Analysis of the bottlenecks in the existing sewage system of Zolder

Elin olde Heuvel - 5th of July, 2022

antea group

UNIVERSITY OF TWENTE.

Internal supervisor: dr.ir. J.H. Damveld
External supervisor: R. Wuyts
Second Assessor: ir. R.N.F. Sloot

Bachelor Thesis report
Bachelor Civil Engineering, Faculty Engineering Technology
Ghent, Belgium 2022

Preface

In this document I present my final version of my Bachelor's Thesis report, titled 'Analysis of the bottlenecks in the existing sewage system of Zolder'. This report describes in detail the process and results obtained during the execution of my Bachelor's assignment at Antea Group Belgium, and is the lest step in fulfilling the Civil Engineering Bachelor's program at the University of Twente. I have conducted the assignment in the period of April until the beginning of July 2022. During this period I have learned a lot about the sewage system of Zolder, located in the East of Belgium, and gained valuable knowledge about the sewage engineering practice in general.

I would like to thank my colleagues at the Antea Group office in Ghent, for welcoming me into their team and helping me with their expertise during my Bachelor's assignment activities. Specifically, I would like to thank Rob Wuyts, my supervisor at Antea Group, for sharing his knowledge of the sewage engineering field with me and for being a daily support in conducting this study and writing the report. In addition, I would like to thank my supervisor at the University of Twente, Johan Damveld, for supporting my process in finalizing this report. Especially, for the feedback on my research proposal and this Bachelor's Thesis.

I hope you will enjoy reading this final version of my report.

Elin olde Heuvel - Enschede, 5th of July 2022

Summary

The effects of climate change have large impacts on how water is being handled in urban living spaces. Over the past years, it has become apparent that the increasing temperature on earth is causing more extreme weather events. This also has a direct impact on the severeness of rainfall events and how they can cause nuisance in dense urban areas. Increased amounts of heavy rainfall events have significant impacts on water management in urban living spaces, specifically when it comes to the management of sewage systems. In Flanders, the optimization of several sewage systems has become an important topic to prepare for the expected extreme weather events. An important tool for these optimizations is the use of sewage modelling.

In this study, an existing sewage system in Zolder (Belgium) will be evaluated using sewage modelling, to make possible improvements possible. The aim can be formulated as follows: Identifying and assessing the bottlenecks in the sewage system of Zolder by means of a model of the existing situation and criteria for identifying the bottlenecks. In addition, initial solutions will be proposed to resolve the bottlenecks in the system.

To evaluate the sewage system of Zolder, a model of the existing situation has been built using the software Infoworks ICM. The model was mainly based on the information that had been provided through the database. This database had been set-up before the start of this study. The model consists out of three components: The network, catchment and boundary conditions. The network was based on the objects in the system like manholes, pipelines and hydraulic structures. The catchment included the modelling of the runoff areas and wastewater in the study area. As for the boundary conditions, incoming and outgoing flows were taken into account in the model.

The criteria used for identifying the bottlenecks were based on criteria stated in the Code of Good Practice (Coordinatiecommissie Integraal Waterbeleid, 2012). This document states the design requirements for sewage systems in Flanders. The criteria were focused on identifying capacity bottlenecks by evaluating the sewage system based on flooding and activation of Combined Sewers Overflows. In addition to the bottleneck analysis, a validation was carried out to determine the accuracy of the model and the credibility of the results. The validation results showed that the model is able simulate the same large bottlenecks that are known according to historical data. The analysis of the bottlenecks showed that the sewage system of Zolder does suffer from a lack of capacity. There are bigger areas of flooding and the majority of the CSOs are activated too often. The biggest pressure is built up at the most downstream point of the sewage network, namely at the RWZI (sewage treatment plant). In general, the solutions to resolve these issues should be focused on creating more delay of the flow throughout the system and increasing the capacity at the flooding locations.

All in all, the study concludes that a proper model of the sewage system of Zolder has been built, which is able to identify the large bottlenecks. Further improvements can be made in the model, mainly by filling up the gaps in the data available about the system. In addition, the model should be validated as well on a quantitative basis, using present-day measurements. The specific solutions proposed in the study should be evaluated in a new version of the model for the future situation.

Contents

List of Figures

List of Tables

1 Introduction

The disposal of sewage water directly into the environment has been proven numerous times to have negative impact on nature and humans. In El Jadida, Morocco, a study has concluded that the drainage of untreated wastewater in the ocean caused spreading of Ascariasis, a parastic disease, among children that lived near the ocean (Lamghari Moubarrad et al., 2007). On Faial Island in Portugal, the contamination of beach sand due to a leaking sewage system underground has been proven to cause skin rashes amongst beach visitors (Brandao et al., 2020). Especially in dense urban areas, it has been proven that wastewater can contain high levels of bacteria, viruses and pathogens that can induce sickness under the population (Andersson et al., 2016). Therefore, the implementation of robust sewage systems to drain and treat wastewater safely from urban areas have been an important step in wastewater management.

In the upcoming decades, the current system of wastewater management will be challenged by the impacts of climate change. Most urban areas have combined sewage systems, that are not designed for extreme rainfall events caused by global warming. In these cases high amounts of stormwater can cause the discharge of diluted sewage water directly into open surface water (Curriero et al., 2001). The impact of excess stormwater has already proven to increase the risk of sewage contamination with the release of bacteria and pathogens (Olds et al., 2018).

To reduce the risks of wastewater contamination due to overburdening of combined sewer systems, the implementation of separate systems for the drainage of wastewater and stormwater has become more prominent (Otterpohl et al., 1997). Also more principles for sustainable ways to handle stormwater in urban areas have become important, like water sensitive urban design (Wong, 2006). However, despite these scientific efforts, the implementation of new sewage infrastructure has been difficult. The main reason for this being the cost and difficulty of innovation of the new infrastructure which has resulted in a sewage engineering lock-in (Eijlander & Mulder, 2019). In addition, sewage is not the most popular topic amongst decision-makers, which causes the topic to not have the highest urgency (Mulder, 2019).

1.1 Sewage management in Flanders

In Flanders, the Northern part of Belgium, the influence of climate change is posed as an important challenge in the field of sewage engineering. The capacity and functionality of existing sewage systems are being re-evaluated based on more intense design rainfall events (Willems, 2014). In addition, the vision for the design of robust sewage systems has been changed. Initially, sewage systems have been designed to limit flooding and the use of Combined Sewer Overflows, that drain sewage water directly into the environment when the capacity of the system is too low. In the last two decades the focus has shifted to the design of sewage systems where rainwater is separately drained from wastewater, to limit the dilution of sewage water (Van Assel & Dirckx, 2007). A high dilution in a sewage system is considered to have several negative effects (Vlaamse Milieumaatschappij, 2019):

- The purifying efficiency of a sewage treatment plant will be lower. In Flanders a sewage treatment plant is referred to as a RWZI (Rioolwaterzuiveringsinstallatie).
- The operational costs of pumping the sewage water through the pipeline system will increase due to the larger volume of the sewage water.
- More frequent use of Combined Sewers Overflows, which means that due to high volume of sewage water, the water is being drained to the environment without being treated.

To boost the transition to sewage systems that can sustain the effects of climate change in Flanders, sewage models are used as a tool to evaluate existing sewage systems and to simulate the effectiveness of proposed innovations. The company Antea Group in Belgium has already performed multiple studies that include sewage modelling and the innovation of existing systems. Antea Group carries out these studies commissioned by the Vlaamse Milieumaatschappij, an organisation that looks after the state of the environment in Flanders. Sewage modelling studies by Antea Group are performed according to a set-out procedure documented in the Hydronautprocedure 7.0

(Aquafin, 2017). This procedure has been established by Aquafin, a company that functions as a regional sewage manager. According to this procedure, a study contains three phases, to evaluate and improve the sewage system:

- Phase 1: Setting up a database
- Phase 2: Evaluation of existing situation
- Phase 3: Evaluation of new situation

During phase 1, all information about the sewage network that should be investigated is gathered and organized. Usually, an initial assessment of the bottlenecks in the system can be carried out by using the gathered information. This can be based on statistics or experiences of the sewage system. During phase 2, the database is used to create a model of the existing situation of the sewage system and this model is used to identify the bottlenecks of the system in a more holistic manner. After the bottleneck assessment of phase 2, solutions are proposed and will be used to create a model that incorporates the solutions. In this way the effectiveness of the solutions can be assessed, and projects can be established to implement the solutions.

1.2 Study area

In this sewage study, the study area is called Zolder and is located in the lower part of the municipality of Heusden-Zolder. In figure 1, the exact location of the study area in Flanders is presented by means of the white line. The demarcation of the study area is based on what parts drain to the RWZI of Zolder.

Figure 1: Study area Zolder *(Determined by Aquafin, 2019)*

The sewage system in the study area is mainly a combined system and therefore aims to drain wastewater and stormwater from Zolder. The system is connected to the RWZI of Zolder and suffers from a capacity problem. The capacity is designed for 13500 IE, while there is 15500 IE connected to the system (Aquafin, 2019). In addition, it has been concluded that the wastewater in the system is highly diluted due to high amounts of parasitic water. It is estimated that around 40-50% of the water in the system is parasitic water (Aquafin, 2019). In figure 2 the dilution index per part in Flanders has been mapped. As can be seen, the dilution index is the lowest in the whole of Flanders (Vlaamse Milieumaatschappij, 2019). A low dilution index indicates a high dilution of the water in the sewage system caused by parasitic water.

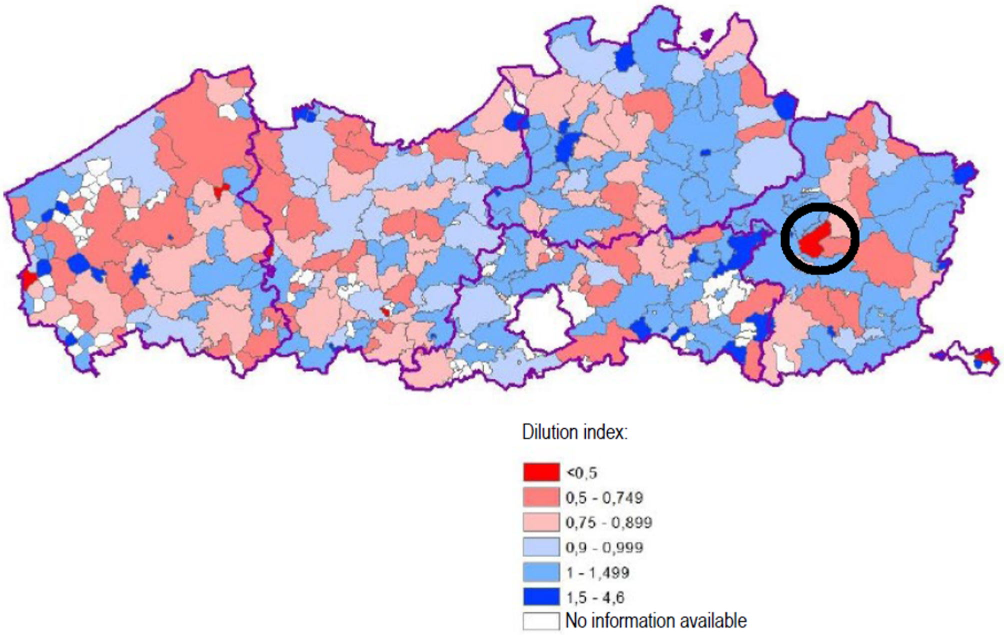


Figure 2: Dilution index in Flanders (Vlaamse Milieumaatschappij, 2019), the study area of Zolder has been marked by the black circle

Parasitic water entering the sewage system and causing dilution is caused by the seeping in of water, which could come from groundwater or surface water (Dirckx et al., 2019). In the case of the Zolder sewage system, the cause of the high level of dilution is believed to be partly caused by the old mine site in the North-East of the study area (Aquafin, 2019). During heavy rain events, the old mines fill up with stormwater and excess groundwater. Since this can cause subsidence of the ground, pumps have been installed to pump the excess water out of the mines. In case of lacking drainage capacity, this water is being drained to the sewage system of Zolder.

During the establishment of the database that has been finished before the beginning of this study, a few bottlenecks have been found in the sewage system. This preliminary analysis also concluded that most of the bottlenecks in the system are related to dilution. The major problems in the sewage system can be summarized as follows according to this analysis:

- Lacking capacity of the system to drain the wastewater and stormwater from the study area, which causes flooding of streets
- Inlets from ditches or streams that contain solely rainwater to the sewage system, causing dilution
- Pumps that belong to mine sites that pump rainwater or ground water from the mines into the sewage system
- Malfunctioning of CSOs due to high water in ditches or streams

In Appendix A, an overview of the specific bottlenecks identified in phase 1 is given in table 7. This overview contains the location of the problem defined by the Node ID, the category of the bottleneck and a description.

1.3 Problem statement

From previous research conducted by Aquafin, the Vlaamse Milieumaatschappij and Antea Group it can be concluded that the sewage system in Zolder has a dilution problem. Too much parasitic water is entering the sewage system which limits the capacity of the combined sewer system and causes negative environmental and economic effects.

1.4 Research objective & questions

The research objective is to identify and assess the bottlenecks in the sewage system of Zolder by means of a model of the existing situation and criteria for identifying the bottlenecks. In addition, initial solutions will be proposed to resolve the bottlenecks in the system.

To be able to achieve the research objective, several questions will lead the proposed study:

1. **How is the sewage system of Zolder structured?**

   The structure of the sewage system of Zolder will consist of the network, catchment and boundary conditions. Once the components of the system have been understood, the structure of the sewage system will be modelled in a software called Infoworks ICM. The modelling will be done according to the Hydronautprocedure 7.0 (Aquafin, 2017).

2. **What is the validity of the model results in the existing situation?**

   A validation of the model will be carried out using historical events of experienced sewage flooding during intense rainfall. This validation can be characterized as a qualitative analysis.

3. **What criteria should be taken into account for identifying bottlenecks in the sewage system of Zolder?**

   During the study, the criteria will be established based on the knowledge of experts, specialized in sewage system studies and literature.

4. **What bottlenecks can be identified using the defined criteria?**

   The results from the model of the existing situation will be used to determine on what locations the criteria for bottlenecks are met.

5. **What solutions can resolve the bottlenecks in the sewage system of Zolder?**

   The solutions for the bottlenecks will be based on solutions that have been effective for other study areas and literature.

A more detailed description of the methods used to reach the research objective and to answer the research questions can be found in Chapter 3.

1.5 Research scope

As has been mentioned before, a sewage study consists of three phases according to the Hydronautprocedure 7.0 (Aquafin, 2017). These phases include: setting-up a database, evaluating the existing situation and evaluating the proposed situation. In this thesis, the research objective is strictly limited to phase 2: the evaluation of the existing sewage system. This means that the database has already been finalized by Antea Group and that the thesis encompasses setting up the model of the existing situation, validating the model, an analysis of the bottlenecks and proposing possible solutions. The proposed solutions will be evaluated by Antea Group itself, after the this thesis has been concluded at the end of July 2022.

As for the bottlenecks, the studied is only focusing on bottlenecks that are located within the specified study area. In addition, the results are focused on identifying bottlenecks caused by lack of capacity and dilution. This means that structural errors of the system that cause bottlenecks in the system are not being taken into account.

1.6 Reading guide

This report starts with a theoretical framework that is described in Chapter 2. The theory encompasses the most important aspects of sewage engineering in Flanders that are necessary to understand the methodology of the study. The research methodology can be found in Chapter 3, shortly followed by an elaboration on the model implementation in Chapter 4. After this the results of the study are presented in Chapter 5 and 6, with Chapter 5 focusing on flooding bottlenecks and Chapter 6 elaborating on the Combined Sewers Overflows bottlenecks. Chapter 5 also includes the validation of the model based on historical data. After the results are presented, the uncertainties, limitations and possible improvements of the model and study are discussed in Chapter 7. The study concludes with Chapter 8, where the conclusion and recommendations are described.

2 Theory

In this chapter, a short overview is given about sewage systems and modelling in Flanders, to provide better understanding of the methods used in this study.

2.1 Sewage systems

In Flanders, three categories of water streams present in urban areas are distinguished in the sewage engineering field (Vlaamse Milieumaatschappij, 2019):

1. Wastewater: All liquid waste caused by households, commercial activity and industries, which should be treated in a sewage treatment plant.
2. Stormwater: Runoff water caused by rain, which is considered to be clean and therefore it is not necessary to treat stormwater in a treatment facility.
3. Parasitic water: Water that is per definition not wastewater or stormwater, and therefore does not belong in the system. The cause is usually open-surface water or groundwater seeping into the sewage system.

Sewage systems have the purpose of draining wastewater and stormwater from urban areas through a network of pipelines and hydraulic structures. This can be done through a combined or separated system (Coordinatiecommissie Integraal Waterbeleid, 2012).

The water from a sewage system that contains wastewater is drained to a sewage water treatment facility. In Belgium this is defined as a 'rioolwaterzuiveringsinstallatie' (RWZI). The amount of wastewater in the sewage system can be expressed in the amount of 'inwonersequivalent' (IE). This refers to the amount of liquid waste that one person produces per day (Vlaamse Milieumaatschappij, 2019).

2.1.1 Combined sewage system

Most sewage systems in Flanders are combined, which means that wastewater and stormwater are drained in the same pipeline network. In figure 3 an illustration of how a combined system in an urban area functions is illustrated. During dry weather the system only drains wastewater and during rainfall events a mix of stormwater and wastewater. Usually, streets and roofs are directly connected to the combined sewage system to drain the stormwater.

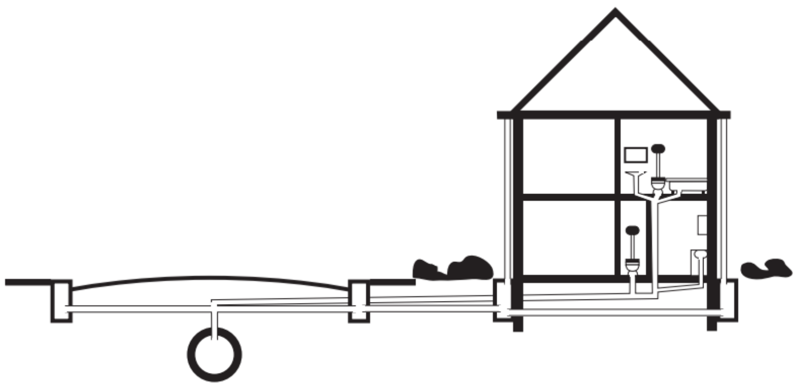


Figure 3: Illustration of a combined sewage system

An important aspect of a combined sewage system is a Combined Sewers Overflow (CSO). This is an hydraulic structure, that drains sewage water directly into the environment through an outlet when a certain limit capacity of the system has been reached. This usually occurs during very intense rainfall events when the sewage system has to accommodate a big share of stormwater. In figure 4, the functioning of a CSO is demonstrated. As can be seen, a CSO usually looks like a type of dam in a pipe or manhole.

