PLUVIAL URBAN FLOOD HAZARD MODELLING

Differences in 1D2D and 1D2D+ D-HYDRO flood models: a case study

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Pluvial urban flood hazard modelling

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FIGURE 1 COVER FIGURE: PLUVIAL FLOODING IN A STREET IN NOORD BRABANT (OMROEP BRABANT, 2021)

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Abstract

Urban pluvial floods and associated damages are increasing throughout the world due to increased urbanization, poor urban design and climate change. Flood hazard modelling software designers are, at the same time, capitalizing on recent advances in computational power as detailed 1D2D and 1D2D+ simulations are now feasible. With these 1D2D-coupled models urban drainage systems and surface flow interactions are tested. Outflow from the 1D- to the 2D domain is modelled the same though inflow is notably different. 1D2D uses a surface parameterization for inflow whereas 1D2D+ uses a surface flow model as inflow which hypothetically should perform better under sloping and high flow conditions. The differences in outcome between these two approaches are however not yet understood and tested. Within D-HYDRO 0.9.9 (beta) the case-study-area of Heemskerk-Beverwijk is modelled in 1D2D and 1D2D+. Several simulation runs with different distinct precipitation events, characteristic for future climate, were made. Special attention was given to an area-of-interest with sloping and flat conditions in order to identify differences between both modelling approaches. First, though 1D2D is calculating faster (+50%) and shows good correlation with 1D2D+ on major trends. When it comes to extreme persistent precipitation both models are of poor agreement. 1D2D+ models up to 6cm or 20% higher water-on-street downstream then 1D2D for a 1/100-year precipitation event. Extremer weather is therefore presumably better modelled in 1D2D+ especially in sloping surface conditions. This research thus has found that, with climate change in mind, urban extreme precipitation events are better modelled in 1D2D+ then 1D2D. Especially in areas, compared to completely flat, with sloping surfaces.

Preface

This research is carried out as the final thesis part of the curriculum of MSc Hydrology at Vrije Universiteit Amsterdam.

D-HYDRO Suite from Deltares is an integrated modelling suite in development which capitalizes on recent advances, by simulating two-dimensional (in either the horizontal or a vertical plane) and three-dimensional flow (Melger, E, 2021). Development of this software happens in the framework of the government of the Netherland's “Topconsortia, Knowledge and Innovation”- or TKI-policy. Within this framework, scientist and entrepreneurs look for innovative services to bring to the market. In 2019 a TKI project named “D-HYDRO, urban-rural” was set up to integrate sewer- and surface water models. To be as efficient as possible, several case-studies have been started (Henckens, 2019). One of these case studies is this report. This research is carried out as internship within Wareco under supervision and support from Deltares and commissioned by the municipalities of Heemskerk and Beverwijk.

I can confidently say that without the help and support from my colleagues at Wareco especially my supervisors Maureen van Rijn and Johan de Waard and my intern colleague Sander Vlaar this research wouldn't have been what it is today. Colleagues that also shouldn't be unmentioned are Guy Henckens, for advice, help and creating the best environment to work in and Arnout, Tiemen and Dennis for their help with several SOBEK and QGIS problems and Freek for the necessary textual checks. Next to that, I must thank the “Deltares helpdesk”: Rinske Hutten and Tjitske Geertsema as well as Didrik Meijer for their help with solving and working around several bugs and problems in the D-HYDRO software. I also must thank my roommate, Tom Ebergen, for helping me with the necessary Python code. And my supervisor from the Vrije Universiteit, Hans de Moel, for helping me with all the essential advice on doing a modelling study, writing a thesis and the supervision along the way of the process of finishing a master thesis.

Finally, I want to thank my family and close friends for the comforting support I got, not only through this research project, but through all those years of study as well.

Patrick Smit

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1. Introduction

Intense localized rainfall may generate overland flows and pooling in urban areas, causing damage to buildings, infrastructure and danger to people. This happens when rainfall overloads- or is for some reason unable to enter the urban sewage system. This process is commonly known as pluvial flooding (Spekkers, et al., 2011). Many cities throughout Europe are currently facing surface water (pluvial) flooding problems that derive from rainfall events causing overflow of sewer-stormwater networks. It is expected that such overflowing will become more frequent throughout Europe (Susnik, et al., 2014). This is thus no different for The Netherlands where only in the past three years the number of pluvial floods registered by insurance companies has risen with 77% with the associated damage costs doubling (AD, 2020). The primary causes of urban floods are an unusual rise in the amount of rainfall and urban design and land-use–land-cover patterns (urbanization) that are not adapted to this rise in precipitation (Natarajan & Radhakrishnan, 2020). Looking at the future, pluvial urban flooding will most likely further increase as KNMI-14 scenario's show an increase in yearly precipitation and a doubling in intensity of precipitation events by 2050 (KNMI, 2015). Costs associated with flood damages will on average exceed tens of thousands of euros per inhabitant when no additional measures are being taken (Klimaatschadeschatter, 2021). This scenario holds not only for Europe and The Netherlands but for many places in the world as well. Extreme rainfall events adversely affect the residents and infrastructure in cities across Africa, China and India in more than monetary terms alone (Yong, Zevenbergen, & Yongchi, 2018). For example, the Mumbai flood of July 2005 provides an insight into the alarming situation of poor stormwater management in Indian cities. Here one less-than-24-hour precipitation event, caused more than 400 deaths in addition to financial losses to the tune of £1.2 billion (Bisht, et al., 2016). Prevention of flooding caused by unpredictable high-intensity rainfall events in urban areas due to lack of adequate drainage systems has become an important issue as risk of flooding is increased due to combined effect of urbanization and climate change (Bisht, et al., 2016). To avoid the nuisance of frequent flooding during ever extremer precipitation events, designing an efficient stormwater drainage system has become the need of the hour for present world engineers and urban planners (Bisht, et al., 2016).

Lots of studies provide an insight into the importance of 1D (sewer-only) and 2D (surface-only) models to deal with location-specific flooding problems (Bisht, et al., 2016). However, thanks to modelling advances and the increase in computational resources in recent years, it is now feasible to perform integrated 1D-2D(+) urban flood simulations at very high spatial resolutions and to conduct flood risk assessments at the scale of single neighborhoods and buildings (Bermúdez & Zisch, 2018). D-HYDRO Suite from Deltares is such an integrated modelling suite in development which capitalizes on recent advances, by allowing simulations in both 1D2D and 1D2D+ (Melger, E, 2021). 1D2D integrates the 1D sewer with the 2D surface domain from the moment the sewer system overflows whereas 1D2D+ simulates overland flow from the moment it precipitates.

Current literature still lacks the direct case-study comparison between coupled 1D2D and 1D2D+ modelling results (Meyer, 2021). Choices made in the model set-up are impacting reliability of the results, as the parameters, resolution of the model and data used differs. Improvement of the quality of integrated models or at least understanding of parameter and data-use-impact is therefore necessary (Rijn van, 2020). Given the recognized impact of model set-up choices and the differences between 1D2D and 1D2D+ models, this study aims to provide improved insight into the differences in performance, using a case study in Beverwijk and Heemskerk.

The main question this research will try to answer is: How are an urban pluvial 1D2D- and 1D2D+ model performing compared to each other in flat vs. sloping areas and with regard to distinct precipitation events (short-, high intensity vs. long-lived low intensity)?

In order to answer this question a number of sub questions have been formulated:

(1) What are in theory the advantages and disadvantages of both types of models. What are for example the effects of choices made in these models by parametrization and in which situations would you expect one model to outperform the other in case-study situations in Beverwijk and Heemskerk.

(2) In which case-study situations does the D-HYDRO 1D2D or 1D2D+ model perform best? What is the added value of the D-HYDRO 1D2D+ vs a 1D2D-model in a sloping vs non-sloping situation and during prolonged- and high peak intensity precipitation events respectively? Zooming in on flood hazard modelling.

(3) With climate change in mind, what type of precipitation is there to be expected and which model can handle this transition the best for which situation.

Using two case study situations (Beverwijk and Heemskerk), extreme pluvial flood hazard events, which are illustrative for climate change, will be modelled in 1D2D and 1D2D+ and compared to each other in agreement tests. As for example sloping and heavy precipitation events should in theory be better modelled by 1D2D+. This way the added value of a 1D2D+ model compared to 1D2D in specific situations is identified. One with certain characteristics in place that a 1D2D model should simulate better and one with characteristics a 1D2D+ model should simulate better. This way, the effect of certain features and the effect of different model types is isolated and quantified. For example, Beverwijk has a lot of sloping surface and Heemskerk is a relative flat city.

The first sub question on the hypothetical advantages of 1D2D+ compared to 1D2D will be discussed in the theoretical background. After which the methods are explained. This is followed by the results where the sub questions on model performance and extreme climate change will be answered. Next, the discussion will put the theoretical background, methods and results in the perspective of literature answering the main question. Finally, the conclusions are presented.

2. Theoretical background

This chapter will introduce common hydraulic modelling practices, the most important assumptions regarding the equations governing 1- and 2-dimensional (1D and 2D) unsteady flow and the effects of choices made in hydraulic modelling on outcome of results. The equations governing 1- and 2-dimensional (1D and 2D) unsteady flow as well as a simplification of these equations and some basics regarding the numerical solution of these equations can be found in appendix A – Theoretical background.

2.1 Hydraulic modelling practices

First, common hydraulic practices are explored by zooming out. Urban drainage systems are frequently analyzed and designed using hydraulic modelling software packages as InfoWorks CS, MIKE-Urban, SOBEK, Iber or Tygron (Linckens, 2021). The use of such modelling tools allows for the evaluation of sewer capacity and the likelihood and impact of pluvial flood events (Rubvinato, et al., 2013). It can thus be seen as a crucial part of determining flood hazard and flood risk at the local spatial scale.

In the set-up of the model, first, the selection of the mathematical model is important. Depending on the scale of the hazard or risk analysis, the complexity of models applied ranges from simple interpolation methods to sophisticated and spatially detailed models solving the water equations in two dimensions. Too much detail could suffer from complex model set-up, high data requirements and long computation times (Apel, et al., 2009). Secondly, when setting up a model, the acquisition or creation of necessary input data (Digital Elevation Model (DEM), hydrological data, land-use etc.) can take a long time and the amount of detail and complexity can vary. Especially, for example the role of the DEM is important since it is the primary data used in the analysis of catchment topography and its accuracy can significantly affect the resulting quality of flood maps (Moore, et al., 1991). In recent years, a complex and integrated approach to flood protection, including integrated one- and two-dimensional hydraulic models, has been used as a digital tool for flood risk assessment (Naiji, et al., 2021).

Within hydraulic modelling different types of models and modelling software utilizing different approaches for 1D, 2D, 1D2D and 1D2D+ simulations are used. The difference in model concept is made by differences in schematization of the most important parts of a hydrological model. The four standard parts used in The Netherlands as defined by RioNED are depicted in figure 2 and are further explained in the following section. The four main parts depicted in figure 2 are:

- The inflow model (neerslagafvoer)
- Sewer system model (riolering)
- Surface model (maaiveld)
- Surface water system model (oppervlaktewater)

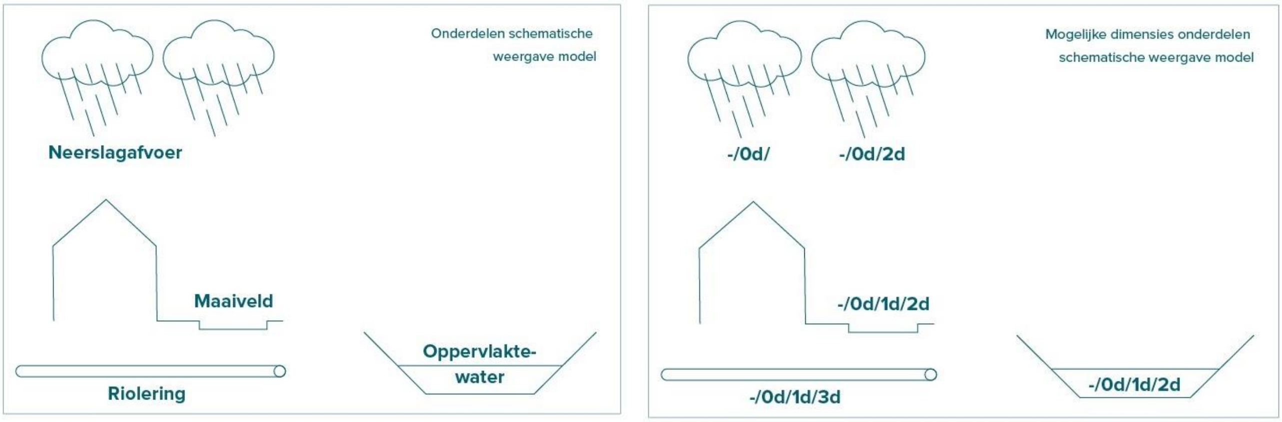

Figure 2 Left: schematization of standard model concepts (Neerslagafvoer = inflow model, Riolering = Sewer system, maaiveld= surface, oppervlaktewater = surface water system). Right: possible dimensions in a hydrological model **(RIONED, 2020)**

Inflow model (neerslagafvoer)
The precipitation drainage process, with the cloud as pictogram in figure 2, is part of the inflow model. This part of the model describes how water will enter the system for example indirect via surface runoff or directly via roofs of buildings or parameterization of the surface area. In a 1D2D model the precipitation is completely accounted for via parameterization of the surfaces of land and roofs and thus 0D. In a 1D2D+ model both 0D and 2D precipitation are used. 0D for the roofs of buildings and 2D for the overland flow.

Sewer model (Riolering)
The sewer system can be schematized as a bucket (0D). Which allocates all storage towards one calculation point. The sewer can also be seen as a network of nodes and polygons (1D). Flow is then calculated through the pipes. In a 1D2D and 1D2D+ simulation, the 1D stands for the network of polygons and nodes used in the model, schematizing the sewer system.

Surface model (maaiveld)
Water on street can be schematized as a bucket on top of a manhole in a sewer model. This would be a 0D approach. A sewer model with flow across only roads would be 1D and when using a Digital Terrain Model (DTM) flow can occur across the surface which would be 2D. In both 1D2D and 1D2D+, the 2D refers to the 2D surface model used.

Surface water system model (oppervlaktewater)
The surface water system consisting of for example ditches and canals can interact with the sewer system via overflowing points, discharging excess water. When schematizing only the storage a 0D bucket representation of the surface water is enough. With 1D, flow along the direction of the polygons can be calculated and with 2D horizontal flow in all directions becomes possible.
In this study the surface water system is seen as a boundary condition and is further not taken into account.

Standard model concept names
The final combination used in schematizations of the four main model parts determines the model concept name. Which is a contraction of the model schematization used. In this research a 0- and 2D inflow-,1D sewer- and 2D surface model are used. Contracting the 1D sewer and 2D surface model makes 1D2D. The inflow used then determines whether its 1D2D or 1D2D+. Only 0D gives 1D2D and 0D together with 2D inflow gives 1D2D+. In the methods section (3.2) both 1D2D and 1D2D+ model set ups will further be explained.

Theoretical applications
The theoretical application varies per model schematization as ad- and disadvantages per model schematization differ. In the next section the main expected applications for 1D, 2D and 1D2D(+) models are explained.

1D sewer model
Despite the simplifications of the 3D-flow pattern within sewer pipes, manholes and street inlets to uniform 1D flow along one axis, hydrodynamic models are quite accurate in calculating water levels and discharges in a sewer network. A 1D sewer model can be used as an indicator where water on street will probably occur. But identifying potential flood locations and the exact hazard are impossible. As calculations of water levels above the manholes and/or street inlets are not considered reliable enough (RioNED, 2019).

2D surface model
A surface model is a model that only calculates 2D flow across the surface and leaves out or simplifies sewer system interactions. A surface model usually gives a good indication for flood prone areas under extreme conditions. Interactions with a surface water system model are also left out. Though interactions with the sewer system can be schematized by two ways: one is by giving every manhole or sewer inlet a fixed drainage capacity, the other is by subtracting the storage and drainage from input precipitation. These two methods however require good understanding and arbitrary assumptions. It is therefore better to integrate the 2D surface- with a 1D sewer model.

1D2D(+) sewer-surface model
For flat areas, the sewer model with surface flow attached can give detailed insights in flood prone areas and potential severity of floodings. This is also possible for sloping areas, if the flooding is caused by overloading of the sewer system only and runoff from precipitation over the surface does not play a significant role. The sewer

model with surface flow is thus expected to underperform during substantial overland flow from and at unsurfaced, non-sewered areas, or at water flow across streets pass street inlets (RioNED, 2019). It is then expected that 1D2D+ will be the better choice. As 1D2D+ combines a surface flow model with a sewer model and calculates accumulation of water at places where this is not only caused by overflowing sewer systems. This is the case at unsurfaced, non-sewered areas, or at water flow across streets pass street inlets (RioNED, 2019).
The downside of 1D2D+ are the many parameters and input data necessary and lengthy calculation times. RioNED (2019) therefore recommends to only use 1D2D+ when simpler modelconcepts are not deemed sufficient enough w.r.t. accuracy or purpose. These expectations thus give an indication to the results of and a hypotheses to this research. As mentioned in the introduction, quantified research has never been done on the differences between 1D2D and 1D2d+ and these differences in application are solely based on proces level understanding of the models and consequent reasoning.

Software packages
Within hydraulic modelling different types of models and modelling software utilizing different approaches for 1D and 2D simulations are used. In this research D-HYDRO Flexible Mesh (beta version 0.9.9.52575) is used using the assumptions discussed in 2.1 and equations discussed in appendix A. For this research a 1D SOBEK and 1D GWSW model have been used as source models.

