Validity assessment of D-Hydro Urban

Comparing D-Hydro with Infoworks ICM in a Beverwijk sewer modelling study


Image: Deltares, 2019

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PREFACE

This is the final report on my bachelor thesis *Validity assessment of D-Hydro Urban*, which I carried out at Wareco from April 6th 2020 to July 21st 2020. Working at the company's office proved impossible for most of this period due to COVID-19. As a result, the main part of the project was carried out from home. Nevertheless, I feel like I experienced what it is like to work for a company, and was warmly welcomed at Wareco, whether it was the few times I worked at the office, or the many times I contacted colleagues online. Therefore, I would like to spend a paragraph expressing my gratitude to everyone at Wareco and otherwise who helped me achieve the completion of this project.

My supervisors Johan de Waard from Wareco and Joost Kranenborg from the University of Twente have been of invaluable help, teaching me the workflows of a modelling study and ensuring its scientific justification. I would like to thank them both for their effort and feedback, as writing this report would have been impossible without them. Furthermore, a special thanks to the other members of the D-Hydro powerunit, Maureen van Rijn and Daniëlle Coster, for their tireless efforts to overcome the difficulties that arose due to working with new software. Additionally, I want to thank Guy Henckens from Wareco for the many evening hours spent on the Infoworks model, without which no comparison was possible. Moreover, I am grateful for the support from Deltares, specifically Didrik Meijer and Rinske Hutten, which helped locating and solving errors that I encountered. Lastly, I want to thank my family and friends for listening to my ramblings and giving support when I needed it.

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ABSTRACT

The Dutch institute for water research Deltares is developing a new software package, D-Hydro, to replace their older water modelling software. D-Hydro will face the widely used Infoworks ICM as its main competitor on the market. The new software gained the interest of Wareco, an engineering firm specializing in the urban water system and providing service for the design and evaluation of sewer systems, including waste water, surface water runoff and groundwater control.

This modelling study is aimed at generating knowledge on the performance of D-Hydro in comparison to Infoworks ICM, both for the validation effort of D-Hydro by Deltares, and for gaining insight in the potential and applicability of the software for Wareco. The case study for this research is the municipality of Beverwijk, the Netherlands. The municipality is located on sloping terrain, making it an interesting place to see how the model behaves in cases where flow across the surface level is relevant.

In the research project, a model of the urban water system of Beverwijk was thus made in both Infoworks and D-Hydro. The two main components of the models were the sewer system and the surface level. The sewer system model contains manholes that allow water to enter the sewer system and leave the sewer system in case of sewer system overload; piping for transporting the water to the wastewater treatment plant; pumps to move the water into the treatment plant and out of the model; and overflows to spill the water into the surface water system. However, an actual surface water system model was not included due to delayed data and time restrictions. Therefore, the water is deleted once over an overflow. Of the sewer system, only parts that carry rainfall are considered.

The surface level model is modelled on a 3x3 meter grid for D-Hydro, and an unstructured mesh of polygons of about 8.75-9.25 m2 each for Infoworks. The cells of the surface level are given a height that was obtained from a DSM map of the Netherlands, as well as a set of values that reflect properties of their type of surface. These include roughness and infiltration, which are important for the calculation of water flow across the surface. The surface level model and the sewer system model are linked at the manholes. Water can thus enter the sewer system if it lands on the grid cell of a manhole, or it can leave the sewer system and begin flowing on the surface from that same grid cell.

Two rainfall events were used to conduct tests in this modelling study. They were retrieved from the Dutch guidelines for sewer system testing, and are also listed in the ambitions of the municipality of Beverwijk. The first is known in the Netherlands as bui09, in which 29.4 mm falls in an hour, with a peak at the beginning of the event. The second is a stress test for climate change: a constant intensity rainfall event of 60 mm in an hour.

The results of both modelled rainfall events indicated that D-Hydro predicts a smaller water depth of street flooding, and less water in the 1D sewer system than Infoworks. This seemed impossible, unless D-Hydro had processed less water than Infoworks. Eventually, evaluation of the results of the model runs led to the conclusion that D-Hydro contains a bug that caused it to lower the amount of precipitation on roofing, while a modelling error in Infoworks caused a doubling of this rainfall . A workaround for the bug was set up and new model runs were conducted, but not enough time was left to thoroughly investigate the improved results. Therefore, this research cannot definitively conclude on where differences between the models originate, and what causes them. However, it can conclude that the workflow of D-Hydro, being in beta-testing, allowed for most elements of the water system to be successfully implemented, although doing so was more challenging than in Infoworks. Still, the research has been a useful experience for both Wareco and Deltares, the former gaining insight in the workflow of D-Hydro and the latter obtaining a lot of information on the performance and capabilities of their software.

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1 INTRODUCTION

Cities house over half of the world's population, and are therefore at the forefront of the global challenge of climate change (Rosenzweig et al., 2011). They have to adapt to more extreme weather: severe storms and extreme rainfall, and long droughts and scorching heat waves. At the same time, more people are moving into urban environments, leading to an even greater need of sustainable city development (Rosenzweig et al., 2011).

As a result of climate change, extreme rainfall events in which a lot of precipitation falls in a short period of time are becoming more frequent (Rioned, 2017). Urban drainage systems might not be able to handle this extreme load. The subsequent flooding can cause nuisance, damage and even casualties. To make matters worse, many cities around the world have combined sewer and storm-water drainage systems, resulting in wastewater spilling from the system into the streets and contributing to health and environmental dangers (Rosenzweig et al., 2011).

As urban water systems are expected to have to handle these extreme cases more often, engineers and managers face many issues and difficulties in creating and upholding a quality water system. In response, knowledge institutes like Deltares develop modelling software to offer an integral approach at tackling these problems. Such modelling software was often separated into different packages, for example (Deltares, 2019):

- SOBEK-Rural/Urban/River, for modelling integrated water systems for water management, design, planning and policy making
- SOBEK-RE, for simulating water quality and quantity in rivers and estuaries
- Duflow, for simulating one-dimensional unsteady flow in open-channel systems
- Simona (Waqua, Triwaq), a hydrodynamic knowledge system for Rijkswaterstaat containing a variety of mathematical simulation models.
- Delft3D 4, an integrated modelling suite for 2D and 3D flow, morphology, and waves amongst others.

As this list illustrates, the five software packages are for different purposes and some are aimed at specific users. To make the structure of their model line-up more coherent, Deltares intends to replace these five with an overarching simulation package: D-Hydro Suite or Delft3D Flexible Mesh Suite. The first is the name for the Dutch market, while the latter is used for international clients. In this research, the name D-Hydro will be used to refer to the package. It aims to provide an integral approach to coast, river, rural and urban water system management (Deltares, 2019).

The engineering firm Wareco, where this research assignment will be conducted, has been using SOBEK and Infoworks ICM to model sewer systems. They operate in the urban water context, particularly in that of climate adaptation, ground water and foundations. The urban water division within the company, *Stedelijk Water,* is tasked with providing service for the design and evaluation of sewer systems, including waste water, surface water runoff and groundwater control. Modelling sewer systems and their interaction with the surface level plays a large role in the workflow of Wareco. This is what this research study focuses on.

1.1 PROBLEM DEFINITION

As of the start of this research project, nearly all of D-Hydro's code has been implemented. However, about half of it has not been completely validated by test models yet. Deltares is now interested in the performance of their model compared to Infoworks ICM. Infoworks ICM is already available on the market, and it is widely using by engineering consultancies (Ball, 2014).

As a part of their verification and validation effort, Deltares frequently organises workshops in which municipalities, water boards and engineering firms come together to work with D-Hydro. The goal of these workshops is to familiarize these users with the new software, to discover bugs and to obtain feedback on the software. Wareco is such a company already working and testing with the beta version of D-Hydro. As they are currently using the SOBEK 2 package of Deltares along with Infoworks, they want to know if upgrading to the complete package of D-Hydro leads to a decreased work load and to more accurate predictions for their customers. Therefore, both Deltares and Wareco seek a validation assessment of D-Hydro in a project environment.

Together with the municipalities of Heemskerk and Beverwijk, a pilot project has been set up to use D-Hydro in such an environment. A master student at Wareco is doing the project for Heemskerk, so the focus of this research assignment will be on Beverwijk. Beverwijk is working together with the local water authority to obtain insight in the functioning of its urban water system during extreme rainfall scenarios, resulting in the need for an integrated model of the sewer system and the surface level rainfall runoff. Additionally, Beverwijk is located in a sloping area, which distinguishes it from other areas in a number of key ways (Henckens, 2019). Water flow across the ground can be significant, leading to less water being picked up by the manholes of the sewer system. Also, water can accumulate in the lower areas, so nuisance can occur after the rainfall itself has subsided. This makes Beverwijk an interesting case study for the validation of D-Hydro. All in all, there is a need for an integrated modelling and validation assignment with D-Hydro in the area of Beverwijk.

1.2 RESEARCH QUESTIONS

The objective of this research is to evaluate the workflow and performance of the D-Hydro modelling software and to compare its results to those of a similar Infoworks ICM model, using the municipality of Beverwijk as a case study. The main question is therefore formulated as:

> *How do D-Hydro's workflow and results of a sewer system modelling study in the context of Beverwijk compare to the workflow and results of Infoworks ICM?*

To tackle the main question, it has been divided into sub-questions that follow the steps of the research. The first is to develop an understanding of the sewer system that needs to be modelled, and to learn how to model these. This requires knowledge of the sewer system and the way this is usually modelled. This leads to the first research question:

1. *What are the sewer system components and urban water system parts used for modelling sewer systems and how do they relate to each other?*

The second question addresses the methods used to incorporate the system knowledge gathered in question 1 into the model of Beverwijk. The main concern in this model building process is the level of detail that can be achieved within the 10 week time period. For example, a larger study area and more refined grid lead to longer computation times, while a scarcity of data results in less accuracy.

An integral part of the model setup process are differences that occur between the two models due to modelling choices or techniques. That is why sub-question A is formed. Another part of the model setup is a clear image of how the models and their outputs should be used. Therefore, sub-question B is dedicated to discussing in which circumstances and using which parameters the models can be fairly compared. The second research question then amounts to:

2. *How can the system characteristics of Beverwijk be modelled in both D-Hydro and Infoworks?*
    a. What key differences originate in the setup process of the models?
    b. How can the models be fairly compared?

The last research question concerns the results of the comparison between the two models. As described in the problem description, Wareco is interested in the workflow of D-Hydro and if it performs as reliably as the already available Infoworks, while Deltares wants to know possible locations where differences may occur. An integral part of this question is finding patterns in the results that point towards possible causes of potential differences.

3. *What are the differences and similarities between the results of the D-Hydro and Infoworks models, and what are their possible causes?*

1.3 SCOPE

This research is limited to a period of 10 weeks, which means that choices have to be made on the scope of the project to avoid missing deadlines. First, learning to use a model is a time-consuming task, which is why it has been decided in advance that learning to model in both D-hydro and Infoworks will take too much time. That is why an expert at Wareco will create the Infoworks model, leaving the D-Hydro model to be constructed in this study.

Furthermore, models are usually employed to assess the effects of measures aimed at combatting water nuisance. No such measures are included in this research, only the base systems are compared. Another point is that sewer systems usually carry both rainwater runoff and foul wastewater from houses, called dry weather flow. This dry weather flow is not included in this research.

2 METHODOLOGY

This section of the report briefly describes the way that answering the research questions posed in the introduction is to be achieved.

Q 1 What are the sewer system components and urban water system parts used for modelling sewer systems and how do they relate to each other?

Research question 1 will be answered by performing a literature review and by close communication with the experts at Wareco. These experts are familiar with the workflow of modelling and assessment, meaning that they can provide up to date information to increase the efficiency of this research. The question concerns knowledge about the sewer system itself and serves the purpose of obtaining a system understanding. De Toffol (2006) has conducted an extensive literature review of sewer systems and how to measure their performance, and Clemens, et al. (2009) has written about design components and criteria for Dutch sewer systems. These research studies will provide the required information to understand the sewer system, as well as how its performance is assessed and what modelling techniques are often used. The results are found in Chapter 3, Theoretical framework.

Q 2 How can the system characteristics of Beverwijk be modelled in both D-Hydro and Infoworks?

a. What key differences originate in the setup process of the models?
b. How can the models be fairly compared?

With knowledge from the theoretical framework surrounding sewer system and their modelling, this questions aims to uncover the possibilities of modelling with D-Hydro in a sewer system evaluation study. This is of particular interest to Wareco, as they want to obtain experience with the new software to assess whether they are interested in using it for their future projects. To answer the question, the model building process is documented, including modelling choices and techniques. Any limitations of D-Hydro that are found are recorded, to gain insight in the software's capabilities and limits. Chapter 4 is concerned with the model setup, particularly section 4.1 and 4.2.

The available time is a major factor that influences the quality and size of the D-Hydro model. The more detailed and the larger it is, the more time it will take to perform a model run. Therefore, tests will be conducted to ensure that the model runtime does not exceed a few hours, via the adjusting of the resolution of the surface level, or the duration of the rainfall event. With this method, the model run time remains within reasonable limits.

An important part of this question is the set of fundamental differences that might exist between the two models: either due to the way they have been developed, or through the modelling choices made in this assignment. That is why it has been posed as a sub question of research question 2. To find these differences, close communication with the Infoworks expert is maintained to understand the way that his model is built. Any differences that originate may affect the results of the model runs, which is why they are registered. This is covered in section 4.3

The last part of the model setup covers the model testing plan, that describes how the models can be fairly compared. The knowledge from research question 1 aides in selecting relevant rainfall events. To measure the performance of the models, parameters are selected from the model output. Both D-Hydro and Infoworks calculate a large variety of performance indicators. To limit the work load, the comparison between D-Hydro and Infoworks is conducted based on a selection of parameters. Additionally, measures that indicate statistical relevance are obtained from literature to introduce a matter of certainty to the observed differences. Section 4.4 covers the model testing plan.

Q 3 What are the differences and similarities between the results of the D-Hydro and Infoworks models, and what are possible causes?

Answering the question of what causes the differences will be achieved via the analysis of the results that are obtained from running the model testing plan of research question 2. This analysis will be quantitative, instead of qualitative. A quantitative analysis has the advantages of illustrating to what degree the differences occur, which enables Wareco to determine whether these differences are significant for their intents and purposes. The results are split in a set of locations, to enable a more in depth view of the results. For each area, the results are displayed graphically, using water depth flood maps of the area and displaying the differences in water depth at certain points. The performance indicators introduced in the model testing plan are used to assess to what extent the models present the same results. The results are shown in chapter 5, and the possible causes for the differences and similarities are discussed in chapter 6.

3 THEORETICAL FRAMEWORK

This chapter lays the foundations for the research to follow and thereby answers research question 1. First, the place of the sewer system in the greater urban wastewater system is discussed. Then, the focus is set upon the sewer system and the components it contains, the way it is assessed, and the possible ways that it can be modelled.

3.1 URBAN WASTEWATER SYSTEM

Historically, sewer systems were mainly used for the objectives of maintaining public hygiene and preventing street flooding. Only later, the objective of minimizing pollution into the water system started to be considered, and the development of mathematical models started to play a larger role in the design and operation processes (Rauch, et al., 2002). This shift was further enhanced in 2000 by the creation of the European Water Framework Directive, WFD. Two goals of the WFD that are relevant to this study are (Vanrolleghem, Benedetti, & Meirlaen, 2005):

- Qualitative, quantitative and ecological protection of all waters, surface waters and groundwater.
- Controlled emissions and discharges via limit values and quality standards, along with the phasing out of hazardous substances

These goals of the WFD have influenced the design and operation processes of sewer systems. As mentioned in the introduction, many cities around the world use combined sewer systems, in which rainwater runoff is mixed with sewage. This sewer system can have large impacts on the quality of receiving water, such as groundwater and rivers, due to the possibility of combined sewer overflows (CSO) during storms (Vanrolleghem et al., 2005). As a result of such overflows, small rivers and streams with little dilution capabilities would turn into sewage water with a very low ecological quality. This is in direct violation of the mentioned WFD goals.

To prevent these situations, the sewer system can be adapted to contain larger pipes or more storage, or real-time control strategies can be implemented (Vanrolleghem et al., 2005). Real-time control of the integrated system takes into account the current system characteristics and uses this data to operate the system in a way that reaches quantity and quality objectives anywhere in the system (Butler & Schütze, 2005). For such an integrated control approach, a thorough understanding of the system should be acquired, in which modelling can play an important role.

The idea of integrated control originated in the 1970s, when the first ideas towards a systems approach were discussed. In the 1990s, the understanding of the urban wastewater system and computational capabilities had increased sufficiently to allow the first steps towards an integrated modelling of the complete system (Butler & Schütze, 2005). Modelling the urban wastewater system is concerned with three main locations: the sewer system, the wastewater treatment plant, and the receiving waters, as seen in Figure 1.

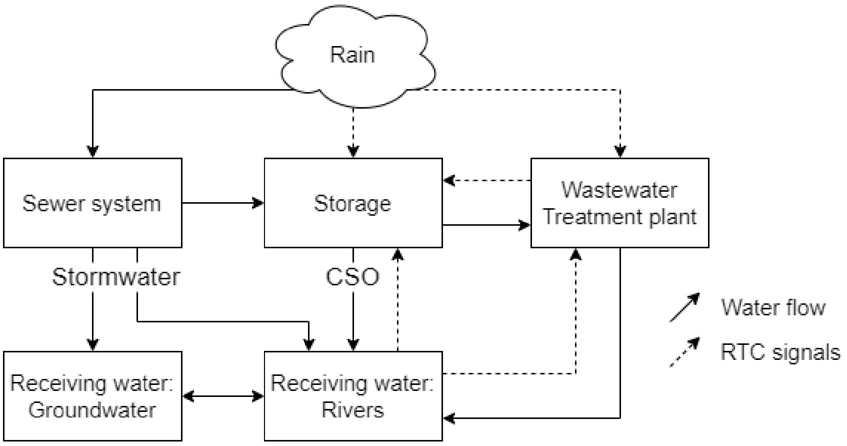


Figure 1 - Model of the urban wastewater system (Rauch, et al., 2002)

This model by Rauch et al. (2002) shows rain flowing into the sewer system, into the wastewater treatment plant along with sewage, and finally into the receiving waters. If the wastewater treatment plant cannot handle the load anymore, wastewater might enter the receiving waters immediately via the discussed combined sewer overflows. Alternatively, minor polluted stormwater from the sewer system can flow to the receiving waters as well, sometimes via a separate stormwater sewer system. In real-time control strategies, signals from measuring devices can be communicated from various points to make decisions and control operations. Within this framework of real-time control and the need for modelling to design, optimize and operate, D-Hydro was developed.