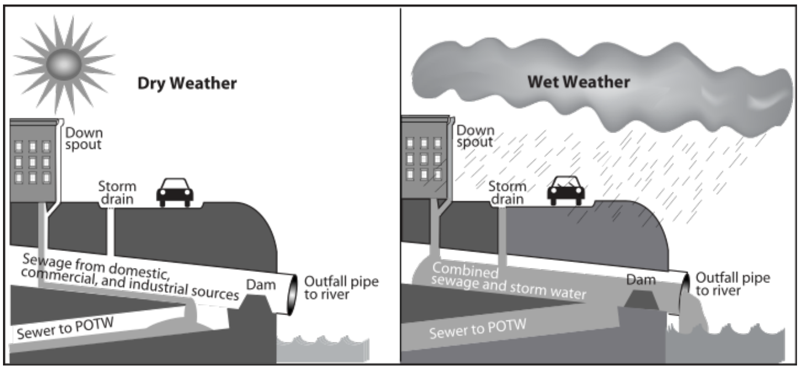


Figure 4: Illustration of a Combined Sewers Overflow, from (U.S. Environmental Protection Agnecy, 2004)

A combined sewage system has several drawbacks because of the fact that a relatively clean flow of water (stormwater) and a polluted stream of water (wastewater) are being mixed in the system (Coördinatiecommissie Integraal Waterbeleid, 2012). The biggest drawback occurs during the intense rainfall events, when untreated sewage water is being drained into the environment through the CSOs, which causes pollution. In addition, the effectiveness of the RWZIs is lower since the stormwater is also being treated, after it has been mixed with the wastewater. Lastly, when the capacity of the sewage system has been breached even with the functioning of the CSOs, streets will be flooded with sewage water that contains wastewater and toilets could function poorly.

2.1.2 Separated sewage system

A rather new type of sewage system is a system in which wastewater and stormwater are drained in separate sewage networks. This is called a separated sewage system, and has the aim of keeping the stormwater clean and draining it back to the environment directly, instead of mixing it with wastewater and treating it in a RWZI. In figure 5, an illustration of a separated system in an urban area is provided. As can be seen, the stormwater coming from the streets and the roofs of houses is directly connected to a stormwater pipeline, while the wastewater from the household is gathered in a separate pipeline.

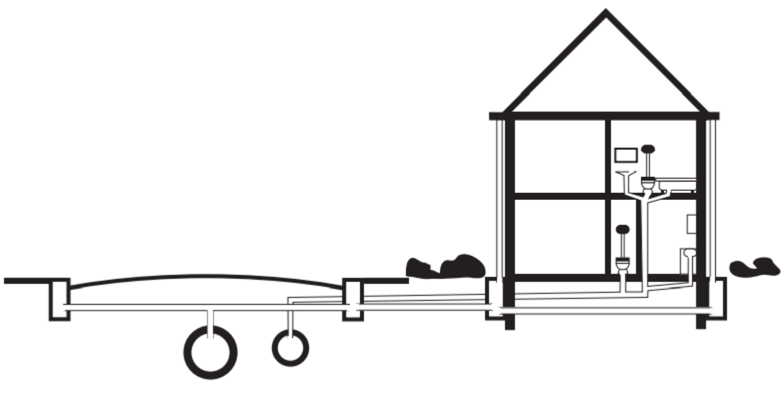


Figure 5: Illustration of a separated sewage system

The implementation of a separated sewage system has significant benefits for the environment, since there is no pollution due to diluted wastewater through CSOs and the RWZIs have to treat less sewage water (Coordinatiecommissie Integraal Waterbeleid, 2012). As has been mentioned before, usually runoff from streets and roofs is directly drained into the sewage system as stormwater for a separated system. This can be done in three different configurations (Coördinatiecommissie Integraal Waterbeleid, 2012):

- Semi separated: Only the streets are drained separately
- Half separated: The streets and 50% of the roof surface is drained separately
- Fully separated: The streets and 100% of the roof surface is drained

The 50% configuration occurs when already built terraced houses are being connected to a separate sewage system, and only the side of the roofs towards the street can be connected without placing a new pipeline under the house. To fasten the implementation of separate sewage systems in Flanders, the Flemish regulations for the environment (VLAREM II) state several rules for houses. This includes that newly built houses, houses under big renovations and houses that are on streets where a separated system is being constructed should disconnect the roofs from the wastewater drainage.

2.1.3 Design criteria

To make sure the capacity of the sewage system is sufficient, criteria have been set-up by the Vlaamse Milieumaatschappij that should be taken into account when designing a sewage system. In this paragraph these criteria will be outlined. The criteria are all based on the Code of Good Practice (Coordinatiecommissie Integraal Waterbeleid, 2012).

During the design phase of a sewage system, a design discharge is used to determine the initial dimensions of the pipelines. The design discharge is based on the wastewater and is calculated by using the following equation:

$$Q14 = p * q * N \tag{1}$$

With:
Q14= Design discharge in L/s
p= peak factor
q= Consumption per person per day in L/s
N= amount of residents in IE

Traditionally, a peak factor of 1.7 is used. This is based on the fact that most of the wastewater is produced in 14 hours during daytime (24/14=1.7). The consumption of a person per day is set at 150 L/s. The combination of the traditional peak factor and consumption is called Q14. The Code of Good practice states that foul pipelines should be designed for 2Q14 and combined pipelines should be designed for 6Q14.

In addition to the design discharge, a newly designed sewage system should meet certain criteria regarding the frequency of sewage flooding and use of CSOs. In detail, this means that newly designed sewage systems should meet the following conditions:

- During a rainfall event with a return period of 2 years, the flow through the system should not exceed the capacity of the pipelines, and the water level in the manholes should be at least 0.5 meters under the ground level.
- During a rainfall event with a return period of 20 years, there should be no water on the streets.
- New CSOs should not drain to the environment during a rainfall event that occurs 10 times per year.
- CSOs that have been redesigned due to the previous criteria, should not work during a rainfall event that occurs 7 times per year.

2.2 Sewage modelling

As has been mentioned in the introduction, modelling of sewage systems has become an important technique in the evaluation of sewage systems in Flanders. In this paragraph an outline of the conceptual model that is used will be given. In addition, some examples of more detailed modelling techniques is given.

2.2.1 Conceptual model

The conceptual model that is used to represent a sewage system can be seen as a storage model of the sewage water, with inflows and outflows (Aquafin, 2017). In figure 6, this storage model has been presented

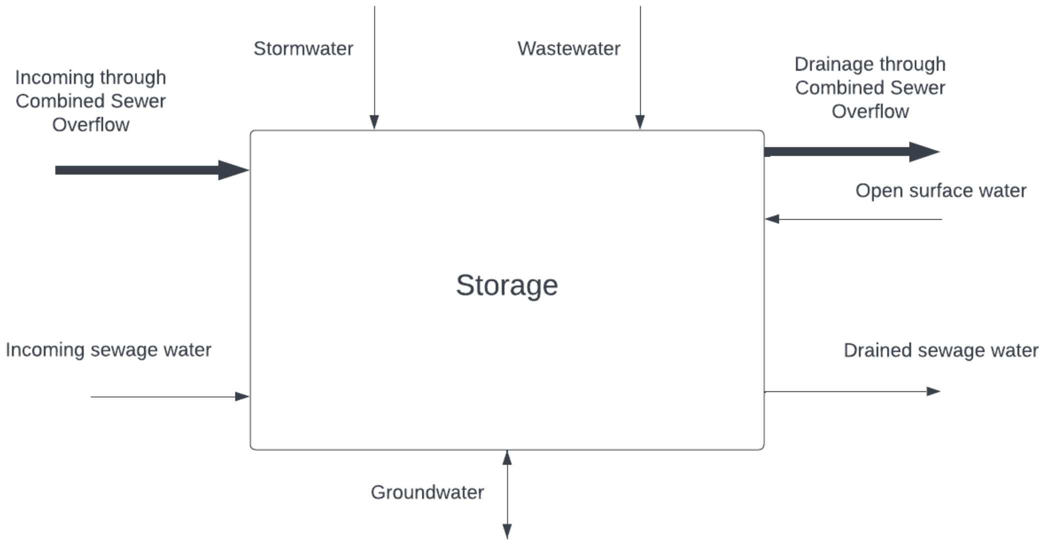


Figure 6: Conceptual model sewage system (Aquafin, 2017)

As can be seen, there are several possible inflows: Wastewater, stormwater, groundwater, open surface water and incoming sewage water from another sewage system (storage). From these sources, groundwater and open surface water can be seen as parasitic water when entering the sewage system. The main outflow of the system is the drainage of sewage water to another sewage system or RWZI. In addition to this, sewage water can seep out of the system back into the groundwater.

All the sewage systems representing a storage are called buckets in the sewage engineering field. When more water is entering a bucket than it is able to drain, the bucket will fill up. When the storage has reached its limit, the sewage water needs to leave the bucket through another point. This is represented by the bold lines, which refer to an important aspect of a sewage system: Combined Sewer Overflows. These hydraulic structures can drain water from the sewage system to open surface waters, or another sewage system, in case of a capacity breach (Coordinatiecommissie Integraal Waterbeleid, 2012). In reality, a big sewage system consists of several smaller sewage systems which are the buckets. The buckets are connected to each other and secured with a CSO, to drain water in case the storage of the bucket is full.

2.2.2 Detailed modelling

The conceptual model as presented in figure 6 presents the sewage system in a very simplistic way. To model a sewage system, software can be used to build a more detailed model. In Flanders, the most common software package used for the evaluation of sewage systems is InfoWorks ICM, which is also the case for this study. InfoWorks ICM is an integrated catchment modelling software that can model flooding up to 2D. In case of a 1D model, the model gives locations and quantities of flooding in the study area, when as for 2D models the flooding can also be more simulated in detail. The software also can incorporate interaction with channels and rivers, which allow for a more broad application of hydrology.

While the current approach of assessing sewage systems by using models focuses rather on the evaluation of flooding on a quantitative basis, also options are being explored to evaluate using qualitative data and modelling. A software called FLEATRAP has been used to evaluate the degree of dilution in Flanders using a tracer isotope (Dirckx et al., 2009). The study showed relevant results, concluding that in general approximately 50 percent of the inflow during dry weather in RWZIs was parasitic water. However, the technique still lacks some validity and further research is necessary.

In addition to the evaluation of sewage systems based on scenarios, more attention is being drawn to the use of Real Time Control (RTC) modelling of sewage systems. In various big cities like Tokyo and Quebec promising results have been obtained that conclude a serious reduction of up to 43% for the use of CSOs for combined sewage systems (Maeda et al., 2005) (Pleau et al., 2005). In Flanders, it has been assessed that certain areas do have a high potential for the use of RTC modelling of sewage systems based on the nature of the catchment and the sewage systems (Dirckx et al., 2007). However, more research for the effectiveness is necessary in Flanders to justify the relatively high operational costs and the complexity of the technique.

3 Research methodology

Several research methods were used to identify the bottlenecks in the existing sewage system of the study area. In this chapter, the methods will be described. This includes a description of how the sewage system was modelled, how the model was validated, and the analysis of the bottlenecks.

3.1 Modelling of the sewage system

The first step in determining the bottlenecks in the sewage system of Zolder, was to build a model that represents the hydraulic behaviour of the system. This model should include three important factors: The sewage network, the flow through the system and the boundary conditions. In this paragraph, it will be shortly discussed which information was used to build the model. In Chapter 4, an elaborate explanation will be given about how the model has been set-up.

The software that has been used to build and simulate the model is Infoworks ICM (version 2021.2). As has been said before the software allows for a relatively detailed model and can be used up to 2D. In this study the model was set-up as a 1D model.

3.1.1 Network

The sewage network consists out of pipelines, manholes and hydraulic structures. The network has been directly loaded into Infoworks ICM through InfoAssetManager, the software that contains the database of the study area. After the conversion of the database to the model network, the hydraulic structures have been programmed. This included checking if the information has been transferred correctly from the database for each structure, remodelling certain structures based on sketches of the structures and the adding of certain missing information. In section 4.1.2, a detailed description of how every type of hydraulic structure has been implemented is given.

3.1.2 Catchment

The catchment represents the flow collection of wastewater and stormwater through the system. The stormwater in the system has been modelled by determining the permeable and impermeable surfaces that generate runoff going into the sewage system. These surfaces have been mapped in a shapefile as polygons using ArcMap software. As for impermeable surfaces, only streets and roofs have been taken into account since these surfaces are directly connected to the sewage system. These impermeable surfaces have been determined by using an already existing shapefile from the 'Grootschalig Referentie Bestand' (GRB), which is a general topographic map containing all roofs and streets of Flanders. This shapefile has been checked and adjusted based on an orthophoto and Google Streetview. As for the permeable surfaces, the polygons have been drawn from scratch using an orthophoto, a slope map, an elevation map and a soil map of the area. To determine the runoff coefficient of these surfaces, a table has been used that determines the coefficient based on slope, vegetation and soil type (De Smedt et al., 1999). Permeable surfaces have only been taken into account when they were suspected to drain to inlets of the sewage system.

As for the wastewater, the flow has been determined using a shapefile containing the address points from the government of Flanders and giving them a value of IE (amount of wastewater one person produces per day). The amount of IE per household address point has been based on information from the municipality, containing the amount of residents per street. This was recalculated into an average amount of residents (IE) per address point per street. As for schools, companies and other facilities, surveys have been sent about how the stormwater and wastewater are being drained, and the amount of people working or attending these buildings to make the model more accurate. In Appendix C.1, the questions that have been asked in the surveys can be found, while in Appendix C.2 the assumptions are stated that have been used to assign IE to the several facilities based on the responses.

3.1.3 Boundary conditions

The sewage network contains several outfall and inflow points where water leaves the network or enters the network. These points can have a significant effect on the simulation of the flow through the system. Therefore, boundary conditions are used for these points to obtain a accurate representation of the system. For the outfall boundary conditions, water level measurements and pictures of the outfall locations available in the database were used. The main inflows of the sewage system were identified to be the Echelbeek and the mine pumps. The inflow of the Echelbeek has been assumed based on observations of the inflow. Inflow discharges of the mine pumps have been based on information that was found in a previous study conducted by Antea Group.

3.2 Validation of the model

The validity of the model has been tested by the execution of historical validation. This validation is a qualitative analysis in which it is tested how well the model simulates flooding caused by the sewage system. For this validation the model was used to identify locations where sewage flooding occurs during high intensity rainfall events. The rainfall events used to simulate these situations had a return period of 2 years, since this is the design discharge of the system. To validate the instances in which sewage flooding occurs, the municipality was questioned about locations where sewage flooding has occurred. By comparing the simulation results and the historical events, the ability of the model to simulate problems in the sewage system was assessed.

3.3 Analysis of the bottlenecks

For the simulation of the model, composite rainfall events were used to simulate the system during periods of rain. Composite rainfall events are designed rainfall events that contain all the possible rainfall events with a certain duration and intensity per a specific return period. The composite rainfall events used in Flanders were traditionally based on a precipitation series in Ukkel from 1967-1933 (Vaes and Berlamont, 1996). However, in 2011 the composite rainfall events have been adjusted to fit better for climate change scenarios and are now based on precipitation series in Ukkel from 1970-2007 (Willems, 2011).

For the identification of the bottlenecks in the system, the model output will be evaluated based on the design criteria as stated by the Code of Good Practice. These design criteria are focused on the frequency of sewage flooding and the frequency of CSO activation and have been discussed in section 2.1.3 of this report. As for flooding it states that there should be no flooding for simulation results based on a rainfall event with a return period of 20 years, and that there should be no pressure on the pipelines for the results based on a rainfall event with a return period of 2 years. However, since it is already known that the capacity of the sewage system is too low, the simulation results for a return period of 2 years will be used to identify the major capacity bottlenecks. This means that a location is defined as a bottleneck when flooding occurs for a simulation with a return period of 2 years. As for the frequency of the CSO activation, The Code of Good Practice states that new CSOs should work only a maximum of 10 days per year, and that CSOs that have been remodelled based on this criteria should only work a maximum of 7 days per year (Coordinatiecommissie Integraal Waterbeleid, 2012). This means, that for identifying the bottlenecks the activation of the CSOs will be evaluated for a rainfall event with a frequency of 7 times per year and a rainfall event with a frequency of 10 times per year.

4 Model implementation

This chapter discusses in further detail how the model has been designed to accurately represent the sewage system of Zolder.

4.1 Network

The modelling of the network includes two steps: Importing the network from the database and the programming of the hydraulic structures in the model.

4.1.1 Database to Infoworks ICM

The database contains all the information about the sewage system of Zolder that is necessary to design a simulation model. This includes the network of the sewage system with the location of manholes, pipelines, hydraulic structures and their measurements. For every object in the database also a ground level is given and a depth (invert level) of each object, to define the location underground. A large part of the information in the database has been acquired through an already existing database of Aquafin, the regional sewage manager. This initial database has been expanded with new information from: Surveys (measurements), as-built plans, observations and assumptions.

To design the model, first the database is exported to Infoworks ICM to create a network based on all information gathered. The network consists of nodes and links representing the pipelines, manholes and hydraulic structures. Each object in the network has been given a system type: Combined, foul or storm. This system type indicates the type of sewage water that drains to these objects. During the establishment of the model, the system type for certain pipelines and nodes has been changed in several places from foul to combined. This is the case for the following streets: Koeltorenlaan, Schuttershof, Kerkeveld, Vagevuurpad, Ganzenstraat, Grootven, Ambachtlaan, Kerkebosstraat, Gravenlaan, Kuilberg, Pannewinning, Borgveld, Schaltusstraat and the Sint Jobstraat. In Appendix B.1, a figure is included with the whole network in the study area.