The Iber 2.4.3 software is a 2D theoretical software that uses a mathematical model that simulates free-surface flow and analyzes the flow processes of a river across the entire flooded area at different time intervals (Naiji, et al., 2021).

The Tygron Platform is an implementation of a 2D grid based shallow water model based on the 2D St Venant equations. The module is further enhanced with infiltration, evaporation, groundwater flow and hydraulic structures (TYGRON BV, 2021).

HECRAS (Hydrologic Engineering Centre-River Analysis System), 1D, 2D and 1D2D. Among 1D modeling methodologies, HEC-RAS which is a non-commercial application has been widely used (Chen, 2014). As it is open-source and can perform water surface calculations for entire networks of channels. However, it lacks an extensive urban module (Natarajan & Radhakrishnan, 2020).

SOBEK is the precursor to DHYDRO Flexible Mesh but is limited to only calculating in 1D.

InfoWorks® ICM (Integrated Catchment Modelling) offers integrated 1D /2D hydrodynamic modelling of both rivers and sewer systems (Innovyze, 2021). And is possibly the closest competitor to D-HYDRO Flexible Mesh.

Urban Water Data Dictionary (GWSW - Gegevenswoordenboek Stedelijk Water)
The Urban Water Data Dictionary or further mentioned in this research as GWSW is an open standard for the unambiguous exchange and disclosure of data in urban water management. As data becomes more and more important in urban water and sewer management this dictionary has been developed by the RIONED foundation to align all parties with the same system and definitions and speaking the same (computer) language. The RIONED foundation is the umbrella organization in The Netherlands for sewer-, waste-,rain-, and groundwater in cities and villages thus “Urban water”.

2.2 Assumptions

D-HYDRO depends for its flow calculations on the 1D- and 2D Shallow Water Equations (SWE). See appendix A for a detailed description of the formulas involved in the flow calculations in D-HYDRO’s 1D2D(+). The 1D- and 2D SWE are based on a set of assumptions that may be suitable depending on the application, and understanding their implications are therefore important. Some important assumptions are the following (Deltares, 2021).

- **Constant density assumption**. The effect of variable density is only considered in the pressure term (Boussinesq approximation). The constant density assumption holds as density changes due to for example differences in temperature are neglectable.
- **The hydrostatic pressure assumption.** Under the shallow water assumption, the vertical momentum equation is reduced to a hydrostatic pressure equation, neglecting vertical acceleration as gravitational acceleration is dominant.
- **Flow is either one- or two- dimensional.** Vertical variations in flow and velocity are neglected

3. Methods

Following the research question the case study area is described and put into perspective, in combination with the methods used, of previous work done. The following paragraphs are all linked to the flow diagram depicted below in figure 3. First the input will be discussed: precipitation, temperature and evaporation. These meteorological input variables are fed in to the 1D sewer model. Input maps, initial water level, infiltration, roughness and a Digital Terrain Model (DTM) are fed in to the 2D surface model by interpolation to a grid. The 1D sewer model is, after a validation with its source SOBEK counterpart, combined with the 2D surface model by generating 1D/2D links at manholes. This way, a 1D2D model is made. In order to calculate in 1D2D+ a roof mask input layer and 2D precipitation is added. The output of both 1D2D and 1D2D+ models, flood hazards maps, are then made for different precipitation events. Output results in the 1D sewer and 1D2D(+) maps are then compared to each other at certain points of interest and discussed. In the final section of this chapter the 1D validation and agreement performance tests used are explained.

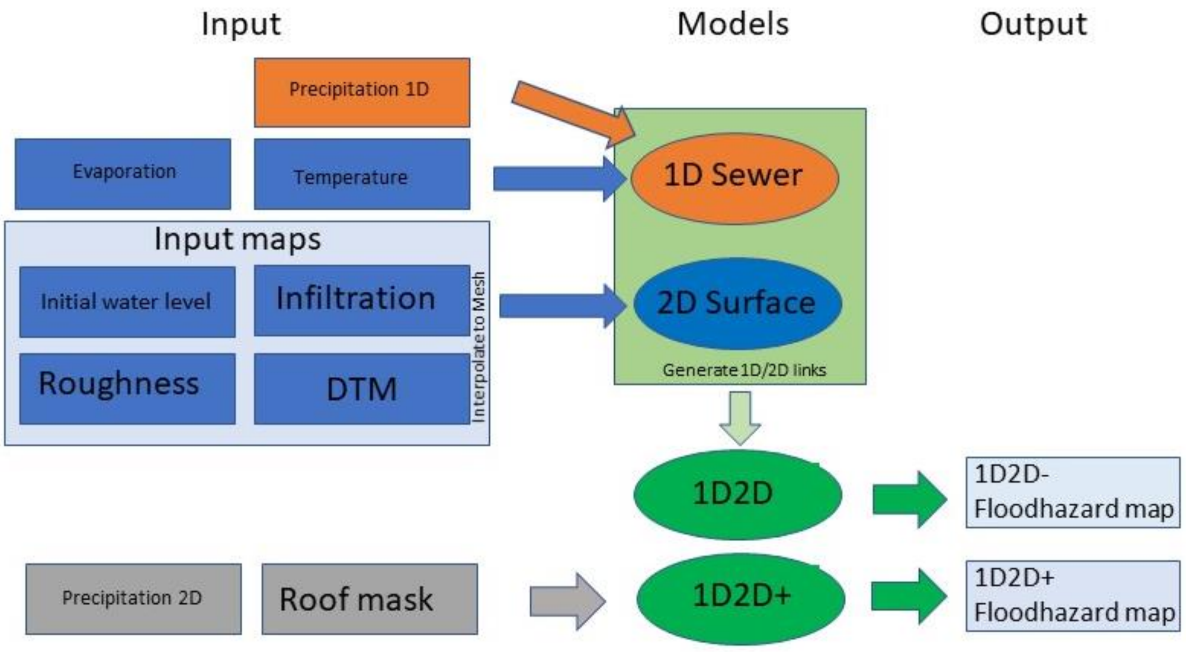

FIGURE 3 FLOWCHART DEPICTING THE DIFFERENT STEPS TAKEN IN THE CONSTRUCTION OF THE 1D2D- AND 1D2D+ MODELS

3.1 Case-study-area

In order to answer the research question the study focused on the case study area of Heemskerk and Beverwijk. The study area is situated northwest of Amsterdam comprising the municipalities of Heemskerk and Beverwijk (figure 4). These municipalities are chosen because of some distinct features in terrain and landcover (Henckens, 2019). Beverwijk and Heemskerk have, for Dutch standards, relatively strong elevation gradient with old dunes in the (south)west with a surface elevation of about 6 meters and to the east and northeast polders with surface elevations down -0,5 m. Also, the area is characteristic for its many types of landscapes among which (old)dunes, peat meadows, reclaimed land (polder and droogmakerij), forests and urban industrial and -residential land.

Regional water plan

Within the case-study-area a water plan has been made containing an integral vision, supported by all parties involved, on the place that water takes in the municipalities of Beverwijk and Heemskerk. The Guideline for Urban Water Plans of the Association of Dutch Municipalities and the Union of Waterboards (Handreiking Stedelijk Waterplan van Vereniging Nederlandse Gemeenten en Unie van Waterschappen) was used as a guideline. The main objective is to increase the quality of the water system and to raise awareness among residents about how to positively impact the water system. As both Heemskerk and Beverwijk drain their sewer towards the southern tip of this research area where a sewer treatment plant is situated. And the main observations are with regards to this research that there is too little water retention to prevent flooding, water should thus be retained longer. This can for example be done by replacing excess paving with vegetation as lots of gardens are over-paved and shedded and giving too much direct burden on the sewer system in the case of heavy precipitation. This direct load on the water system from for example garden paving and -sheds, can be mitigated by good information provision to residents (Grontmij Nederland bv, 2007).

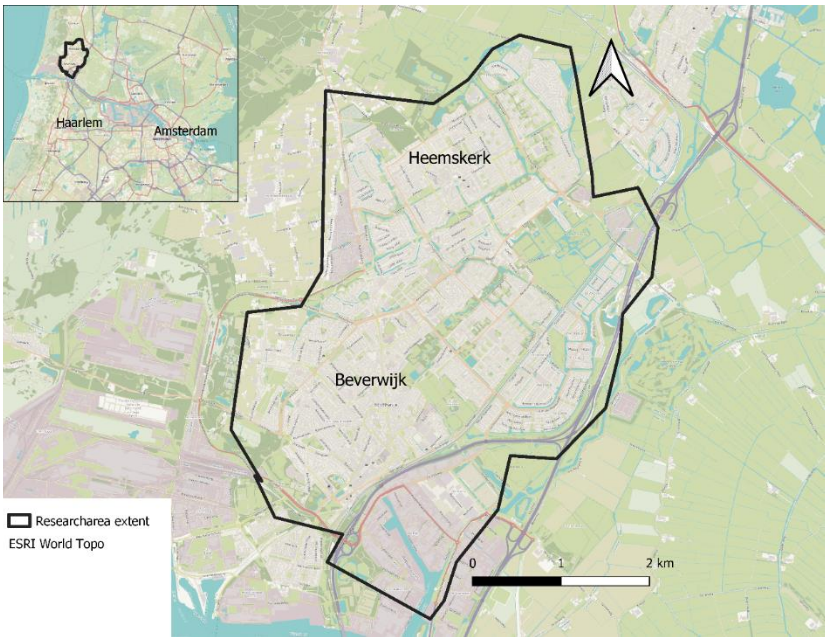

FIGURE 4 CASE-STUDY-AREA OF HEEMSKERK AND BEVERWIJK NORTHWEST OF AMSTERDAM

3.1.1 Area of interest

In order to answer the research question on how 1D2D and 1D2D+ models perform under sloping conditions the Bachstraat area is selected for its distinct slope, along the transect AB (figure 5). The slope is relatively constant from A to B with slope values between 0.1 and 0.2 degrees and a total height difference of about 1.5 meters. The Bachstraat-road has some distinct features as speed bumps, parking spots on the side of the road and a roundabout with elevated median strips in the approach sections of the roundabout. It's asphalted along the entire profile. The low-lying part of the Bachstraat area is known for its sensitivity to pluvial floodings while the upstream, 1,5m higher, Bachstraat area remains relatively dry.

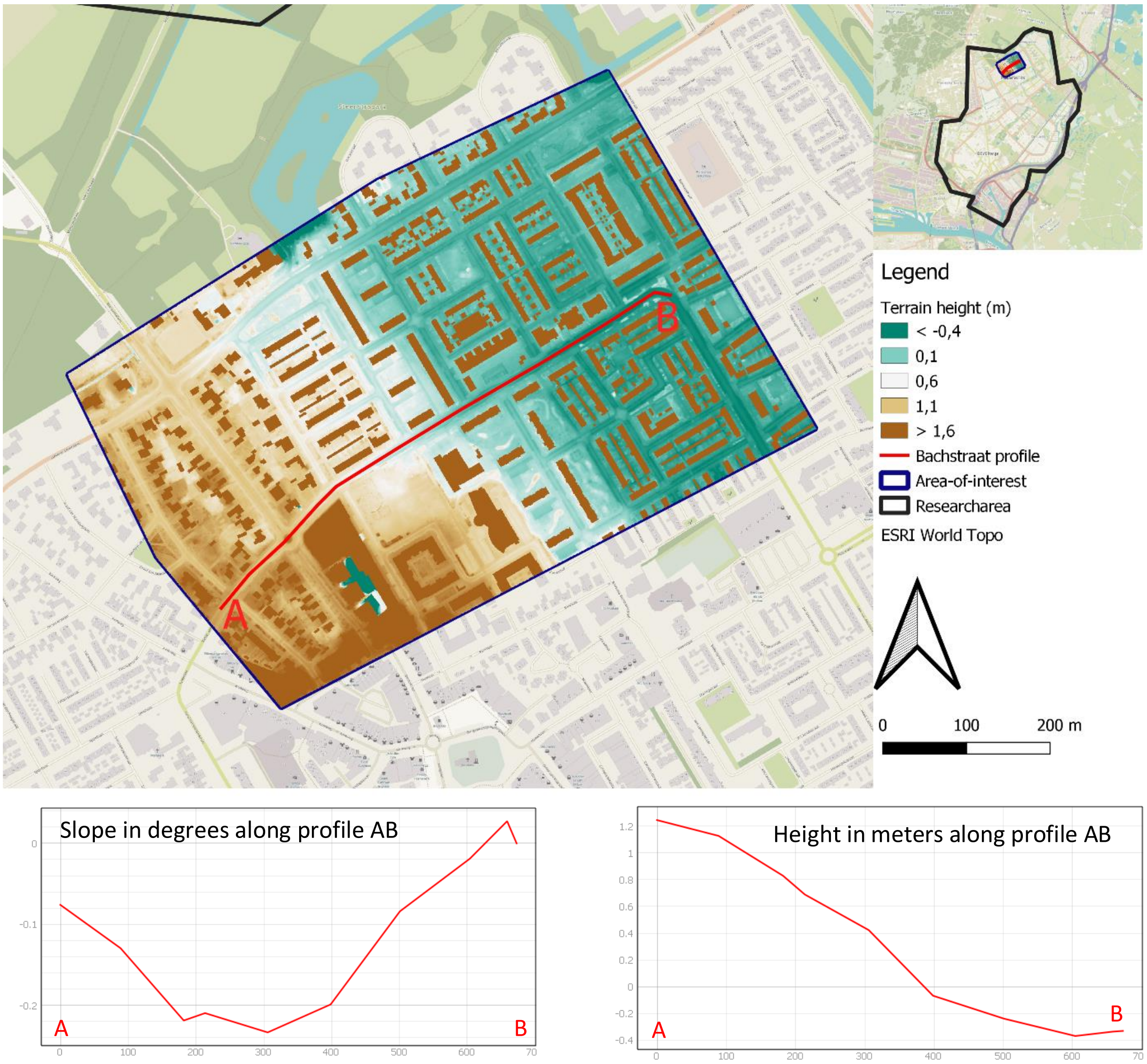

Figure 5 Terrain analysis of the Area-of-interest within the case-study-area. Terrain height is in meters relative to NAP

3.1.2 Previous study's

Besseling (2020) and van Rijn (2020) conducted research and constructed D-HYDRO models of Beverwijk and Heemskerk respectively in earlier beta versions. Both used an integrated model with interaction between the 1D sewage system and the 2D overland flow to simulate precipitation events. Both surface models used a 3x3m grid as higher resolutions were not possible at the time. Van Rijn (2020) used the documented extreme precipitation event of 2014 and compared this to KNMI-climate scenarios. The obtained return periods and corresponding precipitation were used as input for the model. The 2014 precipitation event accumulated 54.1mm/hour. This intensity of precipitation was divided per five minutes following the built-up of test event Bui07 with a peak in the first half hour. Prior to this peak of 54.1 mm/hour it already had been raining (19.1 mm in one hour) and thereby filling the sewage system. This was simulated in the model by adding the test event Bui08, with a similar total volume, before the actual peak. Besseling (2020) used two rainfall events to conduct tests in its modelling study. They were retrieved from the Dutch guidelines for sewer system testing. The first is Bui09, in which 29.4 mm falls in an hour, with a peak at the beginning of the event. The second one is a stress test for climate change: a constant intensity rainfall event of 60 mm in an hour.

3.2 Model type

The discretization of the model domain and the shallow water equations defined on that domain can be done in one, two and three dimensions. In a combined 1D2D model, some parts are modelled as 1D branches (e.g., channel flow or pipe flow) and other parts as 2D horizontal grids.

In this study the sewer system acts as a one-dimensional model. Manholes are connected via sewer pipes, with internal and external weirs to allow for the guidance of water flow and the overflow of excess water respectively. Several pumps are included in the model as boundary condition to feed the water to the wastewater treatment facility in the south of the city. Not included in the model are the foul water pipes of separated systems-, and groundwater drainage pipes. Only pipes that can transport rainwater are considered: combined sewer piping and dedicated rainwater transport piping (Besseling, 2020).

The coupling link between these 1D and 2D domain parts in this research is made via a 1D2D vertically stacked approach. The 1D2D vertically stacked connection is used to model the interaction between a 1D sewer system and the 2D domain above this sewer system. The vertically stacked connection can particularly be used for street inlets and manhole cover openings. See figure 6 for two examples (Deltares, 2021).