In this study, the surface runoff and the way it interacts with the sewer system is assessed. To understand the modelling of such a system, the design of the sewer system and its components are discussed first.

3.2 SEWER SYSTEM DESIGN

Sewer systems have come a long way from their initial state to the modern interpretation, although the basic principles are still the same. For most of the medieval and modern era, efforts mainly focused on the transportation of sewage away from the urban areas, to places where it would be of less nuisance (Clemens, et al., 2009). It was at the end of the 19th century that there was a growing awareness that there are more problems regarding sewage (De Feo, et al., 2014). The impacts of disposal of wastewater on the environment started to be addressed, leading to the aspect of pollution control and to the introduction of wastewater treatment plants (Rauch, et al., 2002).

All in all, the developments of the last 5000 years of sewer engineering have dictated the way the sewer systems of modern cities are shaped and placed in the context of the urban wastewater system. The structure and components of the modern systems are discussed in the coming paragraphs.

3.2.1 Types

Urban drainage systems collect and transport two types of water flows: wastewater, called the dry weather flow, and stormwater. Generally, two types of systems are distinguished, in which the pipes transport either one or both of these flows.

The developments of the sewer systems that were described above all concerned the construction of combined sewer systems. Both the dry weather flow and stormwater are transported to the wastewater treatment plant via the same pipe (Clemens, et al., 2009). However, treating large amounts of stormwater at such a plant is a costly operation. Therefore, the sewer systems are often designed to transport a maximum flow in such situations (De Toffol, 2006). In the Netherlands, the sewer system is designed to carry about 3 times the dry weather flow in case of severe rainfall events (De Toffol, 2006).

Still, this capacity can be exceeded. To handle the excess water, modern combined sewer systems are often equipped with emergency outlet locations, called combined sewer overflows (CSO). These outlets discharge the water into surface waters, such as ponds, lakes or rivers. Such overflows have to be used about five to six times per year (Clemens, et al., 2009). In 2005, about 75% of the sewer systems in the Netherlands were combined systems (De Toffol, 2006).

The combined systems, allowing for CSOs, are much better than the continuous discharging of sewage that had happened in the centuries before. However, numerous drawbacks of CSOs remain: a high fish mortality, bacterial contamination limiting recreational water use, visual pollution, and biodiversity degradation due to the long term effects of heavy metals and pesticides (Clemens, et al., 2009). To prevent such problems, the separated sewer system was invented.

In a separated sewer, the wastewater flow and the stormwater runoff are transported in their own pipes. The wastewater is lead directly to the wastewater treatment plant, while the stormwater is discharged into the receiving waters immediately (De Toffol, 2006). Advantages of this approach are that the wastewater treatment plant can be designed to smaller peak water quantities, and that wastewater is never discharged into receiving waters (Clemens, et al., 2009). Disadvantages are the risks of false connections, leading to stormwater entering the treatment plant, or sewage entering receiving waters. Another disadvantage is that stormwater, especially in urban areas, is not completely clean. Oil, tire rubbings, and heavy metals, amongst others, can still be carried along to the receiving waters (Clemens, et al., 2009).

A variation of the separated system is the improved separated system, in which a part of the runoff is first fed to the wastewater treatment plant. This so-called *first flush* contains the most pollutants from the surface, so the receiving waters are spared of this pollution. However, improved separated systems negate the advantage that separated systems had regarding the reduced capacity required for wastewater treatment plants (Clemens, et al., 2009). In improved separated systems, about half of the stormwater still ends up at the wastewater treatment plant. In 2005, 18% of the Dutch sewer system was separated, and the remaining 7% was improved separated (Clemens, et al., 2009).

All the variants of sewer systems mentioned above consist of a variety of components characterizing the design of the system. The understanding of these components is important for the modelling of the sewer system in the later part of this thesis. That is why these components are discussed in the following section.

3.2.2 Components

Sewer systems contain various elements allowing for transportation of sewage and for the inspection and protection of the sewer system. These basic elements are the sewer piping, manholes, gullies, connections from private property to the sewer piping, pumps, overflows and storage basins (Clemens, et al., 2009).

- *Sewer piping* forms the backbone of the sewer. It can be made from a range of materials in a variety of shapes and sizes. The most common materials are concrete, PVC and clayware pipes. These materials have different characteristics, such as roughness, which is important to keep into account when modelling.
- *Manholes* form the junctions in the sewer system network. Piping can change direction, size, depth and angle at these locations. Furthermore, manholes provide access to sewers for inspection.
- *Gullies* are found alongside streets and collect the runoff from surfaces that do not allow for water infiltration. The runoff is then discharged into the main sewer system piping. Gullies are often not represented in sewer system models, due to the high computational resources this would require (Baronio, et al., 2018). This means that the largest part of the collection network is often not present in models.

  In recent years, more attention is being paid to this simplification, and to the question of whether it is worth changing the way this modelling is done (Sier & Osborne, 2019). Especially in the light of more severe rainfall events due to climate change, the extra precision that modelling the gullies offers might make a significant difference in the design and testing of sewer systems. Currently, methods are being developed to integrate gullies into models, without sacrificing model run speed (Baronio, et al., 2018; Sier & Osborne, 2019).
- *Connections* from private property to the sewer piping can come from the gullies and from private properties. They are most often made from plastic and are connected to the sewer piping via water tight holes. In modelling efforts, these connections are not modelled. Rather, dry weather flow or stormwater flow from roofing is directly discharged into the sewer piping.
- *Pumps* have different functions in sewer systems. Lift pumps are used to transport sewerage from one area sewer area to another sewer area on a different pumping level. This is useful in flat regions, like the Netherlands, where a normal gravity sewer would have to go several meters belowground to ensure a steady water flow. With the lift pumps and sewer areas, the depth can be limited, which results in lowered construction costs. Another type of pump is the main pumping installation, which pumps the water from the sewer piping into the wastewater treatment plant.
- *Overflows* are used to discharge sewerage into the receiving waters once the water level in the sewer exceeds a certain threshold. It then flows over a wall of a specified height that separates the sewer water from the receiving water. Overflows are only present in combined sewer systems, and in the improved separated systems.
- *Storage basins* are used to limit the outflow into the receiving waters by providing extra sewer capacity. One way to achieve this is via external storage, in which rainfall runoff is stored in large tanks before being slowly released into the sewer system. Another option in internal storage, in which a similar system in the upstream part of a sewer system slowly releases sewerage into the downstream system, often via the use of adjustable overflows.

This research study will not focus on the actual design process of the sewer system, since this is beyond of the scope of the project. The knowledge of the components and their functions is sufficient for the purpose of modelling the existing system of Beverwijk. The next section will discuss the ways that sewer systems can be assessed in a modelling study.

3.3 SEWER SYSTEM ASSESSMENT

In order to judge the performance of a sewer system, criteria need to be established. Traditionally, performance is assessed based on emission restrictions. Emissions are defined as the entering of pollutants into the environment. Both sewage and stormwater are pollutants, as the first contains human excrements and the latter can contain metals, tire rubbings and other harmful substances (De Toffol, 2006). Restricting the spilling of these flows into the receiving waters forms the basis of criteria for sewer systems worldwide. That is why the sewer system should have a large enough capacity to properly dispose of this water. Indicators to measure this are mean annual overflow volume, the maximum overflow discharge and the number of overflow events. Factors like initial pollution in the receiving water, self-purification capacity, and sensibility of the ecosystem to environmental changes, can be taken into account in a water quality approach (De Toffol, 2006). However, water quality factors are not included in this research, as the municipality, company and software developers are mostly concerned with the modelling of water quantity in Beverwijk.

In the Netherlands, the most common way to look at sewer system performance in the light of water quantity is via the flooding severity that can occur when a sewer system is nearing its capacity. In such a case, water flows out of the manholes onto the surface, often streets. National regulations define the allowed flooding frequency depending on whether the manholes are located in city centres, residential zones, land or industrial areas (De Toffol, 2006). Cities such as Beverwijk want their sewer systems to handle a range of rainfall events, without causing street flooding (HHNK, 2007). To ensure that floods do not occur, sewer systems are often designed using climate predictions (Clemens, et al., 2009).

In the workflow of Wareco, rainfall intensity parameters and sewer system capacity parameters are usually combined in tests that assess water nuisance in streets in case of extreme rainfall events. Common practice is to use a set of 10 representative rainfall events with recurrence intervals of 0.25 to 10 years, that were based on historical data from 1955 to 1979. These events are named bui01 up until bui10 in the Netherlands, and is what they will be referred to in this research. Especially bui08 and bui10, with recurrence rates of 2 and 10 years respectively, have become the standard for assessing the hydraulic capacity of sewer systems (Rioned, 2019). As a recent development in this research area, a new set of composite rainfall events will be introduced in 2020. These are based on the Intensity, Duration and Frequency (IDF) curves of a particular area, and will be a more accurate representation of rainfall events. Moreover, the composite rainfall events have been created for the four climate change scenarios of the Royal Netherlands Meteorological Institute (KNMI) as well. Composite rainfall events for the Netherlands are not yet available, so this study will use data from the set of representative rainfall events bui01 up until bui10.

Using these events, Wareco often models the sewer system and its interaction with the surface level, particularly the water depth of street flooding. This depth determines the differences between mere nuisance and damages. For municipalities, it also forms the distinction between accepting and acting. Accepting will have to happen more often, since street flooding for temporary storage is a part of climate change adaptation measures (Rioned, 2007). Damages or the blocking of important arterial roads, however, will have to be prevented. Therefore, gaining insight in the street flooding in case of extreme rainfall events is an important objective of modelling, and will be the focus of this assignment. Accordingly, the following section will introduce the modelling of sewer systems.

3.4 SEWER SYSTEM MODELLING

In order to properly model the sewer system for an assessment study, a schematisation of the system has to take place. This can be done in two main ways: hydrologic modelling and hydrodynamic modelling. Hydrologic models calculate storages in different catchments of the sewer system, without representing the sewer system in a network. This is useful in approaches for water quality analysis, in which flows in the system itself do not matter, only outflows via overflows are relevant. Hydrodynamic models, on the other hand, do represent the network of the sewer system, numerically solving the Saint-Venant differential equations for flows in the network (Clemens, et al., 2009).

In this research, a hydrodynamic approach is chosen. Advantages are that a greater precision of predictions of water levels and depths on every location in the system is achievable. For the calculation of street flooding this is required. A large disadvantage is that hydrodynamic models require much greater computational resources and more time than hydrologic models, about 100-1000 times as much (De Toffol, 2006). Still, obtaining insight in the way D-Hydro models 2D water flows is an objective of this study, which is why the hydrodynamic approach is favoured over a hydrologic approach.

In a hydrodynamic model, four subsystems are distinguished. Each system can be modelled in various dimensions, ranging from zero-dimensional to three-dimensional. Systems can also be omitted from a modelling study, if the scope of the project does not require including it.

- *Rainfall*
  Rainfall is the driving force in modelling sewer system behaviour. It can be modelled zero-dimensionally, in which an amount of water is placed directly onto the manholes of the sewer system over a period of time, or it can be modelled in two dimensions, in which the rain is divided over the ground surface over a period of time.
- *Ground surface*
  The ground surface can be represented as a zero-dimensional container above the manholes, that can store water spilling from the sewer system. It can also be modelled one-dimensionally, in which it can represent roads, for example, along which the surface water flows down to the manholes. In areas where flows in multiple directions matter, a two-dimensional approach is desired. For the purposes of modelling flood water nuisance in the environment, a two-dimensional model is therefore best applicable.
- *Sewer system*
  The sewer system can be modelled as a zero-dimensional container, which is mostly for modelling studies that focus on the impacts on receiving waters. In these studies, the flows inside the sewer system are of less interest, only the outflows are relevant. The most commonly used technique for studies into the functioning of a sewer system is one-dimensional modelling, in which the system is represented with a network of piping and manholes. A step further would be the three dimensional approach, in which the water flows are calculated using advanced flow-profiles and resistances. These approaches are useful in studies to find local optimizations of the system, and are beyond the limits of this study.
- *Surface waters*
  Surface waters can be described in zero dimensions as a container that receives and stores water from rainfall and the sewer system. In a one dimensional approach, it is interpreted as a stream of water in which flow matters in only one direction. Two dimensional approaches are useful for larger bodies of water in which flow in multiple directions is relevant.

The next chapter, Model setup, concerns itself with the implementation of this theoretical background on sewer system modelling in the case study of Beverwijk.

4 MODEL SETUP

The model setup section of this report concerns four main parts, and with these parts aims to answer the research question 2. The first part is the definition of the model type that will be used in the comparison between D-Hydro and Infoworks. The second is the building of the D-Hydro model, and the way that the data is gathered and processed in order for it to function. The third section concerns itself with the Infoworks model, and the main differences in its construction compared to D-Hydro. Lastly, the way that the two models will be compared is discussed in the model testing plan.

4.1 MODEL TYPE

In this modelling study of the sewer system of Beverwijk, the model that is constructed is a surface model with a sewer system model, without a surface water system model. It is the fifth of the eight modelling concepts listed by Rioned, the Dutch umbrella organisation for urban water management (Rioned, 2019). In both D-Hydro and Infoworks, this model type is constructed.

This model type gives the most detailed results regarding water nuisance due to street flooding, because water nuisance does not originate from the sewer system alone: excessive flows across the surface can cause nuisance as well, which is what this model type is able to simulate. A large disadvantage of this modelling technique, is that it requires a lot of input data regarding the surface level, as well as considerable computational resources (Rioned, 2019). Still, this modelling concept is chosen for its abilities to render detailed insight into water nuisance, and it offers a view in the simulation capabilities of D-Hydro.

Considering the four subsystems that were described in section 0 on sewer system modelling, the chosen model type takes into account three of the four: the sewer system (1D), the surface level (2D) and the rainfall (0D+2D), as can be seen in Figure 2.

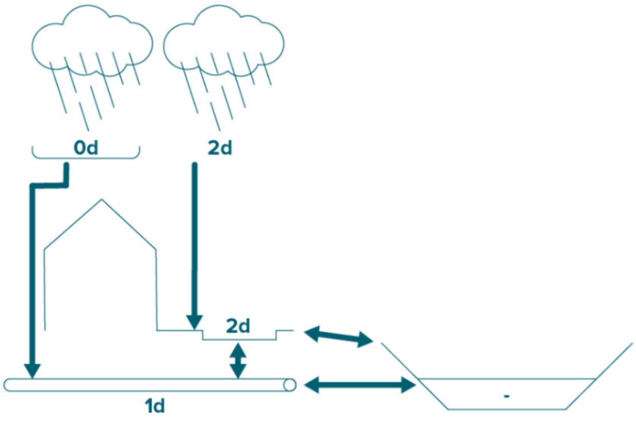


Figure 2 – Surface level model with sewer system model, without surface water system (Rioned, 2019)

Rainfall from roofs is discharged to the nearest manhole immediately, without modelling flow over the surface (0D in Figure 2). Normally, this would only be done for buildings that have downspouts directly connected to the sewer system. Other buildings would have their roofing runoff discharged onto the surface. However, no data is available for downspout connections in Beverwijk. Therefore, it was assumed that all roofs are connected to the sewer system. For a lot of buildings this is the case, and it is only in the light of recent developments regarding climate change and extreme rainfall scenarios that plans are being made to let runoff from roofing infiltrate into the ground instead of transporting it to the sewage water treatment plant (Clemens, et al., 2009). This assumption results in more water flow into the sewer system, and less flow on the surface level.

Rainfall on all surfaces except roofing falls on the surface level (2D in Figure 2). The surface level is therefore modelled as a 2D mesh, containing the necessary data for flow speed and direction. The interaction between the 2D surface level and the 1D sewer system goes two ways: water from the surface flows into a manhole (2D to 1D), or it can be pushed out of the sewer system onto the surface level (1D to 2D) in case of sewer system overload. It can also be discharged into the surface water system, either via a sewer system overflow, or via surface level flows.

Interaction between the sewer system and the surface water system is interesting to model for projects that are on the scale of Beverwijk. Obtaining insight in these interactions is beneficial to the municipality in judging whether the overflows have been designed with a sufficient crest level, and including a surface water system model offers another opportunity to test the capabilities of D-Hydro. However, the data for modelling the surface water system arrived too late for it to be implemented in the model. Moreover, the data could not be imported directly into D-Hydro, as it was delivered in the wrong format. Therefore it is not included in both Infoworks and D-Hydro, as is shown in Figure 2. Still, water will flow towards surface waters in the model because of the slopes leading down to the ponds and ditches. Section 4.2.2 on the surface level grid explains the strategy chosen to deal with this water.

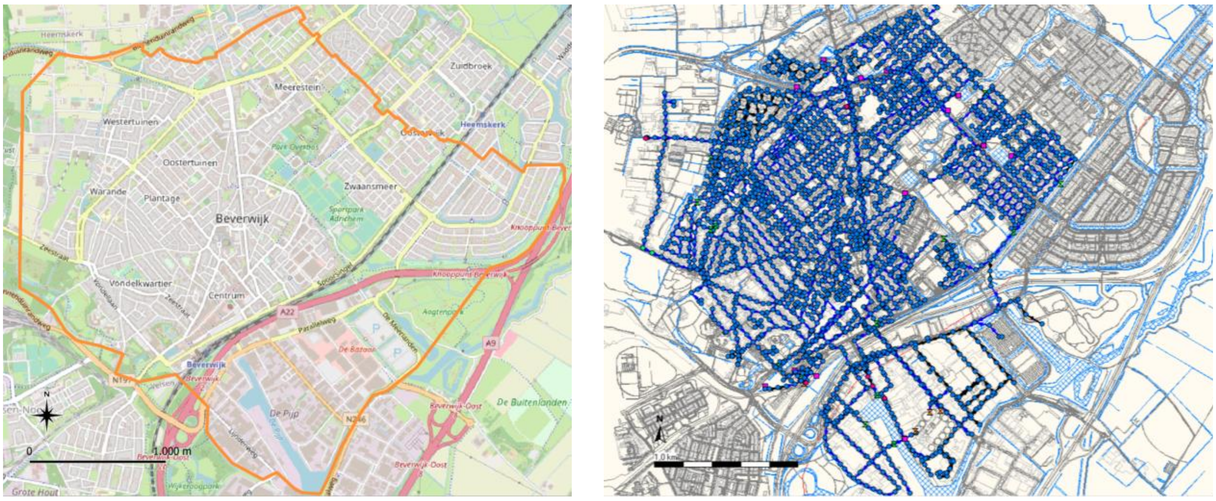
4.2 MODEL COMPONENTS

This section discusses the steps and assumptions taken, and the data required for the sewer system and the surface level. First, the study area for this assignment within the municipality of Beverwijk is limited to the urban core. This means that the sewer system of the village of Wijk aan Zee will not be included in the study. Figure 3a shows the study area.