Figure 7: Example of the network in the model

In figure 7, a zoom has been provided of the model. In this zoom it is illustrated how the network is presented in the modelling software. The orange colour refers to a combined system, while the foul system (wastewater) is indicated with the pink colour and the storm system (stormwater) is indicated with the blue colour. The dark and light polygons represent the permeable and impermeable surfaces.

4.1.2 Hydraulic structures

The study area contains several hydraulic structures that need to be programmed correctly in the Infoworks ICM software. To do this, first the hydraulic structures have been exported from the database to Infoworks ICM together with the manholes and pipelines. After this, it has been checked for every structure if the information in the database has been transferred correctly and if additional information was necessary. In addition, some structures were altered to represent the network better. In this paragraph, the programming of each type of hydraulic structure in the network will be elaborated on. The formulas that the software uses to model each type of hydraulic structure can be found in Appendix D.

Pumps
Pumps stations are installed to pump sewage water from a low level to a higher level. The most commonly used pumps are submersible pumps. These pumps use rotational force to suck the water into a riser pipe. This riser pipe is connected to a pressure pipe, that drains to the next manhole. In figure 8 a schematic illustration is given of a pump.

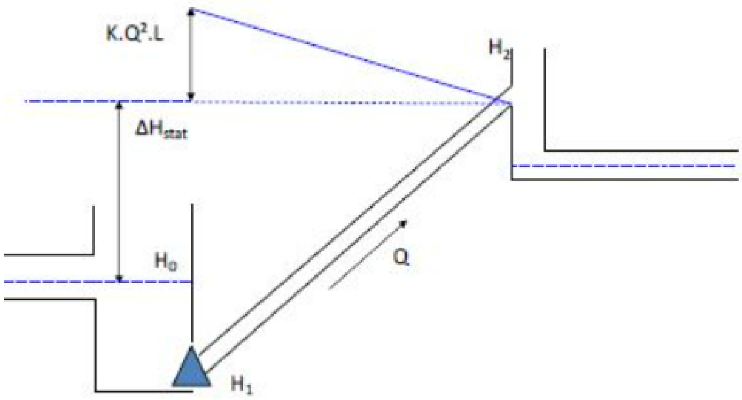


Figure 8: Schematic illustration of a pump

The study area contains 17 pump stations, where usually one or more pumps are located. In most cases, more pumps are installed in case one of the pumps will fail. In the model, pumps are modelled as a link with the function ROTPUMP or FIXPUMP.

With the ROTPUMP function, a Q-h relation is used for the pump and pressure pipeline to determine the discharge through the pump. The Q-h relation depends on the type of pump. The Q-h relations have been based on information provided on the website of the manufacturers of the specific pumps. For the Q-h relation of the pressure pipe, the internal diameter, length, viscosity, roughness, minimal and maximum pumping discharge was used to determine a representative Q-h relation. In case the type of pump was not known, the FIXPMP function was used. This function allows to assign a fixed pump discharge. In these cases, the discharge has been based on the amount of IE connected to a certain pump station. In table 1, an overview of all the pump stations is given.

Table 1: Overview of pumps in the model

Pump station	Configuration	Switch on level	Switch off level	Type	Discharge
Ambachtlaan	1+1	29,29	29,15	ROTPUMP	Q-h relation
Aversbodeshof	1+1	32,4	34,2	FIXPUMP	5,0 L/s
Biesstraat	1+1	32,20	32,10	FIXPUMP	7,0 L/s
Broederspad	1+1	25,29	24,47	ROTPUMP	Q-h relation
De Slogen	1+1	27,74	27,59	ROTPUMP	Q-h relation
Driesstraat	1+1	26,61	26,48	ROTPUMP	Q-h relation
Herdershof	1+1	45,86	45,71	FIXPUMP	3,3 L/s
Ijskelder	1+1	34,45	34,18	ROTPUMP	Q-h relation
Kerkebosstraat	1+1	35,00	34,90	FIXPUMP	11,0 L/s
Kerkstraat	1+1	25,35	24,99	ROTPUMP	Q-h relation
Lillosteenweg	1+1	43,97	43,73	ROTPUMP	Q-h relation
Meylandtlaan	2+1	29,84 30,14	29,3 29,38	ROTPUMP	Q-h relation
Molenstraat	1+1	33,97	33,84	ROTPUMP	Q-h relation
Rijkelstraat	3+1	39,75 39,91 40,07	39,58 39,75 39,91	ROTPUMP	Q-h relation
St Jobstraat	1+1	27,98	27,83	FIXPUMP	3,3 L/s
t Roosterke	1+1	32,18	32,03	FIXPUMP	3,3 L/s
t Wiek	1+1	41,00	40.00	FIXPUMP	20,0 L/s
Vunderstraat	1+1	39,33	39,22	ROTPUMP	Q-h relation
Vogelsancklaan	1+1	30,30	30,20	FIXPUMP	45,0 L/s
Waterstraat	1+1	30,77	30,62	FIXPUMP	88,0 L/s

As can be seen, for each pump also a switch on and switch off level has been assigned. These levels determine when the pump starts pumping based on the water level in the manhole and are given in meters above TAW (m TAW). In most cases, the switch on and off levels have been based on the technical specifications that were available for some pumps. When this information was not provided, assumptions were made based on the dimensions of the manhole in which the pump is installed. The configuration of a pump station indicates the amount of working pumps and reserve pumps.

Combined sewers overflows (CSOs)
CSOs are constructions, where sewage water can overflow and leave the sewage system, in case of a too low capacity of the system. In the model CSOs have been modelled by using the function WEIR. This function is represented in the model as a link without a length and bases the flow through the CSO on the height of the dam (crest), the width of the dam and the free height above the dam. These parameters were checked for each CSO with the information of the database. Using this data the model calculates the flow through the open surface above the dam.

Flap valves
Flap valves are constructions that make sure the sewage water can not flow back upstream of the system, and are modelled using the function FLAP VALVE in the model. This function is displayed as a link without a length, like the WEIR. Flap valves are being modelled using the invert level of the flap valve which is the lowest point of the opening, and the surface of the opening. Flap valves can be round or square, therefore in the model round flap valves are based on the diameter, and square flap valves are based on the width and height.

Orifices
Orifices are constructions where the water needs to flow through a smaller area, to slow down the flow of the sewage water in the network. Orifices in the network have been modelled using the link function ORIFICE, which bases the flow through the orifice on a formula. To successfully model the orifices, the following parameters should be assigned to an orifice in the model: The invert level and diameter of the orifice. The software only allows round openings for the modelling of

orifices. However, in the network there are several square formed orifices. As an alternative these have been modelled using the SLUICE function, that will be discussed in the next section.

Usually orifices are oriented in such a way that the water flows through horizontally. However, the study area contains two square orifices where the sewage water could fall through the orifice vertically. These two orifices have been modelled using the WEIR function.

Gates
Gates are usually placed in front of orifices, to control the area of the opening. Gates are modelled using the SLUICE link function and the flow through the sluices is calculated using the same formula used for the orifices. The parameters necessary to model the gates are the invert level of the gate, which indicates how far the gate has been opened, and the dimensions of the gate. In most cases, the invert levels of the gates of the study area were higher than the top of the opening before the gate. This means that the gate is opened entirely. In these cases the gates were removed from the network.

Vortexes
Vortexes have been modelled using the VORTEX link function and have the purpose of limiting the discharge. The difference between a vortex and other discharge limiting structures, is the fact that the discharge through the vortex does not depend on the water level. In the study area there are three vortexes, which are listed in table 2. To model these vortexes, the model requires the invert level of the vortex and a Q-h relation. The Q-h relation has been based on the exact vortex type, provided in the database.

Table 2: Overview of vortexes in the model

Location	Invert level (m Taw)	Discharge
Abdijlaan	29,326	Q-h relation
Meylandtlaan	30,7	Q-h relation
Nieuwstraat	37,02	Q-h relation

4.2 Catchment

Modelling of the catchment includes the representation of the flow of the stormwater and wastewater through the study area. The stormwater is determined by the runoff on permeable and impermeable surfaces that drain to the sewage system. The amount of wastewater is defined by the amount of IE connected to the system. In this paragraph, it will be discussed how both flows are implemented in the model.

4.2.1 Runoff surfaces

The input for the stormwater through the sewage system in the study area is the amount of runoff coming from permeable and impermeable surfaces. To implement this into the model, for both permeable and impermeable surfaces that are predicted to flow to the sewage system surface files are used that have been created in GIS software. The surface files consist of polygons that each represent a certain surface of a roof, street or permeable zone and the file can be viewed in Appendix B.2. Each polygon is given a specific Runoff Surface ID in the model. This Runoff Surface ID indicates whether the polygon is a roof, street or a certain permeable surface. Per Runoff Surface ID, a Fixed Runoff Coefficient is assigned to indicate how much of the rain will turn into runoff that enters the sewage system based on the type of surface the polygon is representing. In table 3, the Fixed Runoff Coefficient per Runoff Surface ID is presented.

Table 3: Overview of Runoff Surface IDs & Fixed Runoff Coefficients used in model

Runoff Surface ID	Description	Fixed Runoff Coefficient
110	Street surfaces	0,9
130	Roof surfaces	0,9
150	Permeable surface 3%	0,03
151	Permeable surface 6%	0,06
152	Permeable surface 11%	0,11
153	Permeable surface 20%	0,2
154	Permeable surface 25%	0,25
155	Permeable surface 29%	0,29
156	Permeable surface 32%	0,32
157	Permeable surface 35%	0,35

As can be seen, both for roof and street surfaces a Fixed Runoff Coefficient of 0,9 is given. This indicates that 90% of the rainfall on these surfaces will turn into runoff. As for the permeable surfaces, a total of 8 different Runoff Surface IDs is created to be able to implement 8 different Fixed Runoff Coefficients in the model. This is due to the fact that the amount of runoff from a permeable surface, largely depends on the slope, vegetation and soil type.

4.2.2 Assigning of IE

As for the wastewater, a layer file is used in the model that contains the amount of IE per address point. This file has been prepared in GIS software, and the IE has been assigned to the address points according to information from the municipality and from surveys (see Chapter 3).

As has been mentioned before, the amount of IE refers to the amount of wastewater one person produces per day. In Belgium one IE is equal to 150 liters per day (Coordinatiecommissie Integraal Waterbeleid, 2012). However, the discharge of these 150 liters is not constant through the day and therefore a peak factor of 1.7 (24 hours/14 hours) is used in the model. This peak value makes sure that the the 150 liters is distributed during the 14 hours that most wastewater is produced (daytime). In figure 9, it is shown how the discharge of one IE is distributed over the 14 hours in the model.

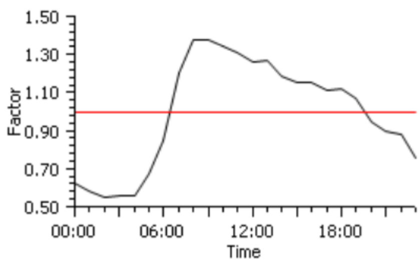


Figure 9: Used IE profile in model, according to the Hydronautprocedure 7.0

4.2.3 Subcatchments

The stormwater and wastewater produced in the study area does not enter the sewage network in the same location. Therefore, subcatchments are used to assign which surfaces and IE sources are draining to specific nodes or pipelines in the sewage network. In figure 10, some subcatchments from the model are being presented. As can be seen, certain polygons and address points are being demarcated with a subcatchment and assigned to the closest pipeline or node.

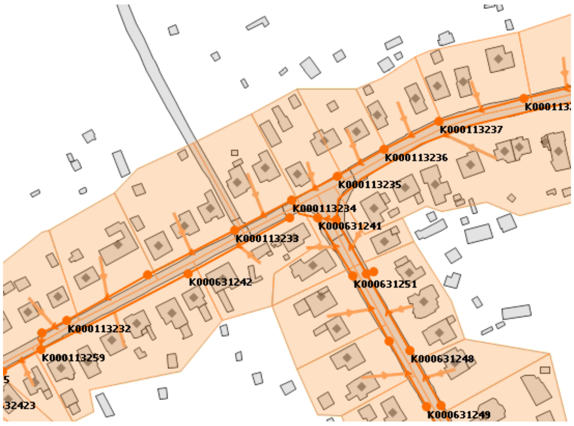


Figure 10: Subcatchments

The subcatchments from figure 10 are connected to a combined sewage network. In this case only one combined subcatchment is sufficient to drain all the water in this catchment to the combined network. However, there are three types of subcatchments, foul, combined and storm, to match the system type of the network. Combined subcatchments can drain both surfaces and IE, while foul subcatchments can only drain IE and storm subcatchments can only drain surfaces.

In cases where a separated system is present, two subcatchments are overlayed, to drain a part to a foul or combined subcatchment and the other part to a storm subcatchment. To make sure that the storm subcatchment counts the correct surfaces based on the type of separated system, a User Number 5 is given to the storm subcatchment. In table 4 an overview is given of the different User Number 5s that can be assigned to a subcatchment.

Table 4: User Number 5 configuration

User number 5	Description	% of roofs separated	% of streets separated
100	Semi separated system	0	100
150	Half separated system	50	100
200	Full separated system	100	100
800	Impermeable surface (100% storm)	-	-

In Appendix E, an overview can be found of the streets where a separated system is implemented in the study area. The overview also states the type of separated system. This is based on information retrieved from the municipality and assumptions made using the dimensions of the pipelines. In Appendix B.3, all the subcatchments can be seen that have been drawn in the model.

4.2.4 Land Use IDs

After defining the separation of the stormwater, by using the subcatchments and User number 5s, every subcatchment is given a Land Use ID. This ID tells every subcatchment (combined, foul or storm), which surfaces should be counted in based on Runoff Surface ID. An overview of the Land Use IDs and which types of surfaces they take into account is given in 5.

Table 5: Land Use IDs configuration

Land Use ID	Description	Includes Runoff surface ID:
100	Combined system	110, 130
400	Foul system	-
600	Storm system	110, 130
800	Storm system with permeable surfaces	110, 130, 150, 151, 152, 153, 154, 155, 156, 157

As can be seen, a combined subcatchment drains both street and roof surfaces with a Runoff Surface ID of 110 and 130, which means that for both surfaces a runoff coefficient of 0,9 is used. For foul subcatchments there are no surfaces being taken into account. For storm subcatchments a difference is made between the ones containing permeable surfaces and the ones that do not.

4.3 Boundary conditions

In the model, boundary conditions for outfalls are implemented by assigning a water level to an outfall node. In the model both constant and variable water levels have been implemented. Variable water levels vary during the simulation based on the average water level and maximum water level. For both the constant and variable boundary conditions, the watercourse level in provided in the database was used as the average water level. Maximum water levels were determined if pictures of the outfall were available that clearly showed how high the water level could rise based on the discolouration of the outfall. A table of all the implemented boundary conditions for the outfalls, including pictures of the location of the outfalls in the network (represented as the green dots), can be found in Appendix F.1.

As for the inflows, only constant boundary conditions have been implemented for the mine pumps and Echelbeek. The locations (indicated by the green dots) and the discharges for the inflows can be found in Appendix F.2.

5 Results of validation and flooding bottlenecks

This chapter discusses the results of the model validation and flooding bottleneck analysis. For both the validation and analysis, the model has been simulated for 3 days, using a rainfall event with a return period of 2 years. The results of this simulation are presented in figures 11 and 12. In these figures, the green colour shows the locations of flooding and the amount of green circles shows the severity of the flooding. It should be noted that the results have been maximized, meaning that the results show for each location the flooding that occurs when the system is most under pressure during the simulation.

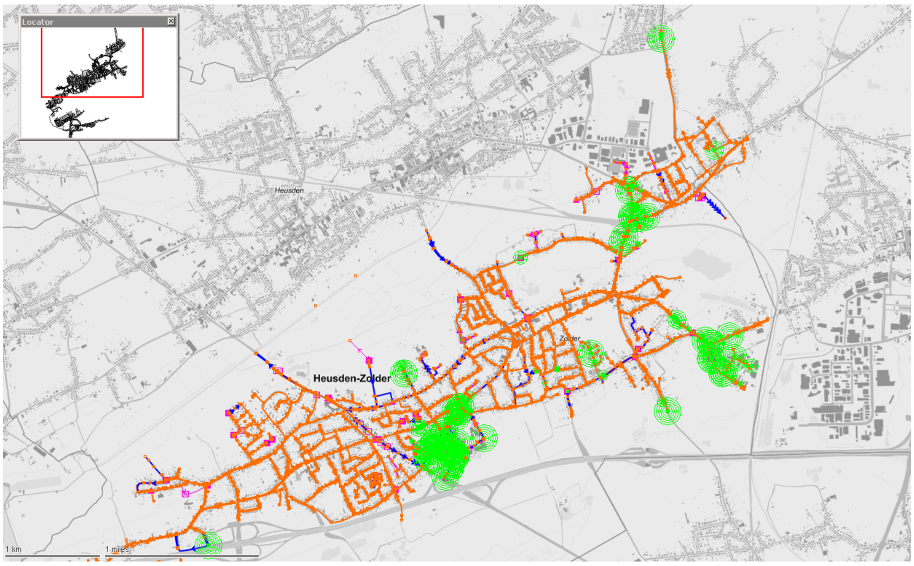


Figure 11: Locations of sewage flooding in the Northern part of the study area based on a T=2 simulation

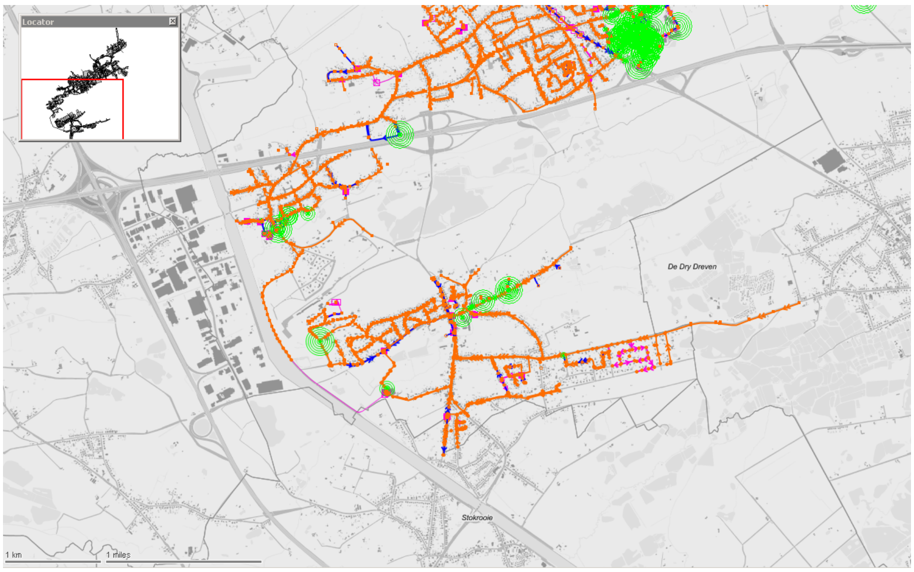


Figure 12: Locations of sewage flooding in the Southern part of the study area based on a T=2 simulation

5.1 Validation

Several locations have been reported at the municipality, where sewage flooding has occurred during heavy rainfalls. These locations have been requested at the municipality and are listed below:

1. Stationsstraat
2. 't Wiek
3. Nieuwstraat, at intersection with Schobbenberg
4. Ambachtlaan
5. Vlamingenlaan/Toekomststraat
6. Jeugdlaan/Broekwinningsstraat
7. Kerkstraat/Laaglandstraat

To validate the model, these locations are compared to the locations where flooding occurs in the model. This is done based on simulations results for a rainfall event with a 2 year return period. According to the Hydronautprocedure 7.0 this is a correct rainfall event to use for the validation, since the intensity of the event is enough to cause flooding in such a way that residents remember flooding events or report this at the municipality.

