is visible. The grey area is the channel void in the 2D grid, this represents the channel area which is included in the 1D channel model and excluded in the 2D surface grid. In the centre of the void 1D channel line segments are visible. The channel sections are connected to each other at calculation points, the yellow dots on the 1D channel line. Each calculation point is connected to a “bank line” (red dotted lines) at each side of the channel with an “inline bank” (red lines) which is connected to another calculation point, see Figure 19 (left). The inline back is a virtual connection with zero length. A bank line represents the elevation of the surface layer at the channel boundaries on the left and right side, see Figure 19 (right). Flow exchange between the 1D channel network and the 2D surface is calculated as flow over an irregular weir where the elevation of the bank line represents the crest level, a bank line cross section can be seen in Figure 19 (right). The flow over the bank is calculated based on the irregular weir equation. For the calculation each bank line is split in multiple different line segments which have a begin and end elevation y_{21} and y_{22} and a length b, see Figure 19 (right). Each calculation node which connects channel section has an upstream water depth y_{11} corresponding to the upstream channel sections and a downstream water depth y_{12} corresponding to the downstream channel section. Y_1 and y_2 are constant for each bank line element. Flow over the different bank line sections may be non-existing, free or drowned. The flow can be positive (from 1D channel to 2D surface) or negative (from 2D surface to 1D channel). Per time step, the total flow over the bank line is a sum of all flows over the different bank line segments, positive and negative. See Figure 20 for zero flow, Figure 21 for free flow (positive) and Figure 22 for drowned flow (positive) equations, where C_d is the discharge coefficient of the weir which is set to 1 in this study. For negative flow the same formulae apply as for mode 1 but with y21 interchanged with y11, and y12 interchanged with y22.

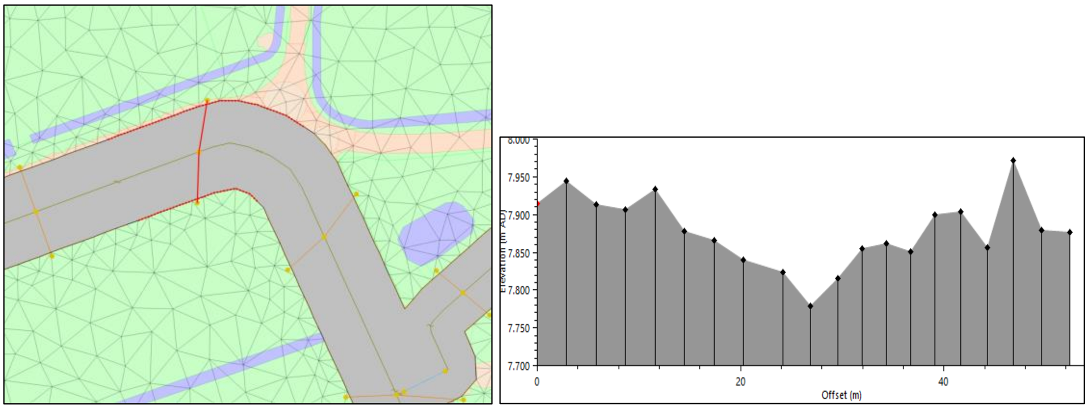

Figure 19: Example of 1D2D connection for channels (left) - and bank line elevation (right)

Condition	The upstream (highest) water level is below the bank level defined in the spill, or the water levels are above the bank level but almost exactly equal.
Equation	$$q_s = 0 \quad (1)$$ where: q_s = flow over segments

Figure 20: Irregular weir equation, Zero flow

Condition	$$(y_{21} + y_{22})/(y_{11} + y_{12}) \leq m$$
Equation	$$q_s = \frac{2C_d b\left(y_{12}{}^2\sqrt{y_{12}} - y_{11}{}^2\sqrt{y_{11}}\right)}{5(y_{12} - y_{11})} \quad (2)$$ where: y_{11} = upstream water depth in river reach; y_{12} = downstream water depth in river reach; y_{21} = upstream water depth in bank connection object; y_{22} = downstream water depth in bank connection object; m = modular limit; b = length of bank

Figure 21: Irregural weir equation, Free flow (positive sense)

Condition	$$(y_{21} + y_{22})/(y_{11} + y_{12}) > m$$
Equation	$$q_s = Ab\{(2/3)y_k D - (4/15)y_i(dy_{22} + dy_{12})\} \quad (3)$$ where: $D = y_{12}\, dy_{21} - y_{11}\, dy_{11}$; $A = C_d / y_k^2 \sqrt{(1-m)}$; $y_k = y_{12} - y_{11} - y_{22} + y_{21}$; $y_i = y_{12} - y_{11}$; $dy_{21} = (y_{12} - y_{22})\ 3/2$; $dy_{22} = (y_{12} - y_{22})\ 5/2$; $dy_{11} = (y_{11} - y_{21})\ 3/2$; $dy_{12} = (y_{11} - y_{21})\ 5/2$

Figure 22: Irregural weir equation, Drowned flow (positive sense)

4.3.4 Groundwater system

In the model of Schijndel there is no groundwater components except and initial saturation of the soil. Infoworks ICM does not offer a capability to model groundwater in combination with a model configuration where rainfall is applied directly to the 2D surface grid. The study area of Schijndel is situated on a sand ridge between the river valleys of the Dommel and the Aa. The soil consists of moderately coarse sands with local peat and loam sheets. In this study long and short duration precipitation events will be evaluated. The short duration rainfall events occur during summer when there is a low groundwater table. This in combination with the coarse sands will probably results in a limited base flow to the channel system. For these events the assumption can be made that the groundwater doesn't influence the runoff during short duration precipitation events. For longer duration precipitation events or precipitation time series this assumption cannot be made that easily. The soil will get saturated over time and the base flow to the channel system can have a significant influence. Not having a groundwater component therefore is a limitation of this model when analysing longer duration precipitation events. For the long duration event total saturation of the soil will be mimics with calculations without infiltration. This helps to investigate the importance of groundwater component and total saturation.

4.3.5 Model boundary conditions

For the model some assumptions were made that influence the results to a certain extent. No initial filling was applied for water bodies that were not present in the 1D system. Ditches and ponds that were only present in the 2D surface grid were therefore empty at the start of the simulations. In reality these water bodies will have some water in them. The 1D channel system was however pre-filled until the crest levels of the weirs. There are three combined sewer overflows (CSOs) that did not discharge into the catchment area of the Schijndelse loop. For these CSOs free discharge out of the model was assumed. In reality these CSOs would react in the same way as the CSOs in the catchment area of the Schijndelse loop which are connected to the combined sewer system. As discussed before it was assumed that all unpaved surface have the same infiltration rates. No differentiation is made based on local soil conditions.

5 Results

In this chapter the results of the case study of Schijndel are discussed. The analyses discussed in chapter three were conducted on the model of the case study as discussed in chapter four. In the results section the model responses for the different analysis are discussed. First a short overview of the case study model area and the two model setups which were discussed in the analysis of chapter three are given. This helps to better understand the results. The results discussed follow the different analyses. At first the model response, maximum flood depth, corresponding to "*bui 9*" is compared to known flood reports, analysis 1. This is followed by a description of difference in model response for the separate and coupled model setups, analysis 2. In the third and last analyses the results of a parameter sensitivity analyses (SA) are given. In this chapter the terms flood depth or difference in flood depth are often used. These flood depths are the maximum flood depths which occur during an event.

5.1 Model area overview

The hydrodynamic model of Schijndel is focussed on the surface water system in the catchment area of the Schijndelse loop and the urban drainage system that interacts with this catchment, see Figure 23. The sewer system is connected to the surface water in the Schijndelse loop at the location of 7 combined sewer overflows (CSOs). In order to get the correct flow dynamics in the combined sewer network the internally connected combined sewer network of the urban core of Schijndel is incorporated with a corresponding surface grid. This means that the 2D grid is extended (green-dotted line) a bit outside the catchment area of the Schijndelse loop. There are two CSOs in the combined sewer network of the urban core that don't discharge in the catchment area of the Schijndelse loop. For these CSOs free discharge out of the model is applied. The results will zoom in on an area of interest in analysis two. This is the sewer district of Borne with the receiving channels as can be seen with the red dotted line. In the background the land use map is visible. As can be seen the catchment area of the Schijndelse loop mainly consists of unpaved areas for which different infiltration capacities are compared in the SA. In the upper north-west corner of the catchment we find the catchment outfall for which outfall hydrographs will be compared in the results of the sensitivity analysis. A description of the separate model (setup 1) and the coupled model (setup 2) is given below.

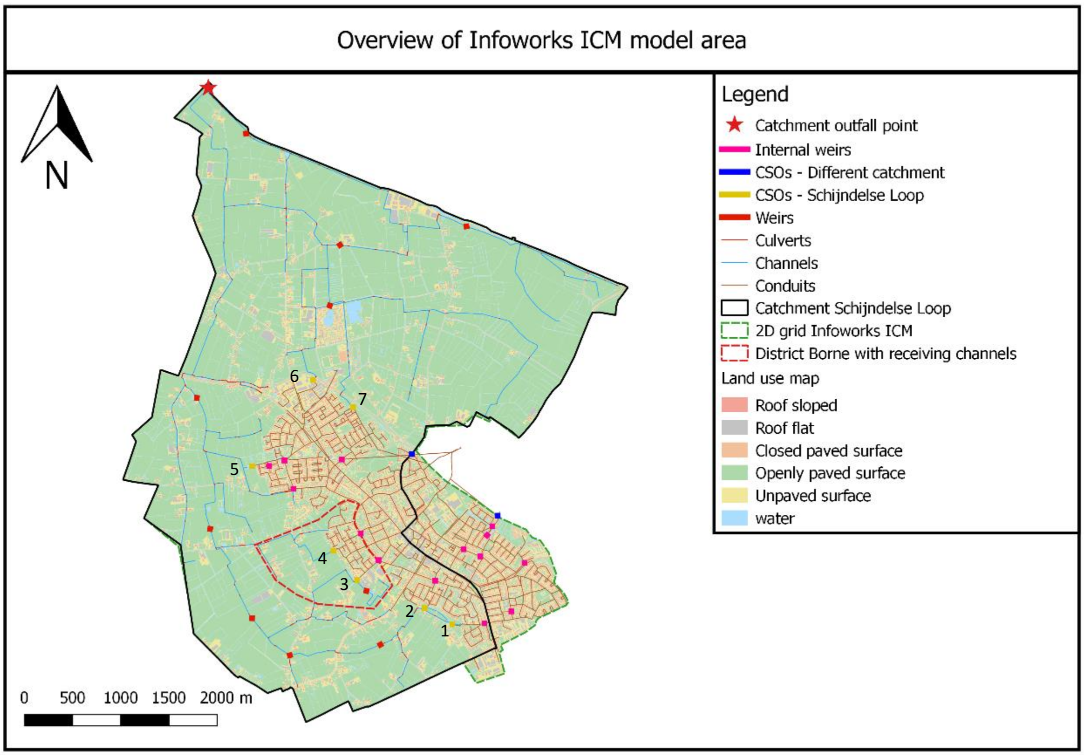

Figure 23: Overview of Infoworks ICM model area

Model setup 1: In the first model setup, the sewer system and the surface water system are not connected at the locations of sewer overflows (Yellow square). The sewer system has free outflow point (Black square) at the location of these sewer overflows and the surface water system does not receive water from the sewer system at the location of sewer overflows, see Figure 24 (Left). In this figure the 1D2D connection between the sewer/surface water and the surface grid is also visible. The blue dots are the gully pots and the blue lines represents sewer pipes or culverts in the channels system.

Model setup 2: In the second model setup the sewer system and the surface water system are connected at the location of CSOs through a discharge pipe, see Figure 24 (right). The discharge pipe connects a calculation point in the sewer system with a calculation point in the surface water system. A dynamic exchange of water at the sewer overflow locations is possible during the duration of the calculations.

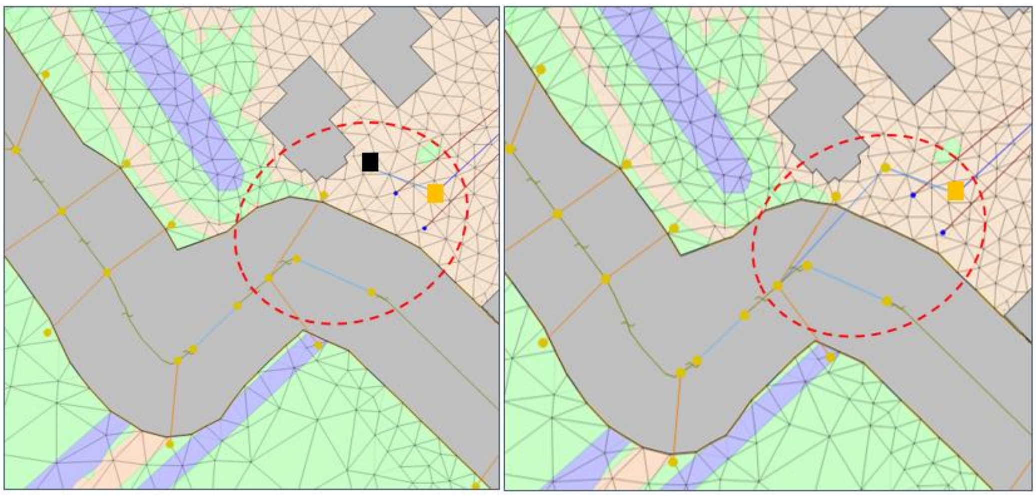

Figure 24: Example of model setup 1 (left) and model setup 2 (right)

5.2 Analysis 1: Check against flood reports

The flood reports from the sewer plan of 2009 are compared with flood depths resulting from calculations with the coupled model setup 2 and the precipitation event "*Bui 9*". This event has a total rainfall depth of 29.4 mm and a return period of 5 years. In Figure 25 the flood reports are plotted on a flood depth map corresponding to "*Bui 9*". In Figure 34 of appendix A an overview of these reports with corresponding street names can be found. The flood reports 1, 2, 3, 4, 6, 8, 9, 10 also arise from the model calculations. The flood reports 5, 7 don't arise as flooding in the model outcomes. It is further visible that there are many more locations where the model predicts flooding in the urban and rural area. There are no more flood reports known so at this point it's not possible to (in)validate this. In the corner south-east of point 8 a lot of flooding is visible. This is an industrial area where also a storm sewer is installed of which no data was available. The storm sewers are not included in this model and the flood results are therefore no valid for this industrial area. This is a separate sewer district which isn't directly connected to the main combined sewer system corresponding to flood reports 1-10.

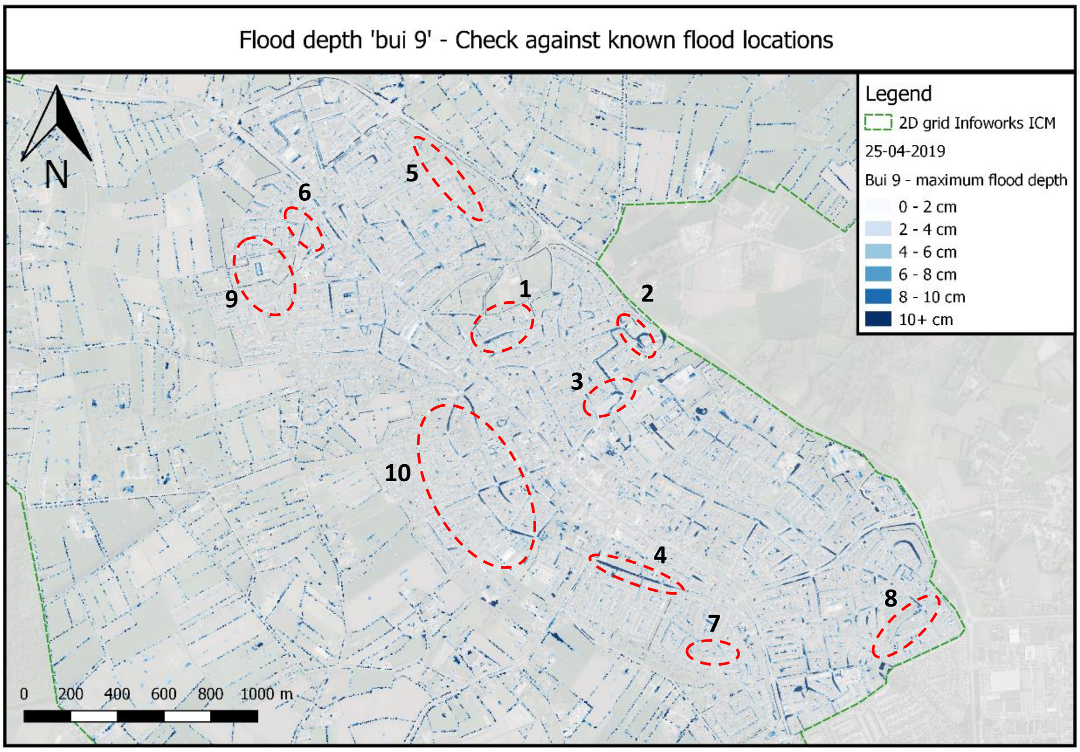

Figure 25: Maximum flooding depths for bui9 (T=5) compared to with flooding reports (Grontmij, 2009)

5.3 Analysis 2: Separate vs coupled model setup

The response of the total study area is discussed for the short and long duration precipitation events with a return period of 100 years in 2050, these are:

- Short duration (T=100): 70 mm in 1 hour
- Long duration (T=100): 120 mm in 48 hours, 80% initial soils saturation.
- Long duration (T=100): 120 mm in 48 hours, no infiltration

The difference in response is compared for the separate and coupled model setup. The difference in response is the model outcome for the coupled model setup minus the model outcome for the separate model setup calculated for each grid cell in the model domain. The response can be analysed based on multiple outcomes as discussed in chapter three. The choice has been made to discuss the results based on a difference in flood depth, flood duration, flood extent and houses flooded. In this chapter only the maps with the difference between the separate and coupled model setup are shown. In appendix B the original maps corresponding to flood depth, flood duration and houses flooded can be found for the separate and coupled model setups. This gives a better overview of the flooding in both model setups besides just the difference. Additionally larger versions of the difference in flood depth and flood duration for all short and long duration events can be found in appendix B. In this chapter the difference is described as:

$$Difference\ (per\ grid\ cell) = Results\ coupled\ model\ setup - Results\ separate\ model\ setup$$

The influence that the urban drainage system and the rural surface water system have on each other is event and location specific. As will be discussed later on it seems like the model setup used in this study isn't suitable yet for the analyses of longer duration precipitation events where saturation of the soil plays in important role. For this reason the longer duration event will only be discussed for the area as a whole. The model setups seemed more suitable for the analysis of short duration precipitation events. For the short duration event differences were found, however the differences are location specific. In order to get a better idea of the local influences an area of interest is selected. This is the sewer district Borne with the receiving channels, see Figure 23. For this area of interest the response is analysed for different intensities short duration precipitation events in order to see how the systems respond. For the area of interest the difference in response is analysed for the following short duration precipitation events:

- Short duration (T=10) 30 mm in 1 hour
- Short duration (T=40) 50 mm in 1 hour
- Short duration (T=100) 70 mm in 1 hour
- Short duration (T=500) 90 mm in 1 hour

5.3.1 Whole study area

In Figure 26, Figure 27 and Figure 28 the maps with differences in flood depth and flood duration can be seen for the short (70 mm in 1 hour) and long duration (120 mm in 48 hours) events. In appendix B larger versions of these maps as well as the original flood depth and flood duration maps for the coupled and separate model setups can be found. In the Table 3 and Table 4 the difference in flood extent and houses flooded is visible. For the flood extent grid cells with a water dept larger than 1 cm are included. Building are considered flooded when the water depth surrounding the building is larger than 10 cm, small sheds smaller than 30 m^2 are excluded from this analysis. The difference is per grid cell is des

$$Difference\ (per\ grid\ cell) = Results\ coupled\ model\ setup - Results\ separate\ model\ setup$$

In Figure 26 it can be seen that a coupled model setup causes local increases in flood depths up to 5 cm and flood durations up to 5 hours for the short duration event. These increases are however very location specific and occur in areas surrounding CSOs. Differences in flooding between the two model setups area observed upstream and downstream of six out of seven CSOs, at some locations more significant than others. In a large part of the catchment there is no difference in flood response between the separate and coupled model setup, the areas further away of the CSOs. The results for the difference in flood extent (Table 3) and houses flooded (Table 4) are in line with the observation that the influence is location specific. For the short duration event the increases for the coupled model setup relative to the separate model setup are only 1% (flood extent) and 2% (houses flooded) for the area as a whole. In appendix B maps that display the houses flooded for the short duration event are displayed, for the separate and coupled model setup. In Figure 39, Figure 40, Figure 47 and Figure 48 of appendix B the original maps corresponding to flood depth and duration of the separate and coupled model setups can be found. In these figures is can be seen that in both the separate and coupled model setups flooding occurs in both the urban and rural areas. This means that both systems have flooding problems but in the coupled model setups these are amplified in the areas surrounding CSOs.