4.2.1 Sewer system network

The starting point of constructing the sewage system model of Beverwijk was a Sobek model that was used in a previous modelling study, displayed in Figure 3b. The model of the sewer system is fully constructed in Sobek, because D-Hydro has not fully implemented all features in the User Interface (UI) to easily modify the system. Furthermore, the experts at Wareco already have a lot of experience with Sobek, meaning that the system can be quickly adjusted and questions can be easily addressed.

As these two figures show, the neighbourhood of Broekpolder, which is on the east side of the city, is not included in the Sobek model. This neighbourhood will be added to the model, and additional changes to the Sobek model are made to make it better suitable for the purposes of this study.



(a) Outline of area (b) Existing Sobek model of sewer system

Figure 3 – Study area of Beverwijk

As described in section 4.1, the sewer system is 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. A number of pumps are included in the model 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.

Using the GIS system that municipalities use to keep track of their sewer system, called Kikker, these missing or incorrect parts were added into the Sobek model. This included the addition of the neighbourhood of Broekpolder, as well as the solving of a number of mistakes and missing data points that were present. This was done in close contact with the experts of Wareco, ensuring that only plausible modifications were made. Additionally, the culverts that are part of the surface water system were removed from the existing part of the Sobek model. A full list of all modifications can be found in Appendix A.1 and A.2.

With the network complete, the last step was to add the surface catchment areas of the roofs to the model. As described in the section on the model type, it is assumed that all roofs discharge their runoff to the sewer system directly. Measuring the roofing areas was done using the Basisregistratie Adressen en Gebouwen (BAG) in QGIS. A detailed description of the areas allocated to sections of the sewer system can be found in Appendix A.3.

Conversion from Sobek

This section briefly describes the way the Sobek model is transferred to D-Hydro. As both D-Hydro and Sobek are developed by Deltares, directly importing Sobek models will be a feature of D-Hydro. However, during this research project, this function did not transfer all necessary data or it resulted in a programme crash. Via the following detour, the Sobek model was imported.

The Sobek model is exported as a SUF-HYD file (.hyd), which is a format first introduced in 1996 by Rioned. This file format contains the information of a sewer system regarding the geometry and surface catchment areas of the system. SUF-HYD files cannot be imported into D-Hydro as well, because the format is too old.

A new file format developed by Rioned in 2005 is the *Gegevens-woordenboek Stedelijk Water* (GWSW). These files can successfully be imported in D-Hydro. To convert the SUF-HYD of the Sobek model to GWSW, the developers of D-Hydro, Deltares, provided a Python script. This means that the Sobek model is converted three times before loading into D-Hydro: Sobek → SUF-HYD → GWSW → D-Hydro.

The D-Hydro model was compared to the Sobek model, verifying that the dimensions and specifications of the system were correctly transferred from each file format to the other. Two data fields were noticed to be wrongly converted in the process: the pumping capacity and the water level outside the external weirs. These were adjusted manually in D-Hydro.

4.2.2 Surface level

The surface level of Beverwijk is modelled on a grid in D-Hydro. The grid cells enable interaction between the 2D surface level and 1D sewer system, as was shown in Figure 2. Each grid cell will contain information on a set of properties. These are its height, roughness, infiltration capacity and the initial water level. The data used and choices made for each of these parameters are explained below.

Height of bed level

As a collaboration project between various levels of the Dutch government, a map of the Netherlands was created that provides height measurements on a raster with a resolution of 0.5x0.5 meters. Two types of measurements are included in this *Actueel Hoogtebestand Nederland* (AHN). A digital surface model (DSM) represents the surface and includes all the objects on it, most notably buildings and the canopies of trees. A digital terrain model (DTM) contains only the bare surface level, without objects. The difference between the two is clearly shown in Figure 4. The latter is of most interest for flood and drainage modelling, since objects such as the canopies of trees do not block water flow.

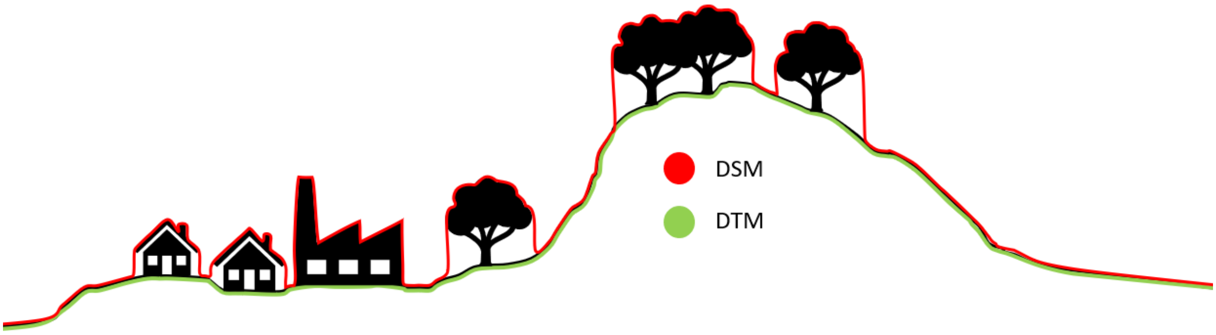


Figure 4 – Difference between DSM and DTM

The download of the DTM raster contains holes at the locations of buildings and trees: no data of the green line in Figure 4 can be obtained from satellite or LIDAR measurements beneath trees and buildings. Using QGIS's interpolation tool, these holes are filled: the function looks for data points closest to the no data cells and averages those. This creates an estimation of the surface level beneath buildings and trees. However, the absence of buildings in this elevation model is not desired, since buildings do block water flow. Therefore, buildings are added into the raster at an arbitrarily chosen height of 50 meters via the Basisregistratie Adressen en Gebouwen (BAG). A map of the elevations is shown in Figure 5a.

As described in the section on the model type, the surface water system is not included. To allow for water to be stored, instead of accumulating in the streets next to ponds and ditches, the bed level for ponds and ditches was lowered by two meters.

Roughness

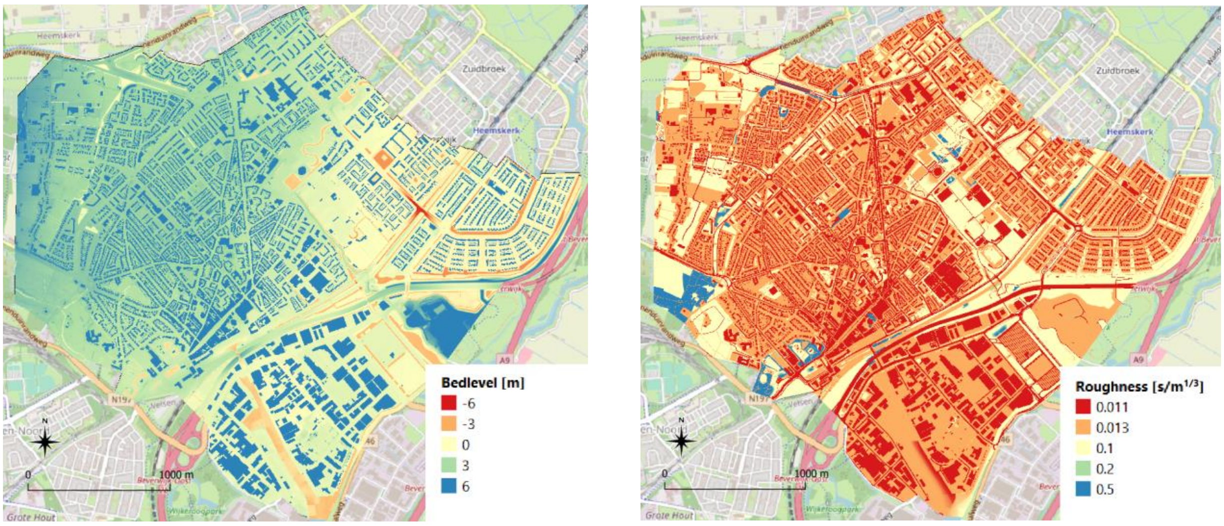
The roughness data for the surface level should be included in a raster as well. In order to assign Manning values of roughness to the various surface types, a map of these surface types has to be created for the study area. For this, the *Basisregistratie Grootschalige Topografie* (BGT) lends itself well. It is a map of the Netherlands that assigns a land use and a surface type to each area, accurate to 0.20 meters. An example would be a road segment made of closed pavement, such as asphalt. Closed pavement can be assigned a Manning roughness value of 0.013 $s/m^{1/3}$, per the table described by Rioned (2019). The values of this table were assigned to the complete study area, in which a few assumptions were made as to which roughness coefficient from the table corresponds to which surface material of the BGT. These are listed in Appendix B, and the resulting map is in Figure 5b.

Infiltration capacity

The infiltration capacity of the surface level is also dependent on the surface type of each raster cell. Grassy areas have a higher infiltration capacity, while most paved areas have little to no infiltration capacity. The raster data was provided by the regional water authority. For areas without pavement, the infiltration capacity is 300 mm/day. This corresponds to 12.5 mm/hr, which is a relatively low infiltration rate (FU Berlin, 2009). A possible explanation for this is that Beverwijk is situated in an area of clay soil (WUR, 2006), which does have a low infiltration capacity. However, sandy dunes are located to the east, for such which the infiltration rate could have been higher. Nevertheless, the data was deemed sufficiently suited for the purposes of this study, which is to analyse the built up area. Infiltration here is limited due to the high degree of paving, which is shown in the raster of Figure 5c.

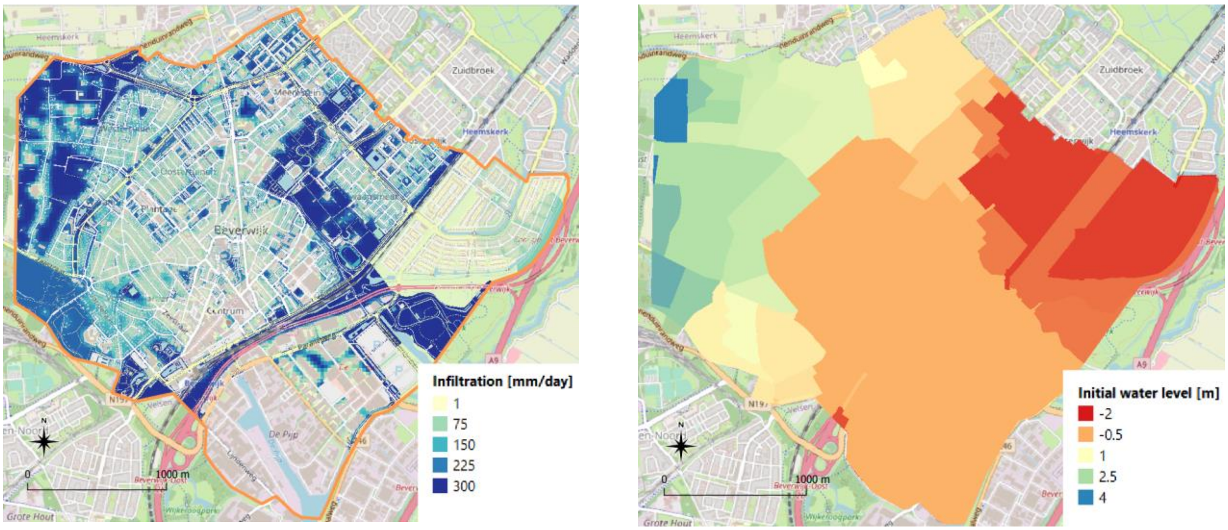
Initial water level

The initial water levels were obtained from the regional water authority. It is a map with the desired water level in the surface water system, dividing the city into multiple areas. For one of these areas, the post-2013 level would allow water to flow from one area to another via the sewer system. This should not be possible, so an internal wall should have been placed into the sewer system. However, there was no data available on the location or height. Therefore, the 2013 water level was used in the model. The resulting water levels are shown in Figure 5d.



(a) Bedlevel

(b) Roughness



(c) Infiltration

(d) Initial water level

Figure 5 - Raster data for surface level properties

The initial water levels were included in all model runs of this research. However, the data is not recognized correctly by the calculation kernel: a uniform value replaced all data points in every run. To combat errors this value was set to -999 m, which is the no-data value of D-Hydro.

This is an unfortunate event attributed to the specific version of D-Hydro that was used. New versions of D-Hydro were released in which the initial water level is correctly taken into account, according to Deltares. Unfortunately, these versions were released too late for this research project, or contained a bug that restricted the construction of the model even more. Therefore, the results do not show initial water levels in the harbour, ditches and ponds of Beverwijk.

Grid size for D-Hydro

The above-mentioned data have to be interpolated on a grid of the desired size in D-Hydro. The smallest grid size achievable is 0.5x0.5 meters, which is the smallest data size available for the AHN. However, the study area is about 8 km^2. This would result in 32.000.000 grid cells, which in advance was deemed too demanding for the computers. However, scaling up the grid size too much means that detail is lost. For example, the height differences between a sidewalk and a road are lost when moving up to higher grid sizes, while these have a great effect on the flow of water. It was decided that a 1x1 meter grid is acceptable, both for sidewalk-road interactions and computation times.

However, D-Hydro is still in development, and it turned out that an essential part of the model construction could not be achieved for a 1x1 meter grid. To enable the interaction between the 2D surface level and 1D sewer system, 1D2D links have to be generated. These links connect a manhole of the sewer system to the grid cell it is located in, allowing water to flow in and out of the manhole on to the surface level, and back. Generating the 1D2D was too demanding for D-Hydro on a 1x1 grid, as well as on a 2x2 grid. Eventually, a 3x3 grid was settled upon. This results in some 900.000 grid cells, which during the first test runs rendered a computation time of 6 hours. Unfortunately, many intricate details of the elevation map are lost at this large of a grid, since 36 data points from the 0.5x0.5 meter AHN are averaged into 1 value for the 3x3 grid. Still it was accepted, as it was the smallest achievable in the current version of D-Hydro and it meant being able to initialize a model run in the evening and working with the results the next day. Grid sizes between 2x2 and 3x3 were not considered in the selection process.

UI vs. DIMR

The interpolation of the data onto the grid was not yet possible in the User Interface (UI) of D-Hydro. Therefore, the bare grid and sewer system model had to be exported as a DIMR (Deltares Integrated Model Runner), which results in the folder structure that is needed to store the model. Via the DIMR, input data files, such as those for bed level and roughness, could be attached to the corresponding input parameter. This part of the workflow made the making of the models less precise and more prone to human errors, as a typing mistake in a file name or parameter could mean that a part of the data was not included in the calculation. A downside of using the DIMR is that its results could not be shown in the UI anymore, once the model had been exported as a DIMR. Therefore, the Crayfish plugin for QGIS developed in part by Deltares was used to evaluate results of model runs.

4.3 INFOWORKS MODEL

The building of the Infoworks model was carried out by an expert of Wareco. In consultation with this expert, the models were constructed to resemble each other in the best achievable way. However, some key differences between D-Hydro and Infoworks exist. These, along with short descriptions of the data used in Infoworks are given in this section.

First, Infoworks uses the same GWSW file that was used to import the sewer system into D-Hydro. The surfaces of roofs of buildings are taken into account in the same way as described in section 4.1. Rainfall that falls on roofs is directly transferred to the sewer system, while rainfall that falls on any area but roofing finds its way to the sewer system across the surface.

Second, Infoworks uses an unstructured flexible mesh instead of a grid of a set size. This means that Infoworks can generate neat curves and angles. It was set to make cells between 8.75 and 9.25 m^2, although Infoworks sometimes creates smaller or larger areas if it feels like it has to. As described in the previous section, D-Hydro is modelled with a 3x3 grid. The effect of this is illustrated in Figure 6. In blue, the flooded grid cells of D-Hydro are visible, as they sometimes collide with a building, or they stay rather far away from buildings. In black lines, the mesh locations where Infoworks models water are shown. These hug around the buildings very neatly, allowing for water to be modelled in the exact correct locations. It is Deltares's ambition and plan to develop a flexible mesh generator for D-Hydro as well, but this was not yet operational at the time of this research.

Figure 6 - Comparing D-Hydro grid to Infoworks unstructured mesh

Third, on the unstructured mesh of Infoworks, the same raster data regarding the parameters of the surface type were planned to be used. However, some modelling choices had to be made that gave rise to some differences. The four types of raster data are discussed below.

- *Height*. The same raster map was used, but a difference between the bed level of the two models arises due to Infoworks using the unstructured mesh, instead of a grid. Namely, the bed level data is interpolated on different points than in the D-Hydro model, resulting in small height differences between the cells in Infoworks and D-Hydro.
- *Roughness*. The raster data of D-Hydro could not be converted to the correct format for Infoworks. It was decided that the roughness raster would be omitted. As a result, the complete surface in Infoworks has the Manning roughness of concrete: 0.0125 s/m$^{1/3}$.
- *Infiltration*. The same raster map was used.
- *Initial water level.* As it became clear that the version of D-Hydro used for the project was not able to correctly process the initial water level input data, it was decided to omit the initial water level map from the Infoworks model as well, in order to eliminate any differences that could occur by introducing the initial water level to Infoworks only.

4.4 MODEL TESTING PLAN

The setup of the model testing plan is important to align the model runs that are performed in D-Hydro with those of Infoworks ICM. Therefore, rainfall events are selected that both models will use. As discussed in section 3.3 on sewer system assessment, common practice for Dutch sewer system performance tests are the ten standard rainfall events prescribed by Rioned, bui01 up to bui10. 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 (HHNK, 2007).

In the plan, the municipalities state that their sewer systems should be able to handle the standard rainfall events of 20 mm/h and 30 mm/h, which are bui08 and bui09 of Rioned respectively (Cruz, et al., 2017). These events have recurrence intervals of 2 and 5 years respectively (Rioned, 2019). Water is allowed to spill on the street, but no severe nuisance may be experienced. The municipality is currently developing plans to comfortably handle the 30 mm/h, adopting strategies such as water retainment on the streets or in green areas, or allowing infiltration via permeable paving.

Additionally, they have set their expectations with regards to climate change to have to regularly face a rainfall event of 60 mm/h. Such an event happens once every 100 years in the current climate, but will be happening once every 50 years in the worst case climate scenario for 2050 of the Royal Dutch Meteorological Institute (Werkgroep standaardisatie stresstest wateroverlast, 2018). The municipalities expect street flooding, and water will flow to the lowest areas. They aim to keep the major roads and services such as hospitals accessible. Nuisance will thus occur, but damage is hopefully avoided.