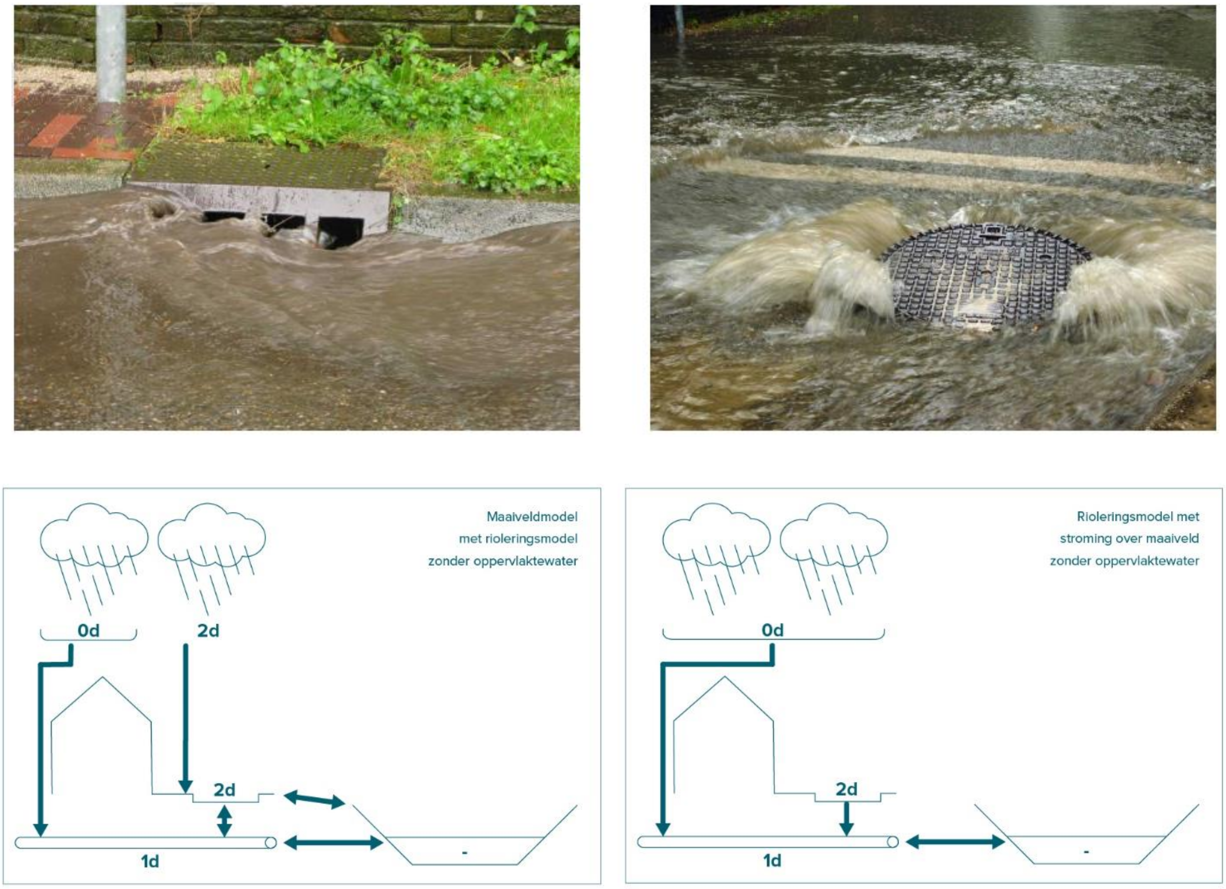

FIGURE 6 1D2D+ (LEFT) FLOW IS FROM STREET TOWARDS INLET AND 1D2D (RIGHT) FLOW IS FROM INLET TOWARDS STREET (RIONED, 2019) NOTE: BOTH TYPE OF MODELS USE 0D PRECIPITATION FOR THE ROOFS OF BUILDINGS

This research capitalizes on 1D2D and 1D2D+ runs of the model. The difference between the two is depicted in figure 6. In a 1D2D model, precipitation falls directly into the model 0D. The distribution of the rain is computed via a surface parameterization given to every inlet (sewer connection) which was obtained by the municipalities. When the 0D rain fills the 1D sewer system to its maximum capacity, 2D overland flow will start from the sewer connections.

In a 1D2D+ model run, precipitation falls in 2D evenly across the grid of the model and in 0D at the roofs of buildings that are directly coupled to the 1D sewer system. The 2D precipitation will either infiltrate (according to the infiltration map) and/or flow via overland flow towards the sewer connections at the manholes into the sewer. Next to that, water can also flow the other way around as in a 1D2D, flow from for example the roofs in to the 1D sewer and from there on to the streets. Thus 1D2D+ will provide, in theory, a more real-world-approximation. Via the roof parameterization provided by the municipalities, precipitation is distributed over the sewer connections that would fall on roofs. At the same time the 2D precipitation falls over the entire grid. In order to prevent the 2D precipitation that falls on the parts of the grid that coincide with roof structures to add to the model (effectively doubling the amount of rain on those locations), a roof mask map is made to correct for this.

3.3 Input

This section discusses the required input for building the integrated model of Beverwijk and Heemskerk, starting with the input precipitation, temperature and evaporation, followed by all of the other input maps. This section ends with a description on the grid construction and specifications used.

3.3.1 Precipitation

The precipitation can be set up for each 2D flow area as a time series of varying rain intensities. Rain is evenly distributed to all cells within the area for 1D2D+. For 1D2D, 0D precipitation is used, and linked to the model via surface parameterization. Bui01 till Bui10 are artificial precipitation events with increasing statistical recurrence time and derived from KNMI precipitation events observed between 1955 to 1979 (RioNED, 2019). These standard precipitation events, Bui01 up to Bui10 are common practice for Dutch sewer system performance tests. The municipality of Beverwijk has also adopted these tests for their ambitions in their water and sewer plan, together with the municipality of Heemskerk and the regional water authority (Grontmij Nederland bv, 2007).

Depicted in figure 7 are the precipitation events used for the 1D2D and 1D2d+ performance tests in this research. Bui06 has a recurrence time of one year, with its peak in the later stage of the hydrograph. Bui 10 has a recurrence time of ten years, with its peak intensity in the early stage of the hydrograph. Blokbui 70mm in one hour is a climate stress test with a recurrence of 1/100y by 2050 (Kennisportaal klimaatadaptatie, 2018) comparable but a bit more extreme then the 60mm used in (Besseling, 2020).

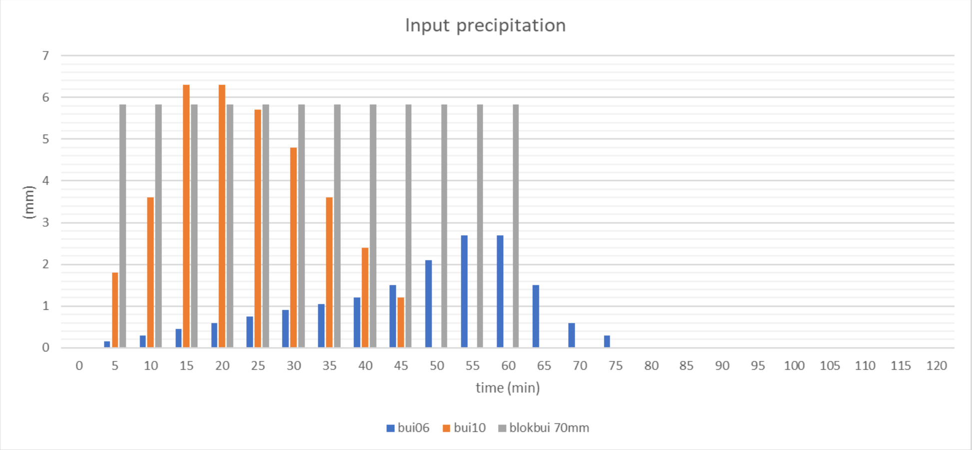

FIGURE 7 INPUT PRECIPITATION BUI06, BUI10 AND BLOKBUI 70MM (RIONED, 2019)

3.3.2 Temperature and evaporation

Temperature is kept constant at 18 degrees Celsius, an average temperature for spring and summer in The Netherlands (Hutten & Geertsema, 2021). Evaporation is kept constant at 0,12mm/hour (Hutten & Geertsema, 2021).

3.3.3 Input maps

Several input maps are interpolated to the 2D mesh by averaging the raster values to the grid. A DEM, Initial water level, roughness, infiltration and roof map are used and discussed in the next sections After, the 2D grid and 1D2D links construction method is discussed.

3.3.3.1 Digital Surface Model (DSM)

For the construction of a DSM first a Digital Terrain Model (DTM) was obtained. A DTM differs from a Digital Elevation Model (DEM) which is a bare-earth raster in which non-ground (man-made) features such as building are not included. A DEM is useful for hydrological modeling, surface analyzing, and soil mapping (Abdi, 2021). Whereas a Digital Terrain Model (DTM) is a 3D model of surface elevation data. A DTM reinforces a DEM by including man-made features of the bare-earth terrain (Abdi, 2021).

Terrain was obtained from the Dutch AHN - digital elevation map as a Digital Terrain Model (DTM). Therefore, areas with buildings were elevated with 20m ensuring overland flow is obstructed by structures. The AHN DEM has a horizontal raster resolution of 0.5x0.5m and a vertical height accuracy of 5cm standard deviation.

Information on the outline of buildings was obtained from the “Basisregistratie Grootschalige Topografie” – basic registration large-scale topography (BGT). The BGT is a digital map of The Netherlands which contains buildings, roads, waterways, railroads and terrains. The map is accurate to 20cm.

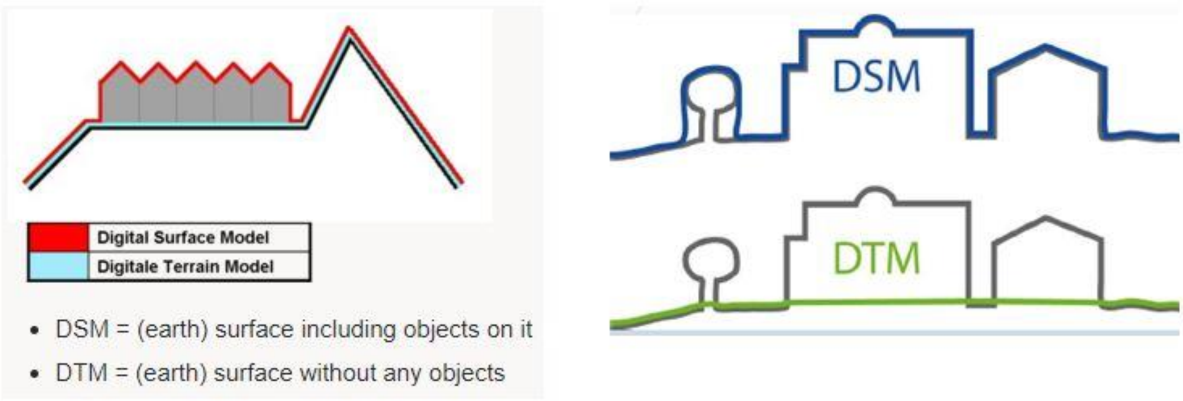

FIGURE 8 DIFFERENCES BETWEEN A DSM AND DTM (CHAUDHURI, 2019)

3.3.3.2 Initial Water Level map

Initial water levels were provided by the water board and are based on their target surface water levels. A map of the initial water levels is included in appendix B. These values determine to what extent the sewer system is able to discharge in surface water system via external weirs. These values are constant over time, since there was no interaction with surface water included in this research. It is expected that the discharge was overestimated due to this assumption, as surface water levels would otherwise rise during (extreme) precipitation. The overestimation however is expected (arbitrarily) to be within limits for this research as the same assumption was made by van Rijn (2020) and Besseling (2020).

3.3.3.3 Roughness map

A roughness map was provided by Wareco (Rijn van, 2020)& (Besseling, 2020) who constructed a roughness map based on land use data maps and roughness constants with Manning units. A distinction was made between fifteen classes of roughness such as, among others, unpaved, open paved, closed paved, grassland, forest and agricultural lands. The map and full table with all classes and corresponding values for roughness can be found in appendix E.1 and E.2.

An error was made which came to light in the writing stage of this research. D-HYDRO has calculated with the manning values as if it were White & Colebrook values. The exact impact is unknown as values are first converted to Chèzy values within the model calculation. The same mistake, however, has been made to all model runs and these runs are therefore still comparable.

3.3.3.4 Infiltration map

Data on infiltration capacity was provided by waterboard HHNK in mm per day, ranging from zero (closed paved) to 300 mm/day (forest) on a 1x1 meter resolution. A graphical overview of the infiltration capacity is attached in appendix D.

3.3.3.5 Roof map

For 1D2D+ model runs only, a roof map was made to act as a mask layer for the roofs of buildings. The BGT (also used in the construction of the DSM) was used. Building outlines were considered as roof outlines. A roof map was constructed for the roofs of buildings because a surface parameterization was attached to the models delivered by the municipalities. 0D rain falls directly from the roofs into the sewer and 2D rain should precipitate everywhere except for the grid cells that correspond to the roofs, to prevent precipitation from ‘falling’ in to the model two times.

3.3.4 Boundary conditions

Boundary conditions are locations in the model where water flows into or out of the model. Next to the precipitation, temperature and evaporation, several boundary conditions in- and outflows are defined. Infiltration and initial water levels are defined by the infiltration- and initial water level map. The first of which is a boundary condition in itself. The second of which forms a boundary condition together with the weirs in the 1D model. Every weir has a height defined to where water will be dammed. Other boundary structures are orifices (sometimes within weirs), pumps and outlets. Provided by the municipalities of Heemskerk and Beverwijk, the SOBEK and GWSW networks contain information about location of manholes, pipes, pumps, weirs and the relevant properties of these structures as material, heights, diameters and capacity. The SOBEK and GWSW networks are the established models for the research area and form a baseline from where comparisons are made to D-HYDRO.

3.3.5 Mesh 2D

A 2D grid in the D-HYDRO General User Interface (GUI) was made by shaping a polygon covering the research area of Beverwijk and Heemskerk and therein generating a grid with 3m-by-3m grid cells. Within this grid an 8x refinement is added to the area of interest. This means, the grid is halved 3 times over (iterations) ending up with a 0,38m*0,38m local grid refinement. The refinement is made because a complete 0,5m grid would be too large for any computer system currently available to handle. And a 3x3m grid is too coarse for speed bumps,

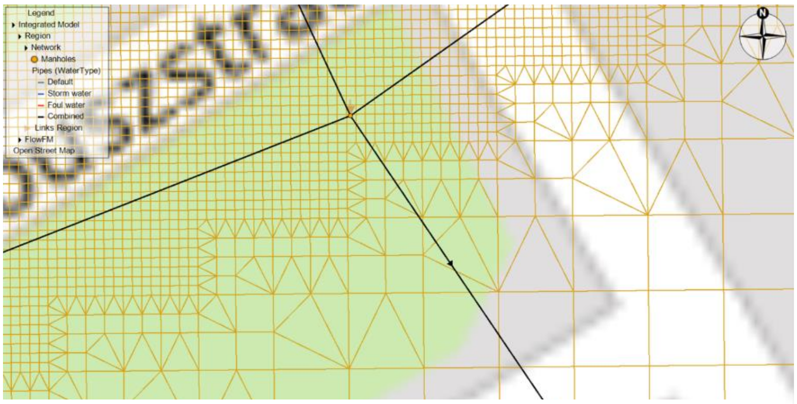

FIGURE 9 SNAPSHOT FROM THE D-HYDRO 3M GRID AND 3X REFINEMENT 0.38M GRID. BELOW THE GRID THE BLACK LINES REPRESENT THE 1D SEWER NETWORK. THE ORANGE ARROWS REPRESENT THE 1D2D LINKS

sidewalks and other street level characteristics smaller than 3m to be distinguishable, possibly underestimating water depths on streets as these structures act as street level dams.

Each grid cell has four cell faces (sides). Cell faces are similar to 1D cross sections and are used to compute flow between cells, except for the outer boundaries of the mesh. Water elevation is computed for each cell at the center of the cell.

This 2D grid consisting of 4.4 million cells is linked to the 1D-coupled Beverwijk-Heemskerk sewage network. Replacing the existing surface area per manhole with a 2D grid-surface. The links were made at the manholes as other structures that could link the 1D- with the 2D domain are not present within the 1D models. The existing surface area in the 1Dmodel was replaced with the corresponding overlying grid cells.

3.3.6 1D2D link construction

Links were constructed between the 1D- and 2D-model in order to perform 1D2D- and 1D2D+ calculations. Figure 10 shows the discretization of internal 1D2D links (Deltares, 2021). 1D nodes are coupled to the center of the grid cells. This is called the “Embedded 1-to-1”-method and was chosen because a 1D2D embedded link is especially intended for small 1D channels where the 2D grid cells overlap the 1D channels, for example in rural areas (Deltares systems, 2021).

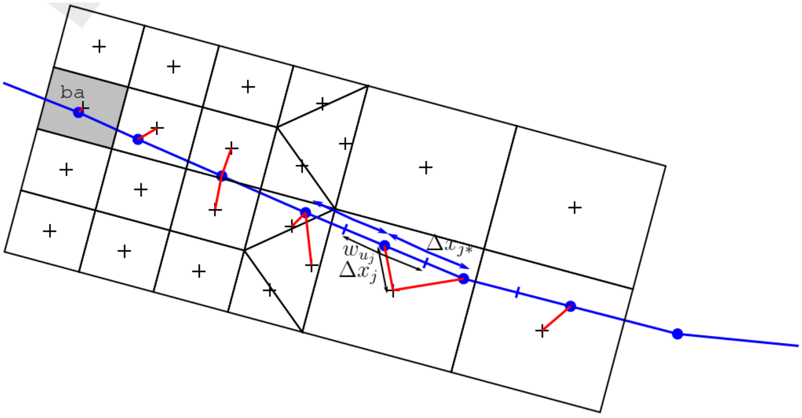

Figure 10 Schematic representation (see figure 7) of the 2D D-HYDRO grid and 1D network below. The figure shows the 1D2D links added to the centers of the grid cells (Deltares, 2021)

An important footnote is that street level inlets are not included in the 1D model. Street level inlets are the inlets usually at the sides of roads, whereas manholes are the sewer openings at the centers of roads from where inspections or maintenance can take place. This results in only coupling at the manholes of the 1D model. The consequence of this is that less precipitation will find its way into the sewage in the model, compared to reality as illustrated in figure 11. Water will form puddles and flow along the side of the road without encountering street inlets as the manholes are placed in the center of the street.