For the long duration event there are no differences between the coupled and the separate model setup for the calculations with 80% initial soil saturation as can be seen in Figure 27. For the calculations with no infiltration at all large differences between the two model setups can be observed in Figure 28, mainly in the west of the study area where all the water need to go under an elevated road with a culvert. The water that needs to be discharged is larger than the capacity of the culvert so it accumulates, especially when the urban runoff is added in the coupled model setup. The results for the difference in flood extent (Table 3) and houses flooded (Table 4) confirm this as there is 0% increase in flood extent and houses flooded for the calculations with 80% initial soil saturation. The calculation with no infiltration at all results in an increase in flood extent of 8% and an increase in houses flooded of 1%. Looking at the original maps corresponding to flood depth and duration for the separate and coupled model setups in appendix B it is visible that no real flooding is observed for the long duration event with 80% initial soil saturation, see Figure 43, Figure 44, Figure 49 and Figure 50. For the calculations with no infiltration significant flooding is observed as can be seen in Figure 45, Figure 46, Figure 51 and Figure 52 of appendix B. However, reality will be in between the calculation with 80% initial soil saturation and the calculation with no infiltration. With the Horton method a final infiltration will remain as discussed in chapter four. This final infiltration rate of 20 mm/hr for unpaved areas and 10 mm/hr for openly paved areas is much larger than the average rainfall intensity for the long duration event, which is 2.5 mm/hr. No infiltration at all means that all water will runoff and accumulate in depressions in the landscape or before narrow passages. I reality some water will infiltrate and the soil can reach total saturation over time. The current model setup used in this study can’t reproduce this combination yet. Because the current model setup doesn’t seem suitable for the analysis of long duration precipitation events it is left out when zooming in further.

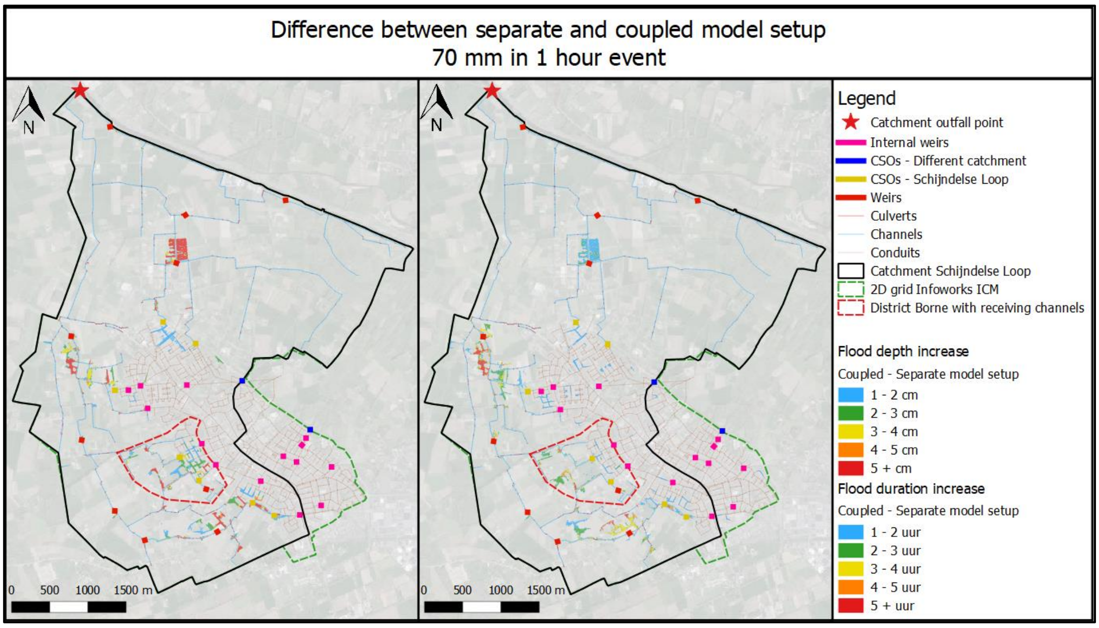

Figure 26: Difference in response between the separate and coupled model setup – 70 mm in 1 hour event

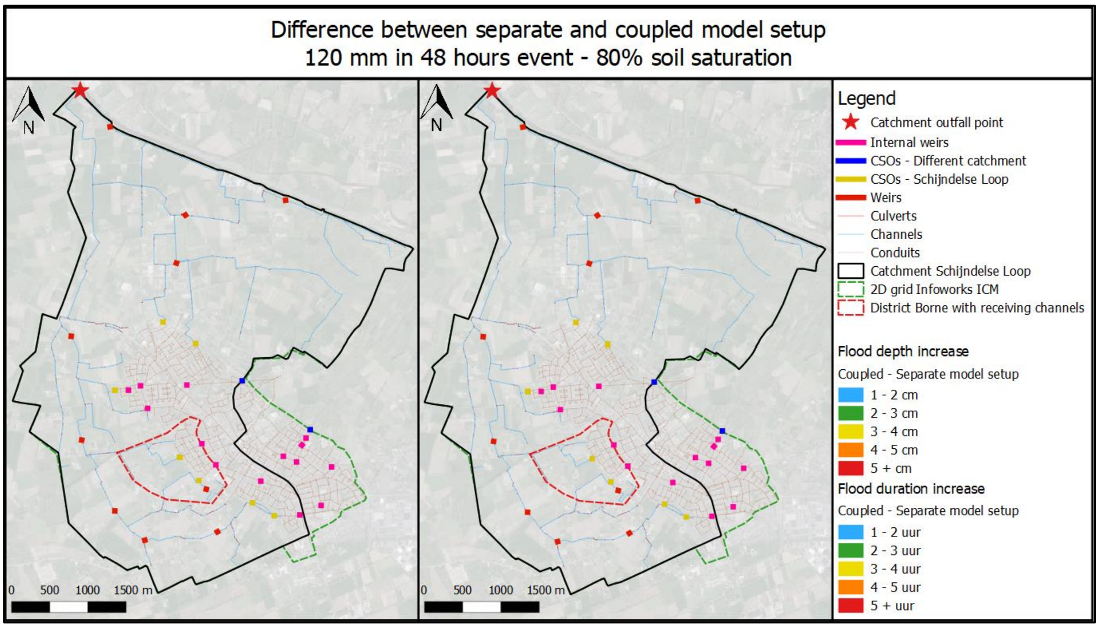

Figure 27: Difference in response between the separate and coupled model setup – 120 mm in 48 hours event – 80% soil saturation

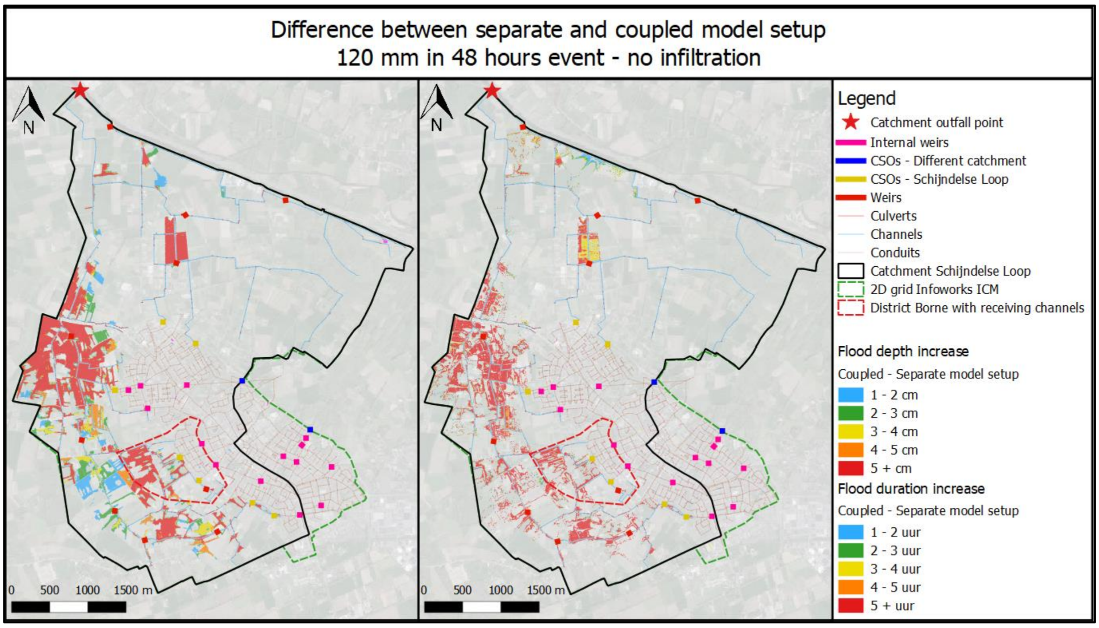

Figure 28: Difference in response between the separate and coupled model setup – 120 mm in 48 hours event – no infiltration

Table 3: Difference in flood extent – whole study area

Precipitation event	Flood extent [ha]		Increase in flood extent [%]
	Model setup 1 (Separate)	Model setup 2 (Coupled)	combined relative to separate model setup
70 mm (1hr)	739	747	1
120 mm (48hrs) - 80% initial soil saturation	40	40	0
120 mm (48hrs) - no infiltration	688	740	8

Table 4: Difference in houses flooded - whole study area

Precipitation event	Houses flooded		Increase in houses flooded [%]
	Model setup 1 (Separate)	Model setup 2 (Coupled)	combined relative to separate model setup
70 mm (1hr)	1880	1921	2
120 mm (48hrs) - 80 initial soil saturation	64	64	0
120 mm (48hrs) - no infiltration	1129	1143	1

5.3.2 Area of interest: Sewer district borne with receiving channel sections

The results for the whole study area showed that locally the sewer and surface water system do influence each other. To get a better overview of this interaction at an area of interest the results zoom in on the sewer district Borne with the receiving channels, see Figure 23. This sewer district is connected to the rest of the combined network with two internal weirs and can discharge into the surface water system via two CSO, see Figure 29. The difference in response is analysed for short duration events of 1 hour with a rainfall depth of 30, 50, 70, and 90 mm. The results are analysed with respect to difference in flood depth, flood duration, flood extent and houses flooded. In appendix B maps corresponding to the difference in flood depth and time can be found for the whole catchment for the different short duration precipitation events. The original flood depth maps corresponding to the coupled and separate models setups can be found in appendix B.

In Figure 29 it is visible that there is an increase in maximum flood depths for a coupled model setup compared to a separate model setup. The increase in flood depth varies between 1 to more than 5 cm. The results show that the influence which the urban drainage system and the rural surface water system have on each other increases with larger precipitation volumes. The increase in flood depth occurs both in urban and rural areas. For the smallest event of 30 mm in 1 hour no differences between the coupled and separate model setup are observed.

For the event of 50 mm in 1 hour we only see a strong local increase in parts of the urban area. As the intensity of the events increase the areas with an increase in flood depth seems to move further into the rural area. This effect is noticed for the whole study area as can be seen in the maps in appendix B. The original flood depth maps for the coupled and separate model setups, which can be found in appendix B, show that for both model setups flooding occurs in the urban **and** the rural area. For the coupled model setup the flooding is amplified in areas surrounding the CSOs when compared to the separate model setup.

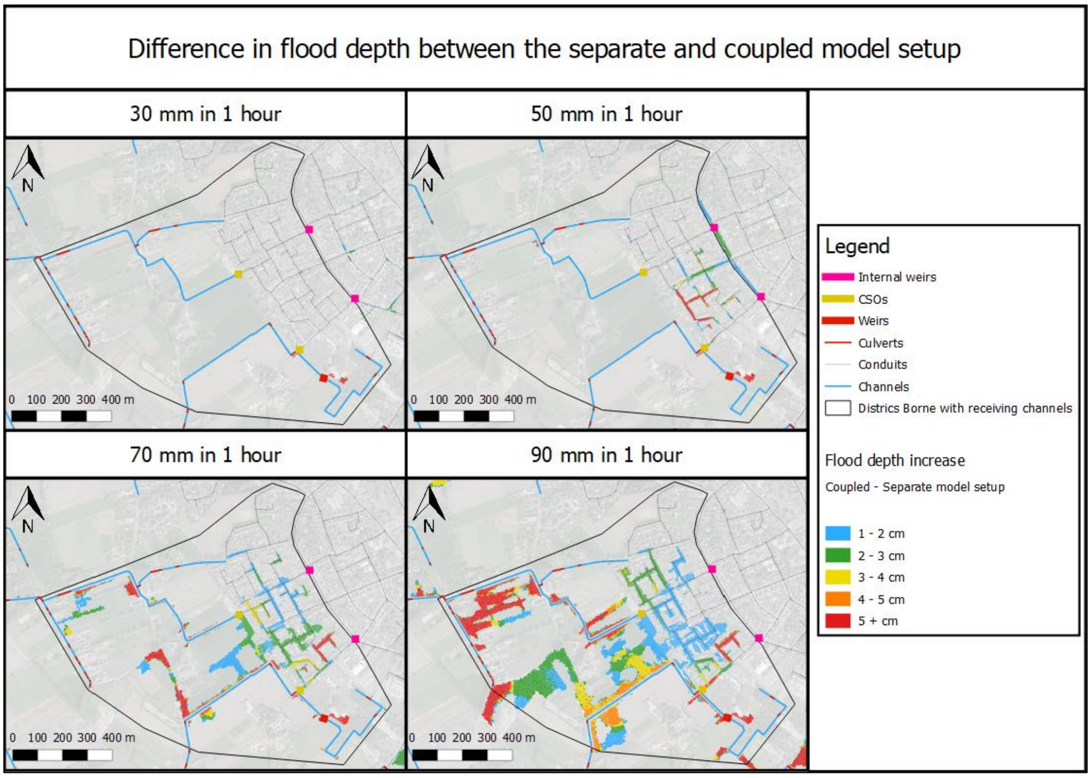

Figure 29: Maps of the difference in flood depth between the separate and coupled model setup

In Figure 30 the difference in flood duration is plotted, increases from 1 up to more than 5 hours can be seen. These results also show that the influence which the urban drainage system and the rural surface water system have on each other increases with larger precipitation volumes. For the smallest event of 30 mm in 1 hour almost no differences are observed. For the 50 mm in 1 hour event the differences are very local in the urban area. As the intensity of the events increase the areas with an increase in flood duration shift from the urban to the rural area.

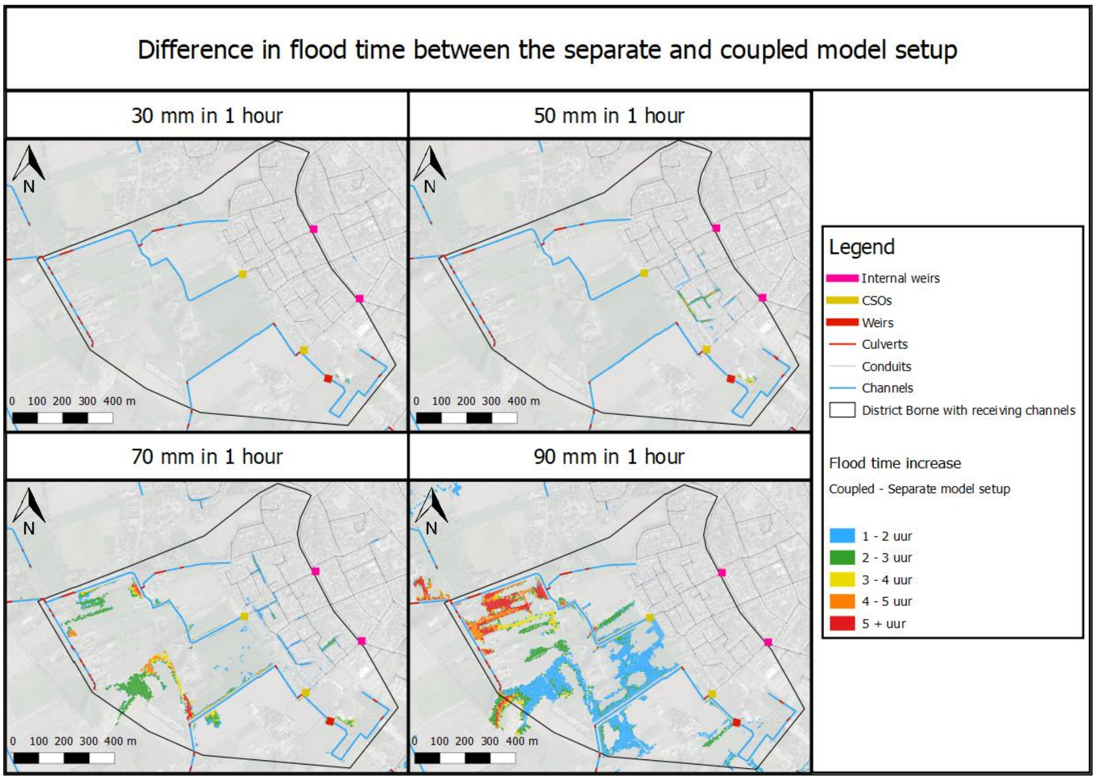

Figure 30: Maps of the difference in flood duration between the separate and coupled model setup

In Table 5 and Table 6 the differences in flood extent and houses flooded is summed up for the area of interest. These results show a different picture when compared to the results of the study area as a whole. The results show that locally the flood extent can increase from 1% for the smallest event to 8% for the largest events. Locally the increase in houses flooded can increase up to 18%. For the smallest event no increase has been observed.

Table 5: Difference between the separate and coupled model setup – Flood extent – Area of interest

Precipitation event	Flood extent [ha]		Increase in flood extent [%]
	Model setup 1 (Separate)	Model setup 2 (Coupled)	combined relative to separate model setup
30 mm (1hr)	5.5	5.6	1
50 mm (1hr)	19.1	19.7	3
70 mm (1hr)	30.0	31.4	5
90 mm (1hr)	38.7	41.7	8

Table 6: Difference between the separate and coupled model setup – Houses flooded – Area of interest

Precipitation event	Houses flooded		Increase in houses flooded [%]
	Model setup 1 (Separate)	Model setup 2 (Coupled)	combined relative to separate model setup
30 mm (1hr)	3	3	0
50 mm (1hr)	34	40	18
70 mm (1hr)	100	117	17
90 mm (1hr)	190	216	14

5.4 Analysis 3: Sensitivity Analysis

A sensitivity analysis is conducted to get a better understanding of the model response to different parameters. The response to surface roughness, mesh size and initial infiltration rate for unpaved areas is analysed in the research. For this parameter sensitivity analysis the coupled model setup, and the short duration 70 mm in 1 hour precipitation event are used. All parameters stay the same during the analysis except for the parameters discussed. The different model parameters are compared based on the modelled flood extent for the whole 2D grid and the catchment outfall hydrograph.

5.4.1 Surface roughness

For the surface roughness, the roughness of the 2D grid cells, multiple Manning n parameters were tested ranging from 0.02-0.05 [s/m$^{1/3}$]. The roughness value is applied to the whole 2D surface so no distinction is made between different land uses which is done in the original model used in analysis one and two. From Table 7 it can be seen that the flood extent slightly increases with a larger roughness value. In the catchment outfall hydrograph of Figure 31 a slight decrease in discharge can be noticed with an increasing roughness value. However, the changes in flood extent and catchment outfall hydrograph are minor.

Table 7: Flood extent - Response to surface roughness

Manning roughness coefficient [s/m$^{1/3}$]	Flood extent [ha]
0.02	867
0.03	881
0.04	890
0.05	895

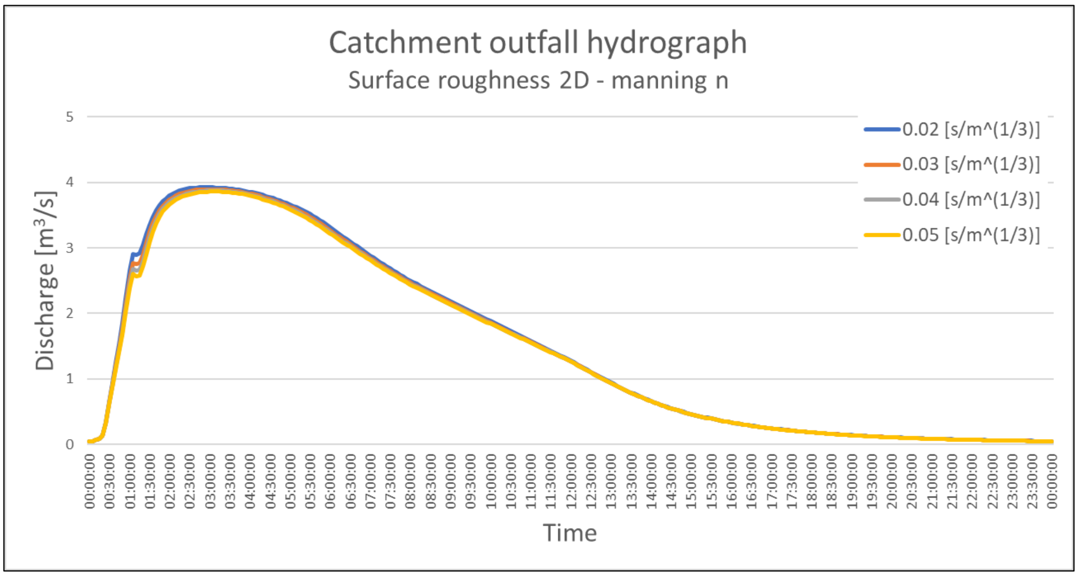

Figure 31: Catchment outfall hydrograph - Response to surface roughness

5.4.2 Mesh Size

In the model setup of Schijndel a mesh size of 2-5 m^2 is used for the urban area and 5-50m^2 for the rural area. Is this SA two larger combinations of grid sizes, for urban and rural areas, are added and compared. The results of Table 8 show that with an increase in grid size the flood extent increases significantly. The catchment outfall hydrographs of Figure 32 show that with a larger grid size the total discharge of the catchment increases and the discharge peak moves more to the front.