Since these rainfall events are clearly mentioned in the water and sewer plans for the municipalities of Heemskerk and Beverwijk, they are considered suitable for the purposes of modelling in D-Hydro and Infoworks. The three rainfall events discussed are displayed in the hydrograph of Figure 7 below.

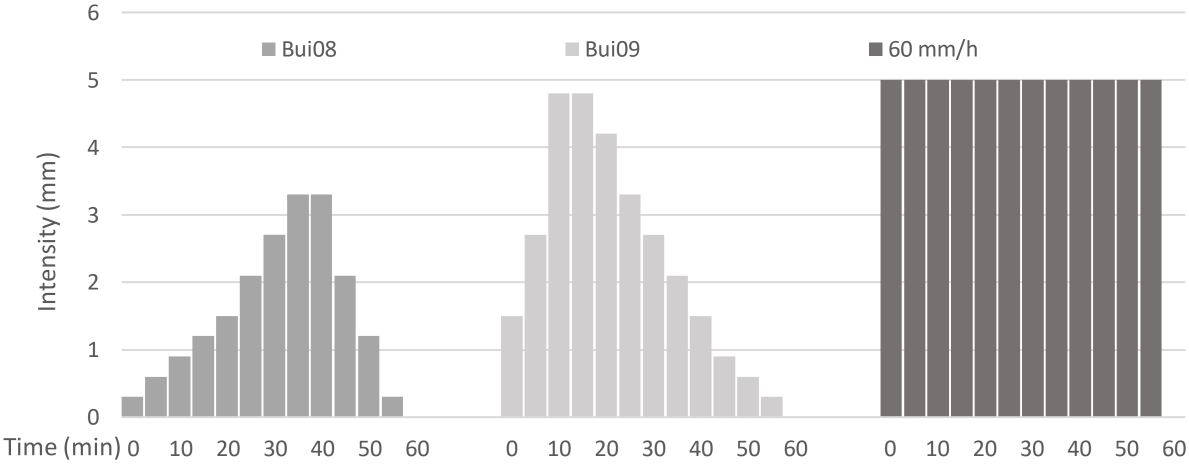


Figure 7 - Hydrograph of bui08, bui09 and the stresstest event of 60mm/h (Rioned, 2019)

As can be seen in the hydrograph, two main differences between bui08 and bui09 occur. Bui09 has a higher total amount of rainfall, and its peak occurs at the beginning of the event. Due to limited time, bui09 will be used in favour of bui08. This is because its higher intensity allows for more extreme modelling of street flooding. Moreover, it is at the top of the municipalities ambitions regarding the sewer system capabilities. Lastly, the peak at the beginning of the event allows for the system to gradually empty in a cool down period of one hour without rainfall. The complete model run will therefore be two hours in simulation length, with one hour of precipitation. All in all, the stress test of 60 mm/h and bui09 are the two events that are modelled, each with a simulation time of two hours.

4.4.1 Outline for comparison D-Hydro – Infoworks

As was introduced in section 3.3, the most important results of this study will be flood depth maps of the study area during and after the rainfall event. A selection of locations is made in which an in-depth view on the results can be conducted, based on known and predicted water nuisance.

A few areas in the city are known to have trouble with handling rainfall events. The ones that are in the study area of this research are the urban area around the city centre, and the urban area along the railway line (HHNK, 2007). These can also be found in an additional modelling study into the effects of an extreme rainfall event of 100 mm in two hours, the results of which are displayed in Figure 8. Two areas with a lot of flooding are selected: the residential area of Oranjebuurt and the industrial area of De Pijp. A third residential area, Broekpolder, is selected to compare in less extreme situations.

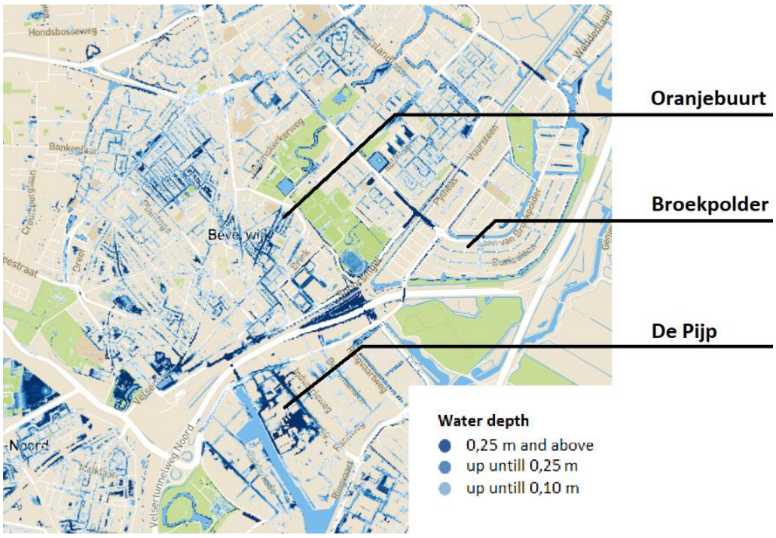


Figure 8 - Water nuisance Beverwijk for a modelled 100 mm/2hr event (HHNK, 2019) and three evaluation locations

To be able to draw conclusions from the flood depth maps, a number of metrics are used to quantify the results. First, the inundation extent is an important metric, showing which areas are flooded and which are not. To quantify the agreement between the models on the inundation extent, feature agreement statistics is used. The Critical Success Index (CSI, or F1) is computed as follows (Lim & Brandt, 2019):

$$CSI = \frac{A}{A + B + C}$$

The CSI divides the area of agreeing predictions (A) by the sum of the areas of agreements and disagreeing predictions B + C. Disagreeing can mean overprediction B, where D-Hydro predicts flooding and Infoworks does not, or underprediction C, where it is the other way round. If the model is 100% accurate, the disagreement is zero, resulting in a CSI of 1. If there are no agreeing predictions, the CSI is 0. Any result in between, for example 0.7, can be interpreted as that 70% of all predictions is correct, while 30% is either overpredicted B or underpredicted C.

The second key metric is flood depth, and it is measured by evaluating the water depths on the locations of the manholes. 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, 2019). It is calculated as follows, with each manhole counting towards the total number of observations N:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(Observed\ depth_{\,i} - Modelled\ depth_{\,i})^2}{N}}$$

To further support or explain findings by the RMSE and CSI, discharges in the 1D sewer system can be compared. To show correlation between the two models, the Nash-Sutcliffe Efficiency (NSE) and the coefficient of determination (R^2) are used. Below, both are introduced.

The NSE is used to compare how well modelled discharges Q_m perform against observed discharges Q_o. A perfect model achieves a score of 1. A bad model can reach values down to -∞. An NSE coefficient of 0, however, already indicates that the average observed discharge $\overline{Q_o}$ is just as good of a predictor for the actual discharge as the modelled values were (Liu & De Smedt, 2004). The equation is as follows:

$$NSE = 1 - \frac{\sum_{t=1}^{T}({Q_m}^t - {Q_o}^t)^2}{\sum_{t=1}^{T}({Q_o}^t - \overline{Q_o})^2}$$

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 below.

$$R^2 = \left(\frac{\sum_{t=1}^{T}\left({Q_m}^t - \overline{Q_m}\right)\left({Q_o}^t - \overline{Q_o}\right)}{\sqrt{\sum_{t=1}^{T}({Q_m}^t - \overline{Q_m})^2({Q_o}^t - \overline{Q_o})^2}} \right)^2$$

5 MODEL RUN RESULTS

This chapter focuses on the results of the model runs, and with these aims to answer the first part of research question 3, on where differences and similarities between the models occur.

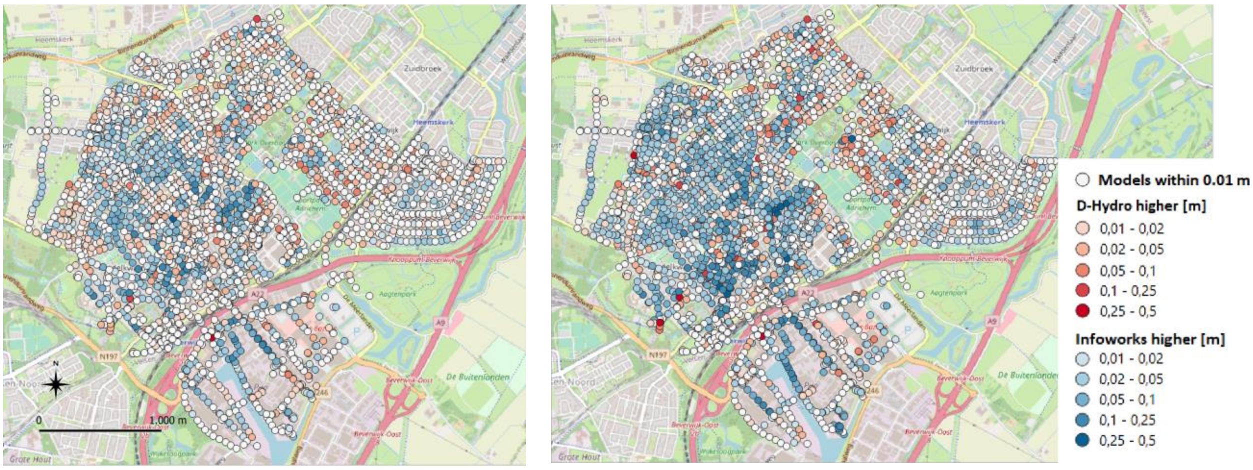
The comparison of D-Hydro with Infoworks to validate the outcome of D-Hydro will solely be based on these two models. For equations that concerned with comparing modelled values to observed values, such as the Root Mean Square Error (RMSE) and the Critical Success Index (CSI), the data from D-Hydro is considered modelled, while the data from Infoworks is considered "observed". Although Infoworks itself is also a model, it is assumed to be accurate to real life, because it has been thoroughly validated over the course of its 10 year existence (Ball, 2014). Moreover, the developers of D-Hydro, Deltares, desire this study to dive into the comparison with Infoworks especially. Validation against real life observations is also part of their validation effort, but not of this particular research project.

A result of this for the interpretation of the results is that it cannot be assessed which model of the two is better in producing accurate results. This is because the assumption that Infowork's predictions are "observed" means that Infoworks will always be the most accurate. Therefore, the aim of this study is not to advice any party on which model is preferred for the urban wastewater system modelling workflow. Rather, it aims to bring to light the differences that occur between the models and try to trace these back to their cause. This is what the coming sections will discuss, starting with the observations from the results.

5.1 MAP COMPARISON

In this section, the maximum water depths and inundation extents of the two models are compared. The three locations of Oranjebuurt, De Pijp and Broekpolder will be the case studies for this comparison. Before each location is discussed separately to clearly show the different predictions of the two models, a general overview of the comparison in the city is displayed in Figure 9.

The figure was constructed by comparing the maximum water depths above each manhole in the network. The manholes for which D-Hydro predicts greater depths than Infoworks are coloured increasingly red. Vice versa, the colours become more blue for locations where Infoworks predicts more water. As both Figure 9a and Figure 9b show, Infoworks generally predicts higher water depths than D-Hydro, although the degree and locations in which this happens varies. Indicators to establish this degree are discussed after the three locations are discussed.

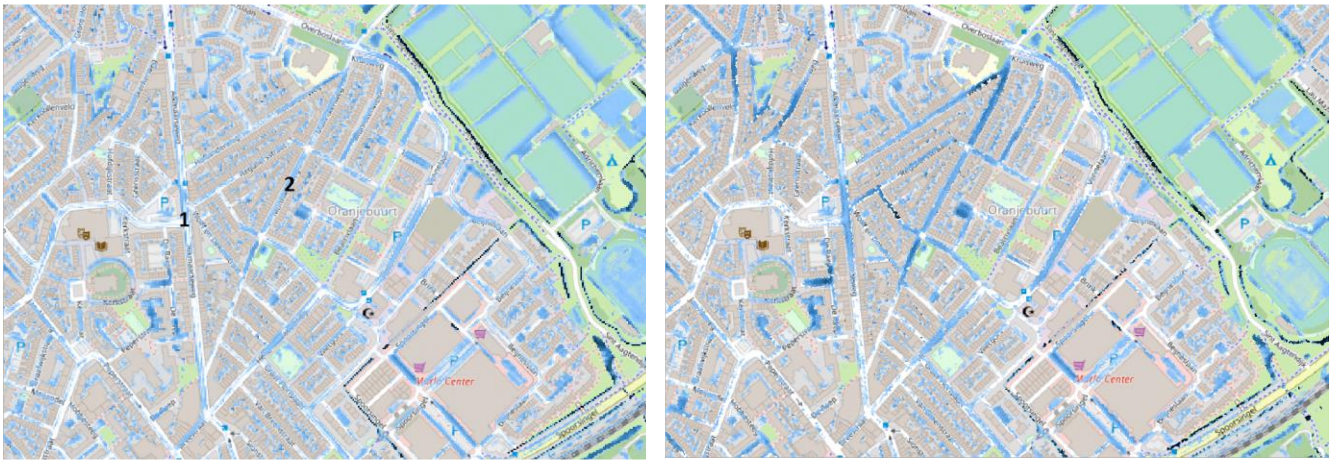


(a) Bui09 *(b) Stress test*

Figure 9 - Water depth comparison

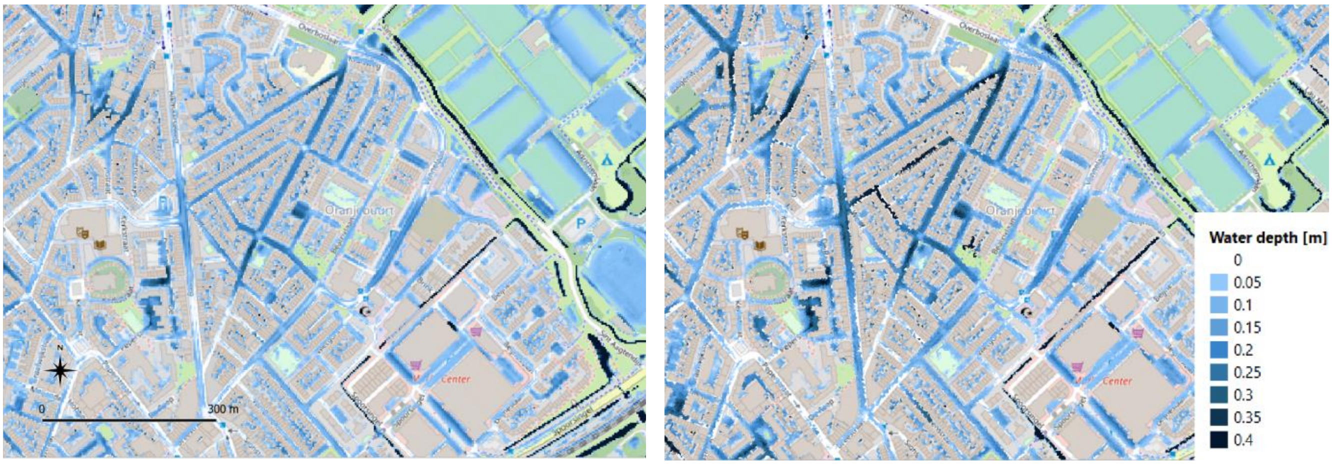
5.1.1 Oranjebuurt

As discussed in 4.4.1, the Oranjebuurt is a place known for water nuisance. Figure 10 shows that this is more clearly predicted by the Infoworks results on the right than by D-Hydro results on the left: Infoworks shows a greater water depth and a greater inundation extent in both rainfall events. The most striking locations displaying large differences are the Alkmaarseweg and the Munnikenweg, number 1 and 2 in Figure 10a respectively. These streets will be examined more closely.



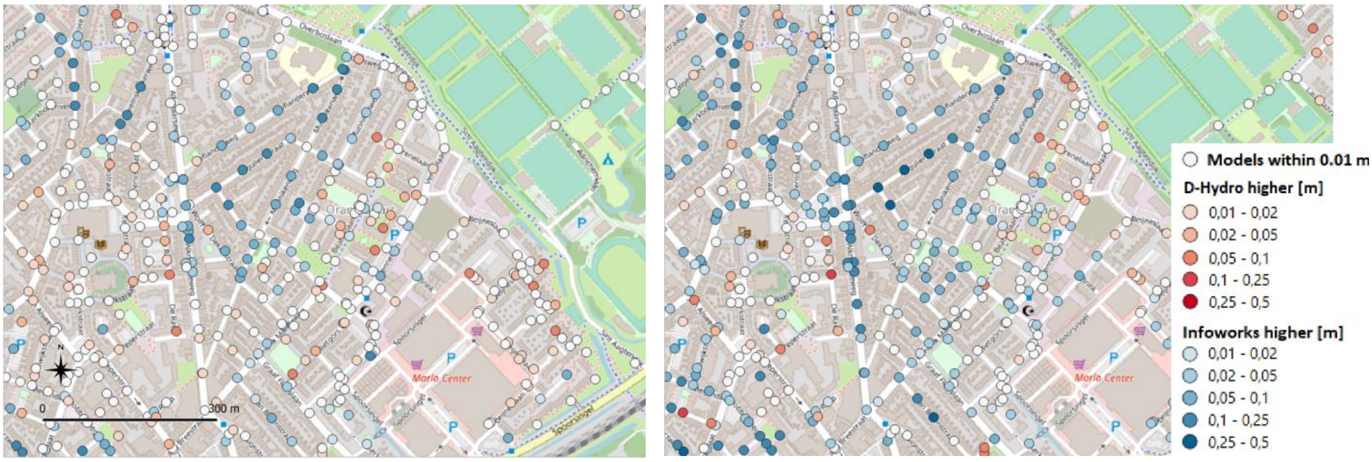
(a) Bui09 D-Hydro

(b) Bui09 Infoworks



(c) Stress test D-Hydro

(d) Stress test Infoworks



(e) Bui09 comparison at manholes

(f) Stress test comparison at manholes

Figure 10 - Flood map comparison Oranjebuurt

5.1.2 Broekpolder

The area of Broekpolder was constructed after the year 2000, and its sewer system is disconnected from the rest of Beverwijk. It is not known as an area of severe water nuisance, which is reflected in the results of both models, shown in Figure 11. Street flooding has a range of about 5 to 10 centimetres in most streets for bui09. For the stress test, both models predict about 10 to 20 centimetres of water. Figure 11e and f demonstrate that the two models predict very similar water levels.