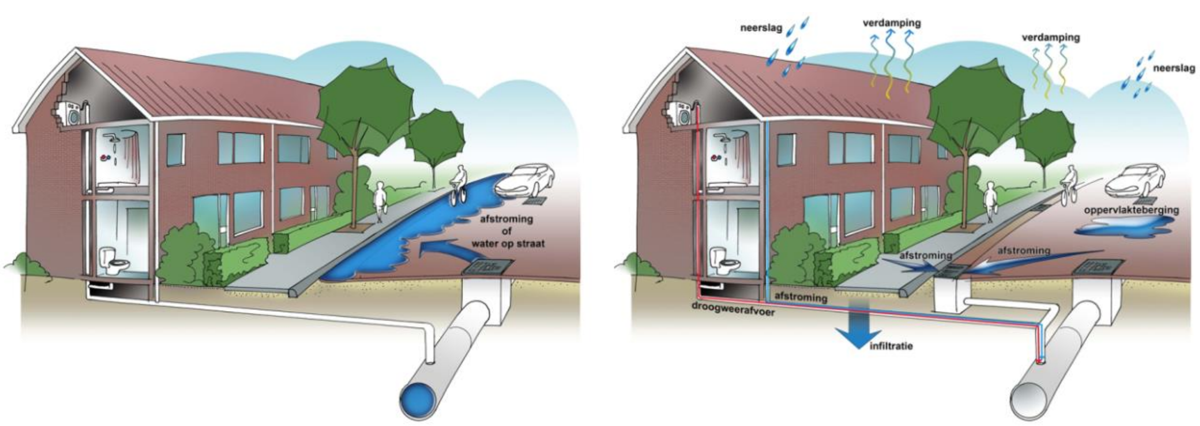

Figure 11 showing the consequence of the model conceptualization (left) compared to reality as no street inlets, only manholes are present in the manhole (right) (Fieldlab, 2019)

3.4 Model set-up 1D2D(+)

The model set-up 1D2D+ is the same as for 1D2D except for the addition of 2D precipitation (instead of 0D), the addition of a roof mask layer and the removal of the parameterized surface areas used in the 1D2D-setup. Therefore, this chapter further only discusses the set-up of a 1D2D model.

The model is built in a number of steps. First the construction of the 1D network. This is done by coupling an existing SOBEK-network of Beverwijk (Besseling, 2020) and an existing GWSW-network of Heemskerk (Rijn van, 2020) by importing in D-HYDRO. After coupling the 1D Beverwijk and Heemskerk models in to one big 1D model the 2D mesh is constructed. All the input maps are interpolated to the mesh and 1D2D links are constructed. The 1D2D model then calculates with 0D precipitation directly to the manholes. In order to calculate the amount of water that falls on every manhole a parameterization of the surface area is made which is explained in the next paragraph.

3.4.1 Surface area parameterization

In order to run 1D2D, the otherwise 2D surface area where rain falls is parameterized and set directly to the manholes. This parametrization is done by estimating the area associated with different classes of terrain that are directly linked to the sewer system. All land use categories except for water categories the 'waterdeel'-water area and 'ondersteundend waterdeel' – supporting water area was left out as this landclass was not considered a contributor to the 1D sewer network. The classes 'closed flat area' – asphalt/paved roads and terrain; 'unpaved flat area' – roadside greenery, playgrounds, etc. and 'open flat area' – parks, sportingfields etc. were calculated on the basis of the BGT (Basisregistratie Grootschalige Topografie). For gardens, a coarse estimation was made by (de By, 2021) who stated that about 20% of all gardens are directly connected to a rainwater sewer and the rest of all gardens relies either on buffering and infiltration or flow towards surface water which is considered a boundary condition in this research. This was followed by an estimation of the paved area in gardens by middling the known paved areas of Beverwijk (48,1%) and Heemskerk (25,9%) (Cobra groeninzicht, 2021) which is ~37%. This course estimation has been made due to time constraints.

The parameterization ended up with dividing the total areas of all classes over the number of nodes, homogenizing the otherwise heterogeneous dispersion of land in the 2D domain.

	Total area in model (m^2)	Total per node (m^2)(5775 nodes)
Closed flat area	4.528.836	784,2
Unpaved flat area	518.298	89,7
Open flat area	786.643	136,2
Total Area	**5.833.777**	**1010,1**

TABLE 1 AREA TOTALS PER NODE (OR 1D2D LINKS)

Total area by 2D mesh 13.349.149 m^2, which is a lot more than the 5.833.777 parameterized but mostly explained by the missing of more than 60 percent of all gardens and the missing of large waterbodies as contributors to the sewer system. This is considered acceptable because waterbodies (surface water) do not contribute to the rainwater sewer system and are not taken into account in this research. The same holds for the missing of the gardens as the 20 percent that contributes to the sewer is taken into account.

3.5 Assumptions

Next to the surface area parameterization, during the set-up of the 1D2D(+) models a number of assumptions have been made. The most important are explained here.

- **Paved area** When importing the 1D SOBEK model with paved areas attached from Beverwijk a bug in the D-HYDRO beta importer prohibited heterogeneous dispersion of surface area. The surface areas are therefore homogenized before importing. The total surface area connected to the sewer system has thus not changed. The dispersion of the areas per node has. The effects of this simplification and assumption on model results are not considered crucial and it is expected that only on the scale of single nodes differences will occur. These differences are not expected to impact the conclusions of this research.

- **Different source models for Heemskerk and Beverwijk** It wasn't feasible to import and couple two SOBEK networks because the SOBEK network of Heemskerk consisted of external structures as weirs and pumps of which the SOBEK import in D-HYDRO was unable to import them correctly. Beverwijk didn't have this problem as all structures in the Beverwijk Sobek model were internalized with a boundary condition attached to it. The same procedure could have been a solution for the Heemskerk source model part, but re-modelling all structures in SOBEK was not considered achievable within the timeframe of this research. Therefore, for Heemskerk a GWSW source-model was used which could cause differences.
- **Spatial component of precipitation** Little is known about the spatial component of extreme precipitation events. It has only recently been proved feasible to gain detailed and precise radar images. These images are necessary in making directed statements about the spatial distribution of rainfall intensity and quantities. More research on this subject is necessary. Therefore, spatial variations in precipitation are neglected.
- **Vegetation and interception** The impact of vegetation is neglected in the D-HYDRO model as it was not yet feasible to import vegetation characteristic input maps containing information about trees, shrubs and other vegetation. Therefore, the impact of interception by these real-world components are neglected.

3.7 Validation 1D

The created 1D-D-HYDRO structure of Heemskerk and Beverwijk was first tested before it was implemented in 1D2D(+). Coupling of both SOBEK source models was not yet feasible due to numerous bugs in the beta (D-HYDRO 0.9.9-) version used. Therefore, the choice was made to validate the 1D SOBEK-SOBEK-model against a SOBEK-GWSW-D-HYDRO model (figure 12).

A 1D-SOBEK model of Beverwijk and a 1D-GWSW model of Heemskerk were imported after each other in to DHYDRO and run with precipitation bui08. Bui08 is a 1/2y precipitation event with its peak in the back of the event.

Output from 1D D-HYDRO model results is validated against the SOBEK-source counterpart. Results from both SOBEK and D-HYDRO are imported in QGIS 3.16.1-Hannover and visualized spatially. Results (water level) per node are subtracted from each other (SOBEK – D-HYDRO) showing the differences.

A model-model validation is made because the SOBEK model is considered as a benchmark. A validation against observed values is not possible because of lack of data on real-world pluvial floods in the research area.

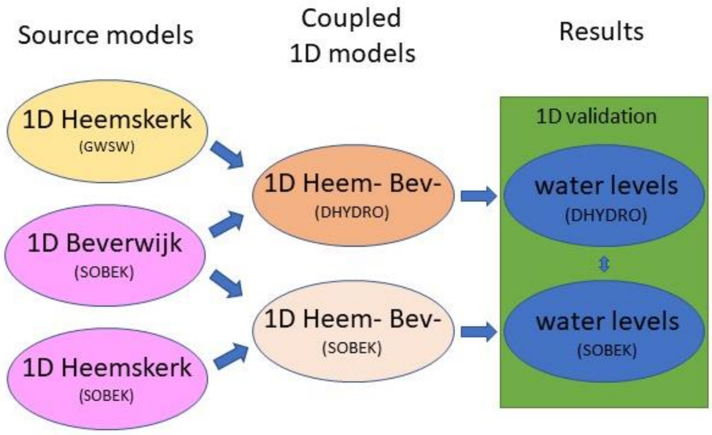

FIGURE 12 FLOW DIAGRAM DEPICTING THE STEPS TAKEN IN THE SET-UP AND VALIDATION OF THE 1D MODEL

3.8 Model performance comparison

In order to evaluate the performance of 1D2D and 1D2D+ against each other, the 1D hydrograph discharge at nodes output, and a series of criteria are used. The performance tests chosen are done on timeseries from arbitrarily placed points lengthwise along the Bachstraat. Six points are placed and timeseries of water depth per point are extracted from the underlying raster output. This method is chosen because directly comparing 1D2D and 1D2D+ raster output would result in disagreements because of the way precipitation is modelled in both types of models. These criteria thus allow for a quantitative evaluation next to the qualitative analysis. The model performance is measured using six different criteria; model bias, Root Mean Square Error, Nash-Sutcliffe efficiency, logarithmic version of Nash-Sutcliffe efficiency for low flow evaluation, the adapted version of Nash-Sutcliffe efficiency for high flow evaluation and for extra support the R^2-value (Andersen, et al., 2001). The same authors have set performance criteria for the Nash-Sutcliffe coefficient, see table 2&3. in other model studies these criteria are used to compare observed and modelled results with each other. Here the same methods are used to compare two different modelling approaches: 1D2D and 1D2D+. In order to obtain a result whereby both models are very much in agreement the Nash-Sutcliffe coefficient should be at least 0.70 or higher. The same target value is also used for the logarithmic and the adapted version of the Nash-Sutcliffe coefficient for low- and high flow examination.

Performance (model agreement)	Nash-Sutcliff
Very Good	>0.95
Good	0.85-0.95
Fair	0.70-0.85
Poor	< 0.70

TABLE 2 PERFORMANCE INDICATORS

The six criteria are described in table 3 and a small description of what the criteria evaluates, based on (de Waard, 2010) and (Besseling, 2020).
'Observed' = 1D2D, 'simulated' = 1D2D+

Criteria	Description
Model bias $CR1 = \frac{\sum_{i=1}^{n}(Qs_i - Qo_i)}{\sum_{i=1}^{n} Qo_i}$	The model bias measures the relative mean difference between both model stream flows. A lower CR1 value indicates a better fit, and the value 0.0 represents the perfect agreement in flow volume.
RMSE $CR2 = \sqrt{\frac{\sum_{i=1}^{n}(Qo_i - Qs_i)^2}{N}}$	To quantify the difference between the models, the Root Mean Square Error (RMSE) is used. It estimates the standard deviation of the error between two datasets, and is a good way to answer the question: "How far off should we expect our model to be on its next prediction?" (Moody, J, 2019).
Nash-Sutcliffe efficiency $CR3 = 1 - \frac{\sum_{i=1}^{n}(Qs_i - \lvert Q_o \rvert)^2}{\sum_{i=1}^{n}(Qo_i - \lvert Q_o \rvert)^2}$	The Nash-Sutcliffe coefficient observes the similarities between two hydrographs. A value of 1 would indicate a perfect agreement between 1D2D and 1D2D+ hydrographs.
Logarithmic version of Nash-Sutcliffe efficiency for low flow evaluation: $CR4 = \frac{\sum_{i=1}^{n}[\ln(Qs_i + \varepsilon) - \ln(Qo_i + \varepsilon)]^2}{\sum_{i=1}^{n}[\ln(Qs_i + \varepsilon) - \ln(\lvert Qo \rvert + \varepsilon)]^2}$	This criterion shows the quality for low flow simulations. Where ε is an arbitrary chosen small value introduced to avoid problems with nil simulated discharges. The value of ε should be low and modelled discharges which are less than ε are negligible. The best value for this criterion is 1.
Adapted version of Nash-Sutcliffe efficiency for high flow evaluation:	Where CR4 evaluates low flow simulations, CR5 evaluates high flow simulations. As seen in the formula more weight is given to high flow simulated discharges. The best value for CR5 is 1.

$CR5 = 1 - \frac{\sum_{i=1}^{n}[(Qo_i + \lvert Qo \rvert)(Qs_i - Qo_i)]^2}{\sum_{i=1}^{n}[(Qo_i + \lvert Qo \rvert)(Qo_i + \lvert Qo \rvert)]^2}$	
R^2 $CR6 = \left(\frac{\sum_{i=1}^{n}\left((Q_m^t - \lvert Q_m \rvert)(Q_o^t - \lvert Q_o \rvert)\right)}{\sum_{i=1}^{n}(Q_m^t - \lvert Q_m \rvert)^2\,(Q_o^t - \lvert Q_o \rvert)^2}\right)^2$	To support the NSE in showing the correlation between the models, the R^2 value of the discharges is calculated. R^2 ranges from 0 to 1, and it shows the goodness of fit of a model to observations. It is important to note that a good R^2 can be achieved if the predictions of the model are very different from observation, as long as they show the same pattern. Namely, R^2 is an indicator for correlation, not for accuracy. To calculate the R^2, Microsoft Excel uses the square of the Pearson correlation coefficient, which is the formula shown here. R^2 values of 0.75, 0.50, or 0.25 can, as a rough rule of thumb, be respectively described as substantial, moderate, or weak. With respect to pattern correlation.

TABLE 3 PERFORMANCE CRITERIA

4. Results

This section will describe the set-up and running of the 1D, 1D2D and 1D2D+ model of Beverwijk-Heemskerk. First, the 1D model results compared to the sobek-1D counterpart will shortly be discussed after which the different 1D2D/1D2D+ comparisons will be made. Parts of two of the sub questions of this research will serve as guidance for this section. (2) What is the added value of the D-HYDRO 1D2D+ vs a 1D2D-model in a sloping vs non-sloping situation and during prolonged- and high peak intensity precipitation events respectively? (3) With climate change in mind, what type of precipitation is there to be expected and which model can handle this transition the best for which situation?

4.1 Validation 1D

Output from 1D D-HYDRO model results is validated against the SOBEK-source counterpart. Results from both SOBEK and D-HYDRO are imported and visualized spatially. Results (water level) per node are subtracted from each other (SOBEK – D-HYDRO) showing the differences (figure 13). For the most part, results are in accordance with each other (less than 1cm difference) with only a few isolated areas (mainly in the south, dark red and blue) differing more than 5 cm. These bigger differences are possibly explained by counter sewage flow (which is calculated differently) and differences in calculation points between SOBEK and D-HYDRO.

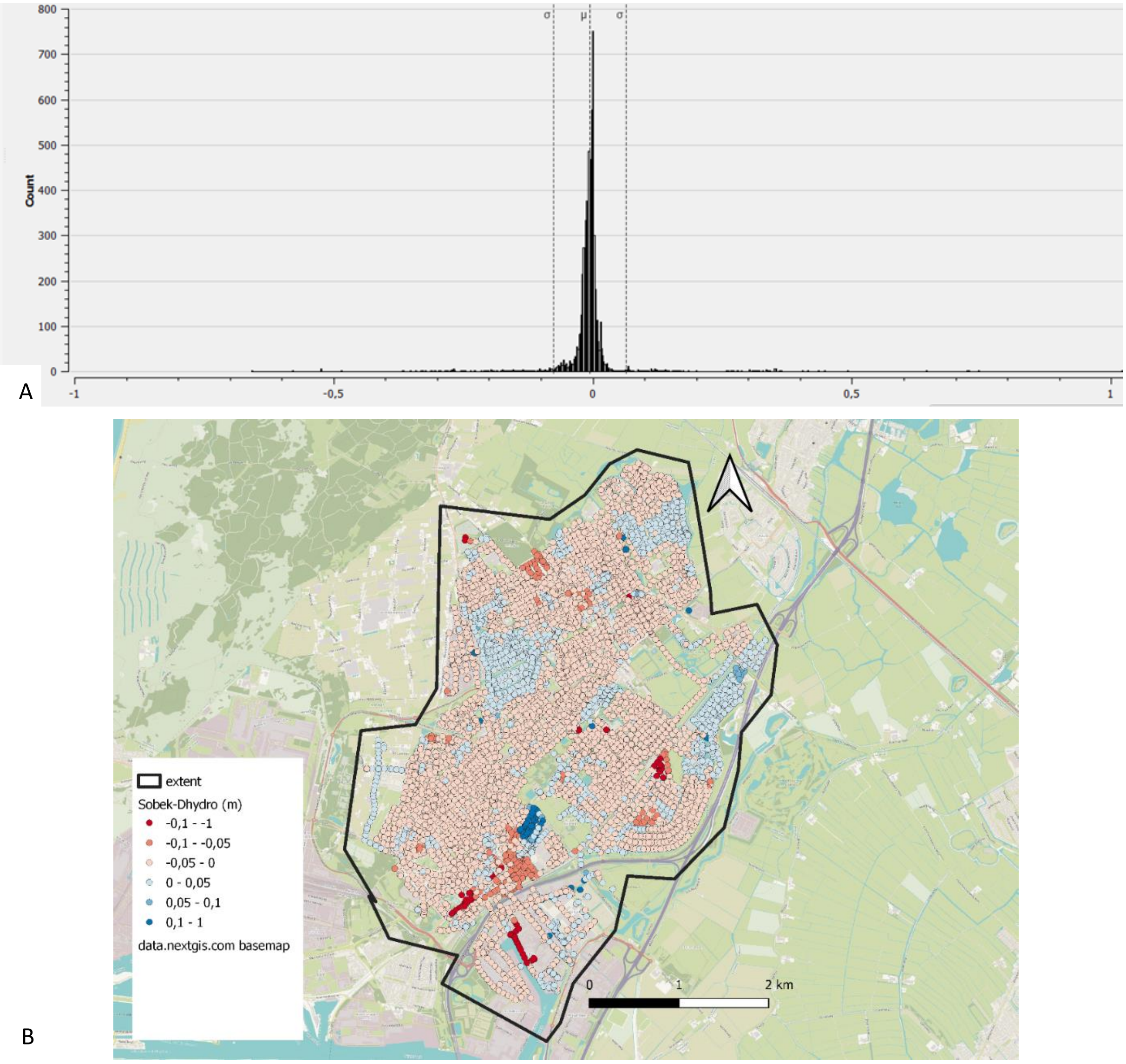

FIGURE 13 1D VALIDATION OUTPUT RESULTS (A) HISTGRAM DEPICTING THE DIFFERENCES BETWEEN SOBEK AND D-HYDRO, X-AXIS IS IN METERS (B) SPATIAL REPRESENTATION OF THE DIFFERENCES BETWEEN SOBEK AND D-HYDRO

With these results for the 1D model aligned with SOBEK, major errors are likely not to occur anymore in the 1D domain. With this the 1D2D and 1D2D+ extension’s results are to be trusted with more confidence.