5.1.1 Flooding locations according to the model

There are several locations that are not marked as problem areas by the information of the municipality, but where the model results show flooding. In a lot of cases, the mismatch in these locations can be explained while looking at the model. In the section below, first these locations will be discussed.

Kolderstraat and St. Jozefstraat
The model simulates flooding both at the Kolderstraat and St. Jozefstraat, while these areas have not been marked as flooding areas by the municipality. For both locations the height profiles show that flooding occurs at a manhole at a high ground level due to a high water pressure, while the slope of the streets and pipelines is steep. At the lower ground level, the water pressure is lower than at the location of flooding. In these cases, flooding is not likely to be noticed since the excess water at the higher level can flow to the lower level and enter the sewage system there. To illustrate how the slope of the ground level is not taken into account in the model, the simulation results of the Kolderstraat are presented in figure 36 and 37, added in Appendix G.

Mommestraat, Laambroekstraat and Broeksteeg
At several locations the model simulates flooding at the transition of sewage system to open surface water bodies, like water streams or ditches. This is the case for the Mommestraat, Laambroekstraat and Broeksteeg, while these locations have not been known as flooding locations. In the simulation results it can be seen that for all these locations flooding occurs at the manhole through which the water should leave the sewage system to an open surface water body. Due to these locations being modelled as a manhole instead of an outfall, the water is not able to leave the system in the simulation and water pressure increases in these manholes, causing flooding. In Appendix G the figures 38 and 39 are added, in which the simulation results for the Mommestraat are presented. These results illustrate the effect of the missing outfall.

Rijkelstraat, Domherenstraat and Vrunstraat
The simulation results of the model show flooding in several locations in the system where larger companies or facilities are connected to the system, while these flooding problems are not known at the municipality. This is the case for the Rijkelstraat, where a business park is located and connected to the sewage system in the model, and at the Domherenstraat and Vrunstraat where larger pension facilities are connected to the sewage system in the model. For these locations, no sufficient data is available with respect to private sewage systems to assess the correctness of the model.

Heikant, Galgeneinde, Vrunstraat and Windestraat
Both at the Heikant and Galgeneinde, flooding is simulated due to a too low capacity of the pipelines. These locations have not been marked as flooding locations by the municipality. When looking at the model, it can be seen that for both these locations, a large amount of contributing areas to the simulated runoff consist of small garden houses that have been included in the subcatchments. An overestimation of the impermeable surfaces could explain the mismatch between simulation results and the data from the municipality.

At the Vrunstraat and Windestraat, the capacity of the pipelines is too low to drain all the incoming stormwater and wastewater. The municipality has not provided these locations as problem areas. From the model it can be seen that large areas of permeable surfaces are drained to the flooding locations in the sewage system. For these locations, the amount of runoff caused by these large areas can cause flooding in the simulation.

5.1.2 Flooding locations according to the municipality

Vlamingenlaan/Toekomststraat and Jeugdlaan/Broekwinningsstraat
There are three locations that the municipality has provided as flooding locations, which are not modelled for a rainfall event with a return period of 2 years, namely Vlamingenlaan/Toekomststraat, Jeugdlaan/Broekwinningsstraat and 't Wiek. For these locations also the simulation results for a rainfall event of 5 years have been checked, and these results also did not show flooding at these locations. As for the Vlamingenlaan/Toekomststraat and Jeugdlaan/Broekwinningsstraat it is not directly clear why the model does not simulate flooding, while it does happen in reality. During a study area visit, the residents of housenumber 198 of the O.S. Lievevrouwenstraat (a street located near the Jeugdlaan and Broekwinningsstraat) mentioned that they have experienced sewage flooding several times during heavy rainfall events. The residents mentioned that the main cause of the problem is believed to be the structural state of the sewage system, rather that the capacity. This information combined with the data available is not sufficient to confirm this cause of flooding.

't Wiek
As for 't Wiek, flooding is located at the pump station. However, this flooding only occurs in the simulation in the pump chamber (node 6061A). For this node an inflow boundary condition equal to the pumping discharge has been implemented, since this pump station pumps water from the mines into the sewage system. However, since the inflow is set to 0 at the the initial time step of the simulation, the initialisation of the simulation is causing an irregular flow in the pump chamber. This can be seen in figure 13, where the flow in the pump chamber is presented in the beginning of the simulation.

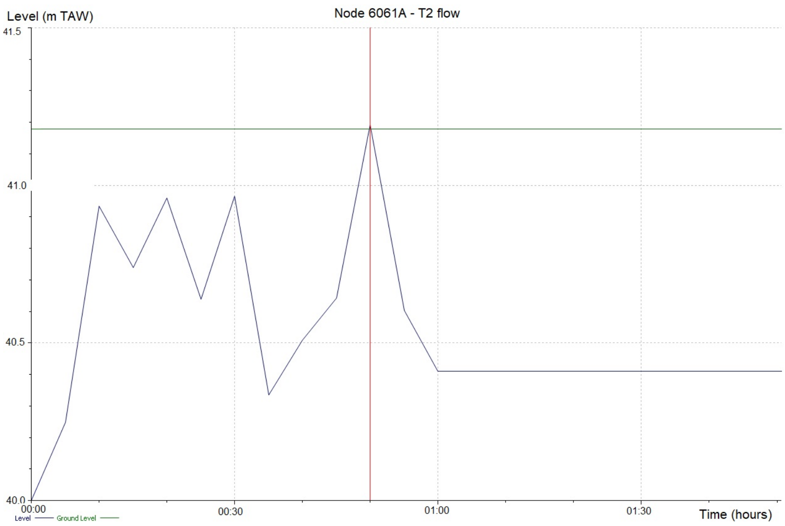


Figure 13: Simulated flow in pump chamber (node 6061A)

The municipality has addressed that there are flooding problems at 't Wiek. However, the flooding simulated in the model is not flooding that will cause problems in reality. It is not directly clear why the model and historical events do not match. Reasons could be that the pumping discharge is not correctly assumed. In Appendix G, two figures are presented (40 and 41, that show the flooding that is simulated in the model at 't Wiek.

5.1.3 Flooding locations according to the model and municipality

There are multiple locations where the model does simulate the flooding at the locations that the municipality has provided. This is the case for the following areas: Stationsstraat, Nieuwstraat, Langstraat, Ambachtlaan, Laaglandstraat and Kerkstraat. In the model, it can be seen that for all these locations the capacity of the sewage system is not sufficient. As for the Nieuwstraat, the exact location addressed by the municipality is not modelled in the simulation (at the intersection with Schobbenberg), however the flooding is simulated 100 meters further down the sewage system. In this case the model does not completely align with the data from the municipality, however the model does simulate the known capacity problem in this collection of pipelines.

The Ambachtlaan is the biggest problem area in the model simulation and based on the reported flooding nuisance reported at the municipality. In the simulation the capacity in combination with the low ground level causes the sewage water to flow out of the system. The sewage system in the street that crosses the Ambachtlaan, namely the Boektlaan is also flooded in the simulation. the municipality has not identified this street as an area prone to flooding. In the model it can be seen that the sewage system in the Boektlaan is connected to the system at the Ambachtlaan through a CSO. Howver, since the Ambachtlaan is already flooded very easily, the water in the Boektlaan can not flow to the system of the Ambachtlaan. This is presented in figure 42 and 43 that can be found in Appedix G. It can not be said in this case if reality is presented well in the model, since the area does contain a business park with large impermeable surfaces where no sufficient information is available to correctly model the drainage of stormwater. In addition, there is no sufficient information about the mine pump at the Vogelsanklaan, to correctly simulate how much of the water gathered in the system at the Ambachtlaan is pumped out of the sewage system.

5.1.4 Evaluation of the model validity

In short, the validation shows that the model does simulate the bottlenecks where the capacity of the system is lacking, which are the Stationsstraat, Ambachtlaan, Nieuwstraat, Langestraat, Laaglandsstraat and Kerksstraat. These locations will be further discussed in section 5.2 and specific solutions will be provided. However, there are still a lot of locations where the model and information from the municipality do not match. For these locations a description has been given and further research and detailing of the model is necessary. How this can be done will be further considered in Chapter 7.

5.2 Analysis of bottlenecks - flooding

The code of good practice states that the system should be designed in such a way that their should be no sewage flooding for rainfall events with a return period of 20 years. However, according to the model there are several locations for which sewage flooding already occurs during a rainfall event of 2 years. The most important problem areas, taking into account the validity discussed in section 5.1, will be discussed below. For each location a height profile of the sewage system is presented to illustrate the bottleneck in the system. In Appendix H, a view of the location in the model where the height profile has been taken from in the network is presented per location.

Stationsstraat

From the height profile presented in 14, it can be seen that nuisance due to flooding occurs. Sewage water will flow above ground from the high ground level towards the lower ground level. In addition, at two locations sewage water will gather above ground at the lower ground levels. The pipelines have a diameter of 400 mm upstream and are bigger downstream with a diameter of 600 mm. The increase in diameter is necessary to accommodate the sewage water entering the system from the Langstraat at node K00631748. According to the simulation, it can be seen that overall the pipe system is under pressure and the capacity of the pipelines is insufficient to drain all the water through the system.

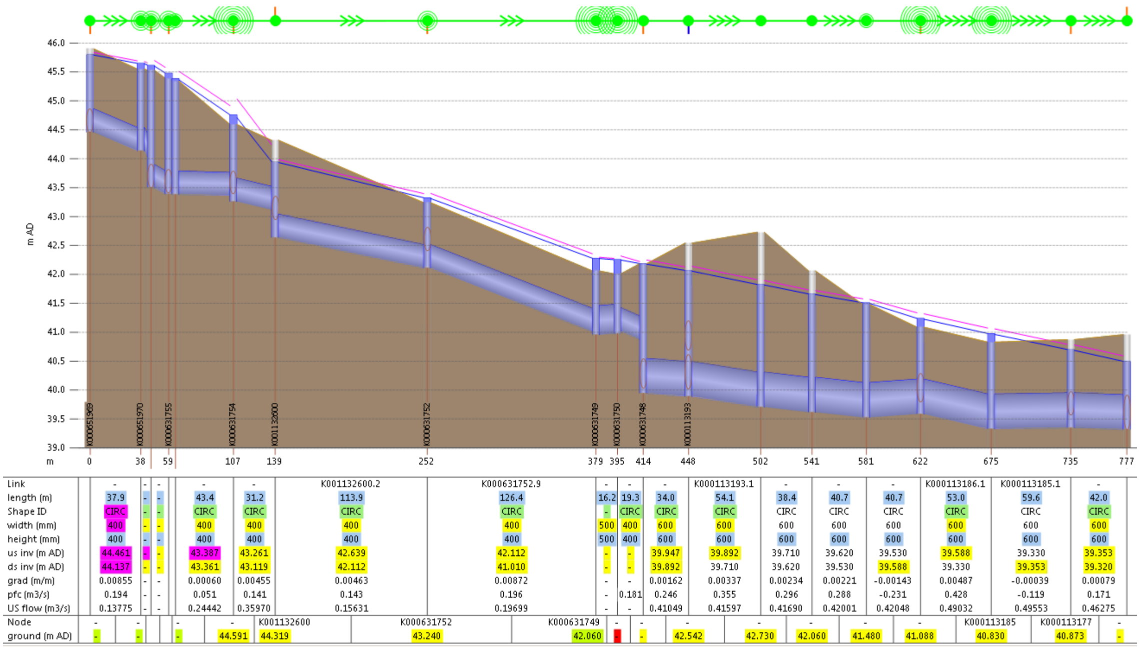
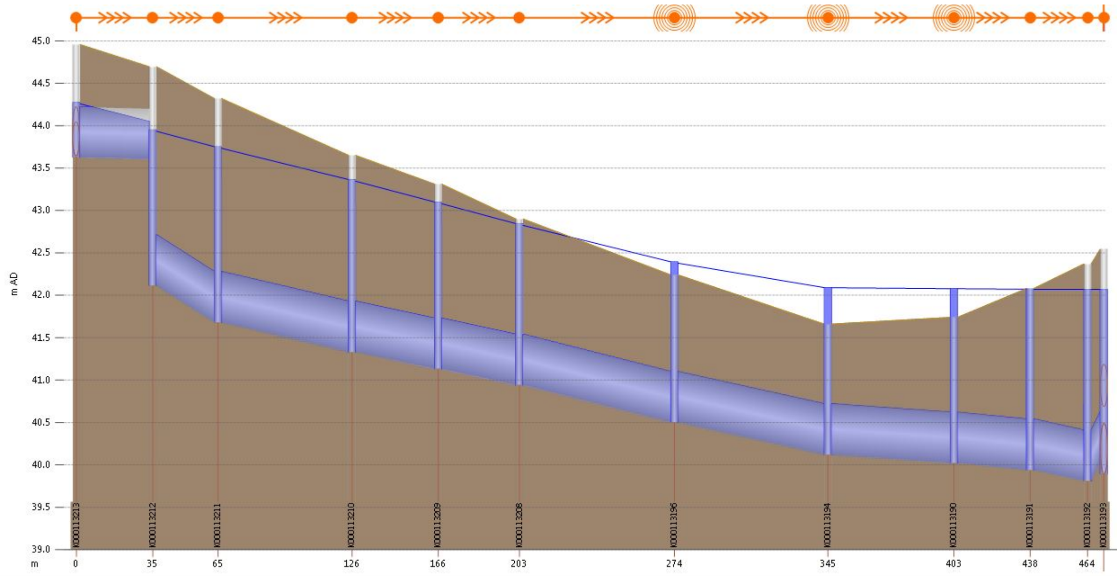


Figure 14: Height profile of Stationsstraat

Langstraat

At the Langstraat a semi separated system is installed, meaning that the stormwater of the street is drained separately in a stormwater pipe system. The combined sewage system in the street is connected to the system at the Stationsstraat and the height profile of this system is presented in figure 15. For a rainfall event with return period of 2 years, the simulation shows that water gathers above ground around node K000113194. At this location the ground level is the lowest. When looking at the simulated and maximum flow in the pipe system of the Langstraat, it can be seen that at some points the simulated peak flow (US flow) exceeds the maximum design flow (pfc) during the peak of the rainfall event. At link K000113194.1, the difference between the maximum design flow and simulated peak flow is approximately 57 L/s. This suggests that the pipelines are under pressure. However, the bottleneck at the Langstraat is mainly caused by the capacity problem at the Stationsstraat, where the difference between the maximum design flow and simulated peak is higher than 100 L/s at some locations. Due to this capacity problem, The sewage water in the system at the Langstraat is not able to flow out of the system.



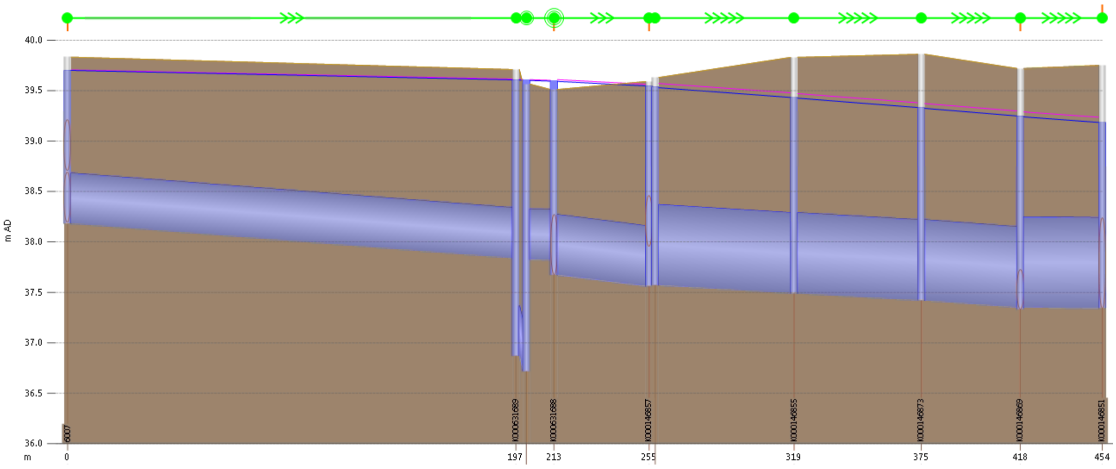
Link	K000113213.1	-	K000113211.1	K000113210.1	K000113209.1	K000113208.1	K000113196.1	K000113194.1	K000113190.1	-	-
length (m)	35.1	29.9	61.5	39.6	37.3	71.1	70.4	57.8	35.0	26.3	7.4
Shape ID	CIRC	CIRC	CIRC	CIRC	CIRC	CIRC	CIRC	CIRC	CIRC	CIRC	-
width (mm)	600	600	600	600	600	600	600	600	600	600	-
height (mm)	600	600	600	600	600	600	600	600	600	600	-
us inv (m AD)	43.626	42.115	41.680	41.330	41.130	40.940	40.500	40.120	40.020	39.940	-
ds inv (m AD)	43.605	41.680	41.330	41.130	40.940	40.500	40.120	40.020	39.940	39.810	-
grad (m/m)	0.00060	0.01456	0.00569	0.00506	0.00510	0.00619	0.00540	0.00173	0.00229	0.00494	-
pfc (m3/s)	0.149	0.741	0.462	0.436	0.438	0.482	0.450	0.254	0.292	0.431	-
US flow (m3/s)	0.45382	0.45708	0.46757	0.47709	0.48627	0.48558	0.43499	0.31069	0.33314	0.33356	-

Node	-	K000113212	K000113211	K000113210	K000113209	K000113208	K000113196	K000113194	K000113190	K000113191	-
ground (m AD)	-	44.695	44.320	43.650	43.310	42.900	42.240	41.660	41.740	42.080	-

Figure 15: Height profile of Langstraat

Nieuwstraat

At the Nieuwstraat a semi separated system is installed, which means that there is both a combined and stormwater system installed. In the simulation results, the combined system is under pressure and causing flooding. In figure 16 the height profile of the combined system at the Nieuwstraat where flooding occurs is shown. As can be seen, the diameter of the pipelines increases from 500 mm to 600 mm to 800 mm, when going downstream. At node K000631688, where the pipeline goes from 500 mm to 600 mm, the most flooding occurs. At this point also the ground level is the lowest. the results suggest that the flooding is caused by a capacity problem of the pipe system. Right before the increase of the diameter of the pipes to 800 mm, two combined pipelines from the Schobbenberg and the Domherenstraat are connected to the system. This means extra water is entering the system. From this point the simulated peak flows in the pipelines start to exceed the maximum designed flows of the pipelines, indicating a lack of capacity to drain all the sewage water.