(a) Bui09 D-Hydro *(b) Bui09 Infoworks*

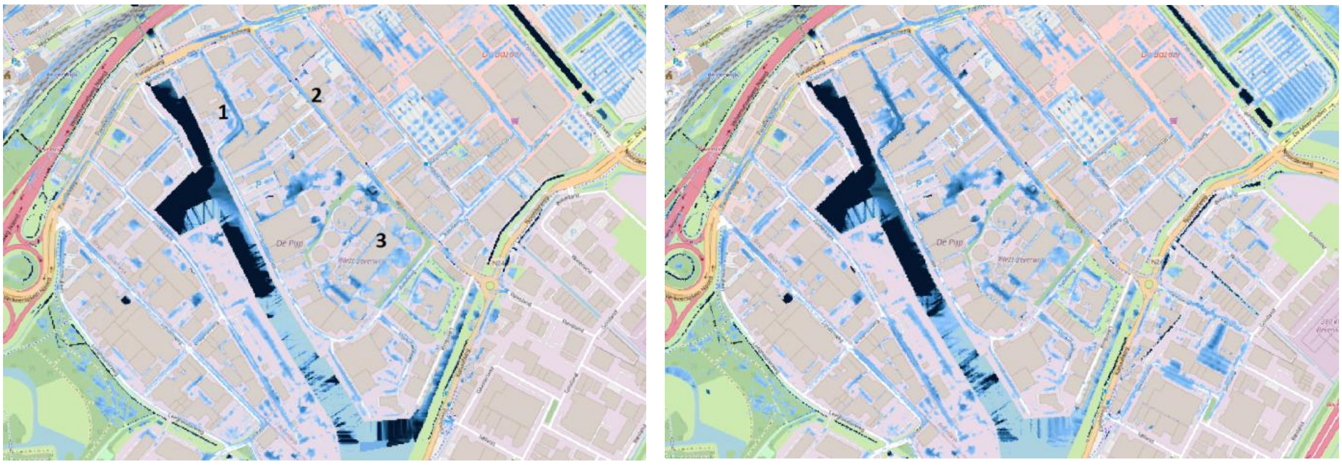
(c) Stress test D-Hydro *(d) Stress test Infoworks*

(e) Bui09 comparison at manholes *(f) Stress test comparison at manholes*

Figure 11 - Flood map comparison Broekpolder

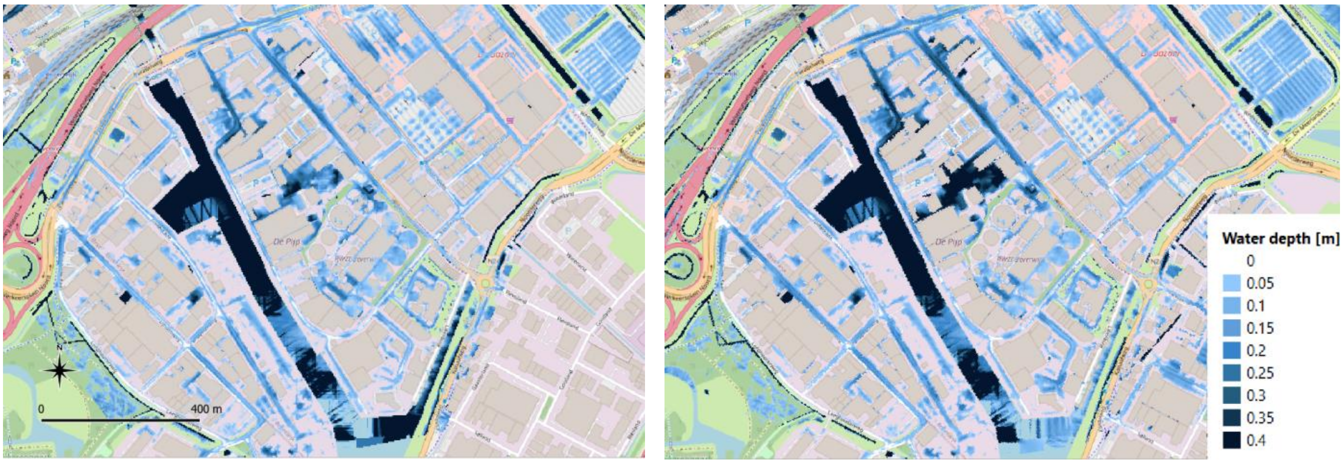
5.1.3 De Pijp

The results of industrial area of De Pijp are shown in Figure 12. The results of the models are generally quite alike, as demonstrated by the flood depth maps of both bui09 and the stress test. The parking lots in the top right corners, for example, are nearly identical. Two areas in particular, however, show large differences. These are the Noorderkade and the Wijkermeerweg, numbered 1 and 2 respectively in Figure 12a. These streets clearly show up in Figure 12e and f as well, showing that Infoworks predicts 10-15 cm more water on these streets. A lot of water coming from the city centre passes through the pipes that lay there, since the wastewater treatment plant is located to the south of these pipes, at number 3. These locations are examined more closely.



(a) Bui09 D-Hydro

(b) Bui09 Infoworks



(c) Stress test D-Hydro

(d) Stress test Infoworks

(e) Bui09 comparison at manholes

(f) Stress test comparison at manholes

Figure 12 - Flood map comparison De Pijp

5.2 MAXIMUM INUNDATION EXTENT

The flood maps of the areas were presented in the previous section, showing agreement between the models in some places, and disagreement in others. In order to quantify the agreement of flooded area between the models, the Critical Success Index (CSI) was introduced in section 4.4.1. To allow for calculating the CSI, first a water depth that constitutes the threshold of “flooded area” has to be set. In this research, the smallest water depth that was exported by Infoworks is 2 cm. Therefore, all D-Hydro and Infoworks grid cells that have a water depth of 2 cm and higher are considered flooded. To see if this threshold has an effect on the resulting CSI, a threshold of 5 cm is also evaluated.

In Figure 13, the areas required for the calculation of the CSI in De Pijp are marked. Locations where D-Hydro and Infoworks both predict a water depth of at least 2 cm are shown in green. In red locations only one of the models predict flooding. These thus constitute areas of disagreement, or error. In large sections of the area, as shown by Figure 13a, the predictions are not that far off: only a thin edge of red is visible around the green areas. As mentioned in the previous section, the Wijkermeerweg and Noorderkade are locations with the largest differences in De Pijp. This is clearly shown in Figure 13b, in which the red area of disagreement shows the larger amount of water predicted by Infoworks.

(a) Overview of De Pijp *(b) Close-up of Wijkermeerweg*

Figure 13 - Agreement and disagreement on flooded area of De Pijp for bui09

Figure 14 shows the agreement and disagreement areas for the Oranjebuurt. Sub-figure A shows that there is a lot more red area of disagreement in this area. As mentioned, this area also saw two streets with large differences: the Alkmaarseweg and Munnikenweg. Figure 14b shows a lot of disagreement on the the Alkmaarseweg, as well as in many of the smaller roads and back yards of houses.

(a) Overview of the whole Oranjebuurt *(b) Close-up of the Alkmaarseweg*

Figure 14 - Agreement and disagreement on flooded area of Oranjebuurt for bui09

5.2.1 CSI tables 2cm

The three areas used for comparing the flood maps are used for calculating the CSI in this section, as well as the complete city of Beverwijk. For the smaller areas, the map extents that were presented in section 5.1 are used as boundaries for determining the agreement and disagreement areas. The resulting CSI are shown in Table 1 for bui09, and in Table 2 for the stress test.

The CSI can be interpreted as showing the ratio of correct and incorrect predictions. A CSI of 0.5 means that the area of correct predictions is the same size as the area of incorrect or missed predictions. In both tables, it can be seen that the harbour area of De Pijp scores better than the residential areas of Oranjebuurt and Broekpolder. These residential areas score a little below the CSI of the complete city. Furthermore, the scores are higher for the stress test than for bui09 in all of the four areas.

Table 1 - CSI statistics for bui09 – 2cm threshold

	Agreement [ha]	Disagreement [ha]	CSI
Pijp	27.2	15.6	0.64
Oranjebuurt	14.1	13.4	0.51
Broekpolder	24.2	20.6	0.54
Beverwijk	139.1	116.1	**0.54**

Table 2 - CSI statistics for stress test – 2cm threshold

	Agreement [ha]	Disagreement [ha]	CSI
Pijp	40.1	14.8	0.73
Oranjebuurt	22.3	14.4	0.61
Broekpolder	35.0	21.8	0.62
Beverwijk	214.4	122.2	**0.64**

5.2.2 CSI tables 5cm

The threshold for a grid cell to be considered flooded was set at 2cm at the start of this section. To see if this imposed limit has any effect on the resulting CSI values, a threshold of 5 cm was also evaluated. The results of this are shown in Table 3 and Table 4.

As the tables show, the CSI of all areas are lower for the 5cm threshold than they were for the 2cm threshold. One area in particular, the Oranjebuurt in bui09, becomes a lot less accurate compared to its 2cm threshold in Table 1.

Table 3 - CSI statistics for bui09 – 5cm threshold

	Agreement [ha]	Disagreement [ha]	CSI
Pijp	16.4	12.1	0.58
Oranjebuurt	6.3	10.1	0.38
Broekpolder	13.2	15.1	0.47
Beverwijk	74.4	83.7	**0.47**

Table 4 - CSI statistics for stress test – 5cm threshold

	Agreement [ha]	Disagreement [ha]	CSI
Pijp	29.8	13.2	0.69
Oranjebuurt	15.9	12.3	0.56
Broekpolder	25.9	17.2	0.60
Beverwijk	154.3	101.5	**0.60**

5.3 MAXIMUM DEPTH

The maximum depth was measured at the manholes of the city sewer system. Maps of the differences have already been shown in section 5.1. To quantify these differences, the Root Mean Square Error (RMSE) is used. As was mentioned at the start of this chapter, the predictions of Infoworks are considered “observed”, while the predictions by D-Hydro are considered “modelled”. The RMSE is calculated for the three regions and the complete city, and can be interpreted as how far off the model can be expected to be on its next prediction.

A series of outliers were cut out of the results. These were locations located in the surface waters of the harbour, ditches or ponds. Differences could amount to more than 1.5 meters in some areas, due to the differently defined grids of D-Hydro and Infoworks. This skews the results to be a lot worse. A list of the removed points and their values can be found in Appendix C. The results of bui09 are shown in Table 5, for the stress test in Table 6. To still show the effect of the outliers, the RMSE of Beverwijk with all outliers is included.

Table 5 - Maximum depth at manholes comparison bui09

	Largest difference [m]	Average difference [m]	RMSE [m]
De Pijp	0.31	0.019	0.037
Oranjebuurt	0.21	0.024	0.042
Broekpolder	0.10	0.011	0.018
Beverwijk	0.37	0.018	**0.032** 0.078 (with outliers)

Table 6 - Maximum depth at manholes comparison stress test

	Largest difference [m]	Average difference [m]	RMSE [m]
De Pijp	0.16	0.028	0.044
Oranjebuurt	0.30	0.039	0.062
Broekpolder	0.22	0.016	0.027
Beverwijk	0.30	0.028	**0.046** 0.095 (with outliers)

The RMSE result for the two rainfall events are fairly close. It is slightly higher for the stress test than for bui09, although it is only 1 centimetre. The results thus indicate that an error of 3 cm to 4 cm can be expected if D-Hydro is to do another prediction of Infoworks results. This error can either be above or below the Infoworks value. In both rainfall events, the RMSE values are worst in the residential area of Oranjebuurt, and best in the residential quarter of the Broekpolder. The values for the industrial harbour area of De Pijp and the complete city are in between those. It can also be clearly seen that the exclusion of the outliers in the RMSE calculation approximately halved the RMSE in both rainfall events.

As the name suggests, the RMSE squares the difference between the models. It is a useful tool to assess the error interval around a parameter, but it fails to show if the error is most likely to be positive or negative. That is why in Figure 15, each cross represents the difference between the maximum water depths at each manhole, calculated by subtracting D-Hydro’s result from that of Infoworks. This way, a positive mark means that Infoworks predicted a greater depth than D-Hydro.

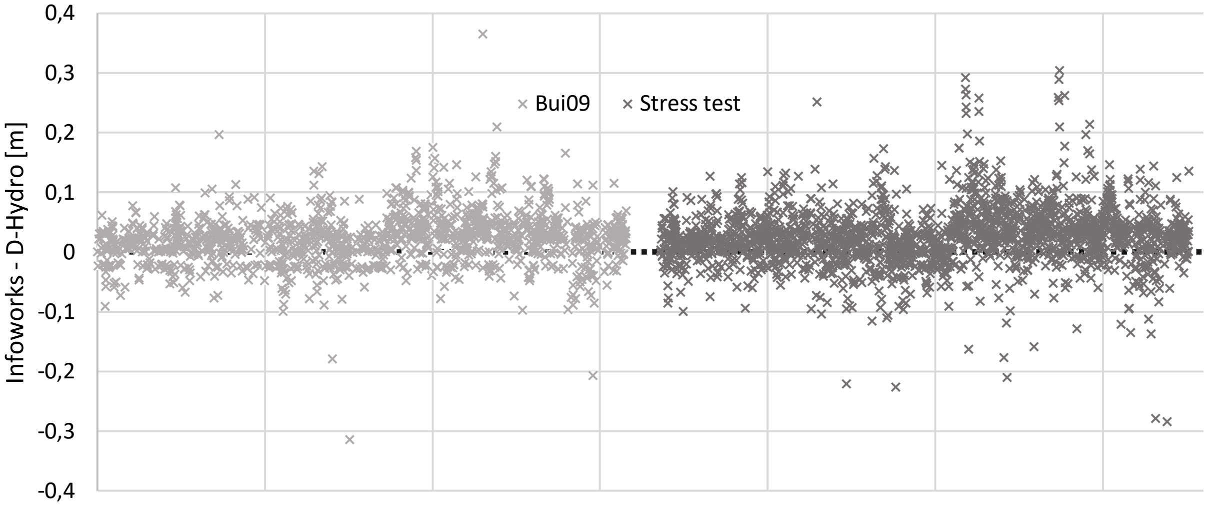
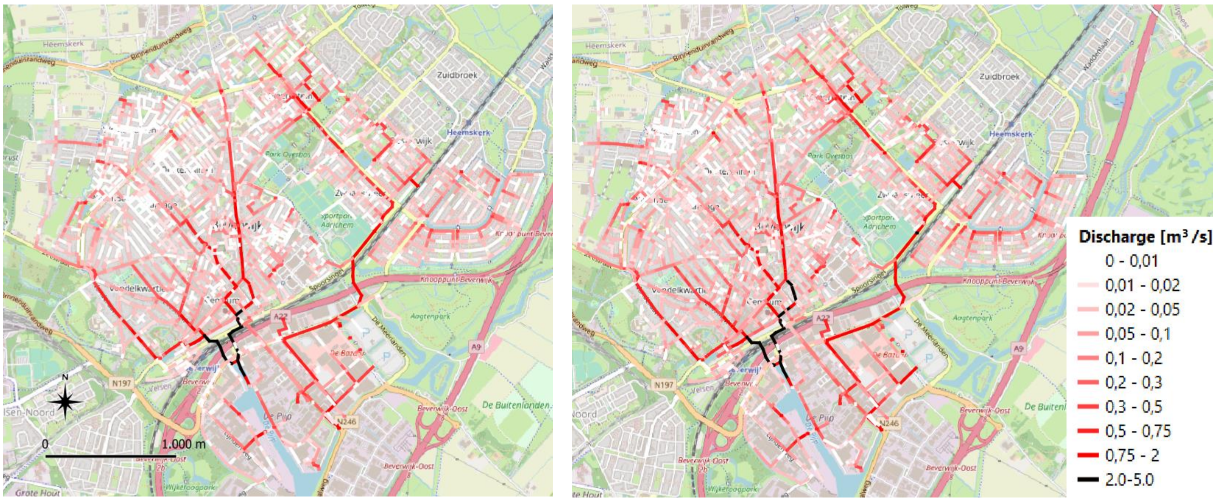


Figure 15 – Water depth comparison at all manholes except outliers for both rainfall events

The figure shows that for both events, most of the manholes had a positive difference. This indicates that Infoworks has generally predicted greater water depths than D-Hydro. This was also illustrated in the maps presented in section 5.1. The two spikes on the right of the stress test data points are interesting locations to further examine. One is located between the Alkmaarseweg and Munnikenweg in the Oranjebuurt. The other spike is at the start of the Koningsstraat, near the railway station. These locations are taken into account in the next section, in which the discharges through the sewer system are considered.

5.4 1D DISCHARGES

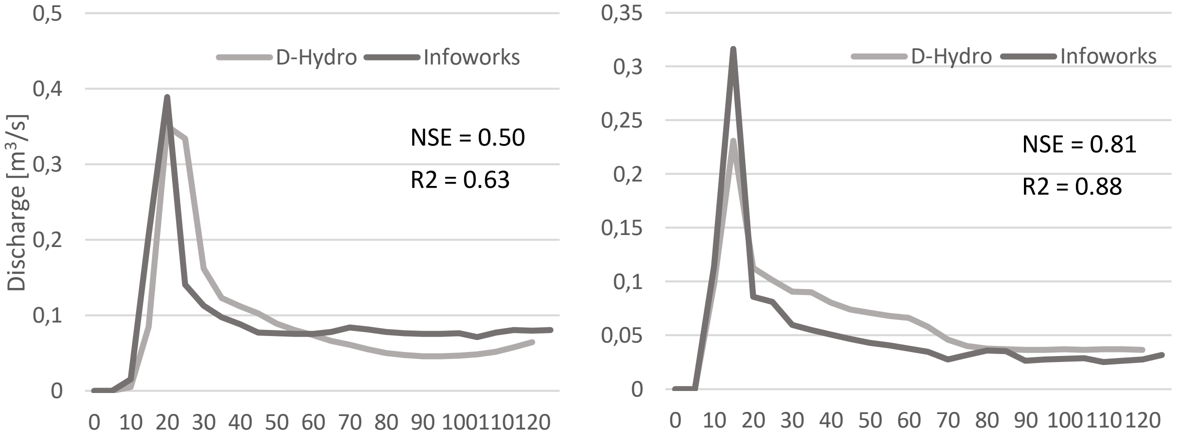
The discharge in the sewer system can offer interesting insights in the cause of street flooding. Figure 16 shows that the water flows from the north of the city towards the harbour in the south, where the wastewater treatment plant is located. The main arteries of the sewer system are clearly distinguishable in these figures, showing up bright red in both models. At first glance, the discharges throughout the complete system are very much alike. The only difference noticeable are in the very low discharge regions, where D-Hydro shows mostly white and Infoworks light pink. However, these differences are very small. To investigate further, a number of locations is chosen to compare the discharges over time.