4.2 1D2D vs. 1D2D+

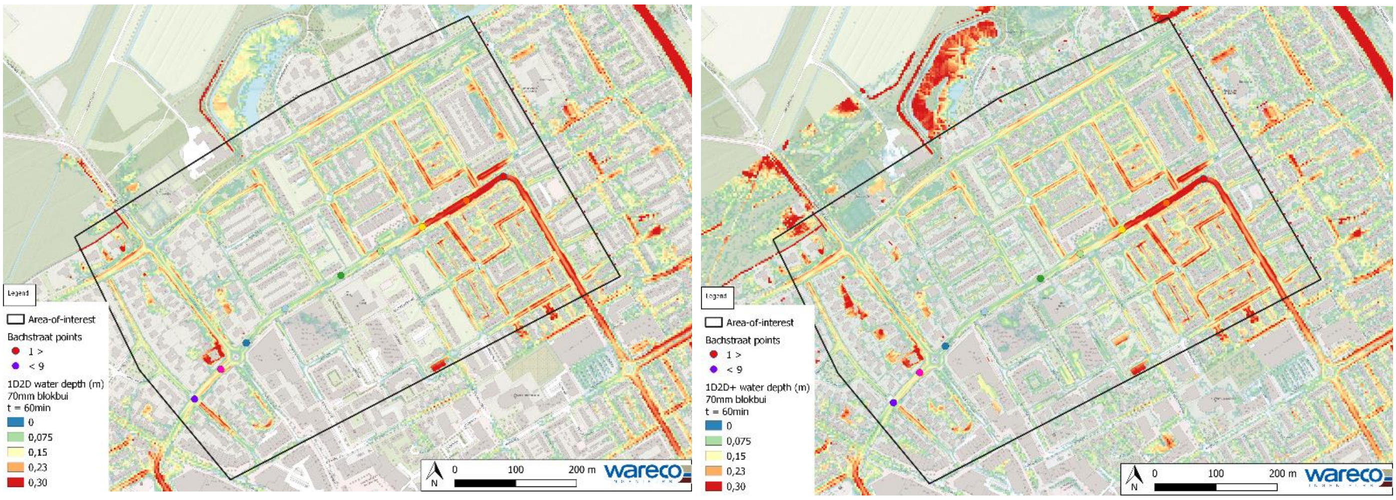

Figure 14 flood map 1D2D (left) and 1D2D+(right) during Blokbui 70mm at 60 minutes.

Before presenting the results of the model the computation time of the model should be mentioned. This is because the biggest difference in terms of running the model is the runtime. A single 1D2D run with 120 one-minute-timesteps took about 30 hours to complete. The same run with a 1D2D+ setup took around 75 hours to complete. Which is more than twice as much. The output files generated contained about 42GB of data per run. The biggest difference in terms of the flood maps between 1D2D and 1D2D+ expresses itself in the map as the 2D input precipitation is visible across the entire map. Especially gardens and low-lying areas far from sewer connections show immediate accumulation of water. This makes the 1D2D maps (0D precipitation only) more focused on the sewer/road interface and less spotty. On the other hand, possible floods in places far from sewer connections could be missed.

Looking at the flood extent and depth in the flood maps of figure 14, areas with water-on-street in the area-of-interest are identified. More than 30cm of water accumulates in both types of models on a large scale downstream on the Bachstraat. Upstream the Bachstraat, inundation of the streets is less pronounced with only the sides of roads showing accumulation of more than 30cm water on street. In between, at the Bachstraat slope no major accumulation occurs with a max water depth of about 10cm. Both models thus look comparable in the major spatial trends. The refinement however shows, in contrast to the coarser 3x3m mesh, finer structures as speedbumps, parking spots and flower/shrub beds.

4.3 Sloping vs non-sloping

In order to answer the research question on the differences between sloping and non-sloping areas in 1D2D and 1D2D+ the Bachstraat area was selected. The main trends described below are visualized in figure 15. The colors of the points placed along the Bachstraat from red to dark purple (downstream to upstream) coincide with the line colors in the corresponding graph. The corresponding graphs show the differences between the timeseries of water depth at the locations of the points between 1D2D and 1D2D+.

First, looking at figure 15A, the trend between the difference in water depth between 1D2D and 1D2D+ up- and downstream the Bachstraat is visualized. At the slope itself, in the middle of the Bachstraat (green points), water depths differ not so much (<2cm), it is at the top and at the bottom of the slope where the big differences between 1D2D and 1D2D+ arise. With at the top of the slope 1D2D+ giving similar to lower values of water depth compared to 1D2D (0 to -2cm, dark blue and purple locations) and at the foot of the slope in the bend of the Bachstraat, values of water depth are higher for 1D2D+ compared to 1D2D (up to 6cm). When comparing these values to the actual modelled water depths from figure 14 where downstream the Bachstraat about 30cm and upstream about 10 to 15cm water depth is modelled, 6cm is a difference of +20%.

Another notable effect, when looking at figure 15B, is the shift of the timing of the peak in the hydrograph for both 1D2D and 1D2D+. The further downstream, or lower in the Bachstraat, the later the peak in the hydrograph occurs with a maximum delay of about 15 minutes.

After the precipitation event of one hour, it takes about half an hour for the model to stabilize (all lines flatten out) as both in 1D2D and 1D2D+ all water is then either drained (upstream) or accumulated to the same places (downstream). With upstream taking notably longer (~20 min) to stabilize compared to downstream. As 1D2D+ upstream initially (first 20min) calculates more water then 1D2D but quickly turns around (after 20min) (purple and pink lines). The upstream underestimation of 1D2D+ compared to 1D2D then holds notably longer (20min) then the downstream overestimation of 1D2D+ compared to 1D2D.

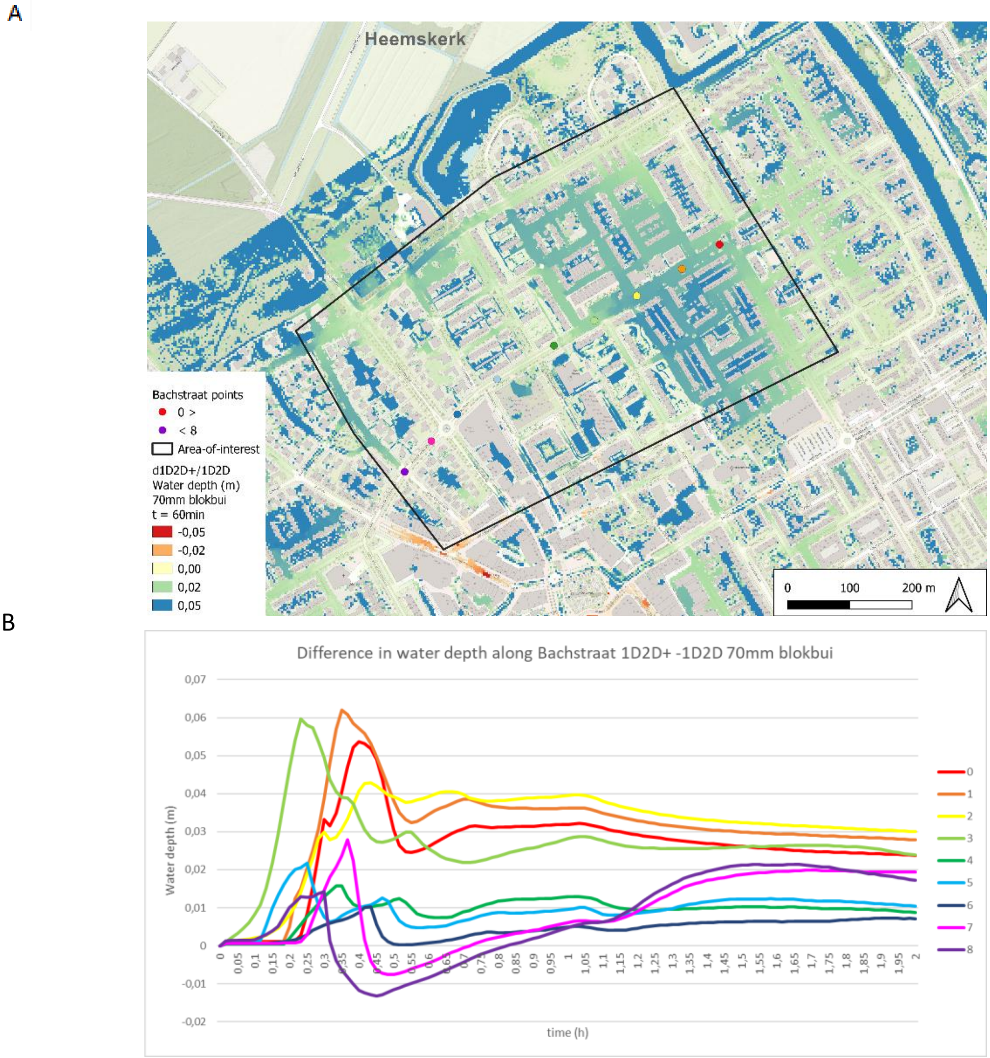

Figure 15 (A) Area-of-interest difference between 1D2D+ and 1D2D during Blokbui 70mm at 60minutes. At the Bachstraat colorized points from red to purple corresponding to the line colors from graph (B) Timeseries per point showing the differences between 1D2D+ and 1D2D along the Bachstraat simulating Blokbui 70mm.

4.4 Different types of precipitation

In order to answer the research question on the effects of different types of precipitation in 1D2D and 1D2D+ different precipitation events, which are explained in the methods section 3.3.1, bui06, bui10 and Blokbui 70mm were selected and used to run the Heemskerk-Beverwijk model. The Bachstraat area-of-interest and points shown in figure 15A are chosen to extract timeseries of water depth. The extracted timeseries are shown in figure 15B and 16.

Figure 16A shows, the results for precipitation event bui06, no differences are visible between 1D2D and 1D2D+, in the early stage (first 60min) of the precipitation event. The later stages however do show a remarkable difference, especially downstream the Bachstraat (points 0 and 1). Here a difference of about ten centimeters occurs for more than half an hour. Also, the points 2 and 3 show a difference of about 5 centimeters. The further downstream, the bigger the difference between 1D2D and 1D2D+, and the higher the water depths in 1D2D+ compared to 1D2D. More upstream the differences are small with a max difference of 2cm and a reversal of the trend with 1D2D showing higher values then 1D2D+ but only relatively small (2cm) differences. After the precipitation event the differences take longer to consolidate, especially downstream the difference holds long (more than one hour) after the precipitation event. This difference is not quickly becoming smaller in the progression after the two-hour simulation period assuming the same trend continuous.
Bui10 and Blokbui 70mm show the same trends. Although Blokbui 70mm has more pronounced differences. Peaks in the hydrographs show a temporal shift of about 0,1 hour or 6 minutes and a peak water depth difference of about 2 cm.
After the 70mm precipitation event of one hour it takes about half an hour for the model to calculate no differences between 1D2D and 1D2D+ . For bui10 the peak of the precipitation event lays at 25 minutes and stops after 45 minutes. After the 45 minutes, it takes about 25 minutes to stabilize. This is comparable to the half an hour time period of Blokbui 70mm.
Upstream is taking notably longer (~20 min) to stabilize compared to downstream. As 1D2D+ upstream initially (first 20min) calculates more water then 1D2D but quickly turns around (after 20min) (purple and pink lines flattening). The upstream underestimation of 1D2D+ compared to 1D2D then holds notably longer (20min) then the downstream overestimation of 1D2D+ compared to 1D2D.

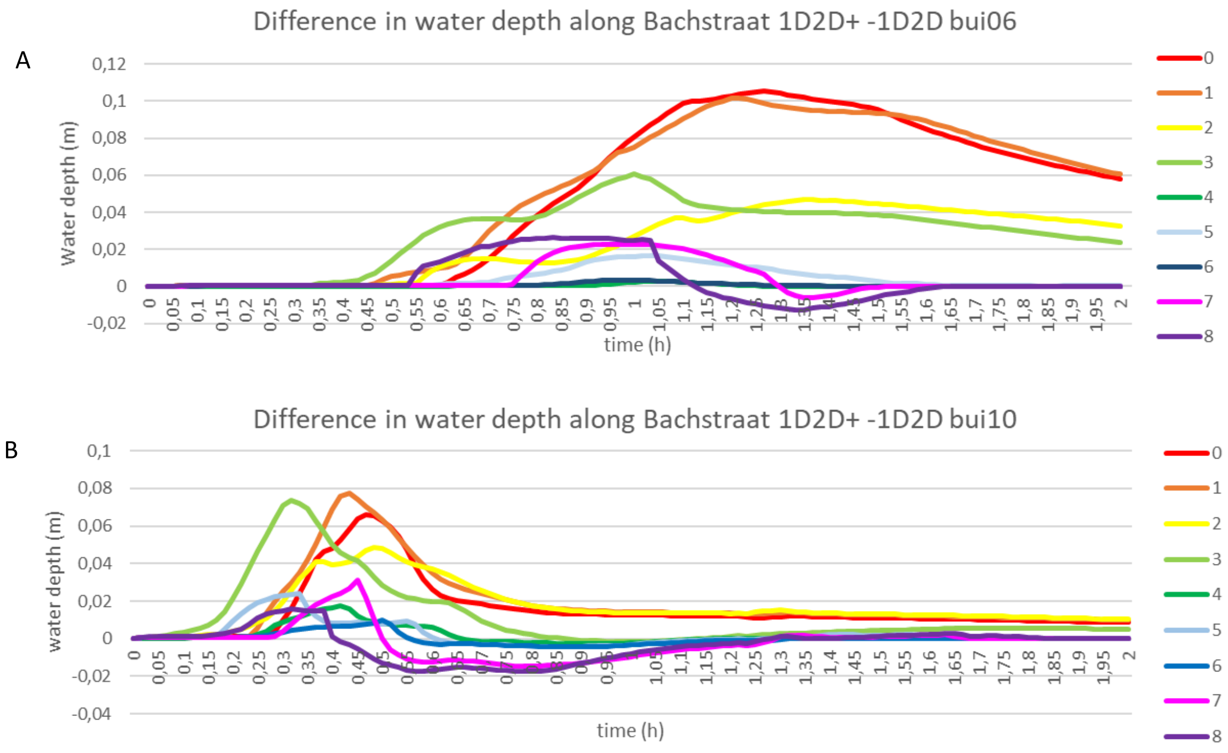

FIGURE 16 (A) DIFFERENCE IN WATER DEPTH ALONG BACHSTRAAT 1D2D+ - 1D2D BUI06 (B) DIFFERENCE IN WATER DEPTH ALONG BACHSTRAAT 1D2D+ - 1D2D BUI10

The differences between a Bui10 and Blokbui 70mm are depicted in the figure below by subtracting the difference between 1D2D+ and 1D2D for 70mm by the difference between 1D2D+ and 1D2D for bui10. The major trends are the same though timing of the peaks in the hydrograph are different. The more downstream the later the peaks occur. In the beginning of both events' precipitation event 70mm accumulates more water on street compared to bui10 and vice versa in the later stage. This is basically the trend of the precipitation event itself as Bui10 has a peak in the later stage of the hydrograph and Blokbui remains constant with high intensity. The difference in water depth has a range of about 8cm and stabilize (flatten) half an hour after both precipitation events have ended. The differences between 70mm however remain relatively bigger compared to bui10 in the hour after the precipitation event ended.