Table 8: Flood extent - Response to mesh size

Mesh size [m2]	Flood extent [ha]
2-5 [urban] 5-50 [rural]	881
5-50 [urban] 50-200 [rural]	913
50-200 [urban] 200-500 [rural]	949

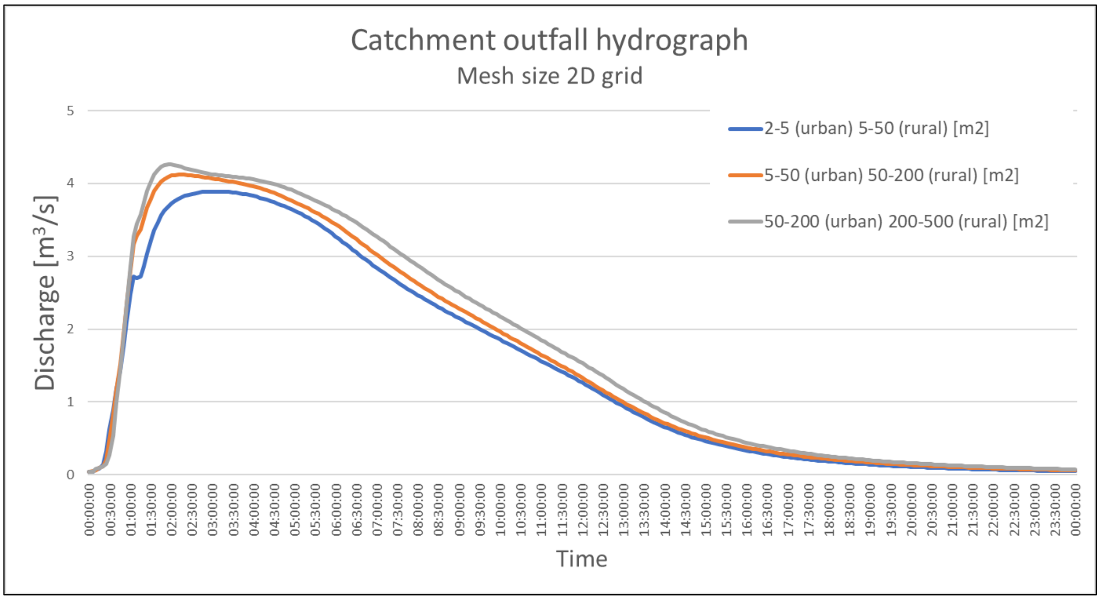

Figure 32: Catchment outfall hydrograph - Response to mesh size

5.4.3 Initial infiltration unpaved surfaces

In the case study area there are a lot of unpaved areas in the rural surrounding of Schijndel. Because it is expected that the infiltration in these unpaved areas largely determines the model response different infiltration parameters were compared. In the Infoworks ICM model the infiltration method of Horton is used as explained in chapter 4.3.2. The method of Horton uses an initial infiltration rate f_0 which can be assigned based on land use, soil type and initial conditions, see Figure 9. In the model for the case study of Schijndel an initial infiltration rate f_0 of 100 [mm/hr] is used, see Table 2. In this SA the model response to different f_0 for the unpaved areas are compared. These values are 50, 100, 150 and 200 [mm/hr].

In Table 9 it is clearly visible that the infiltration for unpaved areas significantly influences the flooding extent in the catchment area. The catchment outflow hydrographs of Figure 33 shows that the total outflow of the catchment decreases significantly. The shape of the outflow hydrograph also changes. The peak discharge corresponding to the smallest infiltration parameter is twice as large as the peak discharge corresponding to the largest infiltration parameter. With a larger infiltration rate we also see a small discharge peak before the main discharge peak. This discharge peak corresponds to paved areas in the rural catchment area of the Schijndelse loop. The runoff from the urban area and the runoff from unpaved areas in the catchment area of the Schijndelse loop together form the second discharge peak.

Table 9: Flood extent - Response to initial infiltration f0 of unpaved areas

Initial infiltration rate f0 unpaved areas [mm/hr]	Flood extent [ha]
50	975
100	881
150	768
200	625

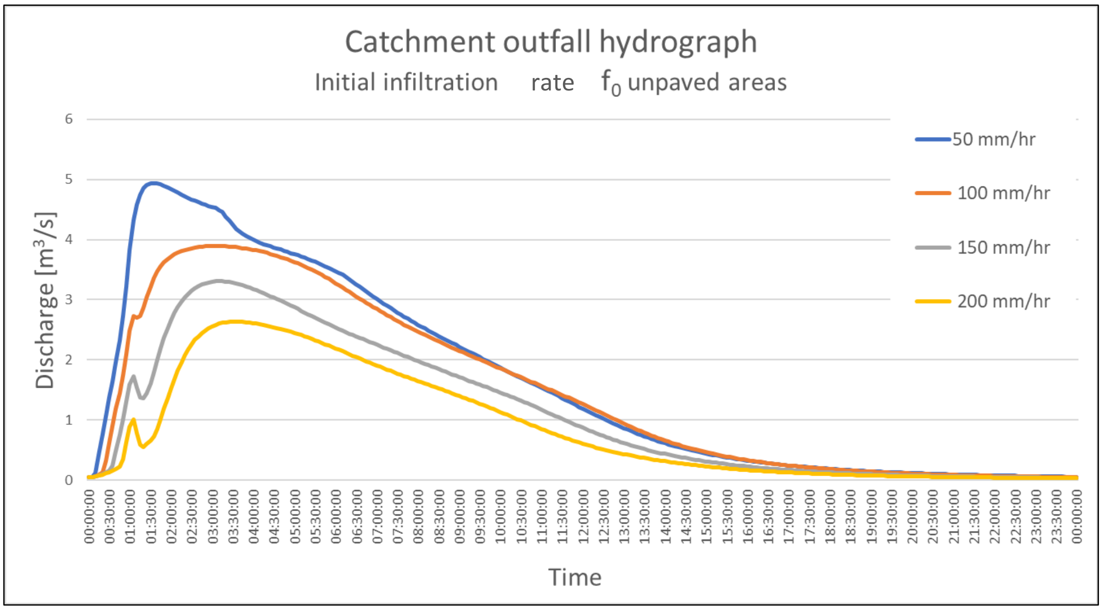

Figure 33: Catchment outfall hydrograph - Response to initial infiltration rate of unpaved areas.

6 Discussion on the overall validity of the results

This research investigated to what extent the urban drainage system and rural surface water system of Schijndel influence each other during extreme precipitation events. In order to analyse this interaction a 1D2D hydrodynamic model has been constructed in Infoworks ICM. The configuration of this model is based on the lessons learned from previous studies. Multiple analyses have been performed with this model in order to evaluate the performance of the model, investigate the interaction between urban and rural and better understand the model response to a change in parameters. In this discussion the hydrodynamic model for the case study is discussed first after which the results are evaluated.

A general limitation of the research is the fact that the model is not calibrated. Because of a lack of field data on water levels or flows no calibration process could be performed. This lack of data is often an issue in water system analysis studies in the Netherlands. Instead of a calibration process the modelled flood locations are compared to known flood reports in the urban area which data was available. In addition, a sensitivity analysis (SA) was performed on model parameters to better understand how different parameters influence the model response. This knowledge can be used in a possible future calibration study. If the model is to be calibrated in the future, level (and/or flow) measurements should be recorded at multiple combined sewer overflow locations and in multiple parts in the surface water network. In order to use the correct precipitation input ideally multiple rain measurements should be taken in different parts of the catchment. These measuring devices should measure for at least a few years and hopefully catch an extreme rainfall event. As can be seen from the model results the urban drainage system and rural surface water system only start to influence each other at the short duration events with a rainfall depth of more than 50 mm in 1 hour. The chance to catch such an event however is limited which makes the calibration process challenging. Another issue is the calculation time of the model, if long precipitation time series are used the calibration process will be time consuming because a single parameter change will take up to a day to adjust and calculate.

6.1 Hydrodynamic model setup

6.1.1 Model configuration

In order to investigate the interaction between urban and rural a 1D2D hydrodynamic model for the study area was setup. The first task of this research was to figure out what this model must look like and which components it must include. Based on recent literature and the analysis that had to be performed a model configuration was composed. As discussed in chapter 2 the different studies each had their strong and weaker points. The model configuration that is based on literature is an aggregation of the strong model components from all the different studies of which an overview is discussed in chapter 3.2. However not all components of the model configuration of chapter 3.2 could be incorporated in the final case study model. The hydrodynamic software package Infoworks ICM didn’t offer the possibility to incorporate a groundwater component in combination with a model setup where precipitation was applied directly to the 2D grid. Infiltrated water is therefore lost to the model and cannot contribute to the channels as base flow. One study also advised to divide the spatial infiltration based on soil type, however in this study all unpaved areas were assigned the same infiltration parameters. Besides these two points, the model configuration for the case study of Schijndel combined all lessons learned from previous studies.

6.1.2 Model limitations

During this research the final model setup also proved to have its limitations. In recent literature the empirical method of Horton was often mentioned for the infiltration which was incorporated in the case study model (Fernández-Pato et al., 2016; Gray, 2008).Horton works with a final infiltration rate which is reached after a certain period of time, in this research 20 mm/hr for the unpaved areas and 10 mm/hr for openly paved area. For the long duration precipitation event, 120 mm in 48 hours (average of 2.5 mm/hr), this means that all precipitation will infiltrate for these permeable areas if the Horton method is used. Because there is no groundwater component in this model the infiltrated water is lost to the model and doesn't contribute to the channel network as baseflow. With this model setup the soil will never get completely saturated and because no groundwater component is incorporated ground water flows are not accounted for. For the short duration intense events in Schijndel, which occur during summer, it might be a valid assumption that the infiltrated water is lost to the system. The soil in the study area consists of moderately coarse sands at a lot of locations so a lot of the water will infiltrate relatively fast. However a detailed soil map was not available. This model setup without a groundwater component and with a final constant infiltration will be less suitable when longer duration precipitation events are analysed where total soil saturation and ground water flows are of influence. This especially applies to areas with low permeable soils and high groundwater tables. The results from the calculations with Horton infiltration and without infiltration for the long duration event show the impact infiltration has on the model response. The calculations with Horton infiltration don't result in flooding at all and the calculations without infiltration result in significant flooding. This underlines the importance of a suitable infiltration method, especially for the analysis of long duration precipitation events.

6.1.3 Model assumptions

For the model some assumptions were made that influence the results to a certain extent. No initial filling was applied for water bodies that were not present in the 1D system. Ditches and ponds that were only present in the 2D surface grid were therefore empty at the start of the simulations. This might result in an underestimation of the flooding extent. The 1D channel system was however pre-filled until the crest levels of the weirs. This is a valid assumption for the short duration event which occur in summer. The system might however be filled more for the events which can occur in autumn or spring. This may result in an underestimation of the flooding extent. There are two combined sewer overflows (CSOs) in the north of Schijndel that do not discharge into the catchment area of the Schijndelse Loop but in a different catchment. For these CSOs free super critical discharge (no downstream boundary conditions) out of the model is assumed because the receiving catchments are not incorporated in the model domain and downstream boundary conditions are unknown. In reality, these CSOs would react in the same way as the seven CSOs that discharge in the catchment area of the Schijndelse Loop. The surface water in the receiving catchment fills up and the flow over the CSOs changes from super-critical to sub-critical which limits the flow. As discussed before, it is assumed that all unpaved surfaces have the same infiltration rate. Recent literature mentions that the infiltration rate has a high spatial variability based on soil type and local conditions (Beek, 2019). This assumption will therefore influence the results but it is unclear if this leads to an over or underestimation of the flooding in the study area. Another assumption which corresponds to the Horton infiltration method is that the permeable surfaces have a constant final infiltration which is larger than 0. This turned out to be a limitation when analysing long duration precipitation events because the soil will never reach total saturation. These assumptions and boundary conditions however apply to both the separate model and the coupled model setup. The model setups will therefore both have the same possible deviations and can therefore still be compared to each other.

6.1.4 Input data

The input data for this study was compared to findings from recent studies. The digital elevation model (DEM) used, which has a resolution of 0.5x0.5m closely connected to the requirements set in a previous study mentioning DEM resolutions between 1-5 m^2 (Adeogun et al., 2015). The 2D grid size was chosen based on the built-up of the area and the desired level of detail. For this study a detailed grid size was used for both the urban area (2-5 m^2) and a slightly larger grid size for rural areas (5-50 m^2). These choices have been made because of the high heterogeneity in the urban area and the more homogenous nature or the rural area. Another advise from recent literature was the application of spatially different infiltration and roughness (Adeogun et al., 2015; Fernández-Pato et al., 2016). Based on a land use map the model differentiated between water, flat roofs, sloped roofs, unpaved areas, openly paved areas and closed paved areas. In future studies different infiltration parameters for unpaved surfaces can be applied based on soil type and land use. Because of the high heterogeneity of the unpaved surfaces this might improve the results. This however only has added value if detailed data is available and the model can be validated or calibrated properly. The sewer system within the study area consists of a combined sewer network. In this study this combined sewer network with all dimensions and hydraulic structure is included in the model. For the 1D surface water network all available data was incorporated. This includes a total of 288 culverts and 10 weirs with corresponding data concerning the shape and dimensions. The channels and ditches that were not represented in the 1D network were represented in the 2D surface grid as depressions and exchanged water with the 1D network via bank lines. Culverts that connect the smaller ditches which are not present in the 1D channel network are not incorporated in the model because no data was available. Because of this not all flow paths which connect these ditches are incorporated and water only leaves these smaller ditches when they are overtopped.

6.1.5 Hydrodynamic software package Infoworks ICM

The calculation tool Infoworks ICM offered sufficient modelling capabilities to model the response for short duration precipitation events. Most of the model components could be incorporated. Detailed flow calculations could be conducted in the 1D and 2D system and a dynamic exchange between channels, gully pots and the 2D grid was possible. Unfortunately, no groundwater component could be included which limited the capabilities to analyse longer duration precipitation events. Modelling the 1D2D interface between channels and the surface grid has been the most difficult part of model setup because of computational instabilities. This is a common problem in different hydrodynamic software packages and proved to be difficult to solve, mainly because of incorrect information in the Infoworks ICM help files. Infoworks ICM has adjusted this information after being notified. Because of the size of the final model and the detailed surface grid the run times and the built-in fault checks took very long. Simple changes to the model would therefore take multiple hours to adjust. It is therefore of utmost importance to perform all possible data checks prior to modelling. Taking the Courant-Friedrichs-Lewy condition into account, the run time of the model will probably significantly increase because of the small grid elements which were produced. This has to do with the input files corresponding to the land use map for the voids and infiltration polygons which in the future can be adjusted with a different land use map.

6.2 Results

The hydrodynamic model of Schijndel was used to perform the different analyses to investigate the model performance, difference between a coupled and separate model setup and the sensitivity to different model parameters. Two model setups were used for the analysis. The first setup where CSOs had free discharge out of the model boundaries. Precipitation was routed via the surface layer to either the sewer system or the surface water system. In the second setup the CSOs were coupled to the channel network which enabled dynamic exchange of water at these locations. For analysis one and three the second model setup was used. In analysis two, results corresponding to the separate and coupled model setups were compared for different precipitation events.

6.2.1 Analysis 1: Check against known flood reports

In the first analysis the calculated flood depths were compared to known flooding locations to see if the coupled model results correspond with reality. 8/10 known flood reports also came forward in the results, 2/10 flood reports did not occur in the results. The results show that most of the located flood reports also arise from the model. It has to be noted that the results show a lot more locations that were flooded for which no flood reports were known. This does not mean that these locations won't be flooded in reality but there are no known flood reports to validate this.

6.2.2 Analysis 2: Separate vs Coupled model setup

In the second analysis the influence which the urban drainage system and the rural surface water system have on each other was investigated. The difference between the separate and coupled model setups were compared. The difference in flood depth, flood duration, flood extent and houses flooded is discussed. The results show that the urban drainage and rural surface water system do influence each other but that this effect is location and event specific. The difference between the two model setups which is discussed below is described as:

$$Difference\ (per\ grid\ cell) = Results\ coupled\ model\ setup - Results\ separate\ model\ setup$$

For the long duration event (120 mm in 48 hours) the response was calculated for two different infiltration settings and compared in order to investigate the role of the infiltration component for long duration events. This first setting was with the Horton infiltration method and an initial soil saturation of 80%. The unpaved areas had a final constant infiltration rate of 20 mm/hr and the openly paved areas 10 mm/hr with the Horton method. The second infiltration setup meant no infiltration at all for the whole study area. For the first setting with Horton infiltration no differences between the separate and coupled model setups were observed. Looking at the flood maps corresponding to this event it can be seen that almost no flooding is observed in the entire catchment for both the separate and coupled model setups. This can mean two things: either the long duration event doesn't cause flooding or the model isn't suitable for the analysis of a long duration event where the soil gets saturated over time. For the study area of Schijndel it is both. The soil in the study area consists of moderately coarse sands which have a decent infiltration capacity so most of the water will infiltrate for the long duration precipitation event. The current model setup also has its limitations and as discussed the model probably isn't suitable for the long duration events at this point. There is no groundwater component and the final infiltration rate of the model is much larger than the constant intensity of the long duration event, which is 2.5 mm/hr. All precipitation that falls on unpaved surfaces is directly infiltrated and lost to the system. In reality, it is likely that after some time the soil gets totally saturated which will results in more surface runoff and ground water base flow to the channel system. This is especially important for areas with low permeable soils and high groundwater tables. The calculations with the long duration event without infiltration resulted in a significant difference between the separate and coupled model setups. Locally the flood depth increases more than 5 cm and the flood duration more than 5 hours. The flood extent increased with 8% and the houses flooded increased with 1%. However, if no infiltration is allowed all water will accumulate in depressions in the landscape and before narrow passages like culverts. Of course, in reality a certain amount of infiltration will happen and the soil only gets totally saturated over time. This means that current infiltration settings, with Horton infiltration or without infiltration at all are both not suitable for the analysis of long duration precipitation events for areas with low permeable soils and high groundwater tables. In reality the amount of flooding will be somewhere in between. The results illustrate the importance of a suitable infiltration method or infiltration parameters for long duration precipitation events which have yet to be found. In future studies lower final infiltration and decay rate parameters can be tested for the Horton infiltration method in order to mimic total saturation of the soil. The incorporation of a groundwater component will also help. However, a hydrodynamic software package must be found that supports this in combination with a model setup where precipitation is applied directly to the 2D grid. Unfortunately, currently the computer power might be a limitation for such a complex model setup with a detailed groundwater component.

For short duration events a difference in response between the separate and coupled model setups can be observed, especially upstream and downstream of the CSO locations. If the study area of Schijndel is considered as a whole for the 70 mm in 1 hour event an increase in flood extent of 1% and the increase in houses flooded of 2% can be observed, which is limited. Locally the difference in flood depth and flood duration can amount to an increase in flood depth of 1-5+ cm and an increase in flood duration of 1-5+ hours for this event. The impact is mostly observed in the southern area of Schijndel surrounding the five CSOs that are present there. For the smallest event of 30 mm in 1 hour the difference is negligible, this means that an equal amount of flooding is observed for the separate and coupled model setup. The difference in modelled flood response between the coupled and separate model setup increases as the events increase in volume (50, 70, 90 mm in 1 hour). This can be explained by the fact that for the smaller events still enough storage capacity is available in the surface water system because most of the water on unpaved surfaces can infiltrate. Therefore, the discharge from the urban area isn't hindered yet because of a lower water level in the surface water system and the banks in the surface water system don't get overtopped yet. With the large events the systems get filled and the infiltration rates decrease. The urban drainage system and the rural surface water system therefore start to influence each other because both systems cannot discharge their water properly. The flow over CSOs changes from super-critical to sub-critical which decreases the discharge capacity and causes an accumulation of water in the urban drainage system. The surface water system drains the extra water from the CSOs which causes extra flooding in the rural surface water system. From the original flood depth maps of the separate and coupled model setups it can be seen that both the urban and the rural areas experience flooding, even if they are analysed separately. However, if they are analysed as one the flood extent and resulting damage get larger in areas upstream and downstream of CSOs.