(a) D-Hydro *(b) Infoworks*

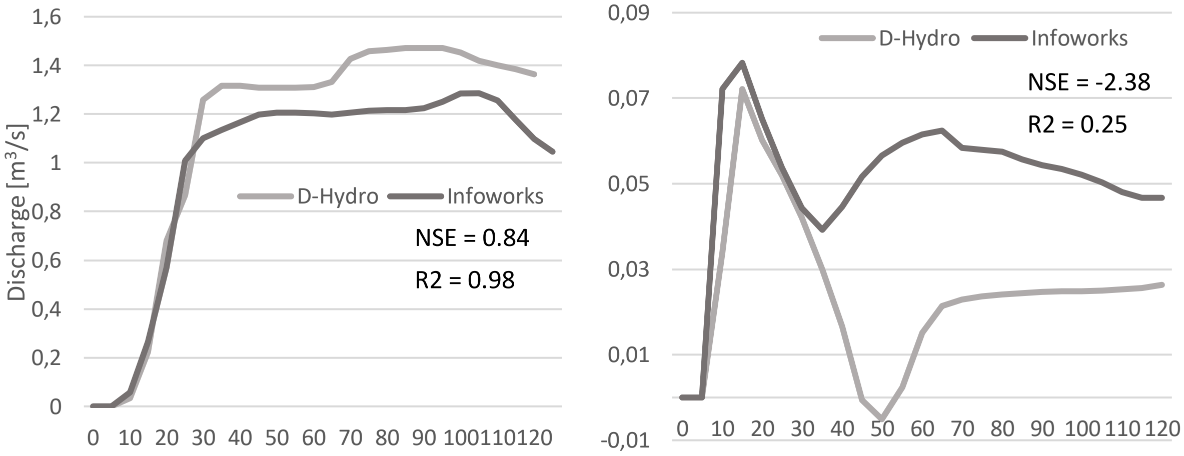
Figure 16 - Discharges through sewer piping at end of the stress test

The locations for which the discharge over time is plotted are the Wijkermeerweg and Noorderkade in de Pijp, the Laan van Broekpolder in Broekpolder, the Almaarseweg and Munnikenweg in Oranjebuurt, and the Koningsstraat that was introduced in the previous section. For each of these streets, the discharge was measured during the stress test at an arbitrarily chosen sewer pipe, and plotted in Figure 17. The R2 and NSE values are calculated and shown in the figures as well.



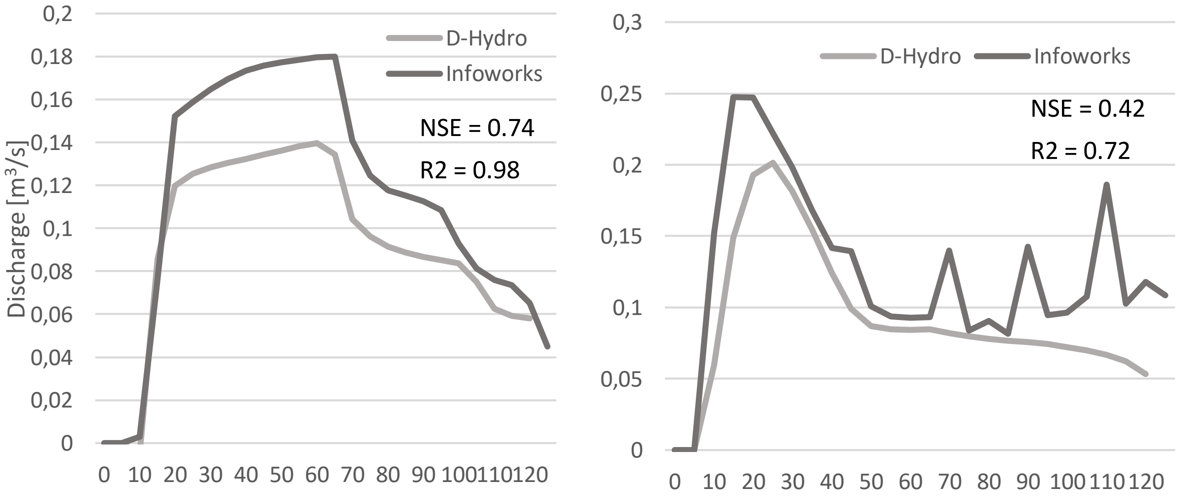
(a) Wijkermeerweg

(b) Noorderkade



(c) Alkmaarseweg

(d) Munnikenweg



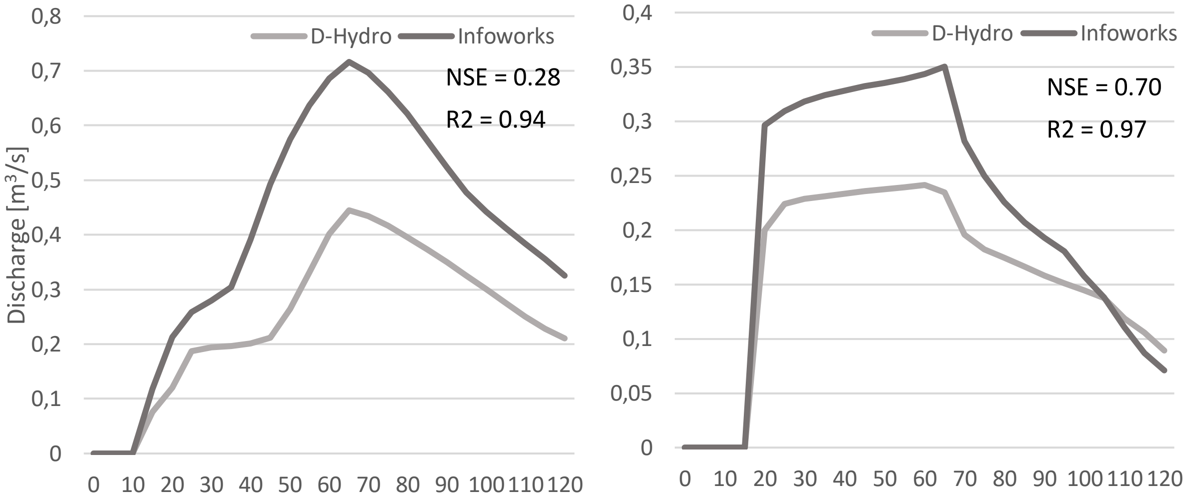
(e) Laan van Broekpolder

(f) Koningsstraat

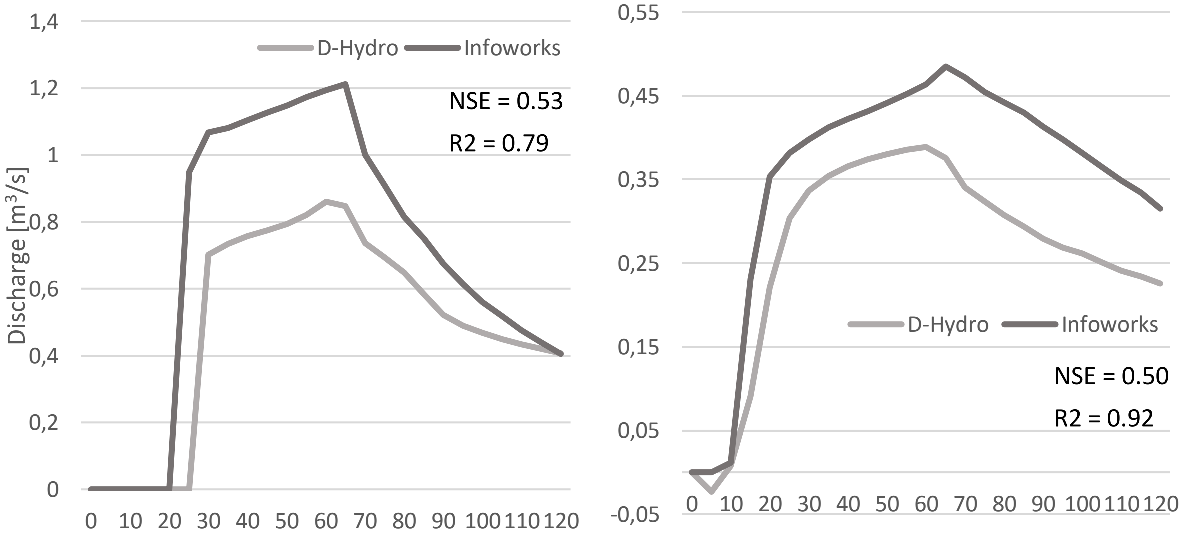
Figure 17 - 1D Discharge comparison in key locations for stress test

A first observation is that the two models show similar patterns for the piping in their respective areas. The NSE and R2 values for most locations indeed show quite a good fit of D-Hydro to the Infoworks results. However, Infoworks seems to predict flows that are a little higher in most locations, except for the Alkmaarseweg. An exception to the good fit is the Munnikenweg in sub-figure D, which has a negative NSE and a low R2. This location shows Infoworks transporting more water in the second half of the run. It should be mentioned that the discharge volume of this location is quite small compared to the other locations, staying well below 0.1 m^3/s. Perhaps this low discharge is the reason for the larger variability in the results.

The general pattern that Infoworks transports more water via the 1D sewer system is evaluated at overflow locations as well. Figure 18 shows the discharges of overflows at the Munnikenweg and the Laan van Broekpolder, since these streets were shown on the previous page as well. Two extra outflows at arbitrary other locations are also shown to see if the pattern holds in Figure 18.



(a) Munnikenweg *(b) Laan van Broekpolder*



(c) Merwedestraat *(d) Wildemanskruid*

Figure 18 - Discharge comparison at overflows during stress test

The results clearly show that Infoworks consistently predicts more water flowing out of the sewer system than D-Hydro during the stress test. For bui09, it was verified that the same patterns emerge. This is a strange observation when combined with the observations that Infoworks tends to predict greater water depths in the streets. If Infoworks has more water both on the surface and in the sewer system, then Infoworks has processed more water than D-Hydro has. This should not be the case, as the models performed the same rainfall event.

The point made about the R^2 showing correlation and the NSE showing accuracy in section 4.4.1 is clearly demonstrated by these four graphs. The NSE are quite low, because the predictions are not accurate. The R^2 values are high, because the shape of the graphs are very similar.

5.5 WATER BALANCE

To check if the two models processed the same water quantities, the quantities from the water balance files that keep track of the cumulative volume of the different in and outflows are shown in

Table 7. Only bui09 is shown, as the log file for the stress test was lost. The table clearly shows that the water balances are not equal. A few peculiar observations can be made. First, Infoworks sets more rainfall on the 2D surface level. This seems strange, but can be explained by the fact that the Infoworks model used a larger area than D-Hydro. It was verified by measuring the areas and calculating the total volume of water, that both models indeed used bui09 on their 2D grids. This can also be seen in areas in the models that do not experience draining by the sewer system, such as the large parking lot in the harbour displayed in the top right of section 5.1.3. These areas showed very similar results.

A more important observation with far-reaching consequences is the doubled 0D rainfall. Using the roofing areas in the initial Sobek model, it can be calculated what the expected volume of 0D rainfall should be. The expected volume of 0D rainfall from roofing is about 44 000 m^3. Both D-Hydro and Infoworks do not meet this number. For Infoworks, it was discovered that a modelling error had resulted in a near doubling of the roofing areas. Infoworks itself is not to blame for this error, it had correctly used the data in the GWSW files. D-Hydro, however, had not read this file correctly, which lead to the discovery of a bug in the programme. If a manhole has multiple roofing areas assigned to it, D-Hydro fails to sum these values. Instead, it uses only the last entry for that manhole. This resulted in the loss of 26 ha of roofing for D-Hydro, which corresponds exactly with D-Hydro's underestimation of the 0D rainfall volume. The water balance explains many of the results displayed in previous sections, as is explained in chapter 6.

A third point to mention regarding the water balance is that it was not possible to retrieve the infiltration volume from D-Hydro's results. Still, it can be verified that infiltration occurs, as the water level steadily decreases by the correct amount per hour in grassy areas without sewer system drainage, such as football fields. Therefore, it is believed that the infiltration in both models is correctly taken into account.

Table 7 - Water balance for bui09

	D-Hydro [m^3]	**Infoworks [m^3]**	**Difference**
Rainfall 2D	192706.06	226493,84	+17,5%
Rainfall 0D	36036.62	72010.93	+99.8%
Infiltration	?	41412.96	
Net boundary outflow	13709.84	58234.79	+324,7664
Inflow (weirs)	*28003.40*	-	
Outflow (pumps, weirs)	*41713.24*	-	

5.6 CORRECTION OF 0D RAINFALL

Since the 0D rainfalls of the previous section did not match, resulting in Infoworks having a larger quantity of water in the sewer system, the results offer a very skewed image of the differences between the models. In the limited time frame left for this study, it was decided to correct the mistakes made by Infoworks and D-Hydro. In Infoworks, the double areas were deleted. For D-Hydro, a script was written that pre-processed the GWSW file to sum up the list of areas per manhole. This circumvented the bug that is present in the programme. The results of this run cannot be fully explored in the remaining time, but an indication of the improved results is still given. Figure 19 shows the results of this run. It can immediately be seen that there are few extreme results anymore, as was the case for a number of locations in section 5.1.

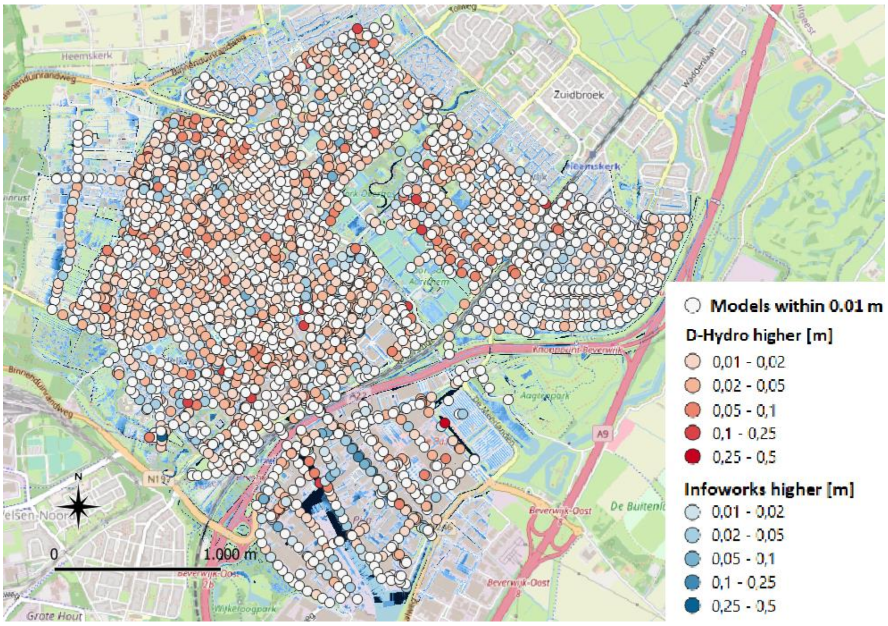


Figure 19 – Water depth comparison for corrected bui09

The RMSE for the complete city of Beverwijk for this model run is 0.022 m (0.074 with outliers). This is about a cm better than the previous result. Visually, the results line up better as well. An example is shown in Figure 20 below. The Wijkermeerweg and Noorderkade in the earlier runs displayed large differences in inundation extent and maximum water depth. The current run shows them much more similar already.

(a) D-Hydro *(b) Infoworks*

Figure 20 - Close-up of Wijkermeerweg and Noorderkade for corrected bui09

6 DISCUSSION

In the first part of this chapter, the model setup is discussed, along with main uncertainties that are introduced in this step of the process. The second part concerns itself with how the observations made in the results can be explained, answering the second part of research question 3.

6.1 MODEL SETUP

During the model setup phase, a number of modelling choices or techniques were employed that lead to structural differences between the models. Other assumptions altered the urban water system and its functioning. This section focusses on these points.

First, the major difference between the models that originated in the model setup are the different 0D rainfall volumes. Infoworks used too much rain due to a modelling error, D-Hydro used too little rain due to a bug in the software. For Deltares, the discovery of the bug is a useful result of this study, but it severely limits the possibility to draw conclusions on differences not related to model errors. Therefore, an additional study that circumvents this bug and evaluates the results in greater detail than was possible in section 5.6 is highly advised. Still, this section points out other differences that originated in the model setup process, as they are expected to also influence the results.

The second point is a main difference regarding model structure. As described in section 4.3 on the model setup, Infoworks uses an unstructured mesh, while D-Hydro uses a grid of square cells. Therefore, Infoworks will uses other sample points than D-Hydro for the interpolation of the AHN height map, resulting in small height differences between the models. These small differences are expected to be decisive in determining whether a grid cell is flooded or not in locations where very little water is present. Deltares aims to implement an unstructured mesh generator to D-Hydro as well, which will allow for an interesting future research study on the differences between D-Hydro and Infoworks.

Another note to make on the grid setup process is the coarse definition of the grid. As described in section 4.2.2, the best achievable resolution in D-Hydro was a 3x3m grid. Therefore, the Infoworks grid was matched to a similar size. However, for the purposes of a detailed study into surface water flows, a resolution of at least 1x1m was desired by Wareco. As was mentioned, the 36 data points of the 0.5x0.5 meter AHN grid are merged into 1 data point for D-Hydro's 3x3 grid. Thus, A consequence of this coarse grid size is that intricate details in the height map map are lost. All in all, the grid size and grid structure are expected to have a noticeable influence on the model accuracy and results.

A third difference mentioned in section 4.3 is that the surface level roughness was not implemented in the same way. The fact that all surface in Infoworks has the roughness coefficient of concrete makes that water flows faster across the surface, ending up in the sewer system faster. In D-Hydro, areas with grass have a greater roughness, leading to a slower flow on the surface.

Lastly, the urban water system also contains the surface water system, which was not included in the models of this study. For the comparison between the models, this should not have an extensive impact, as both models lack this system. Instead, the height map was lowered in locations of surface water. The results presented in the previous chapter clearly showed deep accumulations of water in these areas. For a more realistic view of the performance of the sewer system of Beverwijk, however, it is advised to conduct a future research with an actual surface water system included. This will also allow for another interesting point of comparison between Infoworks and D-Hydro. This also applies to including the initial water level of the surface water system.

6.2 MODEL RUN RESULTS

The integral model differences, assumptions and modelling errors or bugs can be used to explain the major differences that were described in chapter 5.

Starting with the results of the flood maps displayed in section 5.1, Infoworks calculates a larger water depth and a greater inundation extent. This is to be expected, taking into account the fact that Infoworks had 99.8% more 0D rainfall. Namely, the additional water in the 1D sewer system allows for less water from the surface to enter the system via manholes. Therefore, more flooding on the surface occurs.