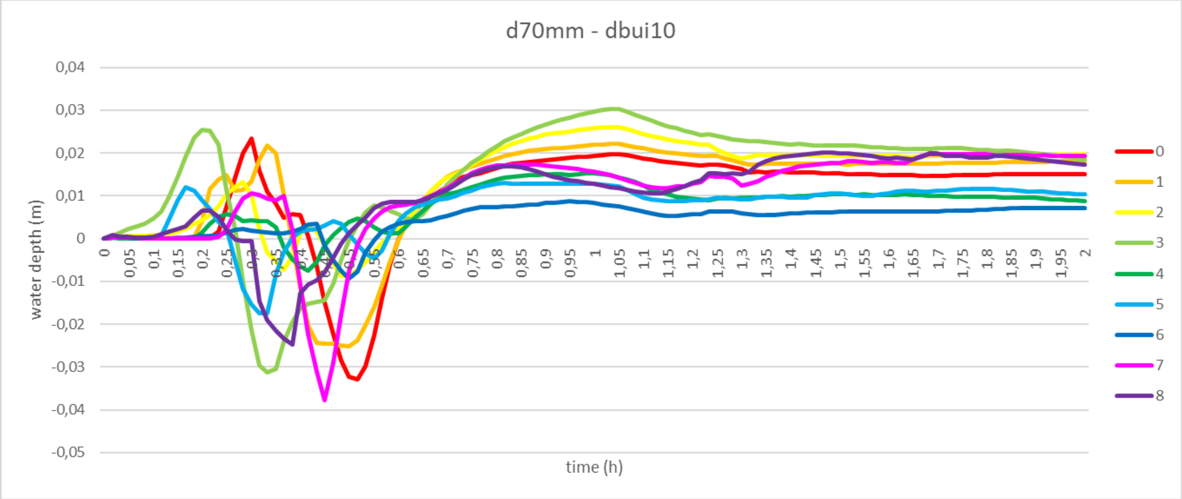

FIGURE 17 DIFFERENCE BETWEEN THE 1D2D+-1D2D DIFFERENCES IN WATER DEPTH OF BLOKBUI 70MM AND BUI10

4.5 Model performance comparison

In order to evaluate the performance of 1D2D and 1D2D+ against each other, the 1D hydrograph discharge at nodes output, and a series of criteria are used described in the methods section 3.8. Because it is not possible to extract the data from all nodes within a reasonable time, six nodes are chosen as representative for downstream, upstream and total discharges. These are depicted in figure 18: 1) Neksloot and 2) Bachstraat bend are two locations downstream the Bachstraat and area-of interest. 3) Bachstraat halfway, is halfway the Bachstraat. 4) Bachstraat upstream is a node upstream the Bachstraat and area-of-interest. 5) Rijksstraatweg and 6) Euratomplein are two points outside of the area-of-interest but within the research area. The Rijksstraatweg is a point which is known for floods and in that sense comparable to the downstream points 1 and 2. Euratomplein is chosen because the point is placed at a node which corresponds to a big sewer pipe that drains several neighborhoods in Heemskerk to the water treatment plant in the South of Beverwijk and can be seen as representative for total discharges.

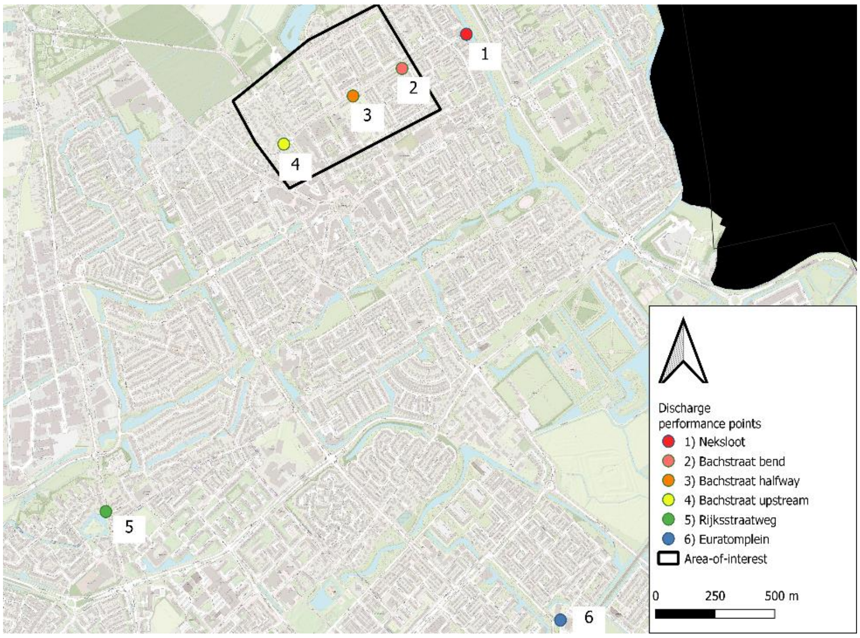

FIGURE 18 DISCHARGE PERFORMANCE POINTS LOCATIONS

First the Model Bias (MB) and Root Mean Square Error (RMSE) (CR1 and CR2) are discussed, after which the Nash-Sutcliffe efficiency (CR3) and Nash-Sutcliffe efficiency for high and low flow (CR4&5) and supporting R^2 (CR6) are discussed. These performance criteria have been used for all three precipitation events (bui06, bui10 and 70mm Blokbui). The results are presented in order of these precipitation events.

Starting with CR1 and CR2 for the 70mm Blokbui, Bui10 and Bui06 event. A map of the differences (for the 70mm event) has already been shown in figure 15A. To quantify these differences, MB and RMSE is used. As was mentioned in the methods chapter, the predictions of 1D2D are considered "observed", while the predictions of 1D2D+ are considered "simulated". The MB measures the relative mean difference between both model stream flows. A lower absolute CR1 value indicates a better fit, and the value 0.0 represents the perfect agreement in flow volume. The RMSE is calculated for the six points. To quantify the difference between the models, it estimates the standard deviation of the error between two datasets and can be interpreted as how far off the model can be expected to be on its next prediction.

Blokbui 70mm	1	2	3	4	5	6
MB CR1 (m^3/s)	-0,61	-1,63	-1,57	-3,89	-4,58	0,01
RMSE CR2 (m^3/s)	0,30	0,04	0,01	0,02	0,20	1,32

Bui10	1	2	3	4	5	6
MB CR1 (m^3/s)	-0,04	-0,05	0,02	0,10	0,01	-0,05
RMSE CR2 (m^3/s)	0,02	0,49	1,35	0,08	0,02	0,00

Bui06	1	2	3	4	5	6
MB CR1 (m^3/s)	-0,40	-0,33	-0,27	-0,20	-0,57	-0,33
RMSE CR2 (m^3/s)	0,11	0,01	0,01	0,00	0,01	0,63

TABLE 4 SHOWING CR1 AND CR2 FOR THE THREE DIFFERENT PRECIPITATION EVENTS.

The Model Biases fairly close to zero for Bui06 and bui10 but irregular for Blokbui 70mm with points one and two close to zero and the rest up to -4,58. The average biases for Bui06 and bui10 are comparable (average between the six points: -0,35 and 0,00 respectively) thus showing hardly any bias. Blokbui 70mm, which has an average bias of -2,04 shows a clear bias towards more flow volume in 1D2D+. The RMSE (CR2) is relatively low for 70mm, Bui10 and Bui06. Only point 6 at bui06 and blokbui70mm shows a significant RMSE to the flow volume of 1,32 and 0,63. Spatially the differences seem to have the trend that there are no big differences between the points and the different precipitation events. Though blokbui70mm has a higher absolute bias between 1D2D+ and 1D2D the more upstream the points are.

Next, CR3 till CR6 are depicted in the graphs below for every different precipitation event, together with the performance criteria threshold values. The performance can be seen as an agreement test between 1D2D and 1D2D+.

NSE indicates how well the plot of 1D2D versus 1D2D+ fits the 1:1 line. Nash-Sutcliffe efficiencies range from -Inf to 1. Essentially, the closer to 1, the more accurate 1D2D+ resembles 1D2D.

1 > NSE > inf = indicates

NSE = 1, corresponds to a perfect match of 1D2D to 1D2D+ output.

NSE = 0, indicates that the 1D2D+ output is as accurate as the mean of the 1D2D output,

-Inf < NSE < 0, indicates that the 1D2D mean is not comparable to 1D2D+.

(Atanaw, 2021)

Performance	R2	NSE
Very good	>0.75	>0.95
Good	0.50	0.85
Fair	0.25	0.70
poor	<0.25	<0.70

BUI06	1	2	3	4	5	6
CR3	0,49	0,46	0,41	0,27	-1,13	-0,35
CR4	0,22	0,21	0,12	0,52	0,89	0,22
CR5	0,23	1,06	1,06	1,02	1,13	0,63
R2	0,73	0,68	0,56	0,39	0,08	0,23

BUI10	1	2	3	4	5	6
CR3	0,37	0,70	0,00	-0,28	0,87	0,72
CR4	0,18	0,33	0,12	0,44	0,10	0,34
CR5	0,17	0,77	0,35	0,99	1,00	1,00
R2	0,40	0,77	0,27	0,03	0,87	0,73

70mm	1	2	3	4	5	6
CR3	-3,67	-31,18	-20,72	-117,43	-13,64	0,05
CR4	0,90	0,65	0,59	0,24	0,38	0,17
CR5	0,87	0,98	0,99	0,99	0,82	0,94
R2	0,05	0,29	0,05	0,35	0,01	0,32

Table 5 showing the performance metrics CR3, CR4, CR5 and R2 for the three precipitation events Bui06, Bui10 and Blokbui 70mm

The Nash-Sutcliffe efficiency (CR3), depicted in table 5 together with CR4, CR5 and R2, shows overall bad agreement between 1D2D and 1D2D+ for Bui06, Bui10 and Blokbui 70mm, with the exception of point 5 and 6 for Bui10 that show fair to good agreement. The higher flow conditions that are associated with Blokbui 70 seem the most out of sync compared to the lower flow conditions of Bui06 and (to a lesser extent) Bui10.

Then for CR4, which is the logarithmic version of the Nash-Sutcliffe, with for $\varepsilon = 0{,}001$ (an arbitrary chosen small value introduced to avoid problems with nil simulated discharges). This agreement test puts emphasis on low flow conditions and shows bad agreement between 1D2D and 1D2D+ for all three precipitation events. This agrees with CR3 which had also poor scores across all points.

The last Nash-Sutcliffe agreement test is CR5 which gives more weight to relative high discharges. Here the scores notably rise, with almost always CR5 producing higher agreement scores then the corresponding CR4 and CR3. With the Blokbui 70mm CR5 having good to very good scores for all points. Bui10 has poor scores in the downstream area (points 1, 2, 3) and good scores upstream and in towards the sewer treatment (points 5&6). And Bui06 showing good to very good agreement except for downstream point 1. The outcome of the values of NSE that are above 1, are to be looked upon with skepticism as normally NSE should not be more then 1. An explanation why the metrics were more than one couldn't be found within the time constraints of this research.

Finally, to support the Nash-Sutcliffe efficiency in showing the agreement between the model types, the R^2 value of the discharges is calculated. R^2 ranges from 0 to 1, and it normally shows the goodness of fit of a model to observations. Here it is used to test the agreement between the two model types. It is important to note that a good R^2 can be achieved if the predictions of the model are very different from the other simulation, as long as they show the same pattern. Namely, R2 is an indicator for correlation, not for accuracy. Correlation is thus, poor for Blokbui 70mm where only locations 2, 4 and 5 show some fair correlation. When looking at Bui10 it's the locations 1, 2, 5 and 6 that show fair, good and very good correlation, the rest is very poor. Bui06 shows just as Bui10, good overall correlation with only points 5 and 6 that show poor correlation. All in all, these results support the hypotheses that high precipitation conditions show the least agreement between 1D2D and 1D2D+.

In order to better understand the differences between the discharges and their corresponding agreement scores some notable score producing discharges are plotted in figure 19. Point 2 represents the downstream and point 4 the upstream Bachstraat area.

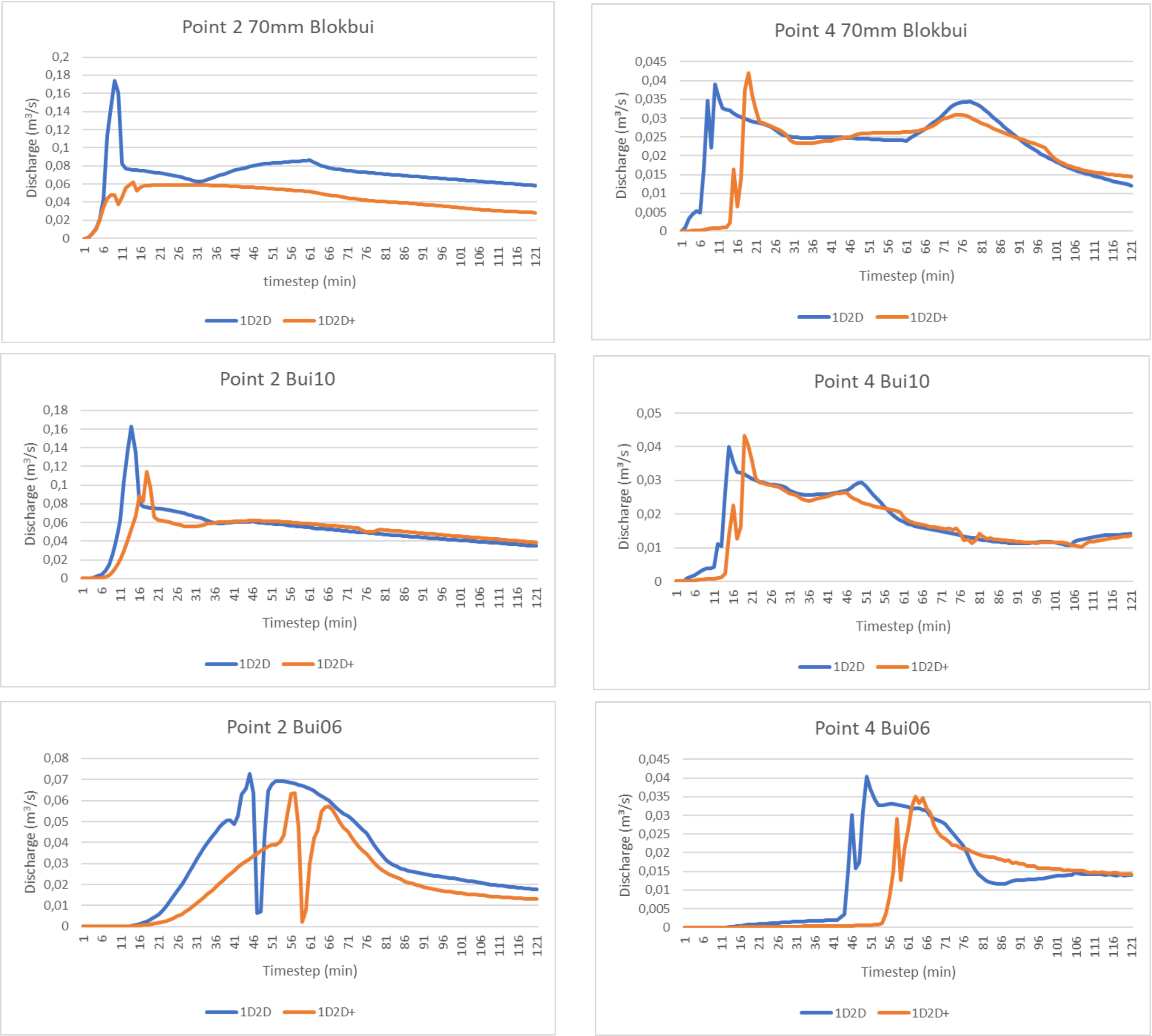

Figure 19 Discharge in sewer system at location 2 and 4 representing down- and upstream Bachstraat area respectively

The graphs from figure 19 show that the more intense precipitation (Blokbui 70mm) has a slighter shift in timing of the peak in the hydrograph compared to Bui10 and Bui06. Also notable is the top of the peak discharge where 1D2D simulates a much higher peak discharge then 1D2D+. In the case of point 2 the peak is completely flattened in 1D2D+. Looking further at Bui06, the peak delay is about 15 minutes while it should be mentioned that the y-axis shows the peak is not comparable to bui10 and blokbui70mm in absolute discharges as Bui06 has much smaller volumes which could affect the results. Generally speaking, these graphs show that 1D2D+ has lower peaks and slower development of the hydrograph compared to 1D2D. Together with the performance metrics, these result show that the more intense the precipitation event in terms of volume, the more 1D2D and 1D2D+ seem to disagree.

Finally, the graphs depicted in figure 20 show point 6 which can be seen as the outlet of the entire sewer catchment of Heemskerk. The most notable difference between Bui06 and Blokbui 70m is the enormous difference in discharge volumes. Where Blokbui 70mm results in peak discharges of almost 1 m^3/s in the peak of the 1D2D+ hydrograph, Bui06 has a smaller peak of 0,6 m^3/s. The shift between 1D2D and 1D2D+ is notable in Bui06 but absent at Blokbui 70mm. The peaks are of the same height at Bui06 but notably different with Blokbui 70mm as the 1D2D simulation only peaked at 0,4 m^3/s. A water balance check was not performed due to time constraints.

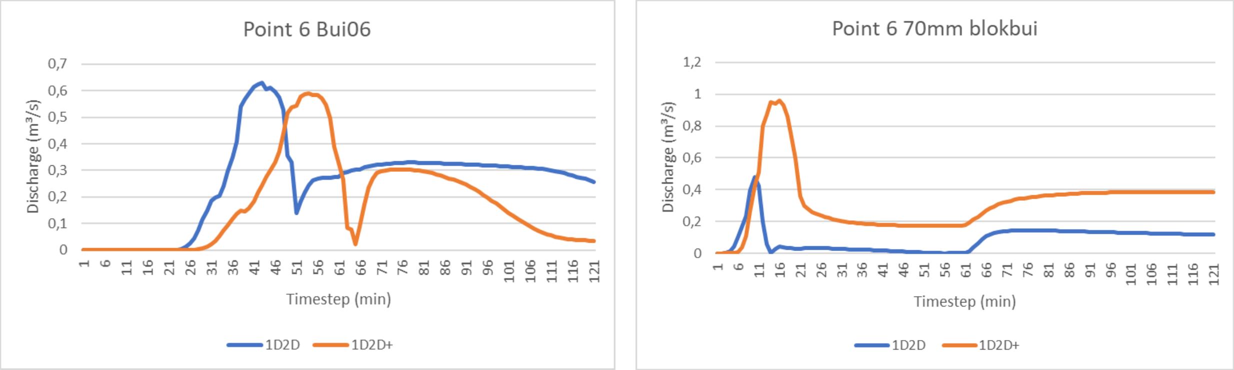

Figure 20 Hydrographs of discharge in point 6 during Bui06 and Blokbui 70mm

5. Discussion

In this chapter on the basis of the sub questions formulated in the introduction the results will be discussed and put in the perspective of previous literature.