Because the differences are location specific the results zoom in on the sewer district of Borne and the receiving channels. Comparing the coupled model setup with the separate model setup for this area of interest, local increases in the coupled model are found for flood depth, flood duration, flood extent and houses flooded. The increase in flood extent amounts to 5% and the increase in houses flooded amounts to 17% for the 70 mm in 1 hour events. This is a significant increase when compared to the model outcomes for the whole study area.

Looking at all the short duration events it can be seen that the flood depth increases between 1-5+ cm and the flood duration between 1-5+ hours. As the events increase in intensity, the difference between the separate and coupled model setups increase as well. The increase in flood extent can go up to 8% (90mm in 1 hour) and the increased percentage of houses flooded can go up to 18% (50mm in 1 hour). These results correspond to recent literature of Sto. Domingo et al. (2010) which noted that the runoff of a rural upper catchment is of influence to amount of water which comes as inflow into the lower urban catchment. In this research it is reversed, the urban area is upstream of the rural surroundings. The results of this research show that besides extra inflow into the channel network there is also extra accumulation of water in the urban area. As the events increase the difference in flood depth and flood durations moved from the urban area into the rural area. This is because water from the urban area starts to move as surface runoff directly into the surface water system outside the CSO locations. The local differences are much higher than the catchment wide differences. This can be explained because besides the connections at the CSOs, nothing changes in the rest of the catchment and the further away from the CSOs the influence is damped out.

The results show the separate urban drainage and rural surface water models can locally underestimate the amount of flooding when compared to a coupled model setup. Differences between the separate and coupled model setups are observed in areas surrounding six out of seven CSOs and at some locations more significant than others. Looking at the catchment as a whole there are also a lot of areas where no difference is observed, these areas are further away of the CSO locations. The importance of a coupled model can be discussed from two viewpoints. The first viewpoint is for the municipality and the second one the waterboard. For the municipality it is important to known if the CSOs have free discharge and if water enters the urban area from upstream so no extra water accumulates in the urban area. A coupled model setup is than important if the difference between the crest level of the CSO and the receiving surface water level is limited. When the surface water gets higher than the crest level of the CSO the discharge changes from super-critical to sub-critical. For the municipality a coupled model setup is also important if surface water runs through the municipality which gets its water from an upstream catchment. During extreme precipitation this could lead to overtopping of the banks which can cause additional flooding in the urban area. The second viewpoint is for the waterboard. The urban drainage system can cause extra inflow into the rural surface water system which can result in an increase in flooding in the rural area. A coupled model is then important to properly replicate the extra discharge from the urban area with the corresponding timing. The discharge peak from the urban area can coincide with the discharge peak from the rural area or it might be earlier or later. This timing and the volume of water can best be predicted with an integral coupled sewer-surface water model.

The original flood depth maps of Schijndel show that flooding occurs in both the urban areas and the rural areas even if they are analysed separately. This means that the flooding problem in Schijndel is a problem of both the municipality and the waterboard. Together they should analyse where flooding occurs and which possible measure could help to reduce the flooding extent. This could be the increase in size of culverts, channels, sewer pipes or the creation of extra storage in the urban or rural area. The most important thing is that the municipality and waterboard should corporate and discuss with each other what is most efficient. This cooperation is also mandatory in the Netherlands as stated in the Delta program 2018 (Rijksoverheid, 2017).

6.2.3 Analysis 3: Sensitivity Analysis

In order to better understand the model response and the sensitivity to different model parameters a sensitivity analysis (SA) was performed. In the SA different values for the surface roughness, grid size and initial infiltration rate for unpaved areas were compared since these were deemed the most influential and spatially different parameters according to literature (Adeogun et al., 2015; Beek, 2019). Different roughness values range from a manning of 0.02-0.05 [$s/m^{1/3}$] were compared. The results showed that an increase in roughness resulted in an increase in flood extent. A larger roughness also results in a decrease of in the total discharge according to the discharge hydrographs. An explanation for this might be that because of a larger roughness the flow speed decreases, the water accumulates and therefore has more time to infiltrate into the 2D grid. However, compared to the result of the study of Adeogun et al. (2015), they found the flood extent decreased with an increase of surface roughness. The difference between the studies is that Adeogun et al. (2015) didn't incorporate infiltration into the model. This can explain the difference in response. For the grid size it can be noted that an increase in grid size results in a significant increase in flood extent and total discharge. The peak of the catchment outflow hydrograph also moves more to the front of the event. According to the study of Adeogun et al. (2015) a smaller grid size would give better results because the topography of the area is better represented. The larger discharge in the catchment can then be explained by this lack in detail for the 2D surface grid. With larger grid sizes it is possible that local depressions are flattened out or accentuated which leads to an underestimation or overestimation of the possible surface storage. Larger grid sizes also lead to data loss because each grid element has one type of land use assigned to is based on the land use map. Land use parameters like roughness and infiltration are taken from the land use map at the centre point of each grid element. This can also influence the runoff volume and runoff speed. The parameter that by far had the most influence on the flood extent and the catchment outflow is the initial infiltration parameter f_0 for the unpaved areas. The catchment outfall hydrograph corresponding to the smallest f_0 of 50 mm/hr had a discharge peak half the size of the largest f_0 of 200 mm/hr. The initial infiltration parameter also influences the shape of the catchment outfall hydrograph. With the smaller f_0 the unpaved areas where discharging water much faster than with the larger f_0 because the infiltration capacity was exceeded earlier. This resulted in a much earlier discharge peak for the smaller f_0 values. For a possible future calibration process it can be noted that it is of utmost importance to investigate the infiltration capacity within the area. This is in accordance with the results for the long duration precipitation event discussed in analysis two. This is also the most difficult parameter to determine because of the large spatial differences in infiltration as described by Beek (2019). It can further be noted that it is important to use small grid sizes for the model even if that means the model has a long run time. The surface roughness is also of importance but has a much smaller impact than the other two parameters.

7 Conclusion & Recommendation

In this chapter firstly the research conclusions are discussed after which recommendation are made.

7.1 Conclusions

The objective of this research was to investigate how severe flooding caused by extreme precipitation is underestimated when the urban drainage system and rural surface water system are analysed separately instead of coupled. This should give an answer to the question if the urban drainage system and the rural surface water system should be analysed as one instead of separate.

From the results of this study it can be seen that the urban drainage system and the rural surface water system of Schijndel do influence each other during extreme precipitation. The influences turn out to be location and event specific and occur upstream and downstream of combined sewer overflows (CSOs). When analysed separately the flooding consequences are underestimated upstream and downstream of CSOs compared to a coupled analysis of the sewer and surface water system. Both the sewer system and surface water system however experience flooding during extreme precipitation, even when analysed separately. This means that the flooding problem in Schijndel is a problem of both the municipality and the waterboard. They should try to combine their stress test in order accurately analyse where flooding occurs and which possible measures could help to reduce the flooding extent. It is therefore advised to model and analyse the system as one. The conclusions are further elaborated based of the three sub-questions defined in chapter one.

7.1.1 **Sub-question 1:** *Which analysis must be performed on the hydrodynamic model of Schijndel in order to be able to analyse the interaction between the sewer and surface water system during extreme precipitation?*

In order to investigate the response of the water system of Schijndel during extreme precipitation and investigate the interaction between the urban drainage system and rural surface water system three analysis had to be performed:

1. The modelled flooding had to be validated in some way to see if the modelled results resemble reality.
2. The interaction between the sewer and surface water system had to be investigated with a separate and coupled model setup. The response of the system had to be analysed with different short and long duration precipitation event of different intensities. Normally long duration events are used for the analysis of surface water systems and short duration events for sewer systems.
3. The sensitivity of the model response to different sensitive model parameters had to be analysed in order to better understand the model response for future studies or calibration of the model.

7.1.2 **Sub-question 2:** *In what way can the urban area be linked to the surrounding catchment in a hydrodynamic model to investigate the interaction between the sewer and surface water system?*

In order to investigate the response of the sewer and surface water system of Schijndel a hydrodynamic model had to be setup which included both the sewer and surface water system and a detailed representation of the surface layer. The interaction between the sewer and surface water system of Schijndel was investigated by comparing the results of two model setups, separate and coupled. In the separate model setup the sewer and surface water system were not connected to each other and could therefore not dynamically exchange water over the course of an event. In the coupled model setup the sewer and surface water system were connected to each other at the location of CSOs. Over the course of an event a dynamic exchange of water was possible at these locations. These two model setups were analysed during multiple precipitation events and the results were compared for the separate and coupled model setup. This way the interaction between the sewer and surface water system could be investigated.

7.1.3 **Sub-question 3:** *How does the case study area of Schijndel react to extreme precipitation and what influence do different model setups and parameters have on the results?*

<u>Analysis 1: check against known flood reports</u>
At first the model response of the coupled model setup was compared to known flood reports to check if the model outcome corresponds to reality. Ideally the model should be calibrated however not enough data was available for this. Flood reports were available and were therefore used to check the model response. The results of this analysis show that 8/10 known flood reports in the urban area also come forward in the flood results corresponding to an event with a return period of five years. The model seems to be able produce results which correspond with reality for the urban area.

<u>Analysis 2: separate vs coupled model setup</u>
In the second analysis the results of separate sewer and surface water model were compared to the results of a coupled model setup. The results were compared for multiple short and long duration precipitation events with respect to flood depth, flood duration, flood extent and houses flooded. The differences area:

$$Difference = Results\ coupled\ model\ setup - Results\ separate\ model\ setup$$

For the long duration event, 120 mm in 48 hours, calculations were done with and without a infiltration component. The calculations with infiltration component did not results in flooding at all because the water infiltrates as the model setup works with a final constant infiltration rate. The infiltration parameters are based on the moderately coarse sand soils which are present in Schijndel. The area seems fairly insensitive to long duration extreme precipitation events because a large amount of the water that infiltrates and percolates to the groundwater. However, the current model setup doesn't incorporate a ground water component nor can it reproduce total saturation. The calculations without infiltration show that these components have significant influence on the resulting flooding and therefore should be incorporated when areas are analysed with low permeable soils and high groundwater tables. For future studies where these conditions apply this should be taken into account. At this point the model setup of this study is not capable of doing so. The current model setup is better suited for short duration precipitation events where total soil saturation is less likely.

The short duration events analysed have a duration of 1 hour and flood depth of 30, 50, 70 and 90 mm respectively. The results corresponding to the short duration events show an increase in flood depth, flood duration, flood extent and houses flooded when the coupled model setup is compared to the separate model setup. The locations where differences occur are however location specific and mainly occur upstream and downstream of the CSOs.

If the catchment is considered as a whole for the 70 mm in 1 hour event an increase in flood extent of approximately 1% and the increase in flooded houses of 2% was observed. Locally the flood depth increased more than 5 cm and the flood duration increased more than 5 hours.

The results zoom in on a separate sewer district (part of the sewer system) with 2 CSOs and receiving channel sections as area of interest because the differences are location specific. For this area of interest the differences between the model setups are larger than when the whole study area is analysed. The increase in flood extent amounts to 5% and an increase in houses flooded amounts to 17% for the 70 mm in 1 hour events.

For the area of interest the response to different events were compared (30, 50, 70, 90 mm in 1 hours). This was done to see if the system response, and the interaction between the urban drainage system and the rural surface water system changed with different events. The results show that as the events get larger the two system start to influence each other more. For the smallest event, 30 mm in 1 hour, no differences between the separate and coupled model setups were observed. For this event the rural surface water system probably has enough storage capacity so the systems don't influence each other yet. As the events get larger (50, 70, 90 mm in 1 hour) the difference between the two model setups increase; a larger difference in flood extent is observed, up to 8% for the 90 mm event. The percentual differences in flooded houses peaks at 18% for the 50 mm event. The original flood depth maps show that flooding occurs in both the urban and the rural areas for both the separate and coupled model setups.

Analysis 3: sensitivity analysis

In the third analysis the model response to changes in the sensitive parameters surface roughness, grid size and initial infiltration rate were compared for the coupled model setup. The flood extent and catchment outflow hydrographs were analysed. This analysis was used to get a better understanding of the model response to different parameters for a possible future calibration process.

The results show that in increase in surface roughness results in a slightly larger flood extent and a slightly smaller discharge at the catchment outfall. The larger friction probably causes the water to slow down and accumulate more on the surface grid where it has more time to infiltrate. The accumulation causes the larger flood extent, the extra infiltration time and a smaller catchment discharge at the outfall.

A larger grid size causes a significantly larger flood extent and a larger discharge volume at the catchment outfall. This might be because the topography and land use aren't represented in detail anymore. With larger grid sizes it is possible that local depressions are flattened out or accentuated which leads to an underestimation or overestimation of the possible surface storage. Larger grid sizes also lead to data loss because each grid element has one type of land use assigned to it based on the land use map. Land use parameters like roughness and infiltration are taken from the land use map at the centre point of each grid element. Larger areas can either be classified as permeable or impermeable. The different land use surface areas can therefore be over or underestimated which can influence the runoff volume and runoff speed.

The parameter that was found to have the most influence is the initial infiltration rate used in the Horton equation. Initial infiltration values of 50, 100, 150 and 200 mm/hr were compared. The smallest initial infiltration rate (50 mm/hr) caused a flood extent and catchment discharge peak almost twice the size of the largest initial infiltration rate (200 mm/hr). The peak discharge also appeared two hours earlier for the smallest initial infiltration rate compared to the largest. For a possible future calibration process and future studies the infiltration parameter will therefore be the parameter that has the most influence on the results.

7.2 Recommendations

During this study some limitations to the model and the analysis were discussed. For future stress test studies some recommendation are made:

1) Better validation
It is recommended to perform a more detailed validation / calibration process.

2) Discharge and water level measurements
In order to validate/calibrate it is advised to install flow or level measurement devices at multiple CSOs and in strategic parts of the surface water system.

3) Rain gauges
Additional rain gauges should be installed in the catchment. Ideally these should measure for a longer period of time in order to catch an extreme rainfall event, this also applies to the discharge and level measurements. This data can then be used to firstly validate the water system response and later calibrate the model based on sensitive model parameters.

4) Soil examination
The soil composition in the area must be investigated because the infiltration parameters turned out to be the most influential model parameters.

5) Different infiltration parameters
In future studies different infiltration parameters for unpaved surfaces can be applied based on soil type and land use. Because of the high heterogeneity of the unpaved surfaces this might improve the results. This however only has added value if detailed data is available and the model can be validated or calibrated properly.

6) Different infiltration methods
It is further advised to investigate the possibilities of different infiltration methods and parameters which are able to mimic total saturation of the soil.

7) Groundwater component
For future studies a groundwater component should be added to the model configuration of this study if hydrodynamic software packages offer this option. Total saturation of the soil and/or a groundwater component are necessary for the analysis of long duration precipitation events in areas with low permeable soils and high groundwater tables.

Additional recommendations for municipalities waterboards and the ministry in the Netherlands:

1) Better co-operation:

For the rest of the municipalities and waterboards in the Netherlands it is advised to better collaborate while performing stress test analysis in their areas. This collaboration is mandatory as stated in the Delta program 2018 of the Dutch government. The results show that in areas upstream and downstream of CSOs the flooding can be underestimated if both the municipalities and waterboards perform stress tests by themselves instead of combined. This underlines the importance of integral analysis.

2) Integral models:

The most extensive cooperation between the municipality and waterboard is an integral model of the sewer and surface water system. It is advised to build such an integral model it the area has one of the following characteristics:

- (1) The urban area is upstream of the rural area, (2) the area is relatively flat and (3) there is little height difference between the crest level of the CSO and the water level of the receiving surface water. The urban area may not be able to always discharge its water freely and it is therefore important to mimic the flow dynamics in the areas surrounding CSOs;
- The urban area is downstream of the rural area and surface water body's that drain the rural catchment flow through the urban area, a sloped upper catchments increases the importance of a coupled model. A discharge peak can come from the rural upper catchment which can coincide with the flooding in the urban area. The combination of flood peaks can best modelled in an integral model;
- The rural area is downstream of the urban area and there are capital intensive or vulnerable pieces of land in the rural area relatively close to the CSOs. The flood peak of the rural area can coincide with the flood peak of the urban area, or not. The extra discharge from the urban area and the timing of the flood peak can best be modelled with an integral model.

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A Flood reports sewer plan 2009

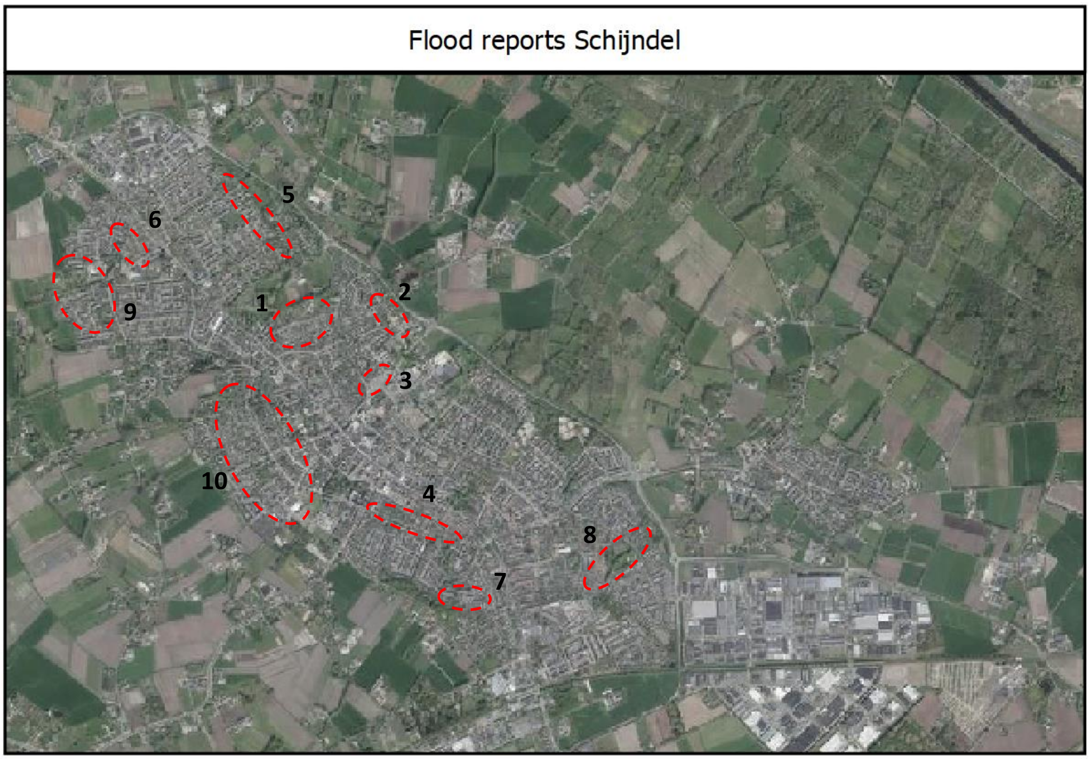

Figure 34: Flood reports Schijndel (Grontmij, 2009)

Known flood reports from the sewer plan of 2009 (Grontmij, 2009):

1. Brouwketel
2. Eekelhof
3. Oude Steeg
4. Heikantstraat
5. Bloemenpad
6. Boskoopstraat
7. Verdipad
8. Zandkantsestraat
9. Diverse locaties in gebied Grevekeur
10. Diverse locaties in gebied Borne

B Result maps corresponding to analysis two

In this appendix maps corresponding to results of analysis two are represented. The following maps can be found in this appendix, ordered according to the list:

Maximum flood depth

- 30 mm in 1 hour – separate model setup
- 30 mm in 1 hour – coupled model setup
- 50 mm in 1 hour – separate model setup
- 50 mm in 1 hour – coupled model setup
- 70 mm in 1 hour – separate model setup
- 70 mm in 1 hour – coupled model setup
- 90 mm in 1 hour – separate model setup
- 90 mm in 1 hour – coupled model setup
- 120 mm in 48 hours – separate model setup – 80% soil saturation
- 120 mm in 48 hours – coupled model setup – 80% soil saturation
- 120 mm in 48 hours – separate model setup – no infiltration
- 120 mm in 48 hours – coupled model setup – no infiltration

Flood duration

- 70 mm in 1 hour – separate model setup
- 70 mm in 1 hour – coupled model setup
- 120 mm in 48 hours – separate model setup – 80% soil saturation
- 120 mm in 48 hours – coupled model setup – 80% soil saturation
- 120 mm in 48 hours – separate model setup – no infiltration
- 120 mm in 48 hours – coupled model setup – no infiltration

Houses flooded

- 70 mm in 1 hour – separate model setup
- 70 mm in 1 hour – coupled model setup

Difference in maximum flood depth between coupled and separate model setup

- 30 mm in 1 hour
- 50 mm in 1 hour
- 70 mm in 1 hour
- 90 mm in 1 hour
- 120 mm in 48 hours – 80% soil saturation
- 120 mm in 48 hours – no infiltration