When zooming in on the flood maps, it seemed that the areas in which only one of the models predicted flooding are mostly along the edges of roads, and in back yards. This is the case in the run that included the modelling error and bug, as well as the corrected run of bui09 discussed in section 5.6. This effect is largely attributed to the different grid shapes. As described in the previous section, these are expected to have an effect in areas where the water depths are small. This is the case at the edges of roads. The subtle height differences that occur due to the different grid shape cause water to accumulate in slightly different places. For back yards, the main difference occurs in that Infoworks is able to curve around buildings, as was demonstrated in section 4.3. This leads to D-Hydro and Infoworks inherently producing water in different places close to buildings, especially in back yards between buildings. Along with the different 0D rainfall volumes, this effect also partially explains the relatively low Critical Success Index (CSI) values found in this study. Because of the different structures of the grid, a thin area of disagreement will always sit around the predicted areas, causing lower CSI values. That might be an indication that the CSI is not a completely fair way to assess the correctness of D-Hydro's predictions.

Another point about the CSI that can limit its effectiveness of being a performance indicator, is seen in the fact that the greater the rainfall quantity, the better the CSI becomes. For bui09, with a "flooded area" threshold of 5 cm, the CSI results are worst. The next best is bui09 with a threshold of 2cm. Then the stress test at 5cm, and the best CSI is achieved by the stress test with a 2 cm threshold. More water on the surface in the stress test results in larger water depths, which means that there are less cells that have very little water depths. As described in the previous paragraph, these small depths can lead to different CSI values. Therefore, the CSI might not be suited well to this study, that employs two models with different grids and the slightly different height maps because of those grids.

Regarding the water depths at the manholes, Infoworks generally predicts a greater maximum, as evidenced by the RMSE and spread of the differences plotted in section 5.3. The points made earlier about 0D rainfall and grid shape are the main reason for this. Another contributing factor is the surface roughness, which allows water in Infoworks to quickly flow down to the sewer system manholes, causing quick spikes in discharges. This effect should be visible in the discharge figures presented in section 5.4. However, the varying 0D rainfall volumes largely overrule the visibility of this effect, as it causes greater discharge volumes in Infoworks's 1D system as well. This is particularly evident in the discharges of the external weirs, which are all much higher for Infoworks.

An interesting observation is that the RMSE for the stress test was higher than for bui09. The error thus seems to increase as the rainfall event becomes more extreme. The presumed reason for this is that the difference in 0D rainfall between the models also becomes bigger in a more extreme rainfall event. In bui09, the difference between D-Hydro and Infoworks was about 36 000 m^3, as was seen in the water balance in section 5.5. For the stresstest, the log file was lost, but it can be calculated using the roofing areas and rainfall intensity that the difference is about 73 500 m^3. This puts a lot of extra stress on the sewer system in Infoworks, resulting in a greater difference in water depth on the surface.

The results of the two models in the run containing the error and bug were more aligned in the area of Broekpolder. The flood depths maps were very similar and the RMSE was quite low, at 0.018 m for bui09 and 0.027 m for the stress test. The effect that the different 0D rainfall had on water depth on the surface in the rest of the city is thus not clearly visible in this area. Still, the sewer pipes and overflows showed a greater discharge here as well, so the modelling error is present. A possible explanation is that the sewer system here is able to handle the rainfall events without reaching its capacity. This means that the discharges in the sewer system can be higher for Infoworks, but that the remaining water on the surface is the same in both models, as is shown by the low RMSE. The fact that the RMSE is not closer to 0 can be attributed to the small variations in grid size, and the height differences that are caused by this.

While Broekpolder scored well on the RMSE, it performed only average on the CSI. The Oranjebuurt performed the worst of the three areas evaluated, while De Pijp scored best. This pattern holds for both rainfall events, and for the “flooded area” threshold of 2cm and 5cm as well. An explanation for the better results of De Pijp is that it largely consists of buildings that have a great surface area. This means that there is a lot of area on which no 2D rainfall occurs. As was described earlier, back yards tend to produce bad CSI results due to the different grid shapes. The harbour area of De Pijp does not have a lot of such spaces between buildings, resulting in less erroneous predictions and a better CSI.

7 CONCLUSION

In this study, the aim was to compare the new software of D-Hydro by Deltares to the existing software of Infoworks ICM by Innovyze. The following main question was posed, along with a set of guiding sub-questions:

> *How do D-Hydro's workflow and results of a sewer system modelling study in the context of Beverwijk compare to the workflow and results of Infoworks ICM?*

Based on the findings in the literature review aimed to answer the first research question, knowledge on sewer systems and accompanying modelling practices was gained that helped the construction of the two models. It provided the necessary information to understand and complete the model setup, which itself forms the answer to the second research question. The model setup resulted in insight in the workflow of both models, allowing for answering the first part of the main question:

The model setup involved all the steps necessary to construct a model in the software, and the models are capable of simulating the same elements of the urban water system. In D-Hydro, some functions cannot be accessed via the User Interface yet, so they had to be added via directly editing the model files. This made the workflow more prone to errors. Still, for the most part, the calculations seem to include these elements correctly. A few exceptions are to be made: in the version used in this study, the initial water level data is not correctly used by the calculation kernel, which should already be patched in the newer versions. However, the bug described regarding the 0D rainfall is still present in more recent updates. These conversion errors and bugs made the workflow experience of D-Hydro certainly more challenging than that of Infoworks. Luckily, Deltares was always prepared to assist on circumventing problems, and updating the software. In the end, D-Hydro will have a working User Interface that allows for all the functions to be smoothly implemented in a model.

The second part of answering the main question involved the interpretation of the model run results, which were presented as part of answering the third research question. It is unfortunate that the errors and bugs present in D-Hydro, along with modelling errors in Infoworks, led to the Infoworks model processing a lot more water than the D-Hydro model. This is the main reason that Infoworks predicted a larger inundation extent, a greater water depth and greater discharges in most locations throughout the area. As a result, it is difficult to draw conclusions on where differences in the two models occur. Smaller differences regarding surface runoff speed or infiltration are trumped by the large difference caused by the modelling error and bug. The results of the corrected run of bui09 are promising, as the RMSE dropped and fewer extreme differences were visible. All in all, this study cannot achieve the level of confidence needed to be able to conclude if D-Hydro performs similarly to Infoworks. Additional research is recommended that takes into account the errors and bugs, and examines the results of these runs in more detail than could be achieved in section 5.6. Still, the opportunity of working with D-Hydro has allowed Wareco to experience what this model will be like, and has allowed Deltares to learn a lot about the performance of their software in the context of a large sewer system modelling study.

8 RECOMMENDATIONS

To allow for a more accurate comparative study that achieves results that are even more relevant to discovering differences in the performance of D-Hydro and Infoworks, the following recommendations can be taken into account.

- It is recommended to perform a model run that is not affected by the D-Hydro modelling bug or Infoworks modelling errors. This seems trivial, but extensive checking and validation of the models should be carried out to make sure that both models use the same volume of precipitation, or that other differences due to modelling errors are filtered out. This is because D-Hydro is still in development, so unpredicted behaviour can occur, and human modelling errors in such complicated software are easily made.
- Both models should take into account the surface roughness in the same way: either use the detailed roughness map, or a uniform roughness. This can affect the flow of water across the surface and determine with what speed the water flows to the sewer system.
- The inclusion of a surface water system makes the models more complex, but it offers an interesting view in the performance of D-Hydro compared to Infoworks. One of the reasons for this, is that the water levels in the surface water system can determine the outflow of a sewer system overflow. D-Hydro should already be able to incorporate the surface water system into its models, so it is a logical step to increasing the accuracy of the model.
- Using a grid of a smaller size in both models can improve the accuracy of the height map, which will have effects on the flow of water. If the generation of a smaller grid size is possible in D-Hydro, it its recommended to use this feature and compare to Infoworks using this greater definition.

REFERENCES

Atlas Leefomgeving. (2019, March 15). *Platte daken in Nederland (BAG).* Retrieved from www.atlasleefomgeving.nl/: atlasleefomgeving.nl/platte-daken-in-nederland-bag

Ball, M. (2014, December 31). *Innovyze Retires InfoWorks SD in Favor of More Powerful Next-Generation InfoWorks ICM Collection Systems Modeling Software*. Retrieved from https://informedinfrastructure.com/12326/innovyze-retires-infoworks-sd-in-favor-of-more-powerful-next-generation-infoworks-icm-collection-systems-modeling-software/

Baronio, F., Chabchoub, A., Esler, G., Field, J., Gaskell, J., Hewitt, I., . . . Franklin, J. (2018). *Hydraulic Modelling of Collection Networks Study Group 2: Maths Foresees project report.* Sweco.

Butler, D., & Schütze, M. (2005). Integrating simulation models with a view to optimal control of urban wastewater systems. *Environment Modelling & Software*, 415-426.

Clemens, F., Van Esch, K.-J., Poppen, J., Stolker, H., & Brouwer, W. (2009). *Module Riolering.* The Hague: KIVI.

Cruz, A., Warns, E., Bos, R., & van der Eem, H. (2017, April). *Verbinden met water: water- en rioleringsplan Beverwijk en Heemskerk.* Retrieved from www.heemskerk.nl: https://www.heemskerk.nl/fileadmin/decos/public/216BF0AF1DF6DC4C81A132C157B3B017/OVERDOC/Water%20en%20Rioleringsplan%20vHeemskerk%20DEF_1.pptx.pdf

De Feo, G., Antoniou, G., Fardin, H. F., El-Gohary, F., Zheng, X. Y., Reklaityte, I., . . . Angelakis, A. N. (2014). The Historical Development of Sewers Worldwide. *Sustainability*, 3936-3974.

De Toffol, S. (2006). *Sewer system performance assessment – an indicators based methodology.* Innsbruck: Leopold Franzens Universität Innsbruck.

Deltares. (2019). *D-HYDRO Suite*. Retrieved from deltares.nl: https://www.deltares.nl/nl/software/d-hydro-suite/

FU Berlin. (2009, August 24). *Infiltration rate*. Retrieved from Freie Universität Berlin: https://www.geo.fu-berlin.de/en/v/geolearning/glossary/infiltration_rate.html

Henckens, G. (2019). *Onderzoeksvoorstel D-HYDRO urban-rural.* Amstelveen: Wareco.

HHNK. (2007). *Schoon water van duin tot meer: Regionaal Waterplan Beverwijk, Heemskerk en Uitgeest.* Heerhugowaard: Hoogheemraadschap Hollands Noorderkwartier.

HHNK. (2019, May 20). *HHNK Klimaatatlas*. Retrieved from hhnk.nl: https://hhnk.klimaatatlas.net/

Lim, N. J., & Brandt, S. A. (2019). Are Feature Agreement Statistics Alone Sufficient to Validate Modelled Flood Extent Quality? A Study on Three Swedish Rivers Using Different Digital Elevation Model Resolutions. *Mathematical Problems in Engineering*.

Liu, Y., & De Smedt, F. (2004). *WetSpa Extension, A GIS-based hydrologic model for flood prediction and watershed management.* Brussel: Vrije Universiteit Brussel.

Moody, J. (2019, September 5). *What does RMSE really mean?* Retrieved from https://towardsdatascience.com/: https://towardsdatascience.com/what-does-rmse-really-mean-806b65f2e48e

Rauch, W., Bertrand-Krajewski, J.-L., Krebs, P., Mark, O., Schilling, W., Schuetze, M., & Vanrolleghem, P. (2002). Mathematical Modelling of Integrated Urban Drainage Systems. *Water Science & Technology*, 81-94.

Rioned. (2007, August 22). *Klimaatverandering, hevige buien en riolering; visie van Stichting RIONED.* Retrieved from riool.net: https://www.riool.net/c/document_library/get_file?uuid=c4bdd91f-179a-4f9b-bab9-cec32e7d27a3&groupId=20182&targetExtension=pdf

Rioned. (2017, April 1). *Grootschalige extreme buien op komst*. Retrieved from rioo.net: https://www.riool.net/grootschalige-extreme-buien-op-komst

Rioned. (2019, Januari 2). *Bui01 - Bui10*. Retrieved from riool.net: https://www.riool.net/bui01-bui10

Rioned. (2019, March 1). *Defaultwaarden inloopparameters inloopmodellen*. Retrieved from riool.net: https://www.riool.net/defaultwaarden-inloopparameters-inloopmodellen

Rioned. (2019, November 1). *Maaiveldmodel met rioleringsmodel*. Retrieved from riool.net: https://www.riool.net/maaiveldmodel-met-rioleringsmodel

Rosenzweig, C., Solecki, W., Hammer, S., & Mehrotra, S. (2011). *Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network.* Cambridge: Cambridge University Press.

Sier, R., & Osborne, M. (2019). Do we need to change the way that we model runoff? *Urban Drainage Spring Conference.* Birmingham: CIWEM.

U.S. Geological Survey. (2018, July 23). *Flood Inundation Mapping Science*. Retrieved from usgs.gov: https://www.usgs.gov/mission-areas/water-resources/science/usgs-flood-information

Vanrolleghem, P., Benedetti, L., & Meirlaen, J. (2005). Modelling and real-time control of the integrated urban wastewater system. *Environmental Modelling & Software*, 427-444.

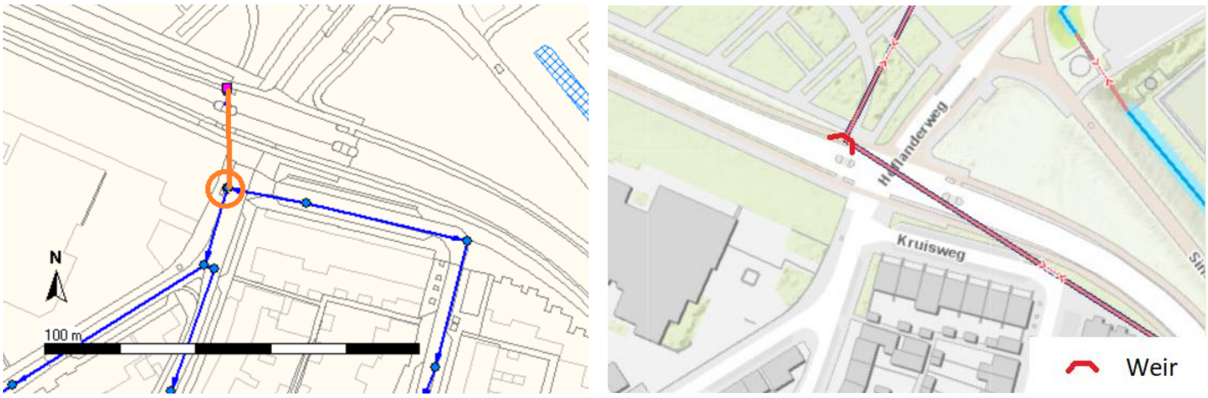
Werkgroep standaardisatie stresstest wateroverlast. (2018). *Standaardisatie neerslaggebeurtenissen stresstest wateroverlast.* Retrieved from library.wur.nl: https://edepot.wur.nl/462352

WUR. (2006). *Grondsoortenkaart.* Retrieved from Wageningen University and Research: https://www.wur.nl/en/show/Grondsoortenkaart.htm

APPENDIX A – SOBEK MODEL CHANGES

A.1 CULVERT REMOVAL

The existing Sobek model of Beverwijk contains various systems of culverts. The model that is needed for this study should only concern the sewer system. Therefore, culverts are removed, as they are part of the surface water system. The following modifications were made regarding these culverts.



Location: Hoflanderweg – Vennelaan

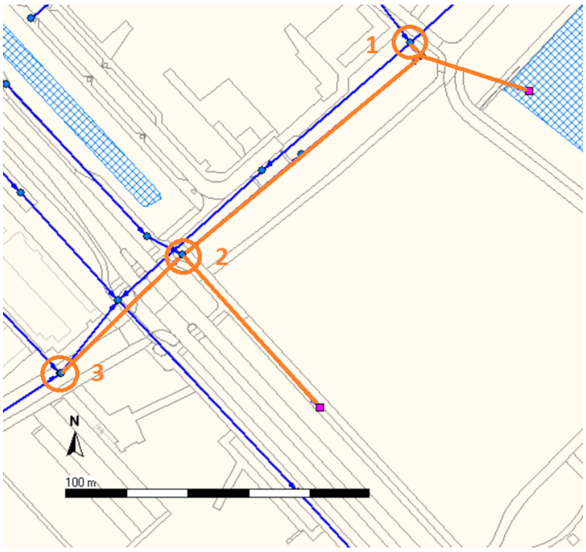
The highlighted branch is deleted. The circled manhole is replaced with an external weir. The data is adapted from the internal weir that was in the model: weir width of 1.84 meters, crest level at 1.2 meters. The boundary condition of the external weir is set to the water level in the culvert that it connects to, seen in the right picture. Assuming that the sewer connects south of the weir, this is -0.1 meters.

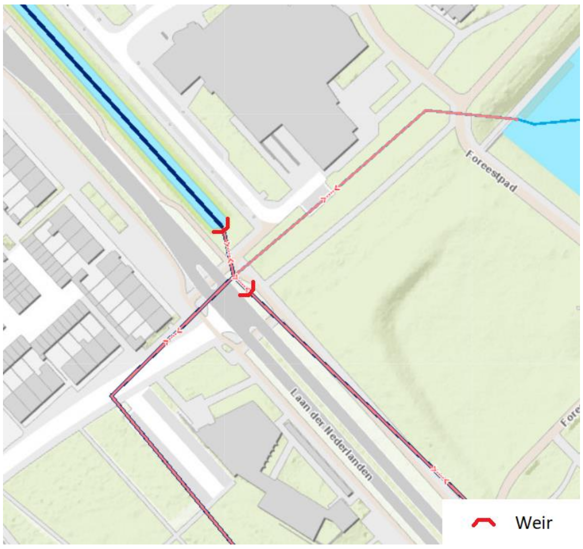
Location: Alkmaarseweg – Plesmanweg

All highlighted branches are deleted. The three circled manholes are replaced with external weirs:

1. Weir width of 0.75 m. Crest level at 1.99 m
2. Weir width of 1.1 m. Crest level at 2.19 m

The boundary condition is set to the water level in the culvert. As the weirs in the image on the right show, this water level equals that of the body of water in the north, at 1.55 meters.