(1) What are in theory the advantages and disadvantages of both types of models. What are for example the effects of choices made in these models by parametrization and in which situations would you expect one model to outperform the other in case-study situations in Beverwijk and Heemskerk.

Both types of models (1D2D and 1D2D+) have some comparable features such as resolution (case-study-area vs area-of-interest) and the 1D network. Though other features are notably different because of choices made by modeling that could impact the results. This first chapter in the discussion will review the general implications of some of these features starting with the impact of the different resolutions used in the model runs together with the impact of the DTM. This will be followed by discussion on the assumptions in the input maps and choices made in precipitation events.

Resolution and DTM

Research has been done on high-resolution topographic data as source to investigate the optimal grid resolution for simulating urban floods. The influence of structured and unstructured mesh resolution up to one meter has been investigated (Schubert, et al., 2008); (Fewtrell, et al., 2008), but no literature is found on sub-one-meter scale hydraulic urban models. Though a recent paper by (Wang, et al., 2018) states that in recent years, the availability of Light Detection and Ranging (LiDAR) data has enabled modelling using high resolution terrain data with a horizontal spatial resolution up to 0.25m and a vertical accuracy of 5cm. However, the authors in their model still used a 1m grid.

Schubert, et al. (2008) stated that grid resolution should be given by the average dimension of buildings and roads, with a resolution of 5m indicated as the upper threshold. According to these authors, such a detailed reproduction of urban topography is at least needed to obtain a realistic reproduction of flow dynamics. In this research the 3m resolution chosen for the coarser research area surrounding the area-of-interest seems thus legit. The grid dimensions used in the area-of-interest (0.38m) are, on the other hand, in unknown fine territory.

Though (Hunter, et al., 2008) compared a number of 2D models of varying complexity in a single urban flood scenario and observed that the overall performance of reduced complexity models was comparable to that of more complex models. This seems in accordance with the results of this research where the main trends in the results from the area-of-interest 0.38m grid are comparable to the 3m grid used in the rest of the case-study area. Though finer elements like speedbumps are better modelled in 1D2D+ as they act as dams or flow diverters.

(Betsholtz & Nordlöf, 2017) who did a study in HEC-RAS showed, from a 2D mesh analysis, that model result is very sensitive to mesh alignment along barriers. In rural floodplains with clear barriers, computational cell alignment is more important than computational cell size. With regards to the 1D-2D model, the results showed that the parameters describing the coupling between the 1D and 2D domain have large impact on model results. Though this research was carried out on rural floodplains the results align with (Hunter, et al., 2008) and this research.

However, it should be considered whether such an approach to urban flood modelling, based on the direct use of extremely detailed topographic data, can provide the best results. Computational efficiency and resources become of course a major concern and crucial issue, but several other problems should be considered as well. In fact, the high precision that characterizes models applied on very high-resolution grids may be misleading because the simulations still rely on many, and partly inevitable, approximations (Dottori & Todini, 2012).

First of all, the terrain is supposed to be obstacle free: the effect of vehicles, trees, fences, lampposts, service cabinets and other typical sometimes temporary features of urban landscapes are not directly considered in the DTM, given that it is not possible to know the exact position of each minor fixed and moving obstacle. Secondly, buildings are supposed to be impermeable to water; however, although building walls certainly modify and deflect the flow path, in most cases, the water eventually enters inside buildings and produces levels similar to outside values. In addition, the interaction between subsurface drainage and sewer network and surface flow is difficult to reproduce in detail, being subject to unpredictable local conditions (e.g. obstructed manholes or pipes; (Chen & Chang, 2000); (Smith, 2006); (Dottori & Todini, 2012) . This was also a problem in this research. As (among other structures mentioned) street level inflows were not even part of the 1D domain and sewer-surface connections were made at the locations of manholes.

Finally, it should be considered that high-resolution data are not always available for urban areas, or their use may not be convenient. For example, for a flood event involving both rural and urban areas, the problem of which level of resolution is more suitable emerges. Unstructured computation grids with varying spatial resolution may be used, but this requires a further elaboration and preparation of data, which may not be convenient especially for wide areas (Dottori & Todini, 2012). In this research, the rural component, thus interaction with ditches, channels and other open water were not considered. Also, the input maps had to be customized for the area-of-interest and clipped to the right extents for the case study area because of the otherwise too large volumes of data. Convenience to a certain degree should thus certainly be considered when refining grids and input maps.

For all these reasons, literature mentions alternative approaches in modelling the topography of urban areas. For example, another possibility to represent the additional resistance given by buildings and minor obstacles on flow is to increase the roughness parameter. (Neelz & Pender, 2007) and (Yu & Lane, 2006) used this method in combination with simplified models; they observed that roughness upscaling allowed the representation of the overall effect of buildings, although it could not compensate for the loss of topographic detail when grid coarsening was applied. Another paper by (Bruwler, et al., 2020) however, showed by modelling 2000 different building layouts in a city, that it doesn't matter which approach you use as it is the layout of the buildings itself that magnify the effects of extreme rainfall. Also, the building layout has a higher impact on water depths and flow variables.

All in all, the DTM chosen in combination with two different resolutions (a not-too-coarse 3m with a refinement of 0.38m) seems to be the best compromise between technical computation power available and maximum refinement advantages. Further refining would be useless without knowing the exact dynamic configuration of the finer (sub-0.5m structures) urban environment.

Hydrologic variability

Roughness, infiltration capacity, initial water level

As opposed to the watershed characteristics mentioned above, surface roughness is often used to determine the time of concentration and largely affects the analysis results of design discharge (Huang & Lee, 2009). In this research a Roughness map with Manning values was used. These values are converted to Chèzy-parameter-values by D-HYDRO to speed up calculations.

Roughness impacts the hydrographs, especially in sloping terrain, speeding or slowing the timing of the peaks in the hydrographs. The corresponding input map is not only representing roughness of large-scale terrain elements as asphalt roads and grass parks but also representing topographic features that are sometimes smoothed out by grid coarsening (Yu & Lane, 2006). Next to that, by affecting the time for which surface runoff remains on the land surface, the roughness coefficient also influences the volume of water that can infiltrate into the soil. Further, erosion and surface depression storage of water are also influenced by roughness considerably (Huang & Lee, 2009). Though, detailed measurements of surface roughness are not always practically available (Huang & Lee, 2009), in this research a roughness map based on surface covering from (Besseling, 2020) and (Rijn van, 2020) was used. This way, the spatially heterogenous distribution of roughness characteristics for urban environments were modelled. The results showed that a long altitude gradients roughness could have a major impact especially as timing of the peaks showed the biggest disagreement between 1D2D and 1D2D+. When dealing with surface roughness parameterization these considerations should be taken into account possibly achieving better 1D2D - 1D2D+ fits.

The two other main input maps used are infiltration capacity, which is also related to roughness in the sense that the longer overland flow takes to cross a certain permeable area the more will infiltrate out of the model (boundary condition, sink). Initial water level acts as a sink as initial water levels are kept constant and act as a sink boundary condition as well because of the exclusion of surface water in the model. This is affecting 1D2D and 1D2D+ equally though 1D2D+ is expected to have more runoff in to surface waters thereby possibly underestimating water depth compared to 1D2D. Infiltration capacity was not a big problem in modelling 1D2D+ as a spatial map was delivered by the municipality. For 1D2D a parameterization had to be made. Assumptions were made on paved surfaces based on the input map. Though it is expected for the future that paved surfaces could lead to more extreme impacts from flood hazard as argued by (Kaspersen, et al., 2017) who found an increase in flood exposure corresponding to an observed absolute growth in impervious surfaces of 7–12 % during the past 30 years of urban development.

As for the research question it can thus be stated that roughness impacts both 1D2D and 1D2D+ simulations from the moment overland flow occurs in the 2D domain. Differences in roughness and roughness parameterization could be of significance as in 1D2D+ roughness of roofs also plays a role. Differing results between 1D2D and 1D2D+ are however not expected from initial water level and infiltration capacity. When a rural or surface water component would be added in future research these parameters however should be reviewed for possible impact.

(2) In which case-study situations does the D-HYDRO 1D2D or 1D2D+ model perform best? What is the added value of the D-HYDRO 1D2D+ vs a 1D2D-model in a sloping vs non-sloping situation and during prolonged- and high peak intensity precipitation events respectively. Zooming in on flood hazard modelling.

Sloping vs. non sloping

The results show that 1D2D mostly underestimates 1D2D+ especially at the foot of the Bachstraat 'hill'. This result is in accordance with expectations as water that would otherwise (1D2D) enter the sewage system immediately, where the first precipitation is buffered. Compared to 1D2D+ where all precipitation directly falls on the surface from where it will start flowing towards the lowest point. If during the journey from high grounds towards low grounds the water doesn't encounter a 1D2D link, being a street inlet or manhole, the runoff remains on the street and accumulates in low lying areas. Other research seems to spot the same trend for 2D modelling only. For example, (Dijk, et al., 2014) showed that, although modelling software is tending to evolve towards coupled one-dimensional (1D)–two-dimensional (2D) simulation models, surface flow models, using an accurate digital elevation model, prove to be an easy and fast alternative to identify vulnerable locations in hilly and flat areas. In areas at the transition between hilly and flat, however, coupled 1D–2D simulation models give better results since catchments of major and minor systems can differ strongly in these areas. During the decision-making process, surface flow models can provide a first insight that can be complemented with complex simulation models for critical locations. Which is in accordance with the results from this research. Whereby both 1D2D and 1D2D+ show the same major trends, whereby 1D2D calculates a lot faster only underestimating the results in terms of water-on-street up to 6cm or 20% for the 1/100y (Blokbui 70mm) scenario.

Precipitation type

For this research three precipitation events were chosen based on their distinct deviant characteristics from each other. Bui06, Bui10 and Blokbui 70mm. The biggest differences between the precipitation events and water-on-street were simulated downstream. Here 1D2D underestimates water-on-street compared to 1D2D+ more than 1D2D+ underestimates water-on-street upstream compared to 1D2D. This is in accordance with expectations as all water from multiple directions flows towards one lowest point which is downstream the Bachstraat in the area-of-interest. However, the underestimation by 1D2D could have been less if the 1D model was fitted with street inlets on the sides of the street. In this research, in 1D2D+ from the beginning of the simulation all water flows directly to the lowest point without encountering many street inlets as only on the manholes 1D2D connections are made. Thus, the extremer the precipitation, in terms of volume, the larger the differences between 1D2D and 1D2D+ become. In terms of peak precipitation 1D2D+ seems to reach similar heights in terms of water-on-street and discharges as 1D2D.

The effect of missing street inlets and consequent lack of buffering in the 1D sewer system becomes especially apparent in the simulations with bui06 in 1D2D+ configuration. As in 1D2D no water makes it to the street at all as water falls directly into the sewer system buffering all precipitation. In 1D2D+ there is hardly any buffering when no street inlets are encountered on the sides of the street making accumulation downstream possible. The difference between 1D2D and 1D2D+ during bui06 is thus effectively the same as 1D2D+ only. Because Bui06 is small enough to be buffered completely by the sewer system.

All in all, prolonged high intensity, or extreme precipitation events are better modelled in 1D2D+. Lower intensity precipitation can best me modelled in 1D2D or only 1D. A threshold for when precipitation becomes high from low intensity is not found though as a rule of thumb low precipitation is when it is expected that no water on street will accumulate and all water is buffered by the sewer system.

(3) With climate change in mind, what type of precipitation is there to be expected and which model can handle this transition the best for which situation.

With climate change in mind, it is expected that more extreme precipitation events will occur more often. The 70mm Blokbui precipitation event is chosen as it is modelled by the KNMI to be the 100-year return period precipitation event by 2050. As was mentioned in the previous paragraph, the differences between 1D2D and 1D2D+ are becoming bigger with heavier precipitation events. The agreement in the model performance became worse with the more extreme precipitation events (NSE-values) comparing bui10 and the 70mm Blokbui. 1D2D is structurally underestimating water-on-street compared to 1D2D+ especially in downstream areas. A real-world validation would be a good addition to this research but beyond the scope of the timeframe and possibilities of this research. All in all, it is expected that 1D2D+ will perform better when testing with even heavier precipitation and heavy precipitation in general. For all situations sloping/non-sloping, downstream, upstream, in a coarse or fine grid and in dense urban area or suburban residential areas.

(Kaspersen, et al., 2017) supports these findings as they made, in contrast to the hazard-analysis in this research, a pluvial flood exposure analysis for four European cities under both the RCP 4.5 and RCP 8.5 scenarios. They found that all four cities will see increases in pluvial flood risk however the timing of impacts varies considerably. For example, for Odense, the impact of urban development is comparable to that of climate change under an RCP 8.5 scenario (2081–2100), while for Vienna and Strasbourg it is comparable to the impacts of an RCP 4.5 scenario.

The variation between these cities is caused by differences in soil infiltration properties, historical trends in urban development and the projected regional impacts of climate change on extreme precipitation. The same variation is expected in the Netherlands as old city centers or neighborhoods are often more prone to pluvial extremes then newer neighborhoods. On a small scale both the 1D2D and 1D2D+ already showed that the older part of Heemskerk coincides with higher water depths.

6. Conclusions & recommendation

This study has highlighted some of the most important differences between 1D2D and 1D2D+ model construction, results and concerns. Important design considerations as the DTM, resolution, boundary conditions and input maps have been highlighted. In the following section, the conclusions are presented.

It is now feasible, on the contrary to (Rijn van, 2020) and (Besseling, 2020), to construct and perform pluvial flood hazard models in 1D2D and 1D2D+ at the scale of 0.5m grid and entire cities. The mesh had a size of almost 4.5 million cells and runtimes were 30- to 75 hours for 1D2D and 1D2D+ respectively, for 120 timesteps.

Within the case study area, flood-hazard-prone-areas have been identified mainly in the downstream and low-lying areas with inundation depths up to 30cm on street with Bui10 and Blokbui 70mm which have occurrence times of 1/10 and 1/100y respectively. Within the case study area an 8x refinement to the grid called the area-of-interest has been added at the Bachstraat area. The low-lying Bachstraat area is known for its sensitivity to pluvial floodings while the upstream, 1,5m higher, Bachstraat area remains relatively dry. The possible cause, the sloping characteristics of the Bachstraat, allowed for analysis on the effects of these elevation differences on 1D2D and 1D2D+ simulations. The refinement therein allowed for a more detail look at local obstructions to flow and local elevated flood depths due to for example speed bumps and sidewalks. These structures however only added value in terms of these local <3m scale structures. As major trends between the research area and area of interest showed to be comparable in 1D2D and 1D2D+. The timing and water depths however did notably differ between 1D2D and 1D2D+. In sloping (not flat) areas for example, taking the Bachstraat area as case, values of water depth downstream are higher for 1D2D+ compared to 1D2D (+8cm). When comparing absolute water depths where downstream the Bachstraat about 30cm and upstream about 10 to 15cm water depth is modelled, 6cm is a difference of 20%. Which in the scale of neighborhoods can mean the difference between a flooded cellar or not.

The right choice of model depends on the detail of input data, area characteristics, desired level of complexity in the output data and project time as 1D2D and 1D2D+ have a fundamentally different approach as input to the 2D overland flow. Based on this case study and literature review, a rough handle for choosing which model is suitable for which situation has been presented and discussed. When overland flow is to be expected and an area has the slightest sloping characteristics (0.1 degrees) 1D2D+ will probably perform better in terms of water on street compared to 1D2D as performance metrics show more disagreement with higher flow conditions (NSE went from very good agreements to fair or poor).

With climate change in mind, it is recommended to model in 1D2D+ as this setup performs better when confronted with extreme precipitation events. Though computation times and setup times could be much lengthier then 1D2D. It is also important to keep in mind the lack of street inlets in this model study. The addition of these 1D structures will probably greatly improve performance compared to reality. Lastly, better understanding of parameterizations in the 1D2D model could solve agreement issues with 1D2D+ (for example timing of hydrograph peaks are impacted by roughness).

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Appendix A – Theoretical background

A.1 1D unsteady flow

In sewer modelling applications it is assumed that the flow is 1D. The flow is then calculated using the 1D formulation of the St Venants equations, which will be presented below.

A.1.1 1D Continuity equation

The continuity equation describes the preservation of mass in a given control volume. It states that the net mass flux equals the change in storage. The 1D form of the St. Venant continuity equation reads:

$$(2.1) \qquad \frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_{lat}$$

Where:

A	Total area (sum of flow area and storage area (m^2))
Q	Discharge (m^3/s)
q_{lat}	Lateral discharge per unit length (m^2/s). Positive values refer to inflow, negative to outflow.

A.1.2 1D Momentum equation

The momentum equation is based on Newtons second law of motion, stating that the sum of the forces acting on an element equals the rate of change of momentum. The formulation of the momentum equation will be different depending on what forces that are being considered. The 1D momentum equation taking; inertia (first term), convection (second term), water level gradient (third term), bed friction (fourth term), wind force (fifth term) and extra resistance (sixth term) into account reads:

$$(2.2) \qquad \frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A_F}\right) + gA_F\frac{\partial \zeta}{\partial x} + \frac{gQ|Q|}{C^2RA_F} - w_f\frac{\tau_{wind}}{\rho_w} + gA_F\frac{\xi Q|Q|}{L_x} = 0$$

Where:

A_F	Flow area (m^2)
C	Chézy value ($m^{1/2}/s$)
g	acceleration due to gravity (m/s^2)
ζ	Water level (m)
L_x	Length of branchsegment, accommodating an Extra Resistance Node(m)
Q	Discharge
R	Hydraulic radius (m)
t	Time (s)
w_f	Water surface width (m)
x	Distance along channel axis (m)
ρ_w	Density of fresh water (kg/m^3)
τ_{wind}	Wind shear stress

A.2 2D unsteady flow

A.2.1 2D (Depth averaged) continuity equation

The 2D form of the continuity equation states, just as the 1D form, that the net mass flux into the control volume equals the change in storage in the control volume. The difference is that the mass fluxes are now calculated in 2 dimensions.