Difference in flood duration between coupled and separate model setup

- 30 mm in 1 hour
- 50 mm in 1 hour
- 70 mm in 1 hour
- 90 mm in 1 hour
- 120 mm in 48 hours – 80% soil saturation
- 120 mm in 48 hours – no infiltration

Maximum flood depth

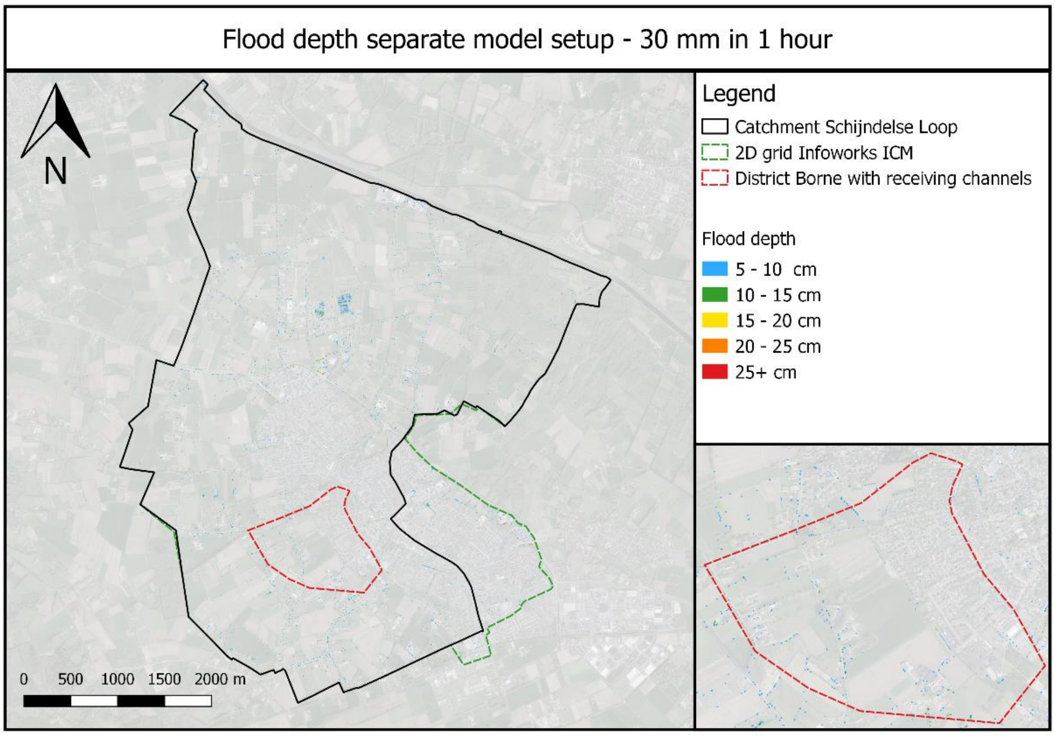

Figure 35: Flood depth separate model setup - 30 mm in 1 hour

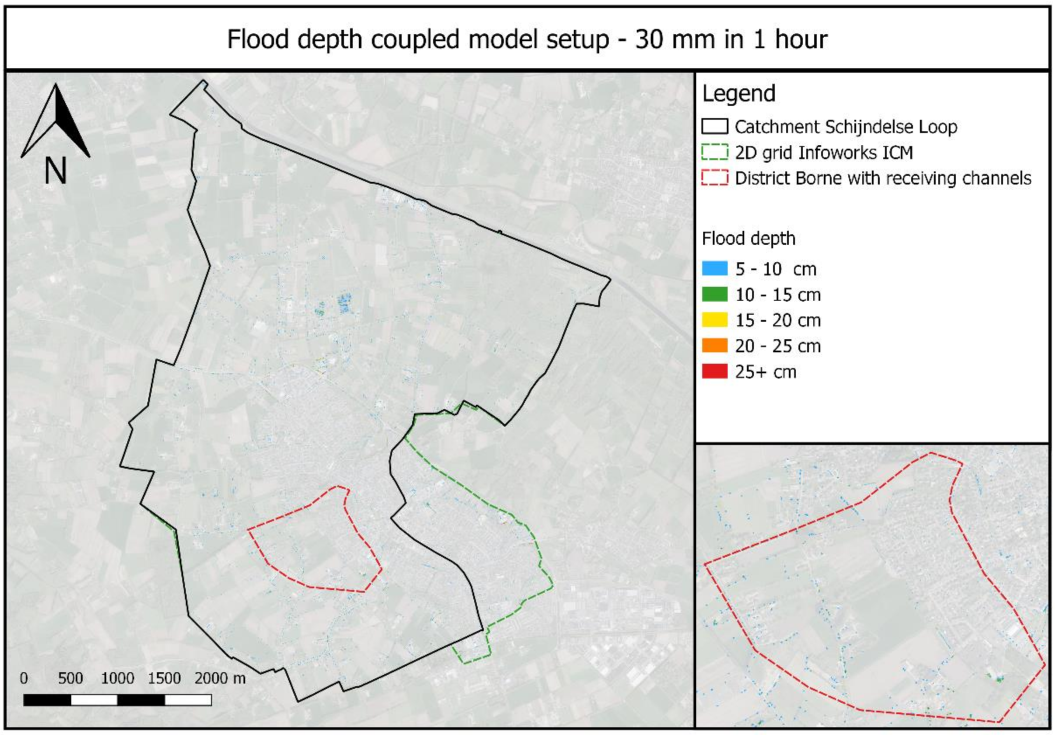

Figure 36: Flood depth coupled model setup - 30 mm in 1 hour

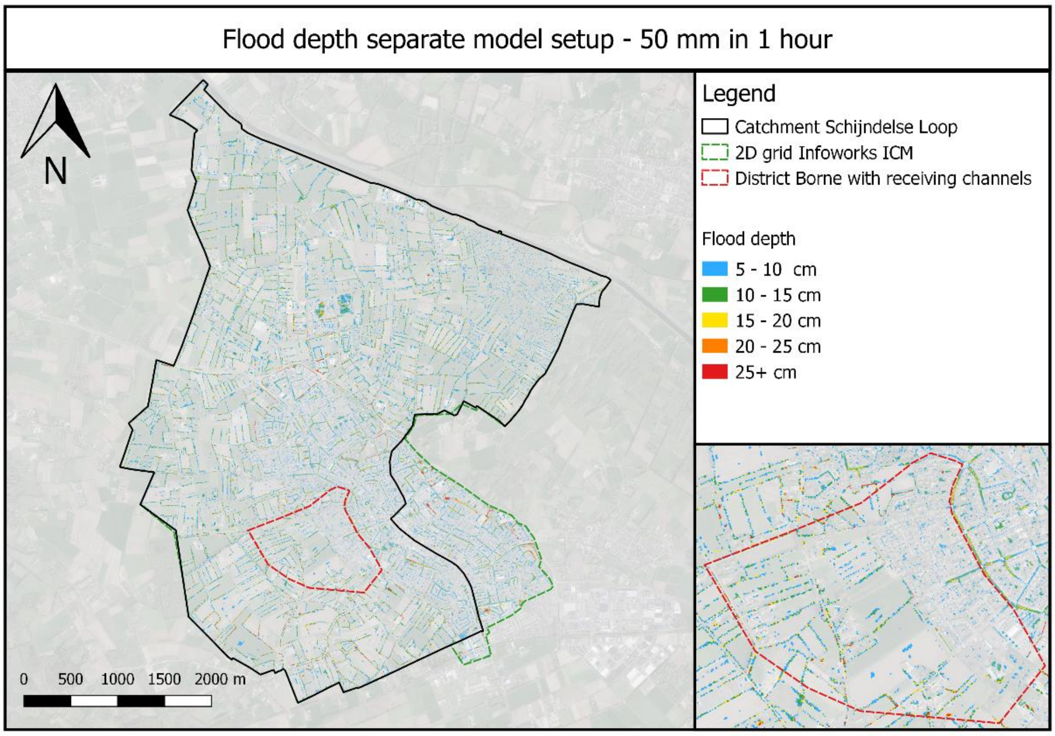

Figure 37: Flood depth separate model setup - 50 mm in 1 hour

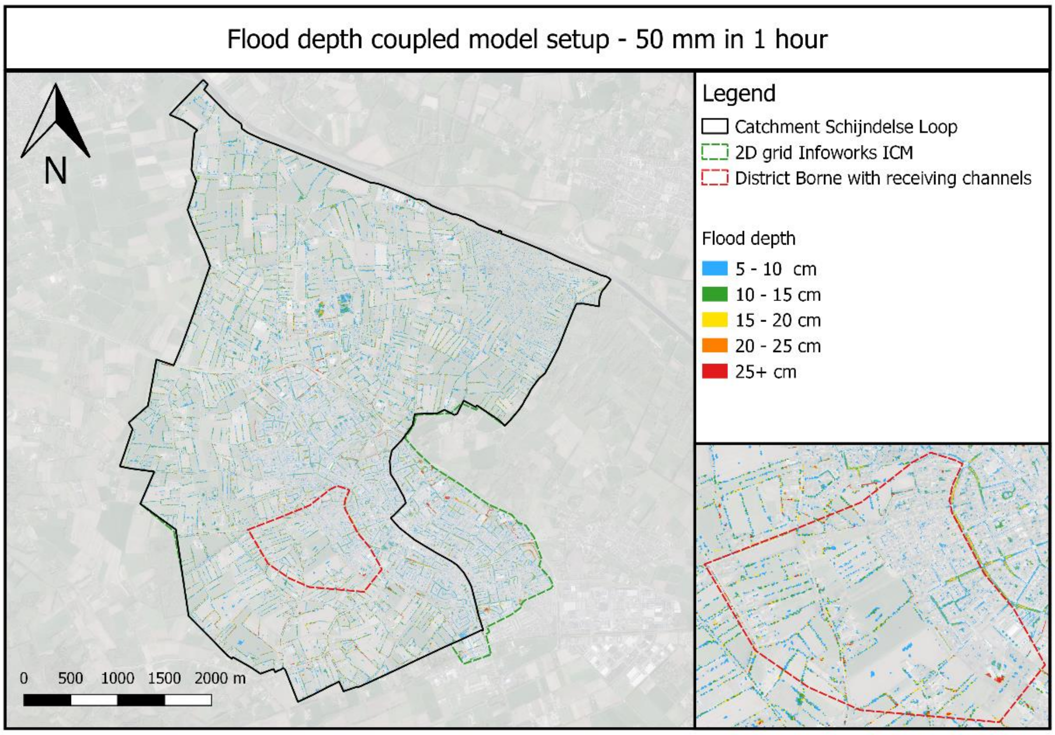

Figure 38: Flood depth coupled model setup - 50 mm in 1 hour

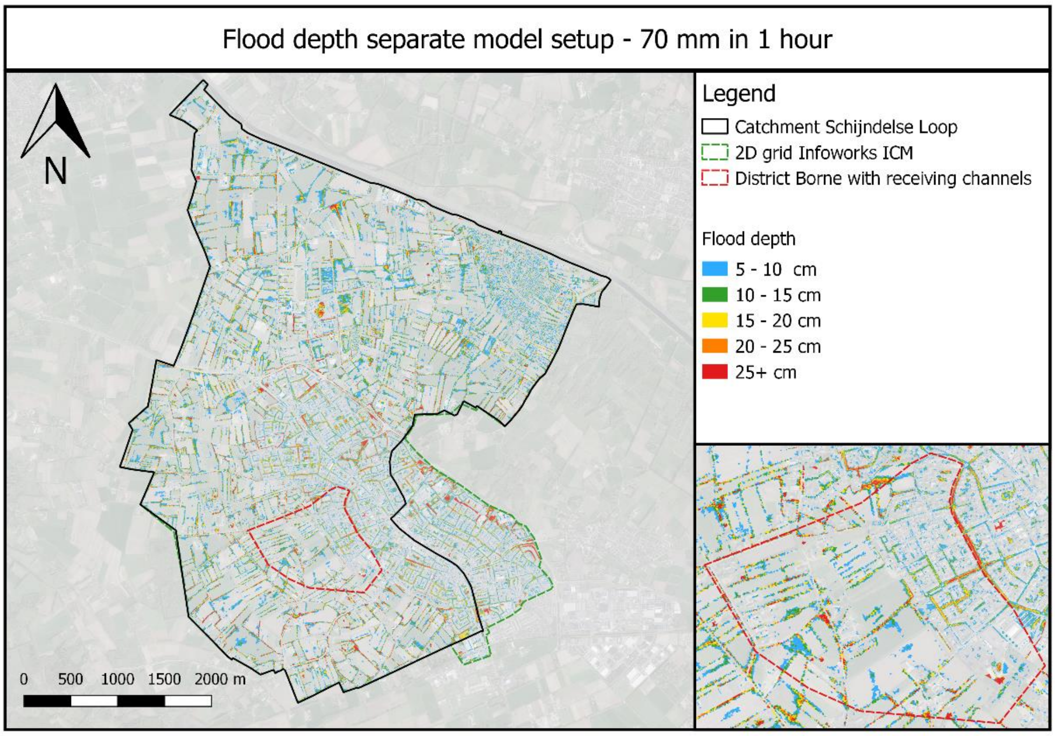

Figure 39: Flood depth separate model setup - 70 mm in 1 hour

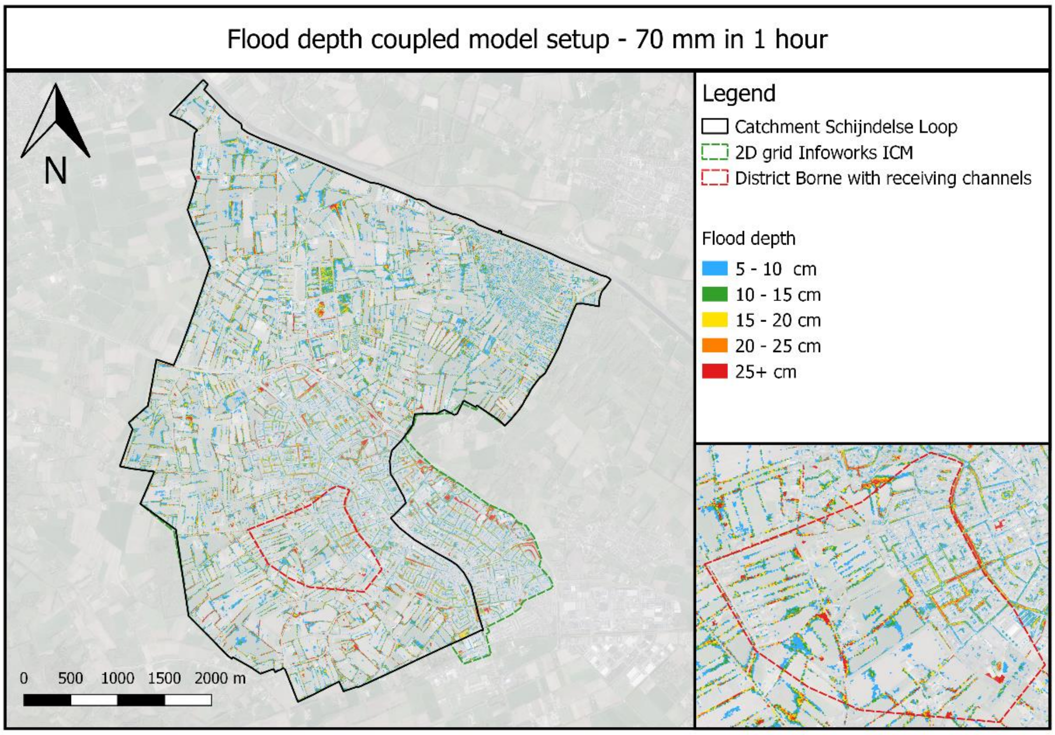

Figure 40: Flood depth coupled model setup - 70 mm in 1 hour

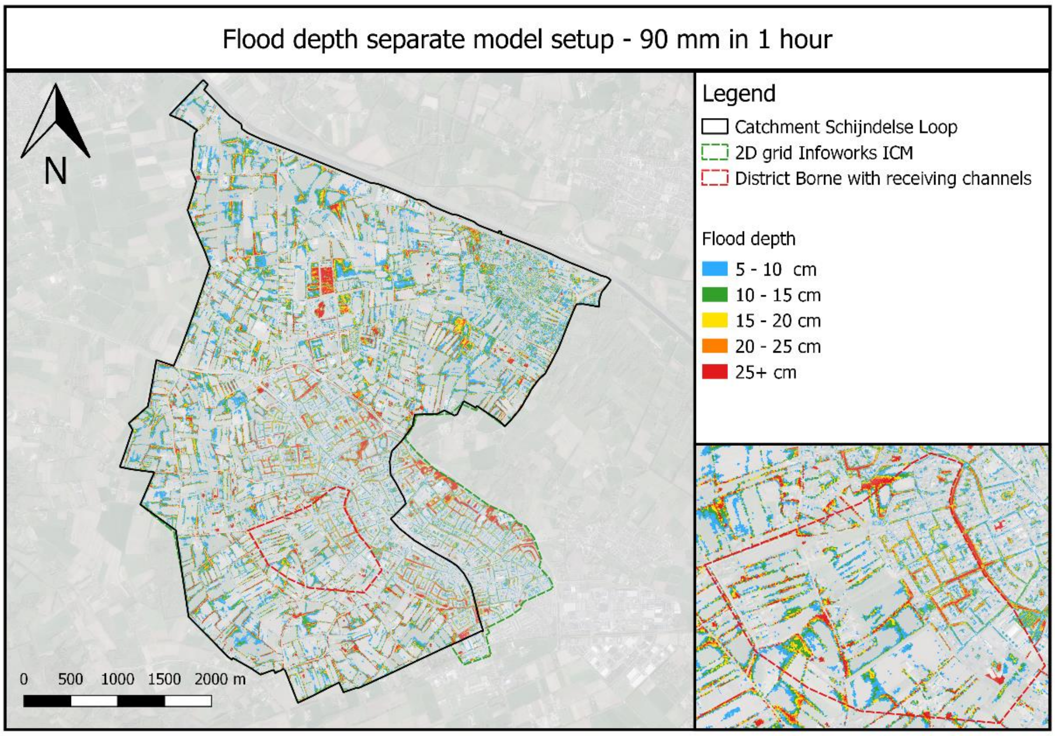

Figure 41: Flood depth separate model setup - 90 mm in 1 hour

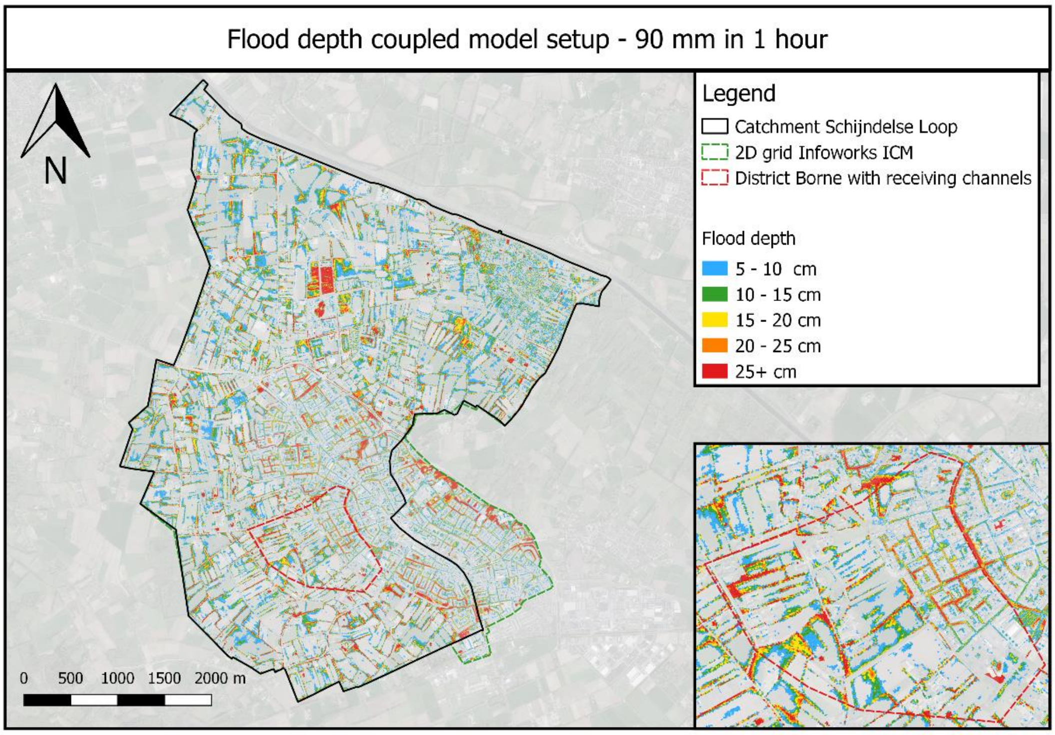

Figure 42: Flood depth coupled model setup - 90 mm in 1 hour

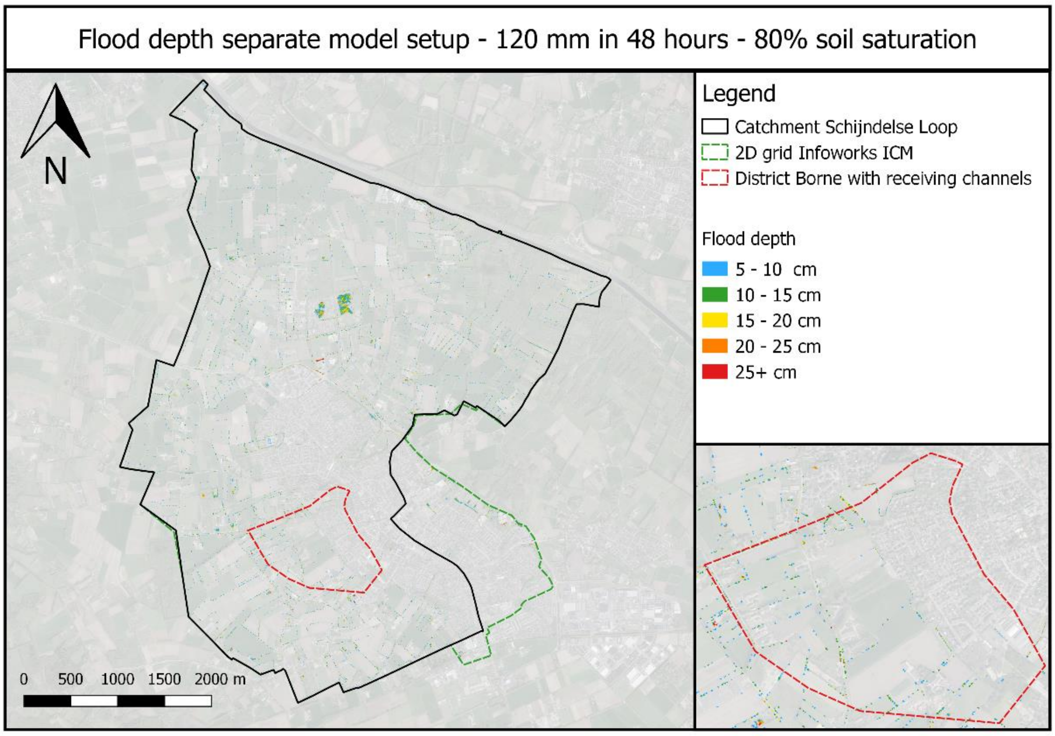

Figure 43: Flood depth separate model setup - 120 mm in 48 hours – 80% soil saturation