Link	6007.7	-	-	K000631688.9	K000146856.1	K000146855.1	K000146873.1	K000146869.1
length (m)	196.6	-	12.1	41.8	60.9	55.8	43.5	35.9
Shape ID	CIRC	-	CIRC	CIRC	CIRC	CIRC	CIRC	CIRC
width (mm)	500	-	500	600	800	800	800	900
height (mm)	500	-	500	600	800	800	800	900
us inv (m AD)	38.182	-	-	37.671	37.570	37.490	37.420	37.350
ds inv (m AD)	37.839	-	-	37.560	37.490	37.420	37.350	37.340
grad (m/m)	0.00174	-	-	0.00266	0.00131	0.00125	0.00161	0.00028
pfc (m3/s)	0.158	-	0.068	0.315	0.473	0.462	0.524	0.295
US flow (m3/s)	0.11779	-	-	0.24494	0.50089	0.51050	0.52269	0.67049

Node	6007	K000631689	-	-	-	K000146856	K000146855	K000146873	K000146869	-
ground (m AD)	39.832	39.709	-	39.511	39.590	39.630	39.830	39.860	39.720	39.750

Figure 16: Height profile of Nieuwstraat

Ambachtlaan

At the Ambachtlaan the stormwater system is causing flooding, which can be seen in the height profile presented in figure 17. The stormwater system in this location has the purpose of collecting stormwater from the roofs and streets, and draining it to one of the mine pumps at the Vogelsanck-laan. This mine pump should pump the water out of the sewage system with a pumping discharge of 45 L/s. When looking at the ground levels of the Ambachtlaan and neighbouring areas, it can be concluded that the Ambachtlaan is the lowest point of the area, meaning that water can easily gather on the street. From the modelling simulation, it can been seen that the simulated flow during the peak of a rainfall event with a return period of 2 years, exceeds the maximum pumping discharge of 45 L/s per second in the model. On the contrary, the simulated peak flow does not exceed the maximum design discharge of the pipes. Therefore, the results show that the bottleneck is mainly caused by the capacity of the mine pump.

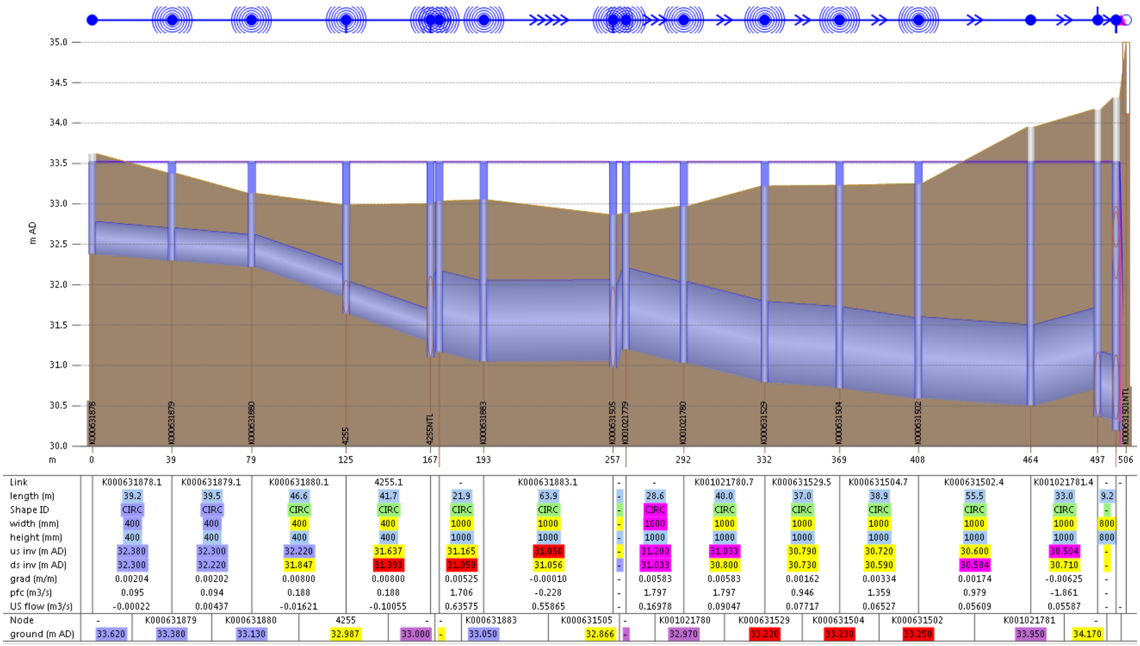


Figure 17: Height profile of Ambachtlaan

Laaglandstraat
The height profile of the Laaglandstraat, is presented in figure 18. The results show that water gathers above ground at the lowest ground level, and that the system is under pressure, which causes sewage water to rise in the manholes and enter the streets.

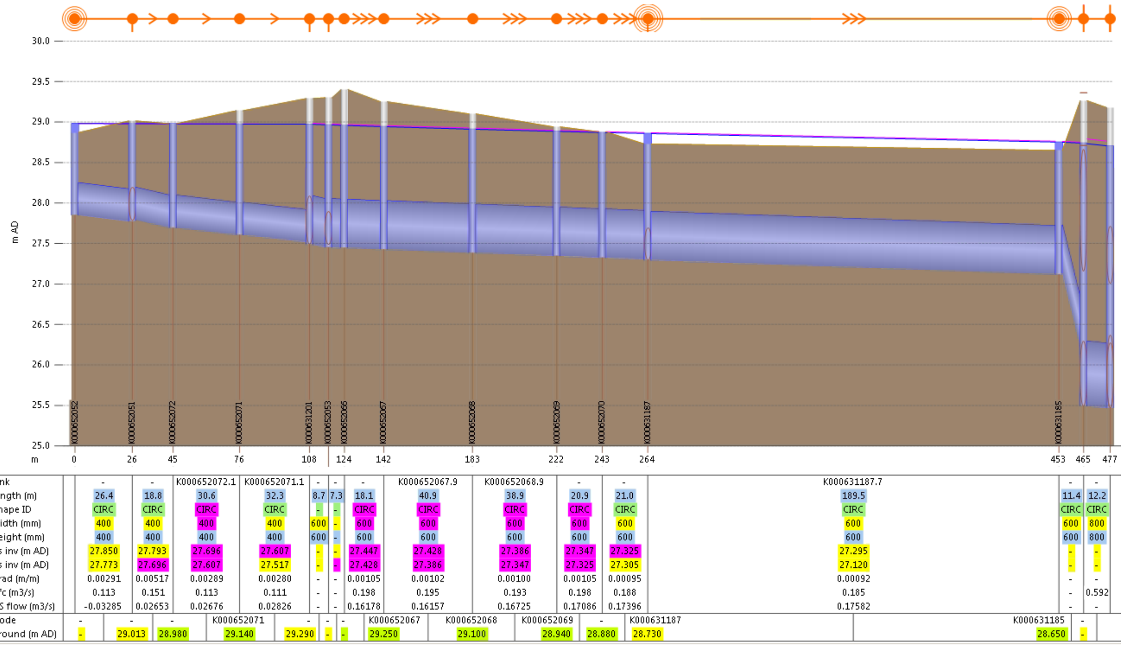


Figure 18: Height profile of Laaglandstraat

The results show that water gathers above ground at the lowest ground level, and that the system is under pressure, which causes sewage water to rise in the manholes and enter the streets. The simulation results do not show that the simulated peak flow for a return period of 2 years exceed the maximum design flow in the pipelines. However, the pipeline from the Laaglandstraat drains together with a pipeline from the Kerkstraat in node K000057737. The pipeline coming from the Kerkstraat is a pipeline that is draining all the collected sewage water from the upper part of the study area, towards the RWZI located at the Kerkstraat. This pipeline has a diameter of 1500 mm and drains together with the pipeline from the Laaglandstraat of 600 mm into a pipeline with a diameter of 800 mm, which is the bottleneck at this location. To relieve the system in this location, a CSO is installed. However, the crest of this CSO is high. This causes the sewage water in the Laaglandstraat to not flow out of the system quickly, and to rise above the manholes. In figure 19, the network in the area of the Laaglandstraat, Kerkstraat and RWZI can be seen. The Laaglandstraat is coloured in green.

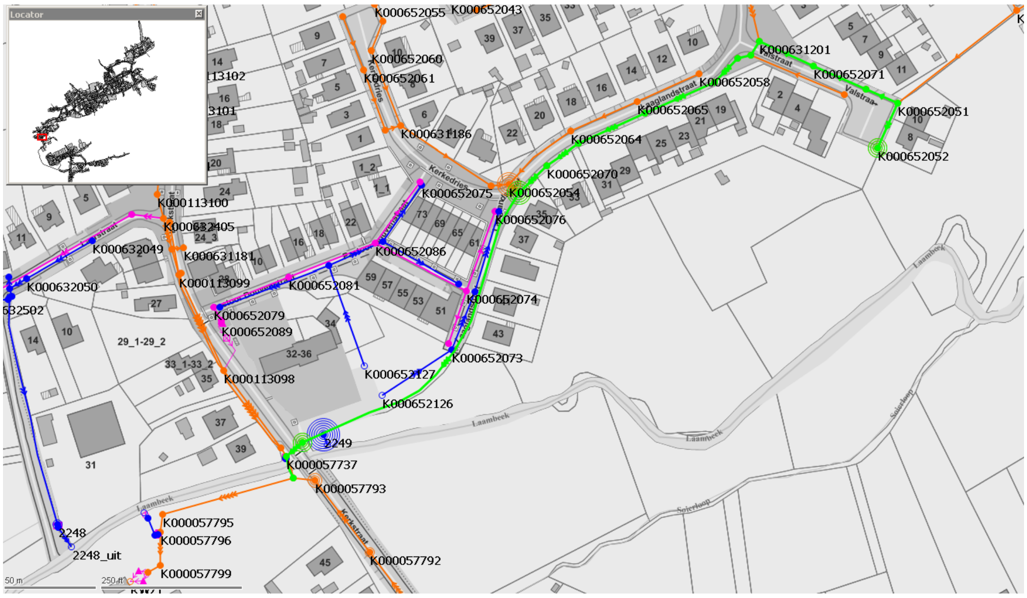
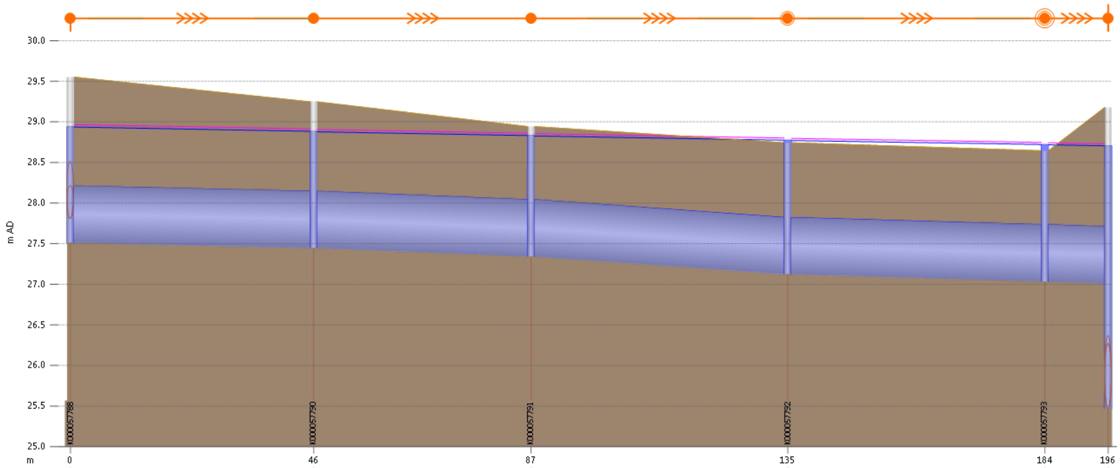


Figure 19: View of the Laaglandstraat

Kerkstraat
The pipeline of the Kerkstraat coming from the south side of the RWZI is a collector draining all the sewage water from the bottom part of the study area. The diameter is consistently 700 mm and the height profile is shown in figure 20. Again, the simulation results show that the simulated peak flow though the pipelines does not exceed the maximum design capacity. However, the collector does drain together with all the sewage water from the upper part of the study area into a pipeline going towards the RWZI. This causes the pipeline at the Kerkstraat to be under pressure, and water rises through the manholes onto the street. It can be said that in this case the capacity of the pipeline towards the RWZI is not sufficient, and causes stalling of water.



Link	K000057788.1	K000057790.1	K000057791.1	K000057792.1	K000057793.1
length (m)	45.8	41.0	48.4	48.4	11.9
Shape ID	CIRC	CIRC	CIRC	CIRC	CIRC
width (mm)	700	700	700	700	700
height (mm)	700	700	700	700	700
us inv (m AD)	27.510	27.446	27.342	27.123	27.034
ds inv (m AD)	27.446	27.342	27.123	27.034	27.008
grad (m/m)	0.00140	0.00254	0.00453	0.00184	0.00218
pfc (m3/s)	0.343	0.463	0.619	0.394	0.429
US flow (m3/s)	0.32547	0.33411	0.34172	0.34811	0.35333

Node	K000057788	K000057790	K000057791	K000057792	K000057793	-
ground (m AD)	29.550	29.246	28.942	28.743	28.644	-

Figure 20: Height profile of Kerkstraat

5.3 Solutions

In general, there are several ways in which the sewage system of the study area could be optimized to reduce the flooding risk. One of the most obvious solutions would be to separate the stormwater from the wastewater and completely, and accommodate rainwater to drain into the environment directly through streams and ditches. However, this solutions is not realistic in terms of costs and feasibility. More local ways in which separation of stormwater could be introduced is to implement local buffering for large impermeable surfaces or to increase the opportunity for infiltration by choosing for permeable materials in urban living spaces, for example permeable pavement. Although some of these solutions could reduce the amount of sewage water in the system and resolve smaller problems locally, the larger bottlenecks that have been presented require more focused solutions.

At the Stationsstraat, the simulation results showed that the capacity of the downstream pipeline was insufficient to drain the upstream water coming from the Stationsstraat and Langstraat. It could also be seen that the water entering through the system of the Langstraat was stalling and causing flooding at the Langstraat as well. In this situation it is important to increase the capacity, by making the pipelines downstream of the connection with the Langstraat larger. This can make sure that the flow through the system goes quicker and water can not build up upstream of the system. Another way to realize more capacity would be, to create a pipeline system on both sides of the street. At some parts at the Stationsstraat this is already the case. However, downstream of the connection with the system of the Langstraat the system only consists of one pipeline.

At the Nieuwstraat, already a semi separated sewage system is realized by the installation of the stormwater system. Therefore, a solution could be to disconnect the stormwater from the roofs to the already existing stormwater system. This could reduce the flow through the combined system significantly since the Nieuwstraat is a long street with a lot of roof surfaces that are connected. An alternative solution could be to increase the diameter of the sewage pipelines to 800 mm more upstream of the connection with the Schobbenberg and Domherenstraat, to avoid stalling of sewage water upstream.

As for the Ambachtlaan, the largest problem seems to be the pumping discharge of the mine pump. Firstly, more information should be gathered about the discharge of the mine pump and where the pump is draining the water to. With the information available now and implemented in the model, it can be said that the maximum pumping discharge should be increased. Another solution could be to install a buffer at the Ambachtlaan, to buffer the large amounts of stormwater. Especially, since the location is the lowest point in the area, which means that a lot of water will flow to this area above ground, a buffer could create extra storage in case of heavy rainfall events.

At the Laaglandstraat and Kerkstraat, the biggest bottleneck seems to be the capacity of the pipelines towards the RWZI and the functioning of the CSO at the Kerkstraat. In this location all the sewage water from the whole study area comes together at the RWZI. Therefore, the capacity of the pipeline towards the RWZI could be increased. In addition, the crest of the CSO at the Kerkstraat could be reduced, to make sure that in case of too much water the system can drain water at this location, instead of the CSO more downstream directly next to the RWZI. Overall, more delay in the drainage towards the RWZI throughout the whole sewage system could be introduced, to make sure that the water enters the RWZI collector more gradually.

6 Results of CSO bottlenecks

This chapter discusses the results based on the criteria for the CSOs. First an analysis of the bottlenecks will be provided. After this, solutions will be proposed to reduce the frequency of CSO activation.

6.1 Analysis of bottlenecks - CSO

In section 2.2.1, the conceptual model of a sewage system has been described. This conceptual model illustrated a sewage system as a bucket in which sewage water can be stored. In case of a capacity breach of the bucket, a CSO is activated to overflow excess water. The downside of this operation, is that diluted sewage water enter the environment directly. The sewage system of Zolder can be viewed as several of these buckets that are connected to each other, with every bucket containing a CSO. In figure 21, the network of the Zolder sewage system is shown. The buckets in the system are illustrated by the different colours. As can be seen, downstream of every bucket a CSO is installed, which is indicated in the figure by means of a number.