D-Flow FM solves the depth-averaged continuity equation, derived by integration of the continuity equation, for incompressible fluids ($\nabla \bullet u = 0$) over the total depth, taking into account the kinematic boundary conditions at water surface and bed level, and is given by:

$$(2.3) \qquad \frac{\partial h}{\partial t} + \frac{\partial Uh}{\partial x} + \frac{\partial Vh}{\partial x} = Q$$

Where:

h	Water surface elevation (m)
t	time (s)
U and V	Depth averaged velocities in the x- and y-direction
Q	Source term, representing contributions per unit area due to discharge or withdrawal of water, precipitation and evaporation:

$$(2.4) \qquad Q = \int_0^h (q_{in} - q_{out})\, dz + P - E$$

Where:

Q_{in} and q_{out}	Local sources and sinks of water per unit of volume (1/s)
P	Precipitation
E	Evaporation

The D-flow FM user manual (Deltares, 2021) remarks that the intake of, for example, a pumping station is a withdrawal of water and should be modelled as a sink. At the free surface there may be a source due to precipitation or a sink due to evaporation.

A.2.2 2D momentum equation

As in the 1D case, the momentum balance is based on the principle that the sum of forces acting on an element equals the rate of change of momentum. Considering forcing from gravity, eddy viscosity (momentum exchange), friction and the Coriolis effect, the 2D momentum balance equations can be written as follows.

In the x-direction:

$$(2.5) \qquad \frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} - fv = -\frac{1}{\rho_0}\frac{\partial P}{\partial x} + F_x + \frac{\partial}{\partial z}\left(\nu_V \frac{\partial u}{\partial z}\right) + M_x$$

In the y-direction:

$$(2.6) \qquad \frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} - fu = -\frac{1}{\rho_0}\frac{\partial P}{\partial y} + F_y + \frac{\partial}{\partial z}\left(\nu_V \frac{\partial v}{\partial z}\right) + M_y$$

Where:

ν_V	vertical eddy viscosity coefficient
P	Baroclinic pressure
F	Reynolds stress
M	external sources or sinks

The first term in the momentum equations represents the local acceleration (∂u/∂t in equation 2.5, corresponding term in 2.6), the second term (u ∂u/∂x + v ∂u/∂y in 2.5, corresponding term in 2.6) is the convective acceleration, the following terms describe the forcing from gravity, eddy viscosity, bed friction, and Coriolis force. Where ν_V is the vertical eddy viscosity coefficient. Density variations are neglected, except in the baroclinic pressure terms. ∂P/∂x and ∂P/∂y represent the pressure gradients. The forces Fx and Fy in the momentum equations represent the unbalance of horizontal Reynolds stresses. Mx and My represent the contributions due to external sources or sinks of momentum (external forces by hydraulic structures, discharge or withdrawal of water, wave stresses, etc.)

In D-Flow FM multiple equations are supported to compute the friction coefficient cf (Chezy, Manning, White-Colebrook, Strickler and de Bos&Bijkerk). Since the equations can both be applied in 1D and 2D, D-hydro uses the 1D formulation based on hydraulic radius R which is typically equivalent to the water depth H in 2D.
In this research, White-Colebrook is used for the 1D (Cf = 0.003) parts of the model as well as in the 2D calculations (roughness model map).
As formulated by (Colebrook & White, Experiments with Fluid Friction in Roughened Pipes, 1937) and (Colebrook, 1939), the friction coefficient cf can be expressed as following (in the x-direction):

$$Cf_{2D} = 18\log_{10}\frac{12R}{k_n} \tag{2.7}$$

where kn is is the Nikuradse roughness length (m) and R the hydraulic radius.

A.3 simplifications

In order to reduce the computation time and reduce numerical instability, the full Shallow Water Equations are often simplified by neglecting different terms in the momentum equation. These simplifications are most often applied in 2D models. These simplifications are only valid for certain flow conditions, meaning that the understanding of their respective use and limitations is necessary if they are to be employed (Babister, Retallick, & Ball, 2009). While several different simplifications exist, this report will only present the main simplification/approximation used in D-Hydro, namely the diffusive wave approximation. In D-Hydro, this approximation can be used instead of the 2D full momentum equations.

A.3.1 Diffusive wave approximation

The diffusive wave approximation of the Shallow Water Equations (SWE) is used to model overland flows such as floods, dam breaks, and flows through vegetated areas. The SWE are obtained from the full Navier-Stokes equations for incompressible free surface flow by introducing the following simplifying assumption: the vertical momentum scales are small relative to those of the horizontal momentum, that is, due to depth restrictions the velocity structures in the horizontal direction are much larger than the ones in the vertical one. This assumption reduces the vertical momentum equation to a hydrostatic pressure relation, which is integrated in the vertical direction and results in a two dimensional system of equations known as the SWE (Collier, Hany, Dalcin, & Calo, 2011).

In the diffusive wave approximation of the momentum equation the acceleration terms as well as the eddy viscosity and Coriolis terms are neglected, and the momentum balance is written as a balance between gravitation and bottom friction forces. The momentum equation can now be written as(in x- and y-direction):

$$\frac{\partial U}{\partial t} + \cdots + \frac{gU\sqrt{U^2+V^2}}{C_{2D}^2 h} + \cdots = \cdots + F_x \tag{2.8}$$

$$\frac{\partial V}{\partial t} + \cdots + \frac{gV\sqrt{U^2+V^2}}{C_{2D}^2 h} + \cdots = \cdots + F_y \tag{2.9}$$

Or even more simplified:

$$g\nabla H = Cf_{2D}V \tag{2.10}$$

Where V is the flow velocity in vector form V=(u,v)

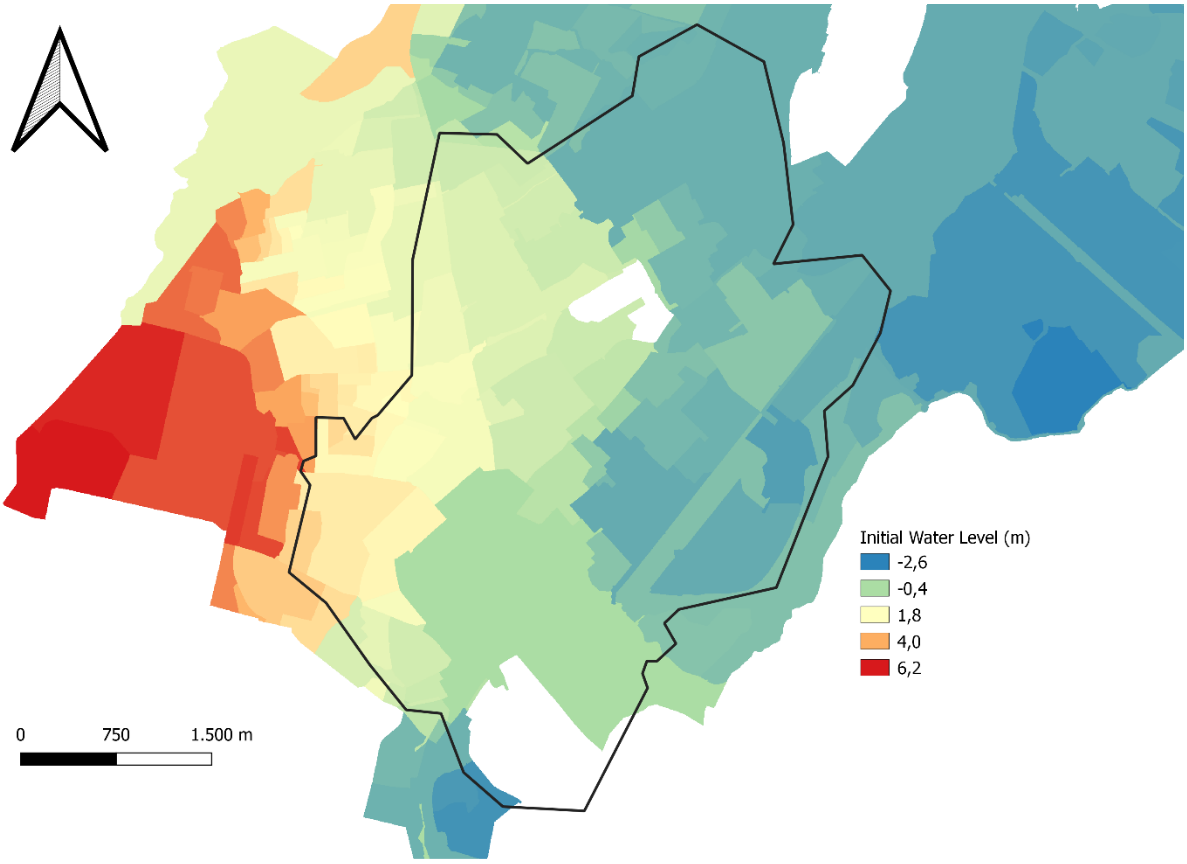
Using the diffusive wave approximation of the shallow water equations the governing equations for 2-dimensional flow (2.3, 2.5 and 2.6) and roughness White-Colebrook (2.7) are thus simplified to expression 2.10. The diffusive wave approximation leads to shorter computation time and may reduce model instability. It may be used to describe varying flow in moderate to steep reaches. However, flow separation, eddies as well as momentum transfer cannot be modeled (Babister, Retallick, & Ball, 2009).

A.3.2 Solving technique

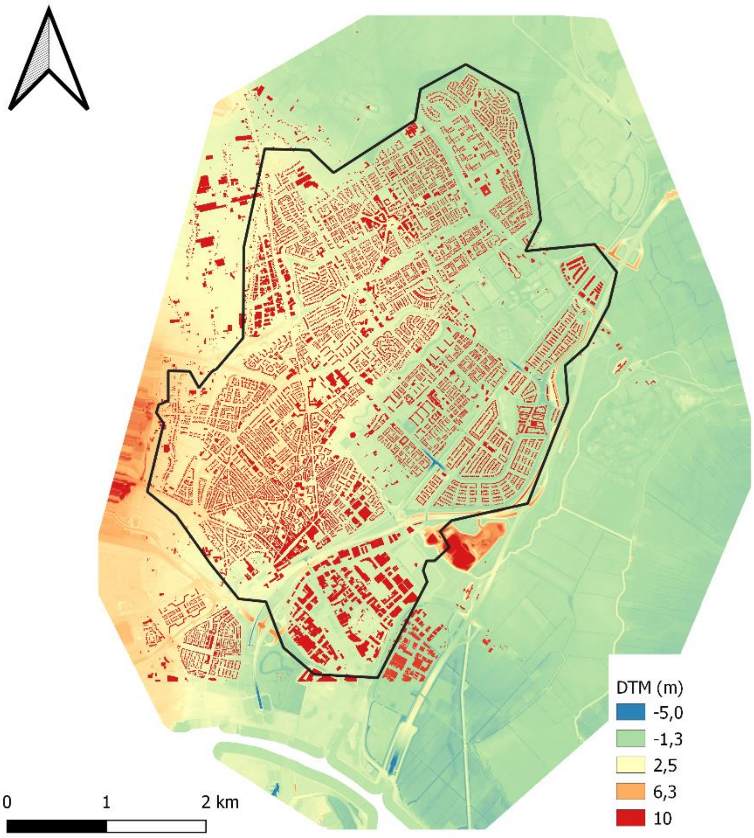
The Shallow Water Equations make up a set of partial differential equations that cannot be integrated analytically. In order to obtain the values of the variables the equations need to integrated numerically. The water surface elevation and the flow velocity varies both in space and in time. For each model time step, the computation engine must determine the value of these variables throughout the model domain. This is done by discretising the equations in space and in time, and solving system of equations that arise for one time step at a time. Different numerical methods varies in the way that the governing equations are discretized in space and time, and how the system of equations that arise is solved. A numerical solution scheme can be either explicit, meaning that the values of the variables at time step n+1 step are calculated directly from the values provided at time step n, or implicit, meaning that the program iterates to obtain the solution for the next time step. Many hydraulic models are based on finite difference, finite element or finite volume methods (Chaudhry, 2008).

D-Hydro implements a finite volume solver on a staggered grid. The continuity equation is solved implicitly for all points in a single combined system. Time integration is done explicitly for part of the advection term, and the resulting dynamic time-step limitation is automatically set based on the Courant criterium. The possible performance penalty that may result from this approach can often be remedied by refining and coarsening the computational grid at the right locations (Deltares, 2021).

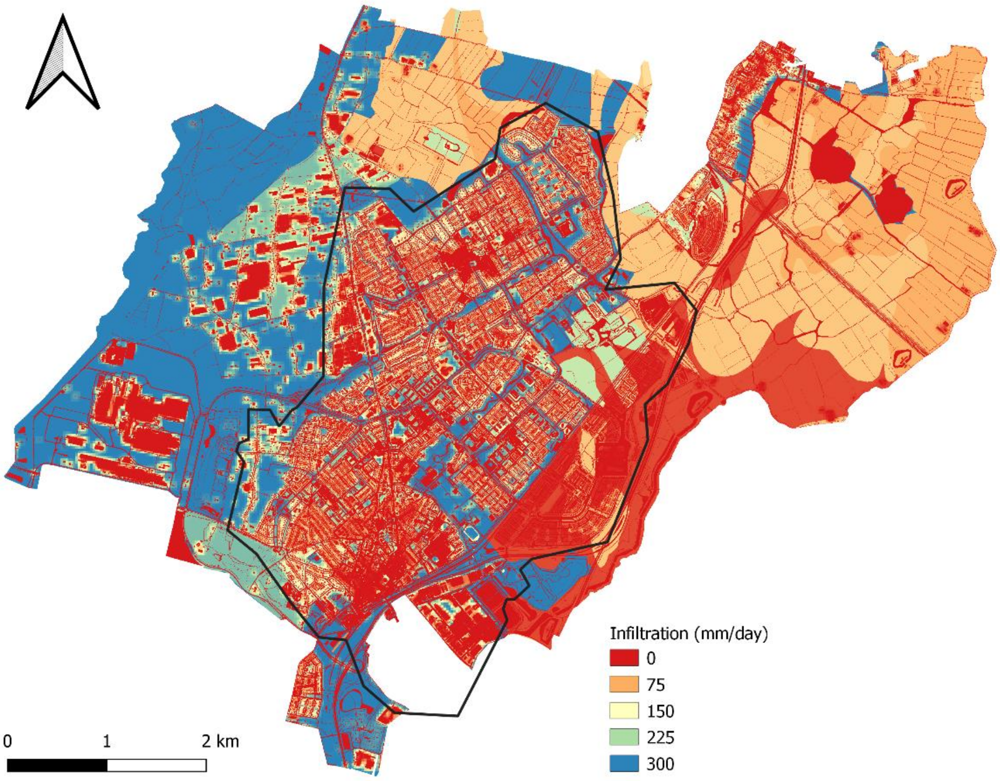
Appendix B – Initial water level map



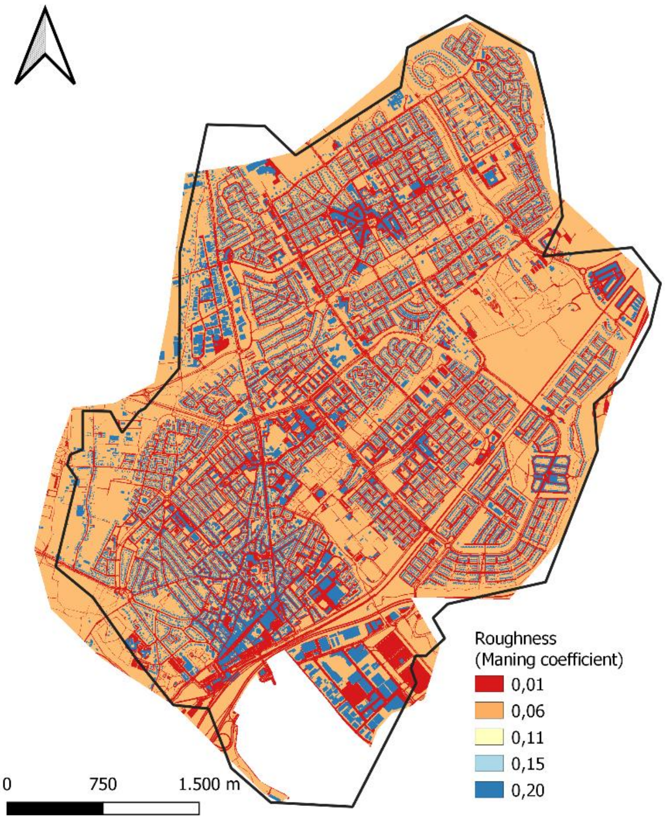
Appendix C – Digital Terrain Model (DTM)



Appendix D – Infiltration map



Appendix E.1 – Manning roughness map



Appendix E.2 – BGT surface to Manning

Surface to Manning translation from (Besseling, 2020).

Surface type	**Manning roughness coefficient (s/m$^{1/3}$)**
Closed pavement	0.011
Open pavement	0.013
Unpaved	0.2
Swamp	0.5
Reed beds	0.5
Deciduous forest	0.5
Mixed forest	0.5
Arboriculture	0.5
Agricultural fields	0.1
Grassland	0.1
Urban green spaces	0.1