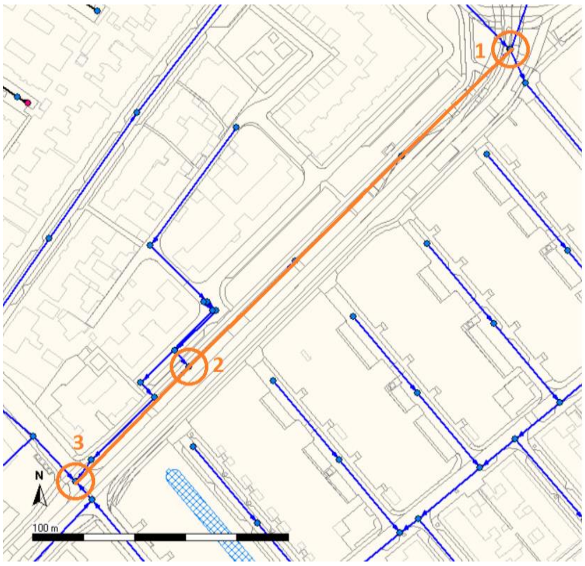


Location: Laan der Nederlanden – Heemskerkerweg

All highlighted branches are deleted. The three circled manholes are replaced with external weirs:

1. Weir width of 5.4 m. Crest level at 0.46
2. Weir width of 5 m. Crest level at 0.22
3. Weir width of 2.3 m. Crest level at 0.9

The boundary condition is set to the water level in the culvert, between the two weirs displayed on the right. This water level is 0 m.

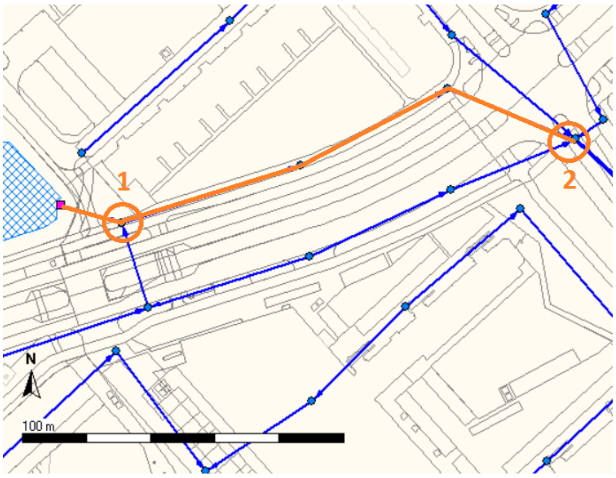


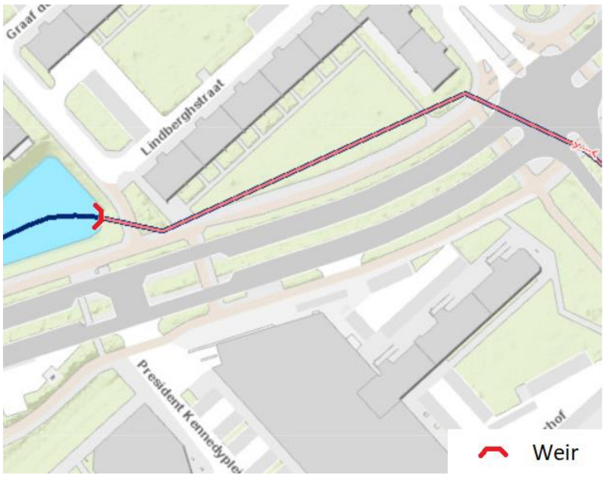
Location: Wijk aan Duinerweg

All highlighted branches are deleted. The three circled manholes are replaced with external weirs:

1. Weir width of 1.1 m. Crest level at 2.19 m
2. Width set to connected link diameter: 0.2 m
   Crest level set to invert level of link: 1.43 m
3. Weir width of 2.05 m. Crest level at 1.95 m

The boundary condition is set to the water level in the culvert: 1.55 m





Location: Laan der Nederlanden – Plesmanweg

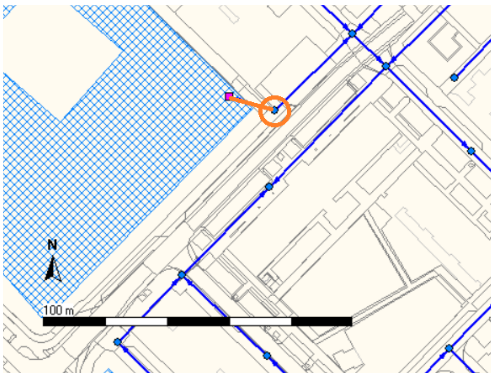
All highlighted branches are deleted. The two circled manholes are replaced with external weirs:

1. Width set to connected link diameter: 0.3 m
   Crest level set to invert level of link: 0.35 m
2. Width set to connected link diameter: 0.3 m
   Crest level set to invert level of link: 0.18 m

The boundary condition is set to the water level in the culvert, behind the weir. This is 0.5 m.

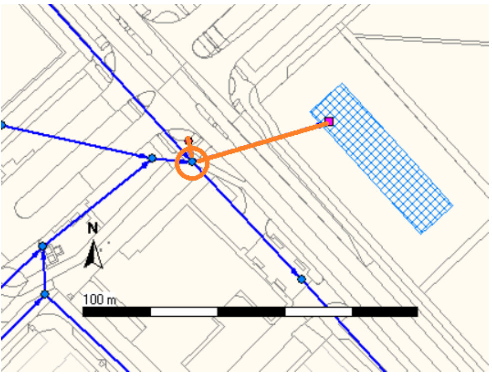
Location: Italiëlaan

The highlighted branch is deleted. The circled manhole is replaced with an external weir. The data is adapted from the internal weir: weir width of 1 meters, crest level at -1.17 meters. The boundary condition is set to the water level of the pond: -1.6 m



Location: Laan der Nederlanden – Beneluxlaan

The highlighted branch is deleted. The circled manhole is replaced with an external weir. The data is adapted from the internal weir: weir width of 2.2 meters, crest level at -0.67 meters. The boundary condition is set to the water level of the pond: -1.3 m



A.2 MISSING SECTIONS

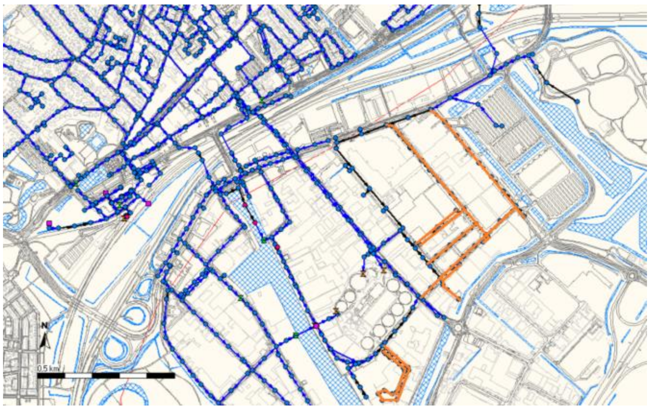
A couple of sections were incorrect or missing. This was the case for the following areas.

Location: Noordwestelijk Tuinbouwgebied

All highlighted branches are part of the foul water system. They were replaced by their rainwater counterparts using the municipal data system Kikker.

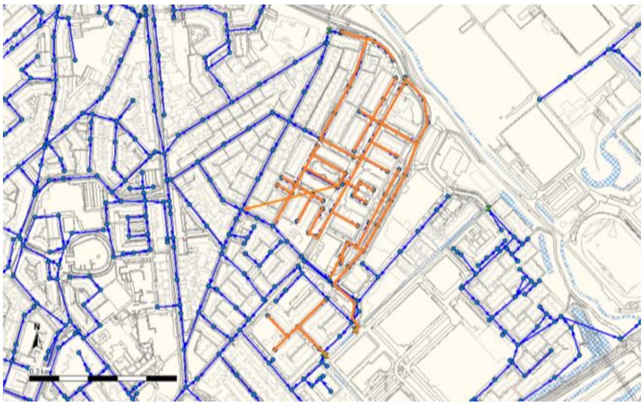
Location: de Pijp

All highlighted branches are part of the foul water system. They were replaced by their rainwater counterparts using Kikker



Location: Oranjebuurt

All highlighted branches were not present in the original Sobek model. They were added using Kikker.

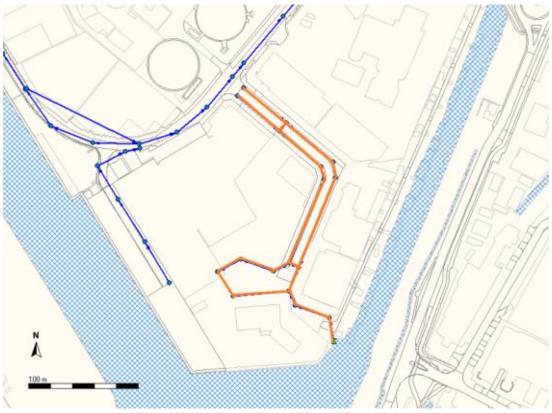


Location: Broekpolder

All highlighted branches were not present in the original Sobek model. They were added using Kikker.

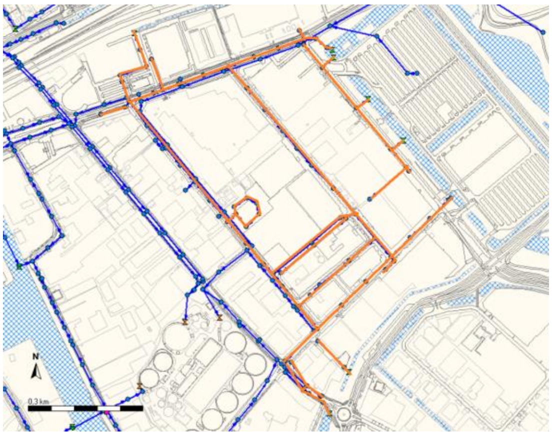
A.3 ROOFING AREA ALLOCATION

The following areas were allocated roofing areas using QGIS. The buildings have mostly flat roofs, and the total area marked in yellow is divided over the sewer pipes highlighted in orange proportional to their length.

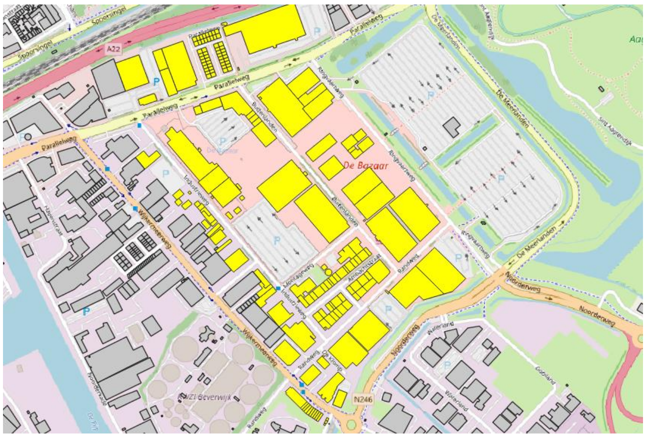


Location: Nijverheidsweg

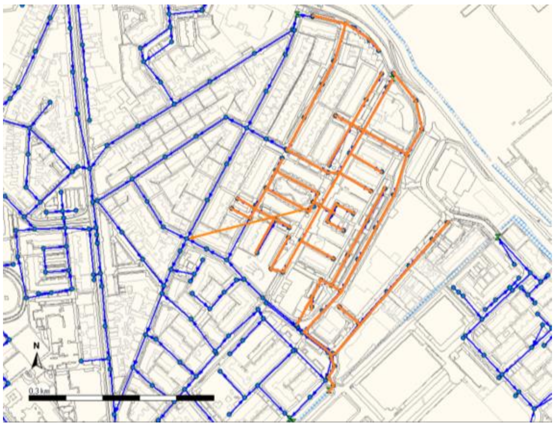
Area distibuted: 14088 m^2 of flat roof



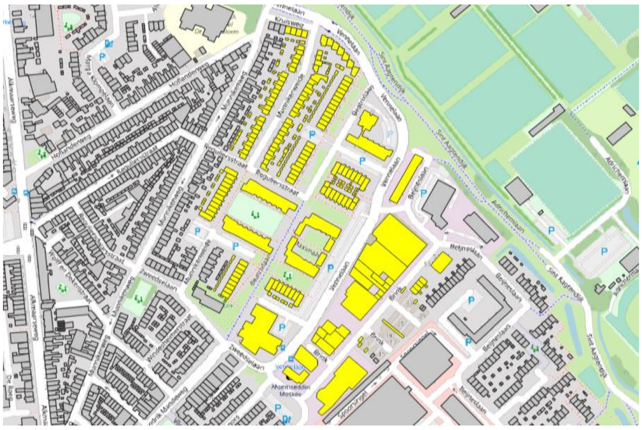
Location: De Pijp



Area distibuted: 146560 m^2 of flat roof

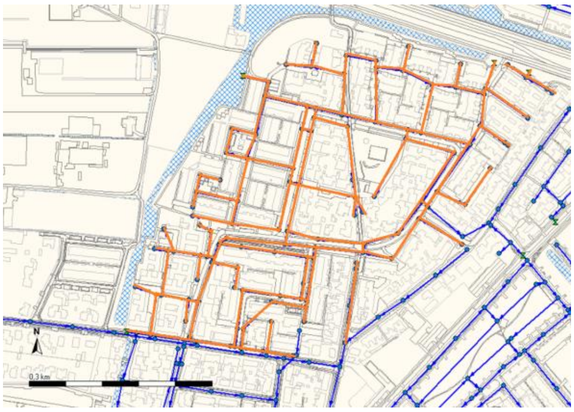


Location: Oranjebuurt



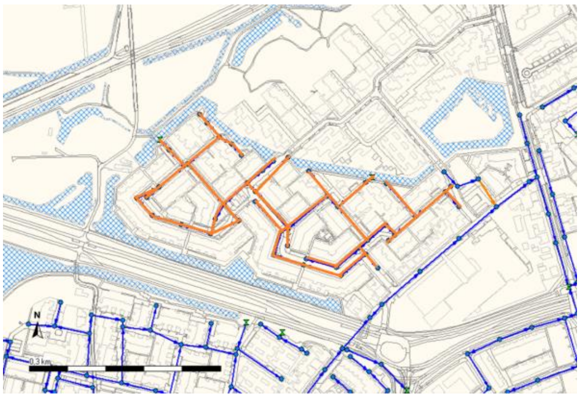
Area distibuted: 25904 m^2 of flat roof.

The following areas do not have fully flat roofs. Therefore, a ratio of 44% flat and 56% sloping roofs is used (Atlas Leefomgeving, 2019). This is derived from the municipality of Heemskerk, instead of Beverwijk. For Beverwijk, the ratio is 69% flat and 31% sloping. Using Google Earth, it could be seen that this ratio is not representative of the neighbourhoods below. The reason for the high percentage of flat roofs is the large buildings at Tata steel. The mostly residential municipality of Heemskerk, which borders Beverwijk to the north, seemed a better fit.



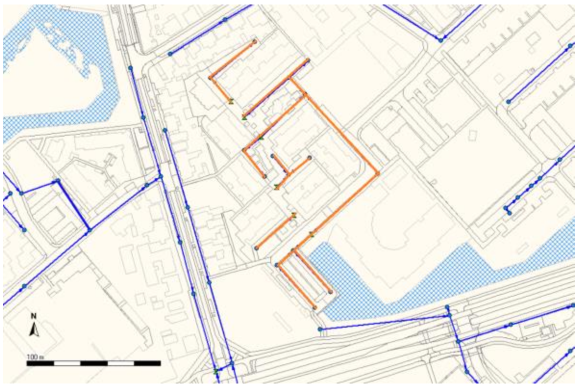
Location: Noordwestelijk Tuinbouwgebied

Area distributed: 18980 m^2 flat, 24156 m^2 sloping

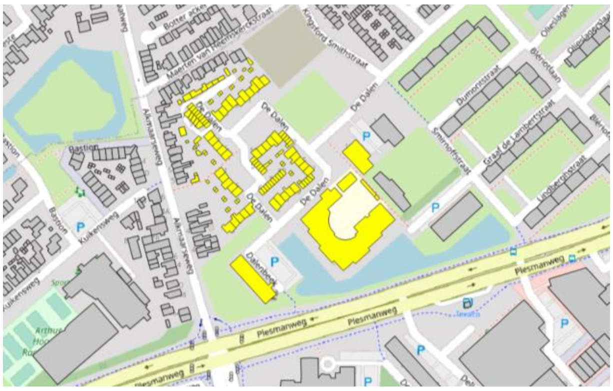


Location: Noordwestelijk Tuinbouwgebied

Area distributed: 8369 m^2 flat, 10651m^2 sloping



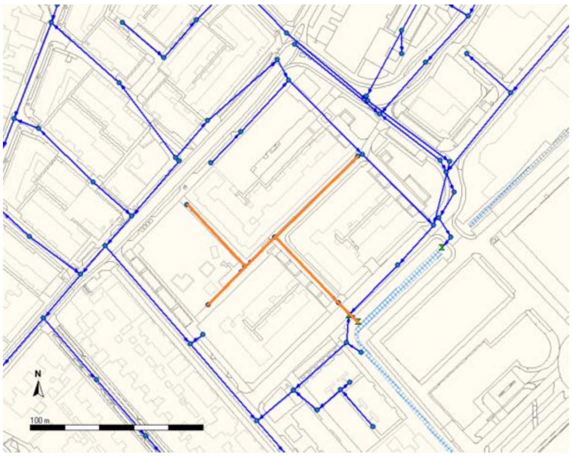
Location: Noordwestelijk Tuinbouwgebied



Area distributed: 3375 m^2 flat, 4296 m^2 sloping

Location: Broekpolder

Area distributed: 65896 m^2 flat, 83867m^2 sloping



Location: Oranjebuurt

Area distributed: 1131 m^2 flat, 1439 m^2 sloping

APPENDIX B – BGT SURFACE

Table 8 - Manning roughness allocated to different BGT surfaces

Surface type	Manning roughness coefficient [s/m$^{1/3}$]
Closed pavement	0.011
Open pavement	0.013
Unpaved	0.2
Swamp	0.5
Bushes	0.5
Reed beds	0.5
Decidious forest	0.5
Mixed forest	0.5
Arboriculture	0.5
Agricultural field	0.1
Grassland	0.1
Urban green spaces	0.1

APPENDIX C – RMSE OUTLIERS

Table 9 - Differences of outliers from RMSE calculation. Calculated by subtracting D-Hydro's water depth from Infoworks

Manhole id	Stress test [m]	Bui09 [m]	Corrected bui09 [m]
1910RW001	-1.17	-1.00	0.62
2690RW020	-1.85	-1.81	-0.89
2690RW024	-1.88	-1.94	-1.94
2910RW001	-1.06	-0.50	-0.45
3020RW001	-1.42	-1.48	-1.95
3020RW005	-0.96	-0.96	-0.48
3020RW009	-1.22	-1.34	-0.88
3090RW001	-1.04	-0.99	-1.77
3920RW009	0.66		
6-N10	-0.41		-1.30
6-O164	-0.83	-0.64	
6-P43B	0.77	0.37	
6-S019001	1.62	1.13	0.63
6-W002004	-0.45		
6-W031002	-0.82	-0.57	-0.52
6-W031003	-1.23		