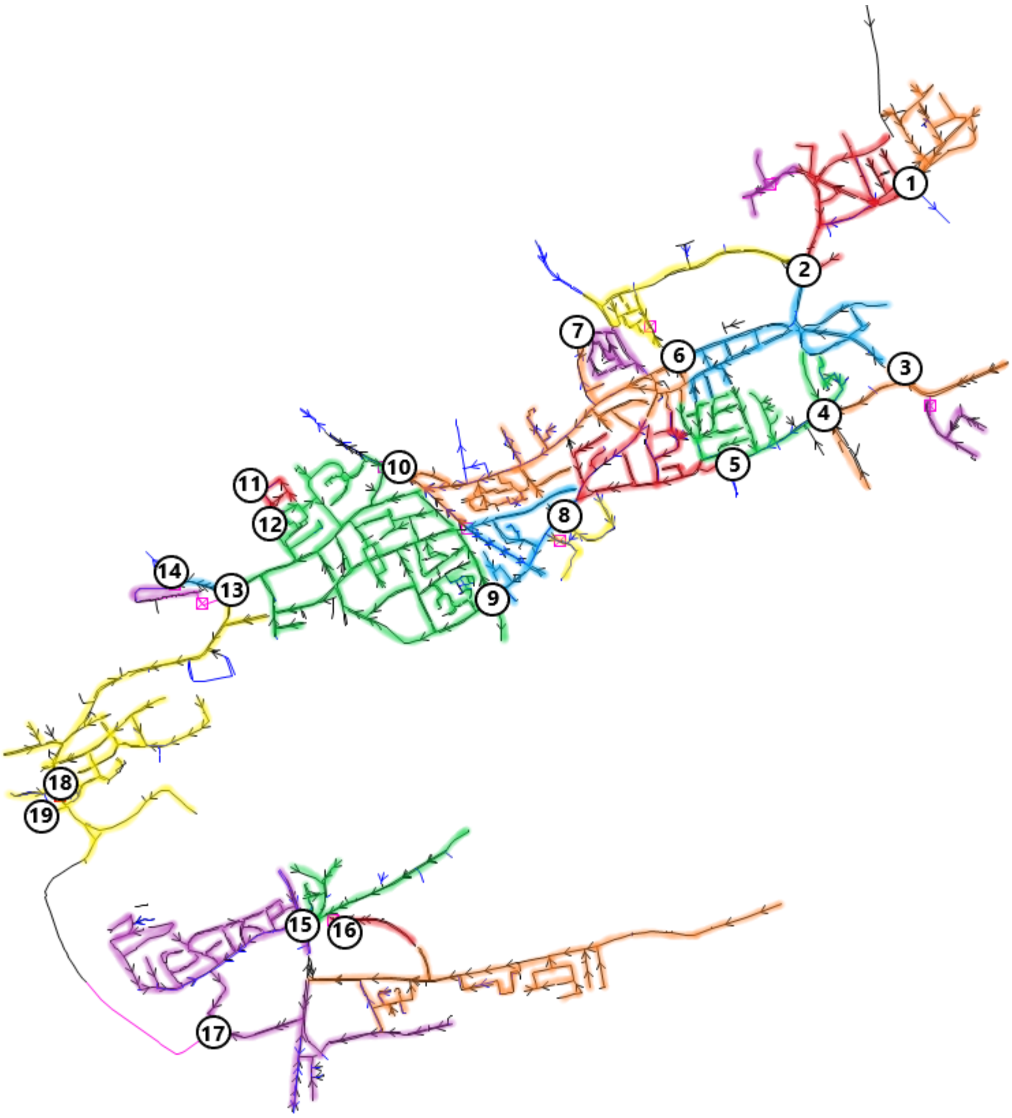


Figure 21: Sewage network of Zolder divided into buckets

The Code of Good Practice states that the activation of CSOs should be limited to a frequency of 7 and 10 times per year depending on when the CSO was renewed as described in section 2.1.3. Therefore, the model has been simulated using rainfall events with a frequency of 10 and 7 times per year (f10 and f7 events) to identify which CSOs are working too often. It should be noted that the results have been maximized, meaning that the results show for each location the flooding that occurs when the system is most under pressure during the simulation. In table 6, the results of the frequency analysis are presented. For each CSO it is stated if they work during a f10 and f7 event. In case a CSO is activated in both cases, it is considered as a location of a bottleneck. The numbers in the table correspond with the numbers in figure 21.

Table 6: Overview of CSO analysis results

#	Location	# of weirs	f10	f7	Discharge (L/s)	IE	6Q14 (L/s)
1	Lillosteenweg	3	Yes	Yes	23,14	1071,2	19,08
2	Stationsstraat	1	Yes	Yes	202,73	2096,29	37,34
3	M. Scheperslaan	1	Yes	Yes	153,6	282,14	5,03
4	Echelbeek	1	Yes	Yes	111,9	532,09	9,48
5	De Drij Dreven	1	Yes	Yes	55,81	1405,75	25,04
6	Molenstraat	1	Yes	Yes	189,85	3290,09	58,6
7	Kerkebosstraat	1	No	No	181,6	1306,19	23,27
8	De Lange Beemden	1	No	Yes	-528,1	2228,07	39,69
9	Belikstraat	1	No	No	58,99	206,64	3,68
10	Meylandtlaan	1	Yes	Yes	219,51	9416,79	167,74
11	Ijskelder	1	No	No	13,32	65,73	1,17
12	Kayenberg	1	No	No	30,67	77,19	1,37
13	O.S. Lievevrouwenstraat	1	Yes	Yes	1138,46	12332,99	219,68
14	Turfstraat	1	Yes	Yes	7,68	37,75	0,67
15	Vrunstraat	1	No	No	383,36	550,24	9,8
16	De Slogen	1	No	No	14,02	141,12	2,51
17	Broederspad	3	Yes	Yes	1262,9	2341,36	41,71
18	Kerkstraat	2	No	No	601,38	13830,54	246,36
19	RWZI	2	Yes	Yes	246,02	16269,05	289,79

In addition to the frequency of CSO activation, the discharge, amount of IE connected to the CSO and the design discharge based on the amount of IE is presented. The discharge has been based on the simulation results of a rainfall event with a return period of 2 years, since this is the design rainfall event. In an ideal situation, every bucket only discharges the 6Q14 discharge, to make sure not too much water is flowing towards the RWZI at the same time. This phenomenon is called buffering, and is usually accommodated by delaying the flow using a transition to a smaller pipeline or a vortex.

In the following sections, first the locations will be discussed that are considered bottlenecks due to their activation at a f10 and f7 event. After this, it will be described how the results affect the study area as a whole.

6.1.1 CSO frequency per location

Location 1: Lillosteenweg
At the Lillosteenweg a pump station is located that contains three CSOs, that all work for a rainfall event that happens 10 or 7 times a year. The sewage water enters the pump station through a 1000 mm diameter pipeline, and leaves the pump station through a pipeline with a diameter of 400 mm. Table 6 shows that the discharge that passes through the pump station (23,14 L/s) is almost equal to the 6Q14 discharge (19,08 L/s). The simulation results show that the pipeline before the pump station contains a lot of sewage water and is under pressure, causing the water to rise above the crests of the CSOs and overflowing to the environment.

Loction 2: Stationsstraat
At the Stationsstraat the flow of the sewage water is delayed by reducing the diameter of the pipeline from a diameter of 700 mm to 500 mm. At the point where the diameter of the pipeline is reduced, a CSO is installed to drain excess water during too much pressure in the pipelines. The simulated discharges as presented in 6, show that the the discharge from the point after the CSO is 202,73 L/s, which is significantly higher than the discharge this location should discharge based on the connected amount of IE (37,34 L/s). This means that the sewage water is not delayed enough at this point. However, as has been described in 5.2, the capacity of the pipelines at the Stationsstraat is not sufficient to accommodate all the water, which causes high pressures in the pipelines. This high pressure causes flooding and the activation of the CSO at a f10 and f7 rainfall event.

Location 3: M. Scheperslaan
At the M. Scheperslaan the CSO works in the simulation during a f10 and f7 rainfall event. In this location the flow of the water is delayed by a reduction of the pipeline sizes from a diameter of 600 mm to 500 mm. The discharge through the pipeline of 500 mm is 153,6 L/s in the simulation results for a 2 year return period rainfall event. This is significantly higher than the design discharge 6Q14 based on the IE (5,03 L/s). It should be noted that at this location the information regarding the amount of IE is lacking, due to unavailability of information from the business park that drains to this location. Still, the results suggest that the crest of the CSO is too low, and the amount of water passing through the smaller pipeline is too high.

Location 4: Echelbeek
At the intersection with the Nieuwstraat and Acht Meilaan, a manhole is located with a CSO to the Echelbeek, which is a provincial water stream. The flow of water in the system is delayed at this location by transitioning a pipeline with a diameter of 600 mm to a pipeline with a diameter of 400 mm. As can be seen, in table 6, the discharge through leaving the manhole is larger than the designed 6Q14 discharge. Again, the amount of IE is unsure due too the connection with the business park. The biggest bottleneck, based on the simulation results in this location is the reversed working of the CSO at both a f10 and f7 rainfall event. This means that the simulation results show that water from the Echelbeek is flowing into the sewage system, instead of the other way around. This means that the CSO is not constructed well, meaning that the water level in the Echelbeek is higher than the water level in the sewage system.

Location 5: De Drij Dreven
At the intersection of the De Drij Dreven with the Nieuwstraat, the water inflow from the Nieuwstraat is delayed by the use of a vortex. The vortex is letting through 55,81 L/s, which is almost the double of the required design discharge 6Q14, which is 25,04 L/s. The simulation results show that the capacity of the pipelines at the Nieuwstraat is insufficient and the system is under pressure, as has been discussed in section 5.2 as well. The working of the CSO at a f10 and f7 rainfall event indicates that as well that the capacity to buffer the water in this location is insufficient even though the discharge through the vortex is higher than it should be.

Location 6: Molenstraat
At the Molenstraat the flow is restricted by the transition of a pipeline with a diameter of 700 to a pipeline with a diameter of 600 mm. Before the reduction in pipe size, a CSO is installed to drain diluted sewage water in the environment in case of too much water in the system. The results of the f10 and f7 rainfall event show that in both cases the CSO works, meaning that too much water is entering the environment untreated at this location. It can also be seen from the 2 year return period rainfall event results that the discharge through the smaller pipeline is higher than the required design discharge based on the IE for this location. This means that there is no sufficient delay of the flow in this location.

Loaction 8: De Lange Beemden
At location 8, a CSO is constructed to overflow the water from the combined system at the Boektlaan to the stormwater system at the Lange Beemden and Ambachtlaan. This CSO works during a f7 rainfall event and not during a f10 rainfall event. This means that the location is not a direct bottleneck. However, it is remarkable that during the rainfall event with a return

period of 2 years, the discharge downstream from the CSO at the Boektlaan is negative. This means that the water is flowing upstream the system, indicating that there is too much water in the system at the Boektlaan, that can not be drained towards the Meylandtlaan and Belikstraat. As has been discussed in section 5.2, the stormwater system at the Ambachtlaan, Lange Beemden and Boektlaan is under a lot of pressure which causes flooding problems at the Ambachtlaan. Therefore, the bottleneck in this area is primarily the capacity problem to drain water out of the stormwater system through the mine pump.

Location 10: Meylandtlaan
At the Meylandtlaan a pump station is installed to pump the water further through the system towards the RWZI. The pump station is connected to a CSO, that works for both a f10 and f7 rainfall event. In addition, table 6 shows that the discharge after the CSO construction (which is equal to the pump station discharge) is higher than the 6Q14 discharge. This means that both the CSO works too often and the discharge at this point is too high.

Location 13: O.S. Lievevrouwenstraat
At the O.S. Lievevrouwenstraat, a CSO is located that overflows from the combined system at the O.S. Lievevoruwenstraat to the combined system of the Abdijstraat. The CSO works for both a f10 and f7 rainfall event and the pipeline with a diameter of 1250 mm is reduced to a pipeline with a diameter of 1000 mm at the location of the CSO. The high frequency of the CSO is not directly a bottleneck, since the water is not directly drained into the environment. In this location the main purpose of the CSO is to increase the capacity of the system during heavy rainfall by making overflowing the sewage water to the Abdijstraat and Driesstraat. The system at this location functions in these cases as a buffer.

Location 14: Turfstraat
At the Turfstraat a vortex is installed with a CSO. The CSO both works during a f10 and f7 rainfall event, while the connected IE for this location is not high (37,75 IE). In table 6, it can be seen that the discharge from the vortex is 7,68 L/s. This means that even though the discharge going through this location is low, the CSO is working. This indicates a low crest of the CSO. This low crest can especially be a problem if water from the O.S. Lievevrouwenstraat is drained to the Abdijstraat and passes the CSO at the Turfstraat.

Location 17: Broederspad
At the Broederspad all the sewage collected from the lower part of the study area gathers. In this location a pump station is installed, to pump the water from this area to the RWZI that is located more North. Since a lot of sewage water is flowing towards the pump station, a buffer is connected to the pump station. This buffer can retain the water in case of high inflow of the system, and drain it back to the pump station during periods of lower inflow. The buffer is secured with three CSOs, that can drain diluted sewage water into the environment when the capacity of the buffer is not sufficient. In table 6, it is stated that all three CSOs work during both f10 and f7 rainfall events. This indicates that the capacity of the buffer is insufficient to meet the requirements of the Code of Good Practice.

Location 19: RWZI
At the RWZI two collector pipelines from the upper and bottom part of the study area converge into one pipeline draining to the RWZI. A CSO is located at the Kerkstraat, connected to the collector pipeline coming from the upper part of the study area. This CSO does not work during a f10 and f7 rainfall event. The pipeline that connects both collector pipelines and goes directly to the RWZI also is connected to a CSO. This CSO does work for both f10 and f7 rainfall events, and drains between 3000 and 4600 cubic meters per working of the CSO depending on the rainfall event. In addition, the results in table 6 show that less sewage water is drained to the RWZI after the CSO construction than should be drained. This indicates that too much water is being drained through the CSO than should, and more capacity of the pipeline is necessary to drain sufficient water to the RWZI.

6.1.2 CSO frequency in the study area

As has been explained in section 2.2.1, a sewage system consists of multiple buckets that connect to each other. Each bucket contains a CSO that can work if the the capacity of the bucket is met. In figure 21, parts of the sewage network that form the buckets in the study area have been indicated by the use of colours. When looking at the results presented in table 6, it can be seen that more than half of the CSOs work during an f10 and f7 rainfall event. This means that the amount for sewage water that is drained directly too the environment is too high for whole system. Per location the bottlenecks have been discussed. For most locations, the high CSO frequency is caused by too little buffering of the sewage water. This can be seen by the high discharges from several 'buckets' compared to the 6Q14 discharge based on the amount of IE. In some areas, the capacity of the system is too low, for example the Stationsstraat and Nieuwstraat, which are also locations that are suffering from flooding problems. Some locations show that too much water is going through the CSO due to a too low crest of the CSO, like at the Turfstraat, Scheperslaan and the Echelbeek, where the low crest causes an inflow through the CSO into the sewage system. In addition, it can be seen that the buffering of the sewage water throughout the system is too low by the large amounts of water being drained through the CSOs downstream of the sewage network at the Broederspad and RWZI.

6.2 Solutions

The Code of Good Practice aims for reducing the frequency of the CSOs to a maximum of seven times a year. This means that the CSOs should not work for the simulation with a f10 and f7 rainfall event. To reduce CSO frequency the sewage system should have enough capacity and buffering to limit the need for CSO working. This means not too much sewage water should leave a bucket to fast. In general, the activity of CSOs can be reduced by limiting the amount of stormwater in the combined system. Again, this means that the implementation of separated systems and sustainable urban stormwater infiltration systems can remove the pressure on the combined system. More applicable solutions are creating more buffering in the sewage system and making the crest of the CSOs higher.

There are several locations where the buffering should be increased: Lillosteenweg, Stationsstraat, Meylandtlaan, Broederspad, De Drij Dreven, Molenstraat and M. Scheperslaan. For the Stationsstraat and De Drij Dreven the most suitable option seems to be to increase the capacity of the pipelines, especially since at these locations also sewage flooding occurs due too lack of capacity. By increasing the diameters of the pipelines and making the crest of the CSOs, more buffering can be created. In addition, the drainage from upstream at the Stationsstraat should be more delayed by installing a construction that can reduce the flow. As for both the pump stations at Lillosteenweg and Meylandtlaan, the buffering should be increased to reduce the frequency of the CSOs. For the Meylandtlaan the pumping discharge could be reduced to delay the flow more based on the design discharge. At the M. Scheperslaan, more buffering could be created at the pump station of the Rijkelstraat, upstream of the CSO at the M. Scheperslaan. Finally, at the Broederspad, the size of the buffer that is already installed should be increased.

At the Turfstraat the CSO works already for a very low flow. From this it can be seen that the crest of the CSO is very low. This can especially be a problem if the sewage water is being drained through the CSO of the O.S. Lievevrouwenstraat to the Abdijstraat and passes the CSO at the Turfstraat. Therefore, the crest of the CSO should be constructed higher, to prohibit large amounts of diluted sewage water to enter the environment. At the Echelbeek the biggest bottleneck is the inflow of the Echelbeek into the sewage system through the CSO. This is an example of parasitic water entering the sewage system. In this location the CSO construction should be changed in such a way that the flow of the Echelbeek can not flow into the sewage network. This can be done by making the crest of the CSO higher, too make sure that the water level at the side of the Echelbeek can not be higher than the water level in the sewage system. In addition a flap valve could be installed making sure that the water from the Echelbeek can not enter the sewage system.

7 Discussion

In general, the validation has shown that the model is able to identify the larger problem areas of the study area. This indicates that the model has a certain degree of validity. In this chapter, the validity of the results in this study will be elaborated on, by addressing the uncertainties, limitations and possible improvements.

Uncertainties
It should be noted that the model that was built using the Infoworks ICM software is not an exact representation of the reality, but always an approximation that can be improved in terms of accuracy. The validation shows that the model obtained in this study is able to simulate the larger problem areas in the study area. However, still the model is subject to a number of uncertainties that influence the outcomes of this study.