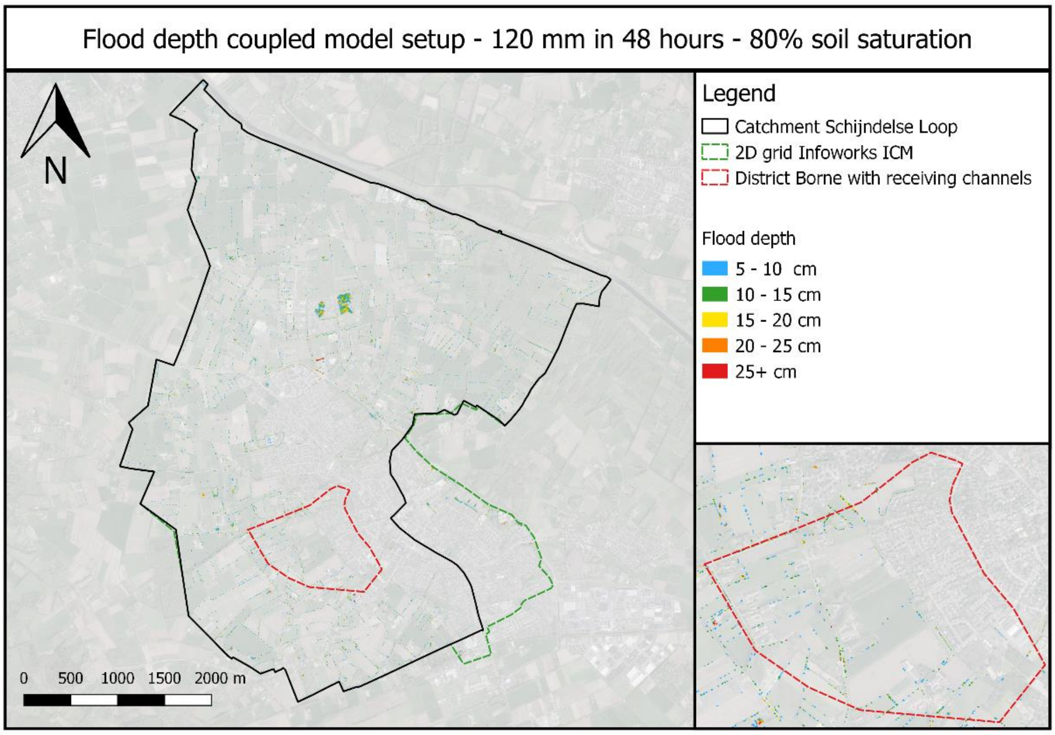

Figure 44: Flood depth coupled model setup - 120 mm in 48 hours – 80% soil saturation

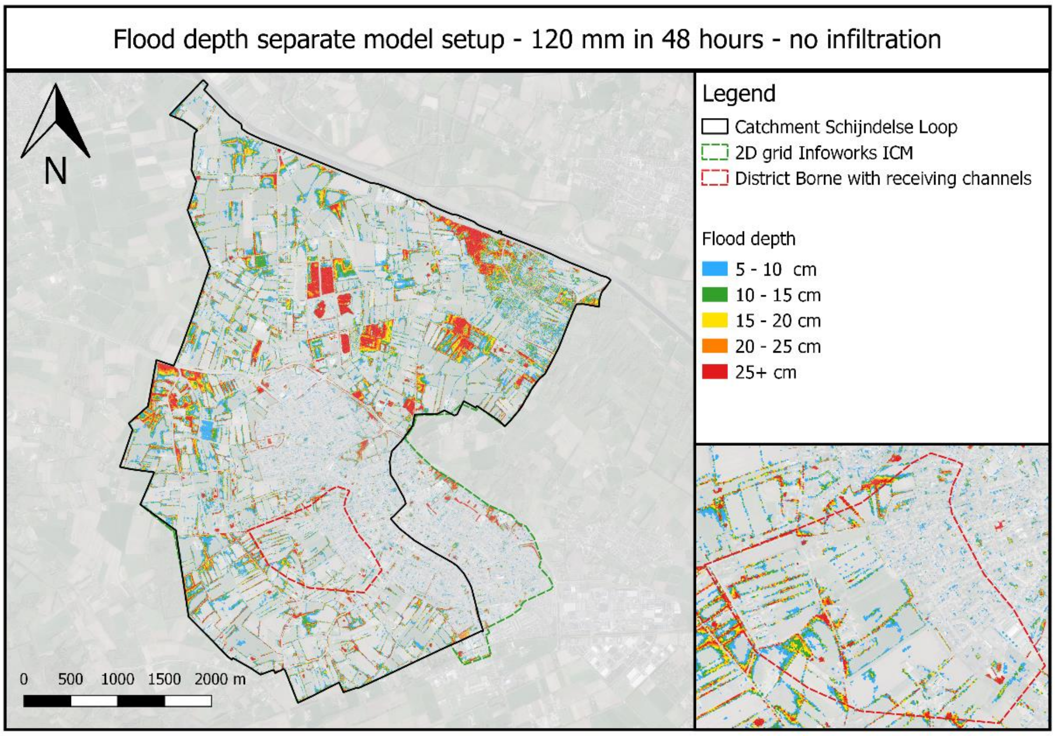

Figure 45: Flood depth separate model setup - 120 mm in 48 hours – no infiltration

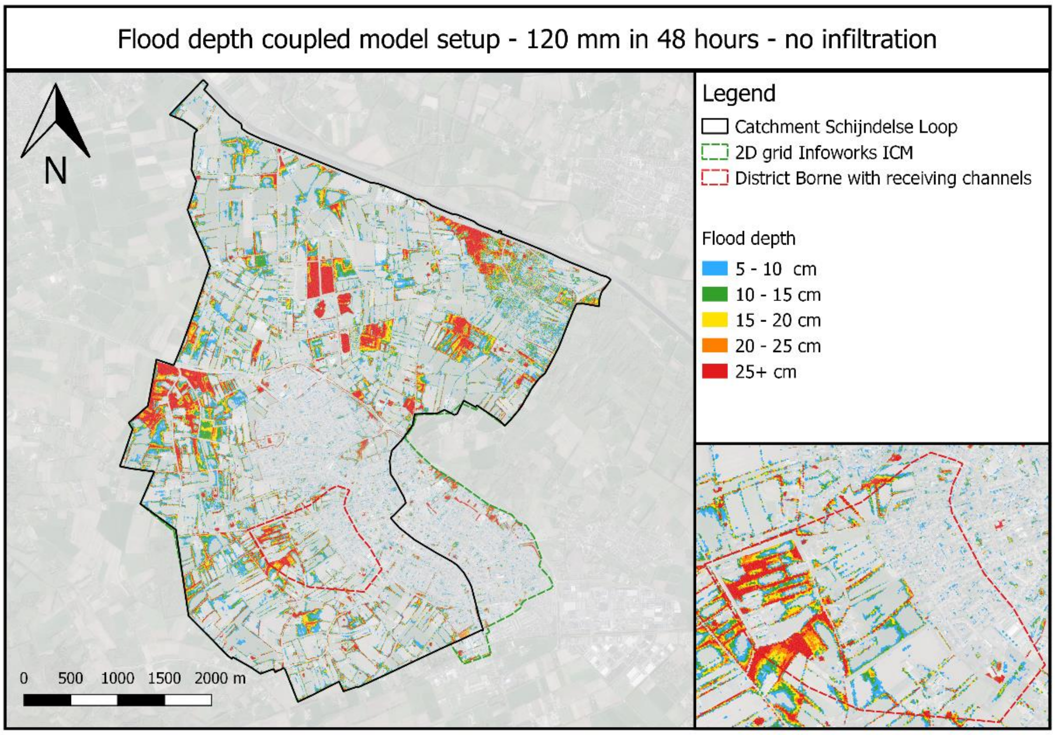

Figure 46: Flood depth coupled model setup - 120 mm in 48 hours – no infiltration

Flood duration

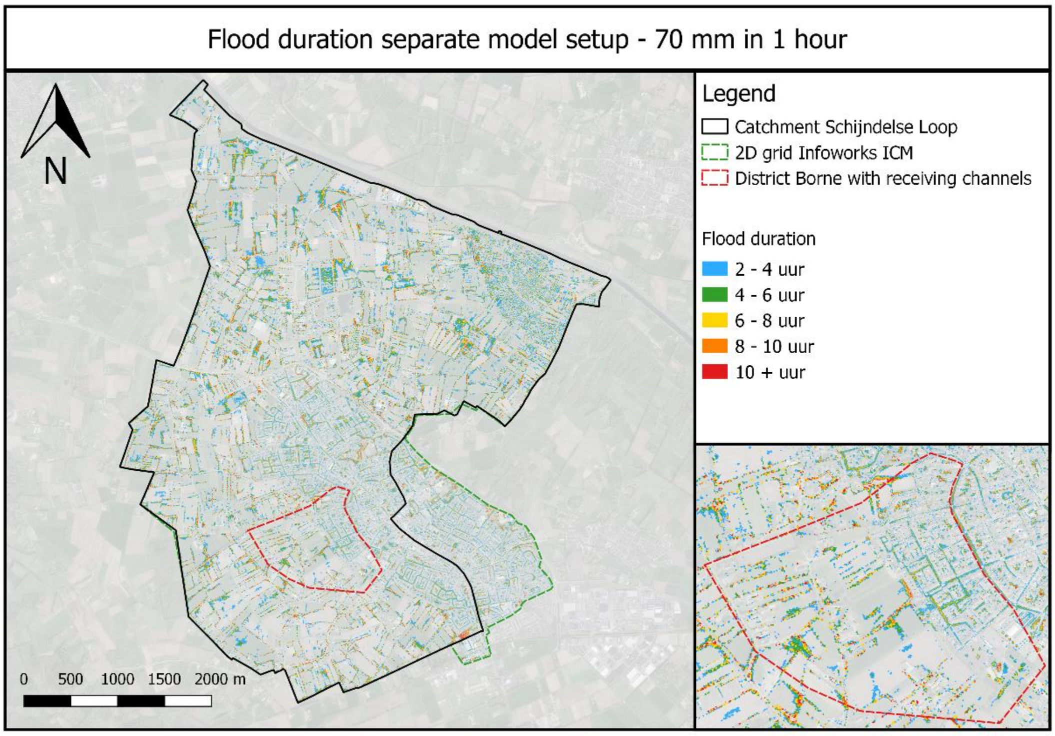

Figure 47: Flood duration separate model setup - 70 mm in 1 hour

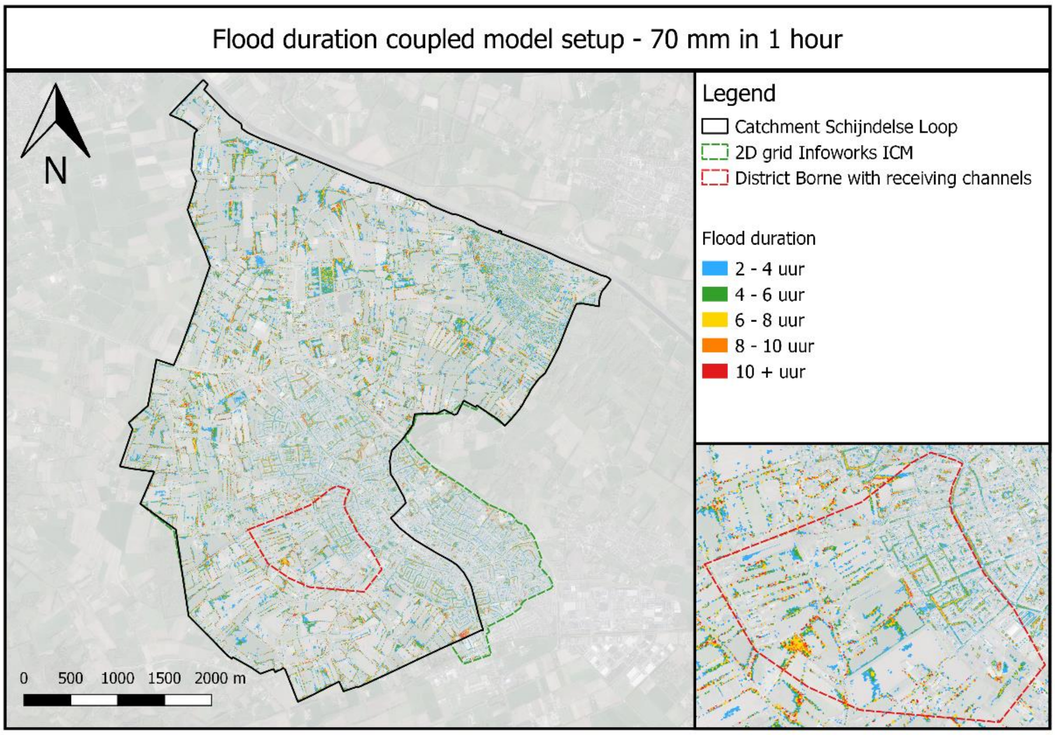

Figure 48: Flood duration coupled model setup - 70 mm in 1 hour

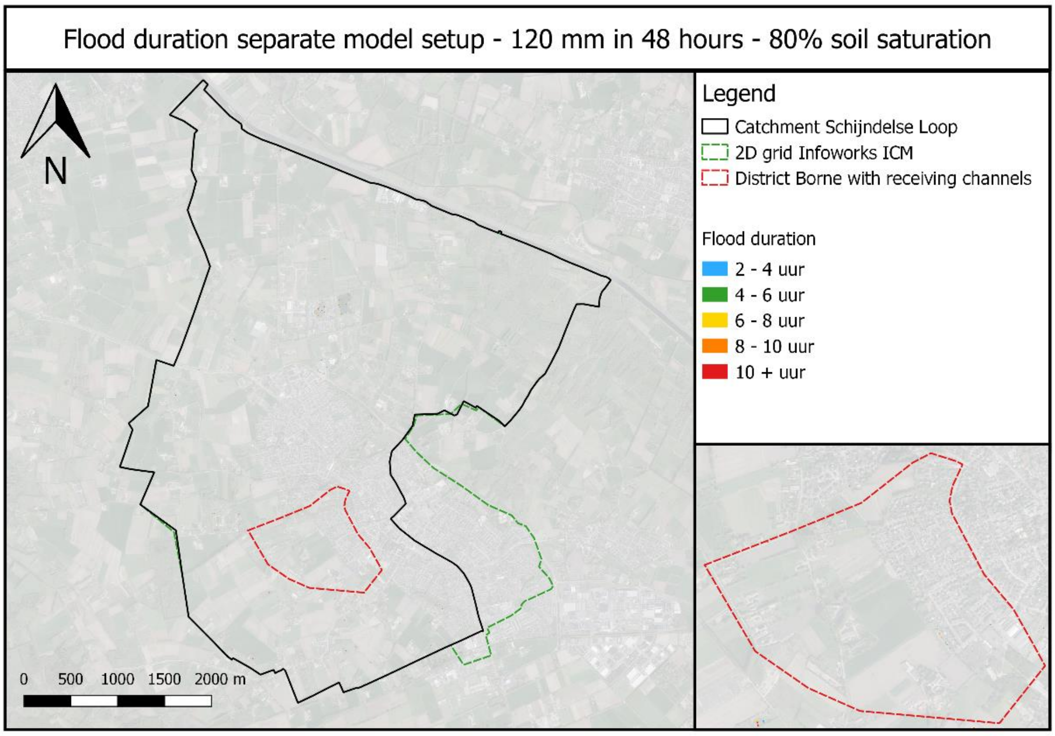

Figure 49: Flood duration coupled model setup - 120 mm in 48 hours – 80% soil saturation

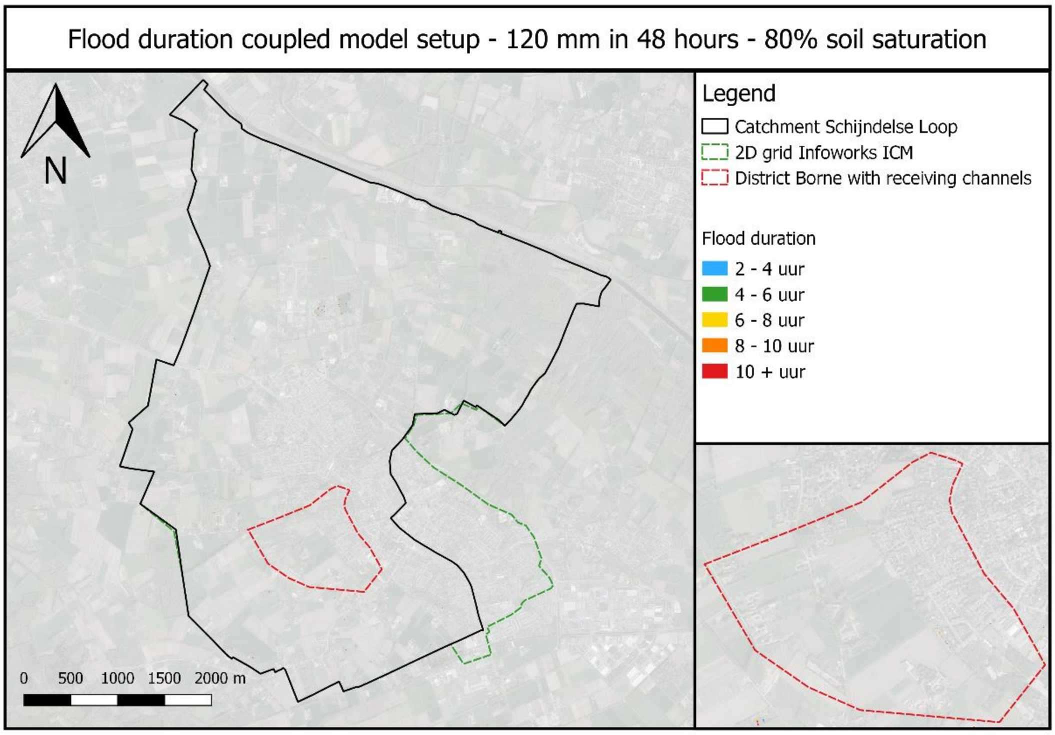

Figure 50: Flood duration coupled model setup - 120 mm in 48 hours – 80% soil saturation