First of all, the database that has been used to built the model lacks information and contains assumptions for several locations. The database has been built using an initial database provided by Aquafin. This database has been completed with information by carrying out inspections and measurements on several locations. However, this was not possible for all the parts of the system. There were several locations that could not be accessed or inspected, for example due to manholes that could not be opened. In addition, some objects like inlets or outfalls were not found during inspections, while the initial database from Aquafin suggested that these objects are part of the system. In these instances, additional information has been used from As-Built plans. If these plans or other information was not available, it was necessary to make assumptions.

In addition to the database, information is lacking throughout other aspects of the study. Surveying has been carried out to obtain information about private sewage systems and the number of IE at larger facilities, companies or schools. Responses at these surveys have been limited. Therefore, a lot of information that influences the sewage system is lacking. Specifically, this influences the accuracy of the model and its results at the Rijkelstraat and De Lange Beemden, where larger business parks are located.

The study area also contains several mine pumps that pump surface water into the sewage system. For the majority of the pump stations not a lot of reliable information was available, especially for the pump station connected to the system of the Ambachtlaan. As for the other pump stations and hydraulic structures, assumptions have been made occasionally when data was not available. Especially for the pump stations throughout the study area this can be of influence. Some of these pumps have been modelled as pumps with a fixed discharge, because the type of pump was unknown.

Another source of uncertainty of the model implementation is the runoff generated in the model due to impermeable surfaces. The size of the areas has been determined by the use of flow accumulation maps and runoff coefficients have been based on the slope, vegetation and soil. For most impermeable surfaces it is assumed that all the runoff enters the sewage system at the same time, while in reality there is some delay between the rainfall event and the runoff reaching the inlet of the sewage system.

The use of composite rainfall events to simulate the model can give a wrong impression of the flow through the system due to the extreme peak. The peak in composite rainfall events is very short and very intense. In reality, this type of rainfall event does rarely occur. Especially, in the case of larger runoff areas, using composite rainfall events can give the wrong impression because a lot of runoff is generated in the model and instantly enters the sewage system.

Finally, a validation has been carried out, showing that the the model is able to model the larger problem areas in the study area. This validation has been based on historical events, meaning it is a qualitative analysis. This means that no conclusions can be drawn about the quantitative results, like the discharges or water levels, based on the model.

Limitations
The model has several limitations, that affect the results. Firstly, according to the Hydronaut-procedure 7.0, only eight runoff coefficients for impermeable surfaces can be implemented. This

means that there is a limited amount of combinations that can be used for the determination of the runoff coefficient. Secondly, the model only simulates in 1D. This can generate simulation results in which flooding occurs, while in reality these problems do not occur when sewage water flows above ground somewhere else into the system. Especially for the study area of Zolder this can be of influence on the results, since the area contains several high slopes. Finally, the model only considers bottlenecks due to capacity problems of the system. Bottlenecks due to structural deterioration are outside the scope of the study and not considered in the model. Due to this, several bottlenecks that do exist in reality, are not considered in the analysis since the model does not include this.

Suggestions
Overall, several suggestions can be given for further research or for improving the model.

First of all, the uncertainties caused by lack of information can be reduced. This could be done by acquiring more information about the larger facilities, companies or schools. This will especially make a difference for the accuracy at the Rijkelstraat and De Lange Beemden. Other information that could be further gathered is about the mine pumps in the study area. A lot of flooding is simulated at the Ambachtlaan, it seems that the pump discharge in this location is not correct. Also the switch on and switch off level is assumed for this pump because no information was available. As for the uncertainty caused by the large impermeable surfaces, concentration times could be determined for the large areas. Especially for the Windestraat and Vrunstraat improvements on the concentration time could benefit the accuracy of the model.

In general, it can be recommended to carry out a present-day data validation. This is a validation that compares the results of the model with measured data. Carrying out a present-day data validation can solidify the validity of the model on a quantitative basis. This validation has not been executed for this study due to time constraints and insufficient measurements.

Finally, updating the model to 2D model could give more specific insights in how the water flows through the model in case of flooding. Specifically for this study area an update to a 2D model would have added, due to the large slopes that some locations are subjected to.

8 Conclusion and recommendations

In this final chapter, a conclusion is formulated based on the results obtained in the study with respect to the research objective and questions. After this, recommendations will be given for future research.

8.1 Conclusion

The research objective was to identify and assess the bottlenecks in the sewage system of Zolder by means of a model of the existing situation and criteria for identifying the bottlenecks. In addition to this the objective was formulated to propose possible solutions.

The main activity for achieving the research objective has been to build the model of the existing situation. It can be said that majority of the sewage system of Zolder is combined system, with sporadically a separated system at newer neighbourhoods or busy streets. As has been illustrated in the results, this combined system in Zolder is conceptually based on several smaller combined sewage systems connected to each other. Every small 'bucket' is secured with a CSO, in case of a capacity breach. To structure the model in better detail, Infoworks ICM has been used in which additional hydraulic structures influence the hydraulic behaviour of the sewage system.

The validation results of the model show that the model can indicate the larger bottleneck areas based on a qualitative analysis. Flooding results of simulation with a return period rainfall event of 2 years were compared to flooding areas reported to the municipality. Some areas simulated in the model did not match the information from the municipality, for these locations the mismatch could be accredited to a lack of information or insufficient detailing of the model.

Criteria for the identification of the bottlenecks have been based on the Code of Good Practice (Coordinatiecommissie Integraal Waterbeleid, 2012). This means that bottlenecks were identified using criteria regarding flooding and CSO activation in the simulation results. More specifically this means that bottlenecks were identified when flooding occurred for a simulation with a 2 year return period rainfall event and when CSOs were activated for a simulation with a f10 and f7 rainfall event.

As for the flooding criteria, the following locations were identified to be the larger bottlenecks: Stationsstraat, Langstraat, Nieuwstraat, Ambachtlaan, Laaglandstraat and Kerkstraat. In most locations, it was found that the capacity of the pipelines was insufficient. Specifically for the Ambachtlaan, it was found that the pump discharge was too low to pump out all of the water fast enough. For the CSO activation, it was found that most of the CSOs present in the study area of Zolder were activated for both an f10 and f7 event. For most cases, the buffering of the sewage water in the system was too low, creating a fast flow through the system towards the RWZI. This causes extra pressure at the system at the RWZI.

To resolve the bottlenecks, it is most desired to create a large number of separated systems in the study area, and to invest in infiltration in the more denser areas of the study area. The reduction of stormwater through these techniques can relieve the combined system significantly. More specific solutions, are to increase the capacity of the sewage system at the larger flooding bottlenecks, to make sure that flooding is prohibited. In case of the Ambachtlaan, this means that a higher pump discharge should be aimed at. As for the CSOs, the solutions should be aimed at delaying the flow more throughout the system, to reduce the pressure downstream at the RWZI. This means that at several locations more buffering should be created by installing buffers or increasing pipelines. In some cases the crest of the CSOs should be altered to reduce the activation frequency of the CSOs.

All in all, it can be concluded that a model of the existing situation was created that is a good starting point for the evaluation of the existing sewage system of Zolder. An analysis was carried out to identify the first bottlenecks. This analysis shows relevant results that can be used to improve the sewage system of Zolder where this is most necessary.

8.2 Recommendations

For further research several recommendations can be made.

First of all, the model could be improved to increase the accuracy of the results. The lack of information for several aspects of the model could be resolved. Specifically, this means gathering more information about the larger facilities, schools and companies. In addition, more information regarding the mine pumps and several open surface water stream is desirable for the accuracy of the model. If possible, the model could be expanded to 2D model, to give a more holistic view of how the water flows through the system both in the sewage system and above the ground level.

Secondly, it is advised to carry out a present-day data validation. This validation uses measurements carried out in the sewage system of the study area, to validate the model results on a quantitative basis. This type of validation can increase the credibility of the model and results, can give a more narrow indication as to where the model could be improved further and gives more insights regarding where parasitic water is entering the sewage system.

Finally, it is advised to further develop and evaluate the proposed solutions in this study. This can be done by setting up a model that incorporates the solutions. In this way, the effectiveness of several solutions can be assessed and altered based on their performance.

References

Andersson, K. and Dickin, S. and Rosemarin, A. (2016). *Towards "Sustainable" Sanitation: Challenges and Opportunities in Urban Areas. A Contextual and Dynamic Understanding of Sustainable Urbanisation.* (Consulted on 11th of April) doi: \url{https://doi.org/10.3390/su8121289}

Aquafin. (2017). *Hydronautprocedure 7.0.* (Retrieved from Antea Group Belgium, January 2022)

Aquafin. (2019). *Projectvoorstel OP2021.* (Retrieved from Antea Group Belgium, March 2022)

Brandao, J. and Albergaria, J. and Albuquerque, J. and Jose, S. and Grossinho, J. and Ferreira, F.C. ... Solo-Gabriele, H. (2020). *Untreated sewage contamination of beach sand from a leaking underground sewage system. Science of The Total Environment, volume 740.* (Consulted on 10th of May) doi: \url{https://doi.org/10.1016/j.scitotenv.2020.140237}

Coordinatiecommissie Integraal Waterbeleid. (2012). *Code van goede praktijk voor het ontwerp, de aanleg en het onderhoud van rioleringssystemen.* (Report D/2012/6871/034. Retrieved from Antea Group Belgium, January 2022)

Coördinatiecommissie Integraal Waterbeleid. (2012). Technische toelichting deel 2, afwateringssystemen.
(Consulted on 2nd of June)

Curriero, F.C. and Patz, J.A, Rose, J.B and Lele, S. (2001). *The Association Between Extreme Precipitation and Waterborne Disease Outbreaks in the United States, 1948–1994. American Journal of Public Health 91, no. 8 (August 1, 2001): pp. 1194-1199..* (Consulted on 10th of May) doi: \url{https://doi.org/10.2105/AJPH.91.8.1194}

De Smedt and Yongbo and Deng. (1999). Hydrologische en hydraulishce modellering van de ijs. *Vrije Universiteit Brussel.* (Consulted during May)

Dirckx, G. and Bixio, D. and Thoeye, C. and De Gueldre, G. and Van De Steene, B. . (2009). Dilution of sewage in flanders mapped with mathematical and tracer methods. *Urban Water Journal*, *6*(2), 81-92. (Consulted on 11th of June) doi: 10.1080/15730620802541615

Dirckx, G. and Bixio, D. and Thoeye, C. and De Gueldre, G. and Van De Steene, B. (2007). Passt een rtc strategie in vlaanderen? *Rioleringswetenschap*(25). (Consulted on 11th of June)

Dirckx, G. and Fenu, A. and Warnbecq, T. and Kroll. S. and Weemeas, M. (2019). *Dilution of sewage: Is it, after all, really worth the bother? Journal of Hydrology.* (Volume 571, 437-447) doi: https://doi.org/10.1016/j.jhydrol.2019.01.065

Eijlander, S. and Mulder, K.F. . (2019). *Sanitary Systems: Challenges for Innovations. Journal of Sustainable Development of Energy, Water and Environment Systems, 7 (2), 193-212.* (Consulted on 10th of May) doi: \url{https://doi.org/10.13044/j.sdewes.d6.0231}

Lamghari Moubarrad, F. and Assobhei, O. (2007). *Health risks of raw sewage with particular reference to Ascaris in the discharge zone of El Jadida (Morocco). Desalination, volume 215, issues 1-3, pages 120-126.* (Consulted on 10th of May) doi: \url{https://doi.org/10.1016/j.desal.2006.10.030}

Maeda, M and Mizushima, H and Ito, K. (2005). Development of the real-time control (rtc) system for tokyo sewage system. *Water science and technology*, *51*(2), 213-220.

Martin Pleau, M. and Colas, H. and Lavallée, P. and Pelletier, G. and Bonin, R. (2005). Global optimal real-time control of the quebec urban drainage system. *Environmental Modelling Software*, *20*(4), 401-413. (Consulted on 11th of June) doi: https://doi.org/10.1016/j.envsoft.2004.02.009

Mulder, K. . (2019). *Future Options for Sewage and Drainage Systems Three Scenarios for Transitions and Continuity. Sustainability, 11 (5).* (Consulted on 10th of May) doi: \url{https://doi.org/10.3390/su11051383}

Olds, H. and Corsi, S. and Dila, D and Hamlo, K. and Bootsma, M. and McLellan, S. (2018). *High levels of sewage contamination released from urban areas after storm events: A quantitative survey with sewage specific bacterial indicators.*
(Consulted on 11th of April) doi: \url{https://doi.org/10.1371/journal.pmed.1002614}

Otterpohl, R. and Grottker, M. and Lange, J. (1997). *Sustainable water and waste management in urban areas. Water Science and Technology, Volume 35, Issue 9, 121-133.* (Consulted on 11th of April) doi: \url{https://doi.org/10.1016/S0273-1223(97)00190-X}

Vaes, G. and Berlamont, J. (1996). *Composietbuien als neerslaginvoer voor rioleringsberekeningen.*

(Consulted on 5th of April 2022)

Van Assel, J. and Dirckx, G. (2007). *Huidig en toekomstig gebruik van rioolmodellen in Vlaanderen.* (Consulted on 15th of May)

Vlaamse Milieumaatschappij. (2019). *Waterverontreiniging in Vlaanderen in 2018.* (Report D/2019/6871/034)

Willems, P. . (2014). *Klimaatverandering en riolering.* (Retrieved from: `https://bwk.kuleuven.be/hydr/CCI/Reports/vakantiecursustudelft2014-bijdragepwillems.pdf`, consulted on 15th of May)

Willems, P. (2011). *Evaluatie en actualisatie van de IDF-neerslagstatistieken te Ukkel . KU Leuven, Faculty Engineering Sciences.* (Retrieved from `https://bwk.kuleuven.be/hydr/CCI/Reports/pwillems-actualisatie-idf.pdf`, consulted on 25th of April)

Wong, T.H.F. (2006). *Water sensitive urban design - the journey thus far. Australasian Journal of Water Resources, 10:3, 213-222.* (Consulted on 10th of May) doi: \url{https://doi.org/10.1080/13241583.2006.11465296}

A Preliminary bottlenecks

Table 7: Preliminary bottlenecks in the sewage system of Zolder, established during the establishment of the database

Node ID	Category	Description
Unknown	Flooding	Flooding of the street at Ringlaan between Stationsstraat and Kuiperstraat, and flooding at St Jobstraat 108
Unknown	Flooding	At Galgeneinde, the capacity of the system is insufficient because of slib in the sewage system, this causes flooding
K000632516	Dilution	At Vrunstraat, between number 54 and 56 a ditch is connected to the sewage system
1097	Dilution	At Vrunstraat between number 76/80 and 77/81 is connected to the sewage system
K000632518	Dilution	At De Slogen number 40, a larger ditch is connected to the sewage system
Unknown	Dilution	The stream 'Schaamloop' is connected to the sewage system, location of inlet is unknown
6061A	Dilution	Groundwater is being pumped to the sewage system (pump station of mine site) with a permanent discharge of 21 l/s
Unknown	Dilution	Ditches that drain rainwater from the highway are connected to the sewage system
6009 & 6011	Dilution	Ditches at the Verlorenkost are connected to the sewage system at Nieuwstraat
K000632478	Dilution	Ditches connected to sewage system at Laambroekstraat
K000632525	Dilution	Ditches connected to sewage system at L. Hoelenstraat
1224	Dilution	Ditch from Wulpenstraat aand Tulpenlaan connected to sewage system
K000632529	Dilution	Ditch from Begonialaan, Chrysantenlaan and Lobelialaan connected to sewage system
K000632520	Dilution	Ditch from Irislaan and Anjelierenlaan connected to sewage system
K000632526 1082	Dilution	Ditch from Wolverik and Vredestraat connected to sewage system
K000632533	Dilution	Inlet of larger stream to sewage system at St Jobstraat
K000632534	Dilution	Inlet of ditch at Heidestraat
Unknown	Dilution	Inlet of ditch to pumpstation at De Slogen, which disturbs the capacity
K000631669	Dilution	Private sewage systems are connected to the main sewage system at Mommestraat
K000631501	Dilution	Pumpstation of mine sites is pumping a lot of surface water, it is unknown to where this water is being pumped
Unknown	CSO	CSO connected to a stream, sometimes water from the stream flows back into the sewage pipelines

B Model maps

B.1 Model network

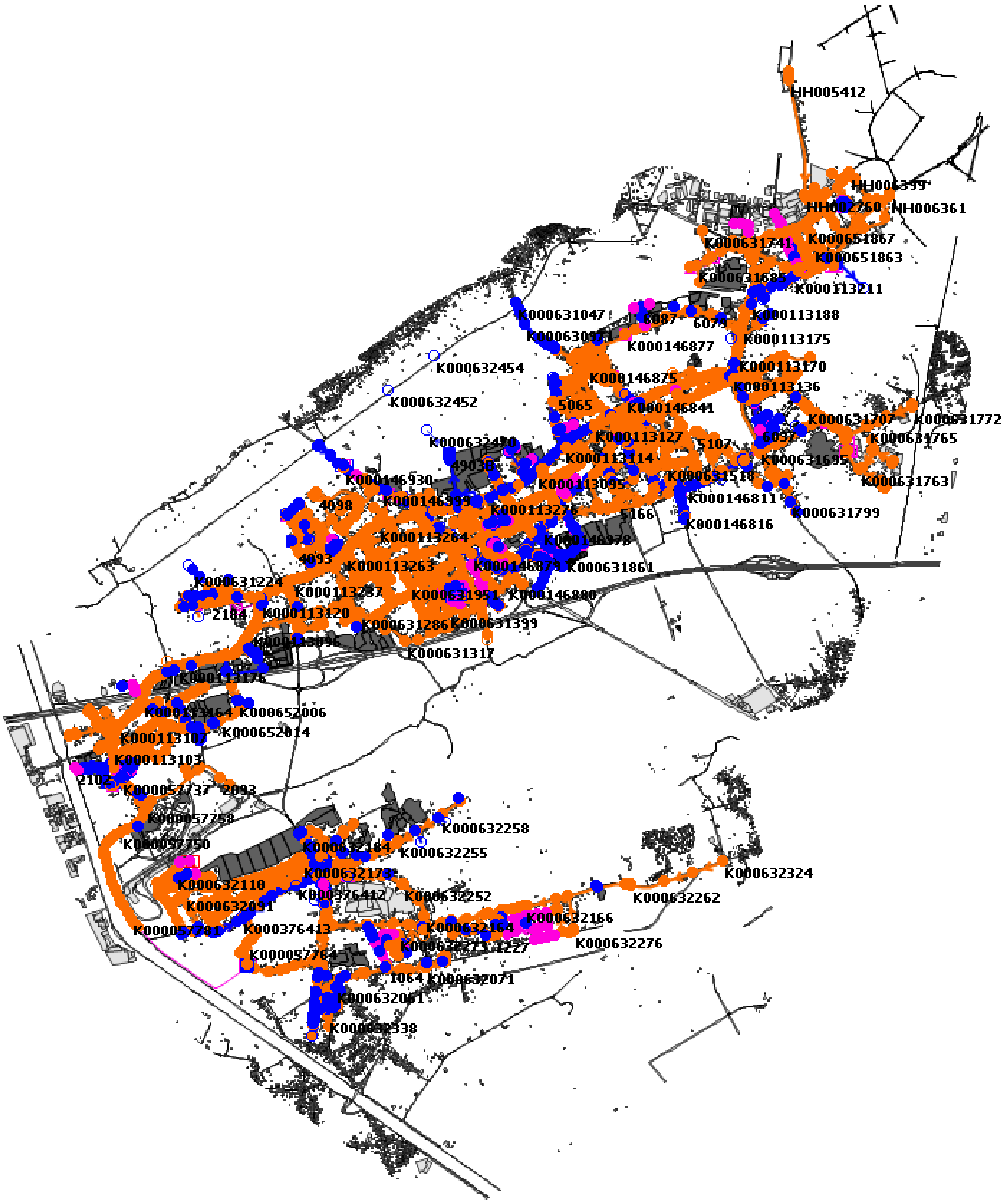


Figure 22: Model network

B.2 Runoff surfaces (permeable & impermeable)