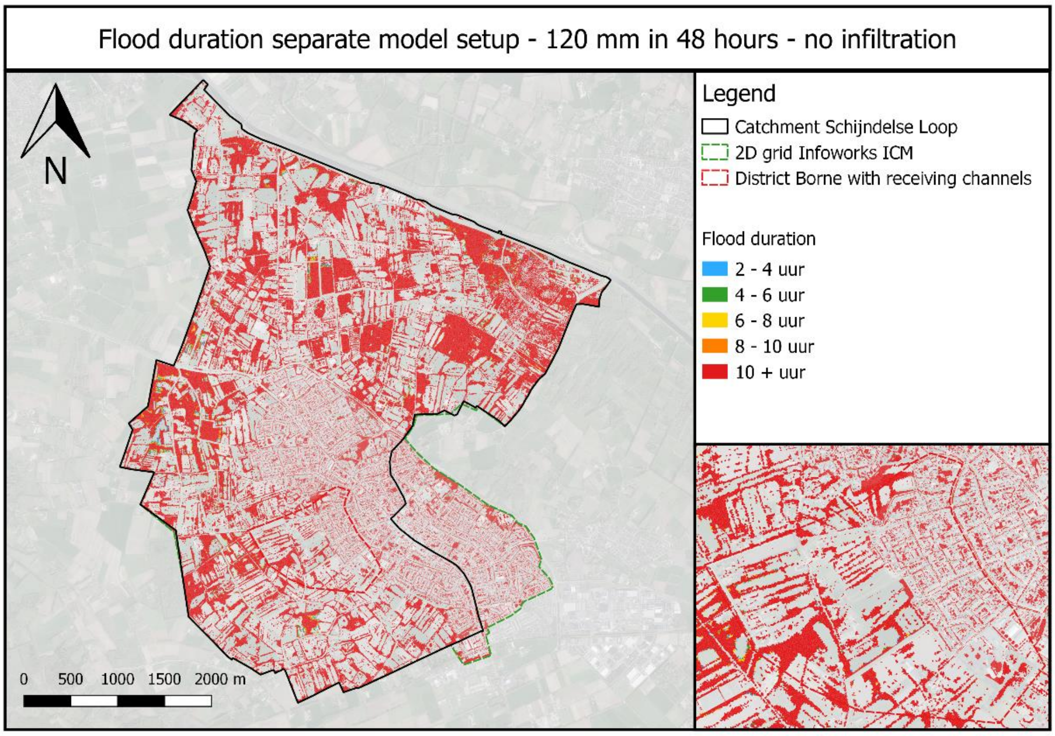

Figure 51: Flood duration coupled model setup - 120 mm in 48 hours – no infiltration

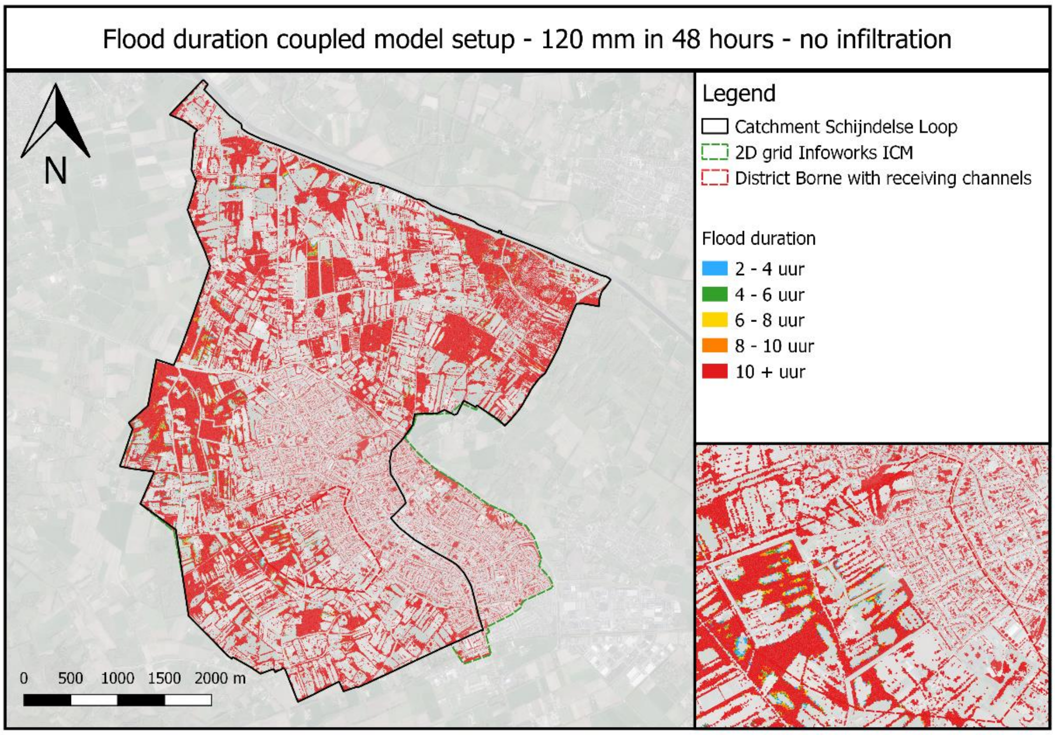

Figure 52: Flood duration coupled model setup - 120 mm in 48 hours – no infiltration

Houses flooded

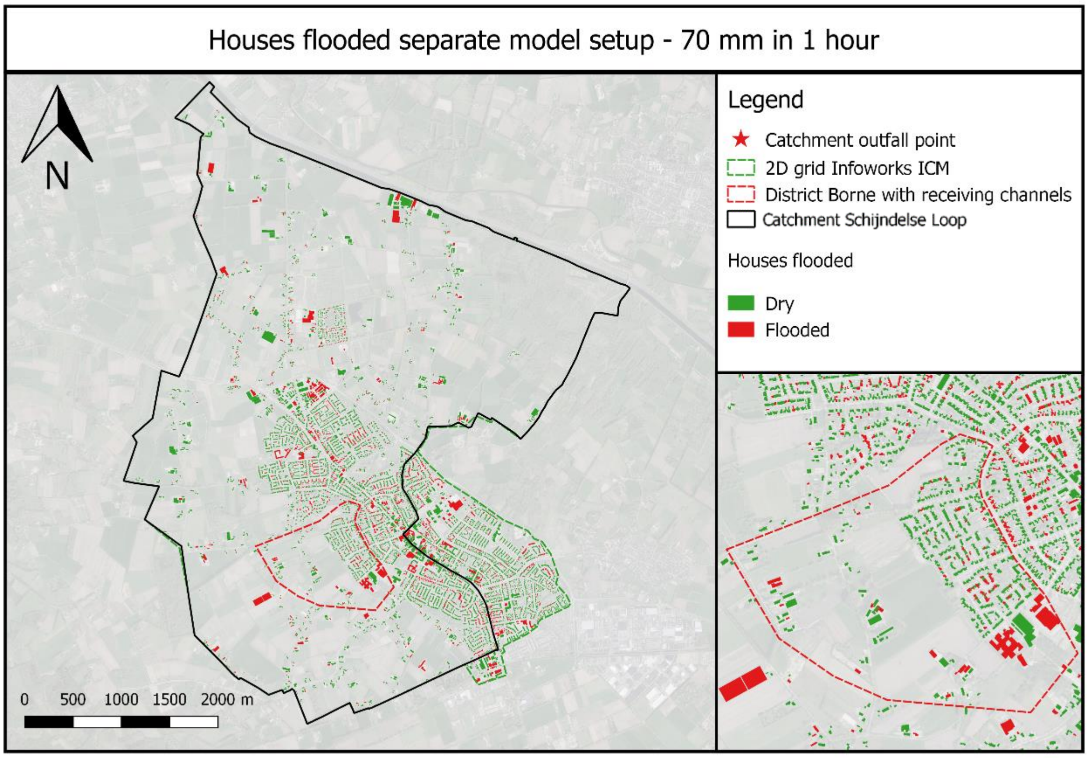

Figure 53: Houses flooded separate model setup - 70 mm in 1 hour

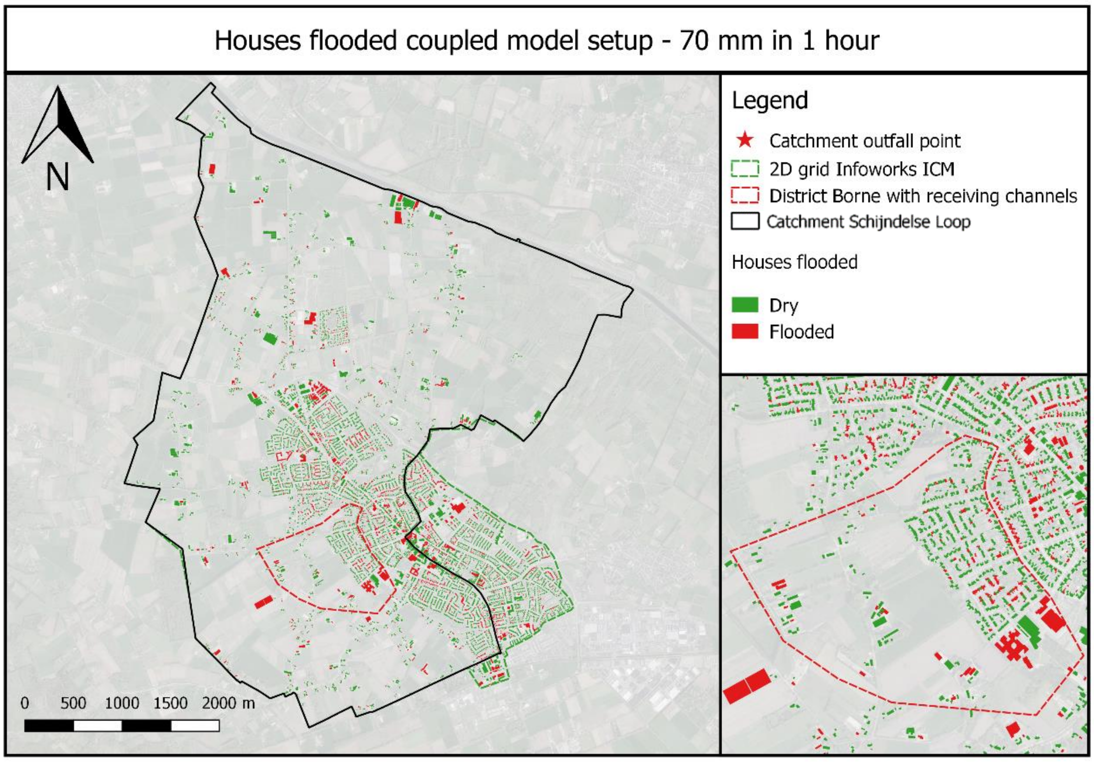

Figure 54: Houses flooded coupled model setup - 70 mm in 1 hour

Difference in maximum flood depth between coupled and separate model setup

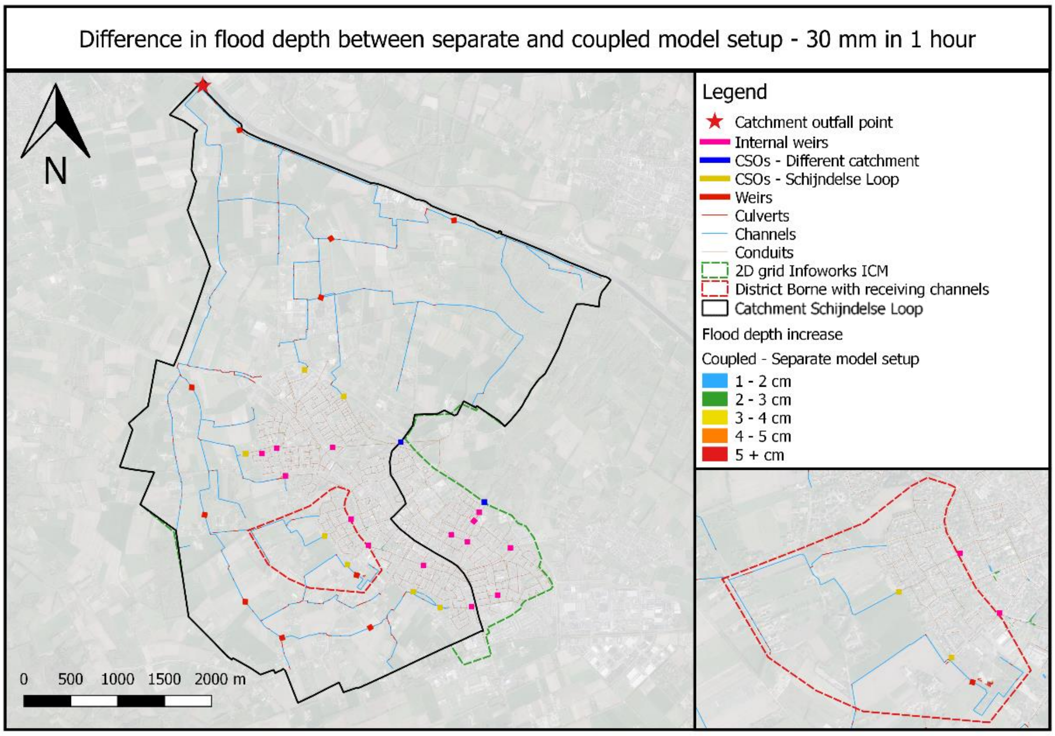

Figure 55: Difference in flood depth between separate and coupled model setup - 30 mm in 1 hour

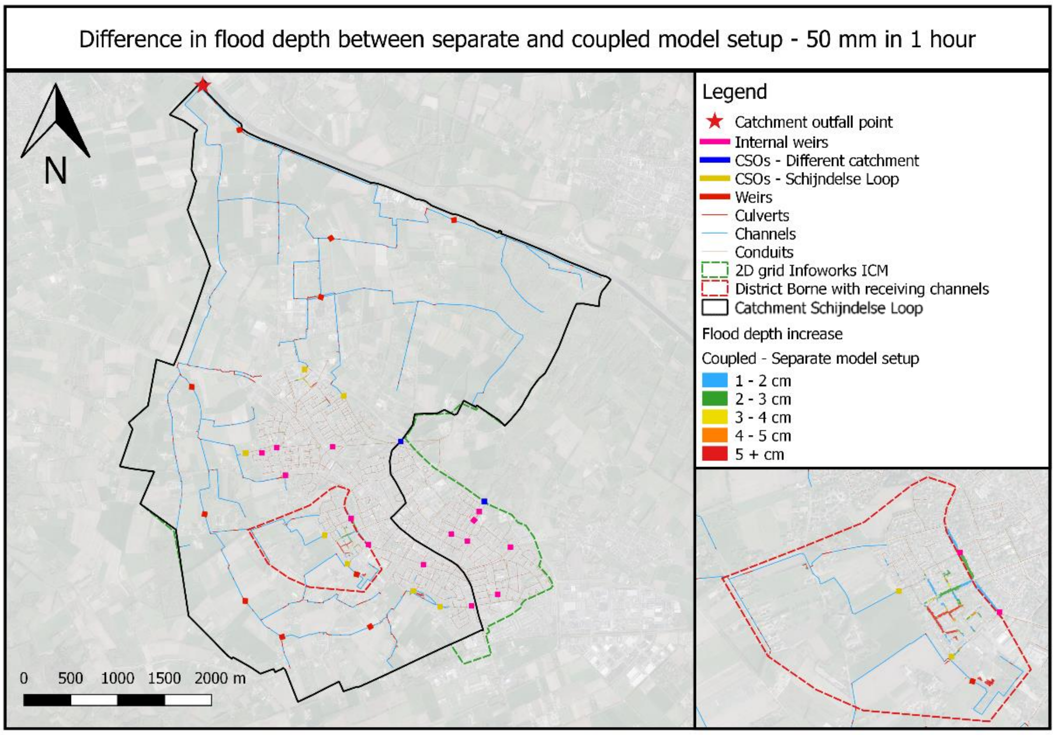

Figure 56: Difference in flood depth between separate and coupled model setup - 50 mm in 1 hour

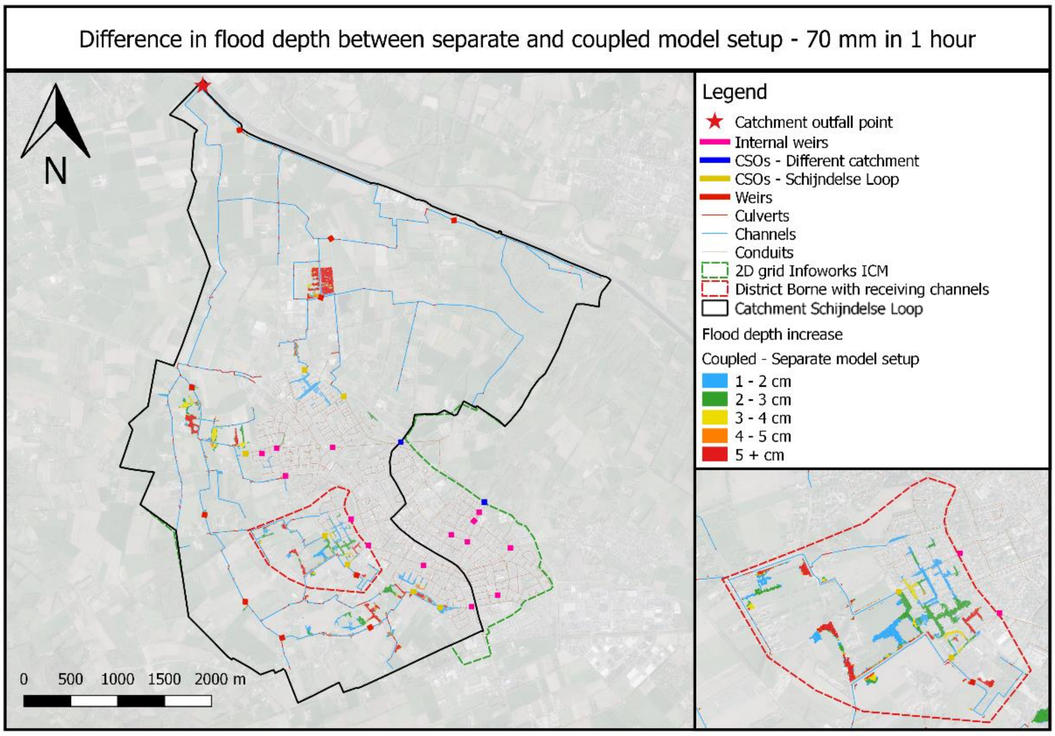

Figure 57: Difference in flood depth between separate and coupled model setup - 70 mm in 1 hour

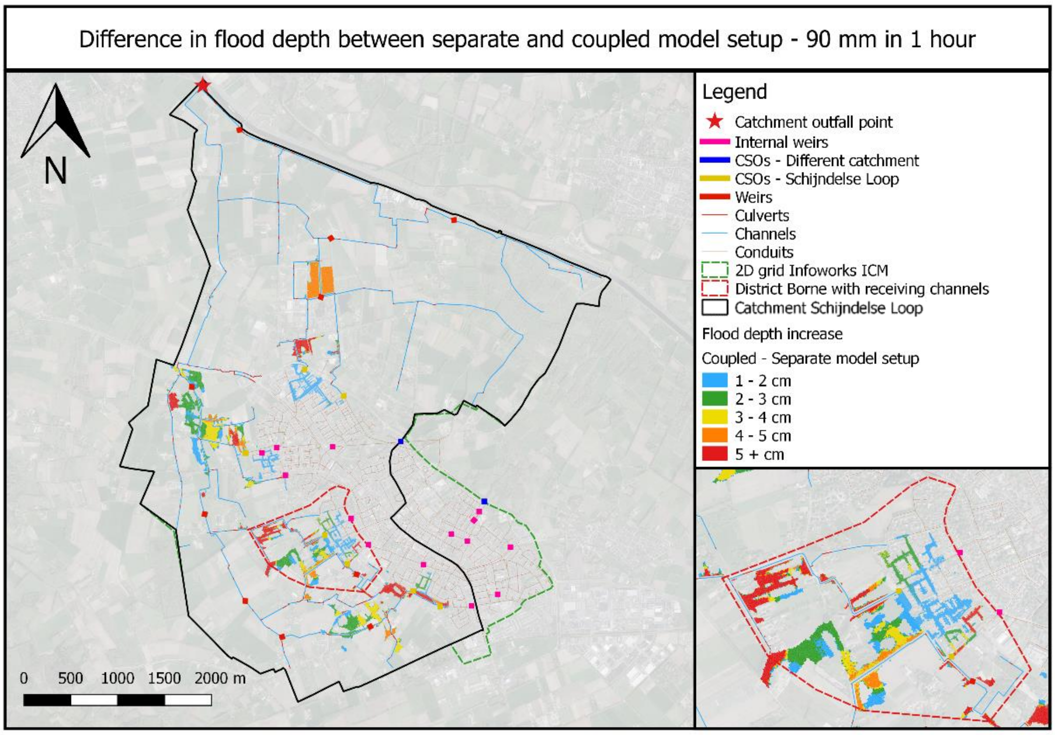

Figure 58: Difference in flood depth between separate and coupled model setup - 90 mm in 1 hour

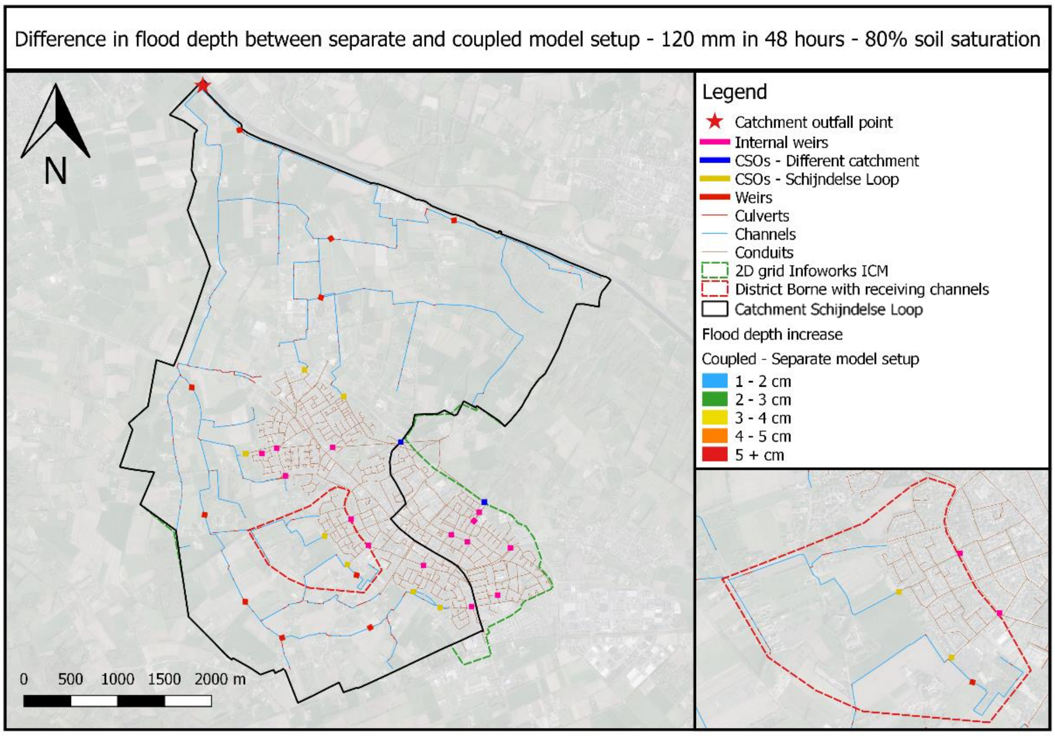

Figure 59: Difference in flood depth between separate and coupled model setup - 120 mm in 48 hours – 80% soil saturation

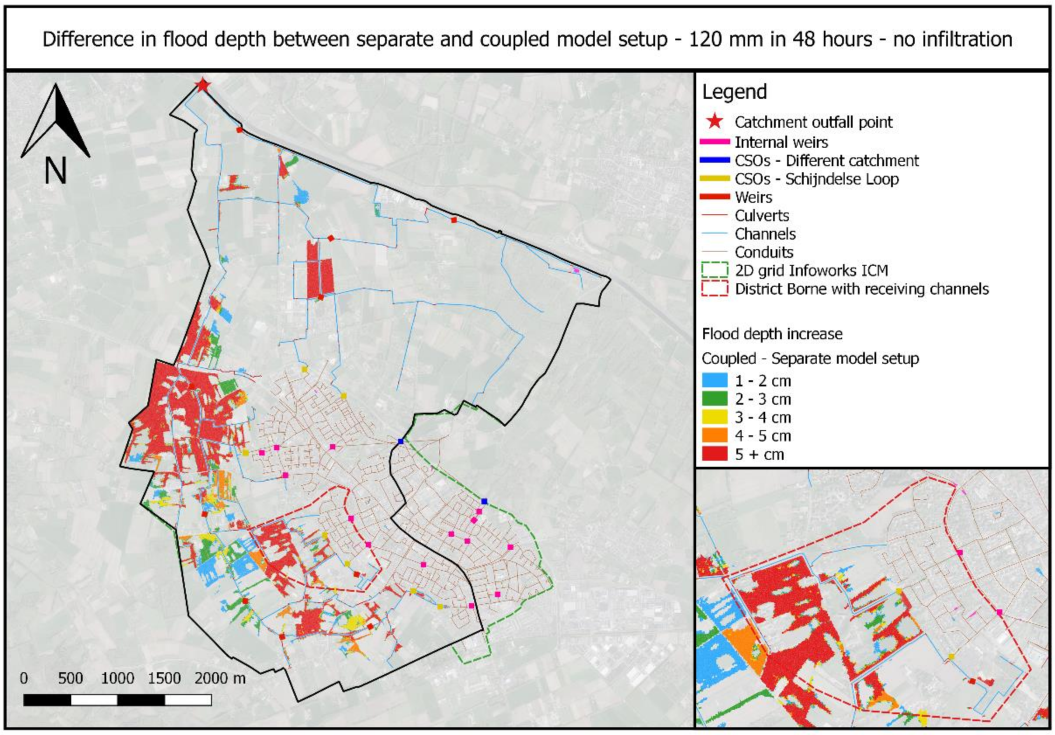

Figure 60: Difference in flood depth between separate and coupled model setup - 120 mm in 48 hours – no infiltration

Difference in flood duration between coupled and separate model setup

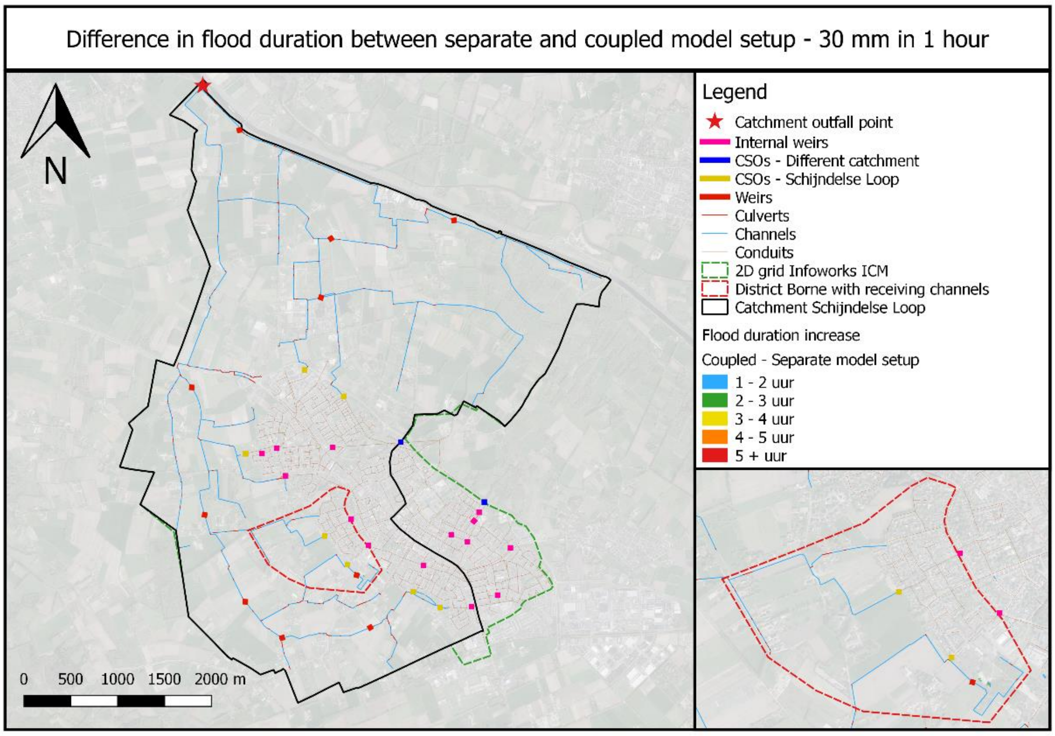

Figure 61: Difference in flood duration between separate and coupled model setup - 30 mm in 1 hour

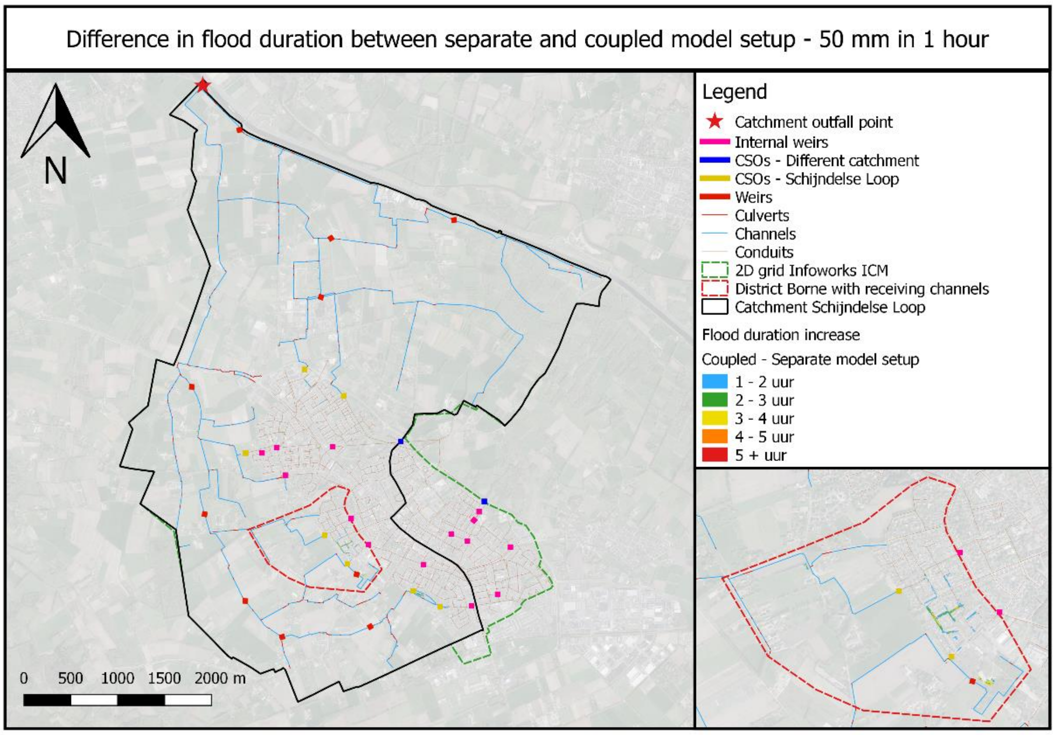

Figure 62: Difference in flood duration between separate and coupled model setup - 50 mm in 1 hour

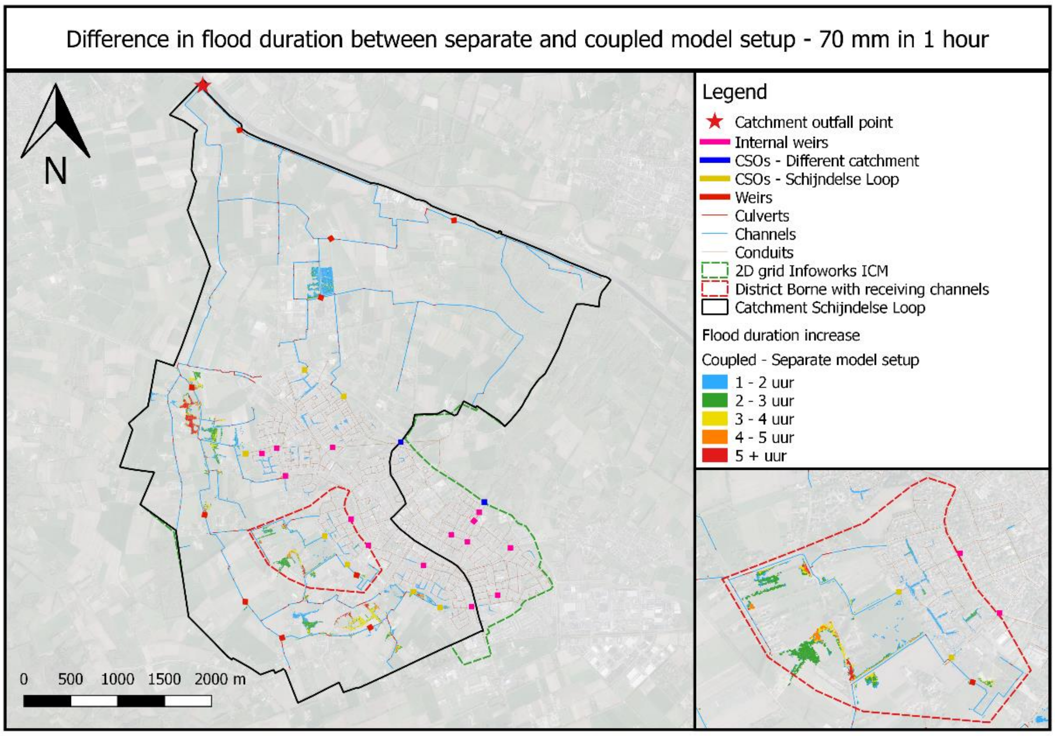

Figure 63: Difference in flood duration between separate and coupled model setup - 70 mm in 1 hour

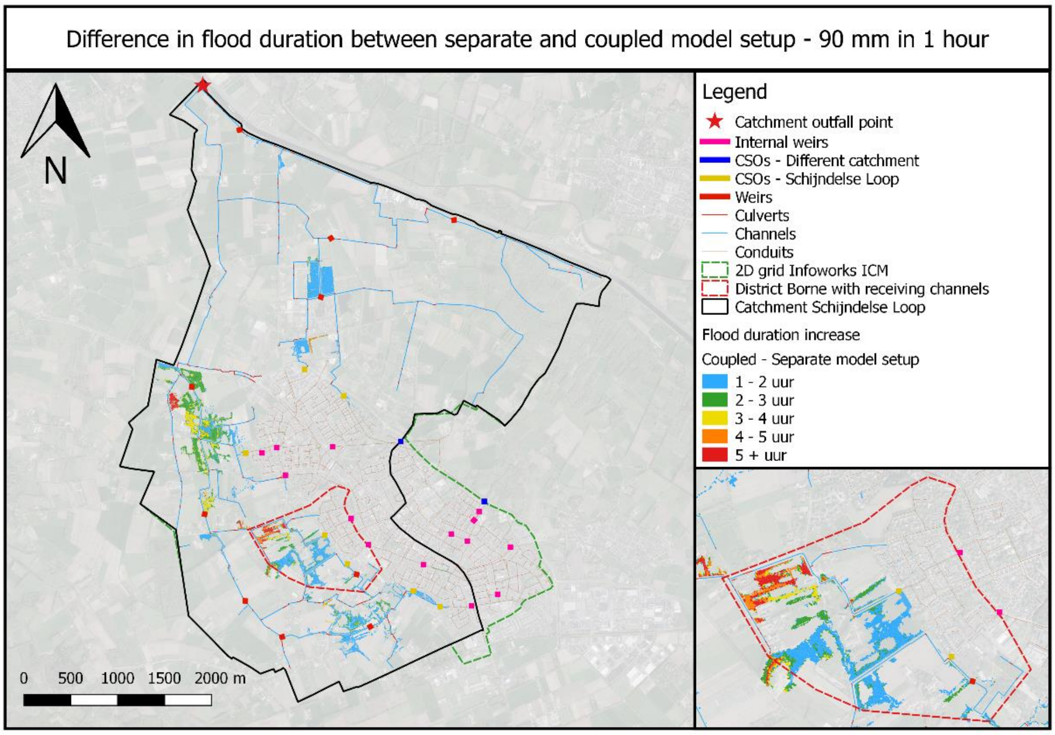

Figure 64: Difference in flood duration between separate and coupled model setup - 90 mm in 1 hour

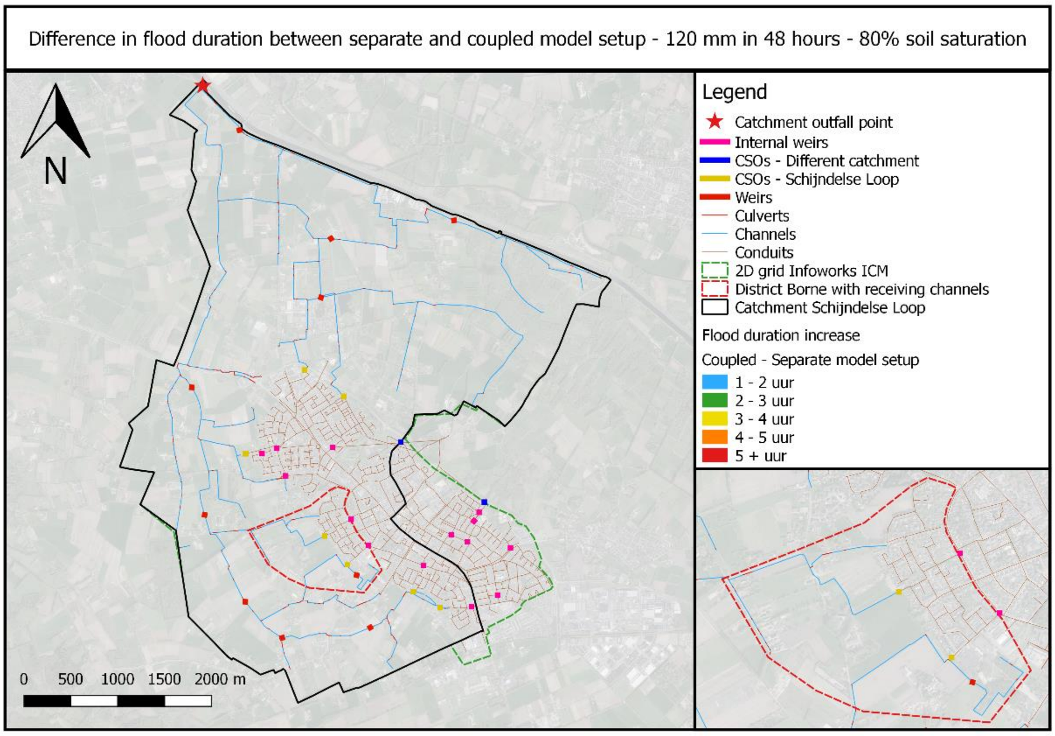

Figure 65: Difference in flood duration between separate and coupled model setup - 120 mm in 48 hours – 80% soil saturation

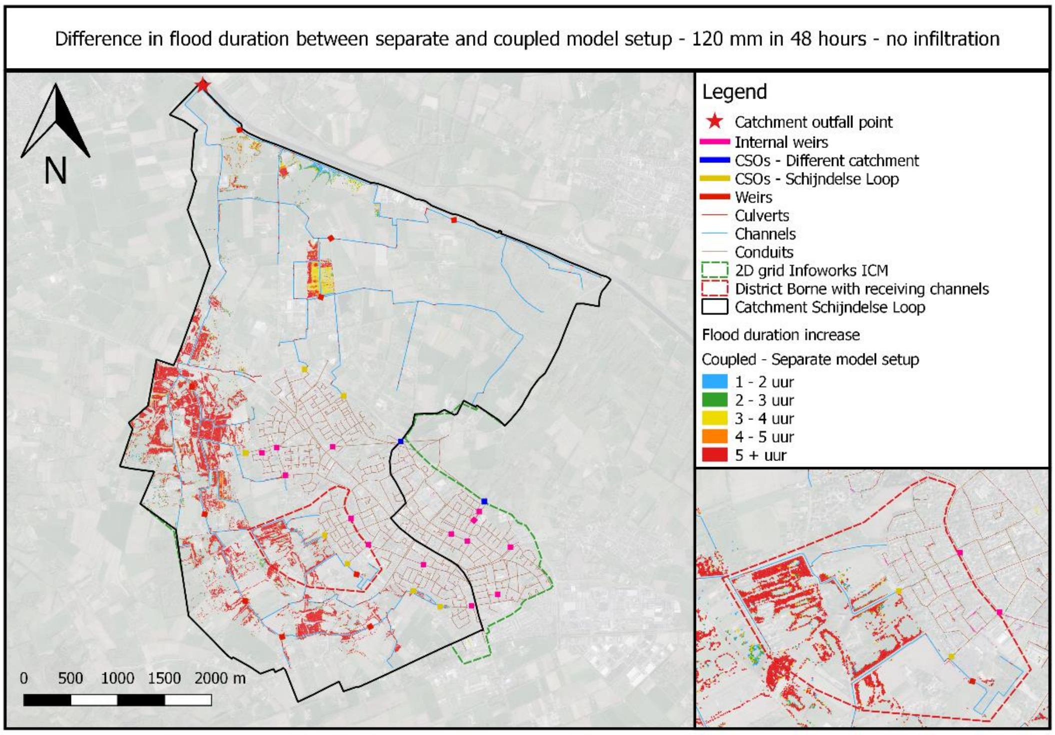

Figure 66: Difference in flood duration between separate and coupled model setup - 120 mm in 48 hours – no infiltration