Figure 23: Permeable and impermeable runoff surfaces

B.3 Subcatchments

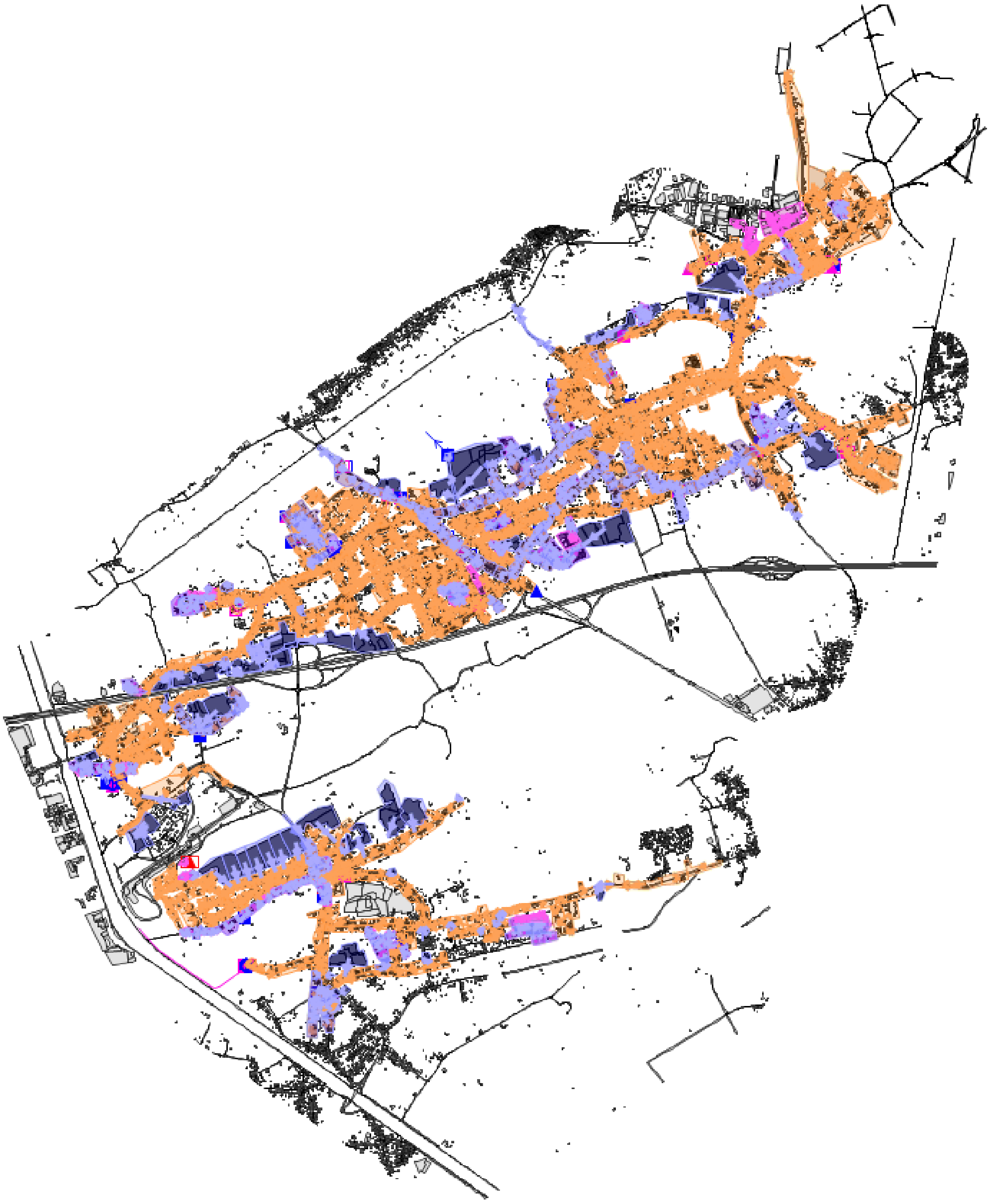


Figure 24: Model subcatchments

C Surveying IE and private sewage systems

C.1 Survey questions

The following questions were asked in the surveys regarding the stormwater and wastewater drainage and production for large non household buildings.

General questions (asked to all facilities):

- Is the stomrwater and wastewater separately drained? Where is it connnected to the sewage system?
- How is the drainage of the parking arranged?
- Is the water being buffered? If yes:
  - What is the capacity of the buffer?
  - What is the diameter of the orifice under the buffer?
  - At what depth is the invert level of the pipeline on the inside?
  - At what depth is the drainage of the buffer and to where is it drained?
  - Is the buffer used for other activities?

Questions for factories, working places or offices:

- Which activities are being carried out at the location?
- How many workers are active on site?

Questions for schools:

- How many students are registered at the school?
- How many person work at the school?
- Does the school include a boarding school?
- Does the school have a kitchen to prepare warm meals?
- Does the school have showers?

Questions for hotels, pensions, hospitals and prisons:

- What is the maximum capacity (in terms of beds)?

Questions restaurants:

- How many people are present approximately on a daily basis?

C.2 Assumptions IE

The following assumptions were made regarding the amount of IE, based on the surveys:

Table 8: IE assumptions for facilities

Facility	Amount of IE
Factory or workplace	1 worker= 1/2 IE
Office	1 worker= 1/3 IE
School without showers, pools or kitchen	1 student = 1/10 IE
School with showers but without kitchens	1 student = 1/5 IE
School with showers and kitchen	1 student = 1/3 IE
Hotel, pension, hospital or prison	1 bed = 1 IE
Restaurant	1 person = 1/4 IE

D Formulas hydraulic structures

In this appendix, the formulas are presented that the modelling software uses to calculate the flow through several hydraulic structures. The formulas have been retrieved from the Innovyze documentation, included in the Infoworks ICM software

WEIR
The WEIR function uses the following formula:

$$Q = C_d * \sqrt{g} * B * D_u^{3/2} \tag{2}$$

With:
Q= Discharge
C_d= Discharge coefficient
g= Gravitational force
B= Length of the CSO
D_u= Water depth from the height of the CSO

In the model, a first and second discharge coefficient has been filled in. The discharge coefficient determines the amount of water passing the CSO. For the WEIR functions, a first discharge coefficient is given of 0.66. As for the second discharge coefficient, a value of 1 was given which will be used in case of demand for a very high capacity.

ORIFICE & SLUICE
The ORIFICE & SLUICE function uses the following formula:

$$Q = C_d * A * \sqrt{g} * {D_{cl}}^{1/2} \tag{3}$$

With:
Q= Discharge
C_d= Discharge coefficient
A = Area of the cross-section
g= Gravitational force
D_{cl}= Water level with respect to the invert level of the orifice/gate

Also for the orifices and gates, there is a first and second discharge coefficient, that both have been set to 1.

FLAP VALVE
The FLAP VALVE function uses the following formula:

$$Q = (1/C_d) * A * V \tag{4}$$

With:
Q= Discharge
C_d= Discharge coefficient
A = Area of the cross-section
V= Average flow velocity

Also for the flap valves, there is a first and second discharge coefficient, that both have been set to 1.

E Overview of separated sewage systems in the study area

Table 9: Overview of separated systems in the study area - 1

Street	Pipe systems	Seperated:
Abdijstraat	Combined & storm	Semi
Alice Nahonlaan	Foul & storm	Fully
Ambachtlaan	Combined & storm	Semi
August Vermeylenlaan	Foul & storm	Fully
Beatrijslaan	Foul & storm	Fully
Bieststraat	Combined & storm	Semi
Bloemelingen	Foul & storm	Fully
Boekterheide	Combined & storm	Semi
Boektlaan	Combined & storm	Semi
Borgveld	Combined & storm	Semi
Bredestraat	Combined & storm	Semi
Broeksteeg	Combined & storm	Semi
Dorpshof	Combined & storm	Semi
Driesstraat	Combined & storm	Semi
Galgeneinde	Combined & storm	Semi
Ganzenhof	Foul & storm	Fully
Ganzenstraat	Combined & storm	Semi
Grootven	Foul & storm	Fully
Hadewijchlaan	Foul & storm	Fully
Heidjesstraat	Combined & storm	Semi
Herdershof	Foul & storm	Fully
Holstraat	Combined & storm	Semi
Inakker	Combined & storm	Semi
Kayenberg (and area)	Combined & storm	Semi
Kerkebosstraat	Combined & storm	Semi
Kerkenboshof	Combined & storm	Semi
Kerkeveld	Combined & storm	Semi
Kerkstraat-Laaglandstraat	Foul & storm	Half
Koeltorenlaan	Foul & storm	Fully
Korenhof	Foul & storm	Fully
Kromvenhof	Foul & storm	Fully
Kuilberg	Combined & storm	Semi
Laarstraat	Foul & storm	Fully
Lange Beemden	Foul & storm	Fully
Langstraat	Combined & storm	Semi
Meylandtlaan	Combined & storm	Semi
Mijnwerkerslaan	Foul & storm	Fully
Molenstraat	Combined & storm	Semi
Narcissenlaan	Foul	Fully
Nieuwstraat	Combined & storm	Semi
Oude Heidestraat	Foul & storm	Fully
Paardenbloemstraat (and area)	Foul & storm	Fully
Pannewinnning	Combined & storm	Semi
Pastoor Oomshof	Foul & storm	Half

Table 10: Overview of separated systems in the study area - 2

Street	Pipe systems	Seperated:
Schaltusstraat	Combined & storm	Semi
Schapenpad	Foul & storm	Fully
Schuttershof	Combined & storm	Semi
Sint-Jobstraat	Combined, foul & storm	Partly semi & partly fully
Slagmolenstraat	Combined	Semi
Stukkenstraat	Foul & storm	Fully
t Roosterke	Foul & storm	Fully
Vagevuurpad	Combined & storm	Semi
Verlorenkost	Combined & storm	Semi
Wolverik	Foul & storm	Fully

F Boundary conditions

F.1 Outfall boundary conditions

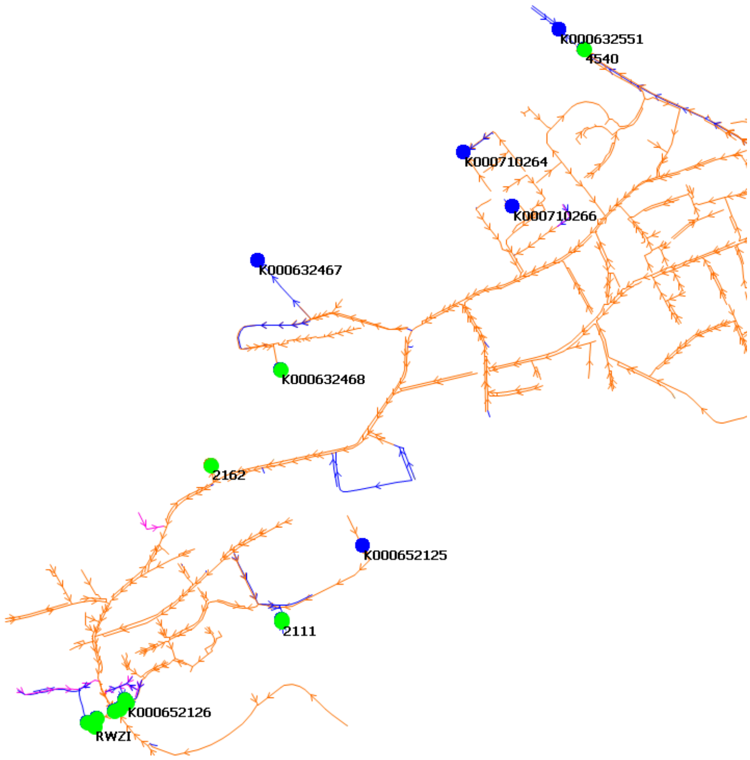


Figure 25: Outfall boundary conditions on the left part of the study area

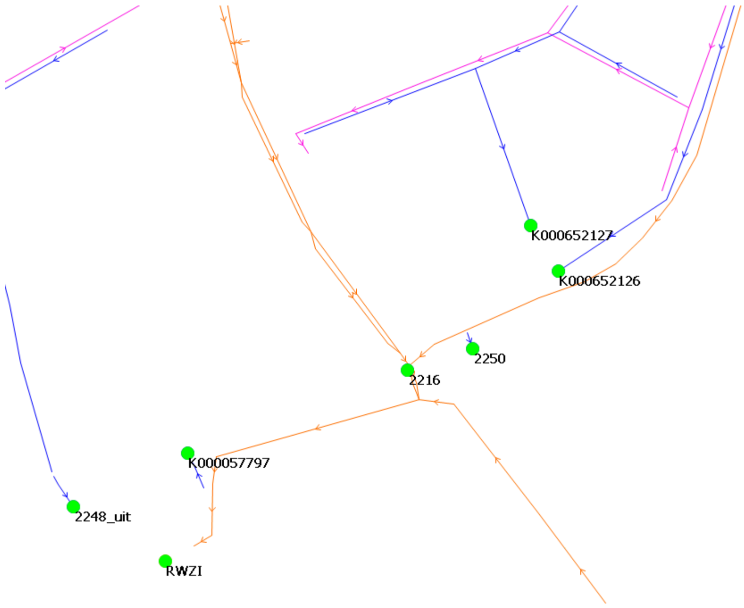


Figure 26: Outfall boundary conditions zoomed at RWZI

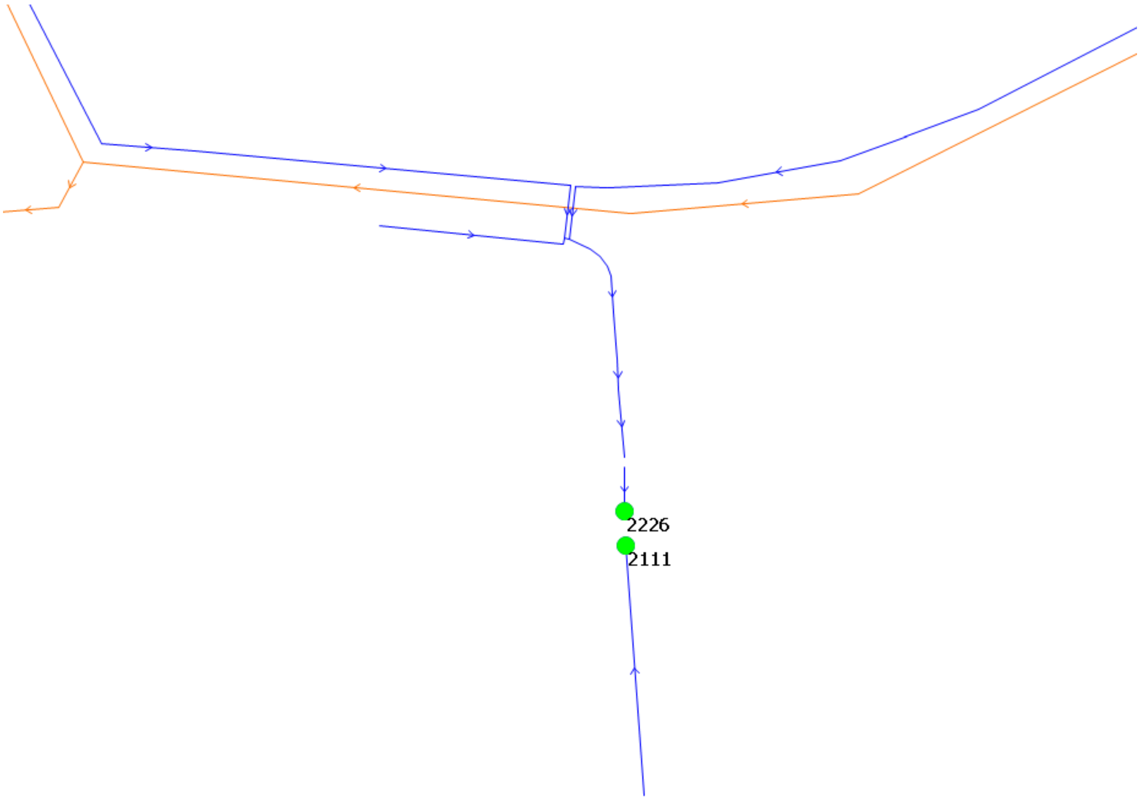


Figure 27: Outfall boundary conditions zoomed at node 2111

Table 11: Outfall boundary conditions left part of the study area

Node ID	Watercourse level (mTaw	Maximum level (mTaw)
4540	30,593	x
K000057797	27,635	x
K000632468	29,21	29,405
K000652126	27,66	27,912
K000652127	27,68	27,912
2111	28,62	x
2162	29,01	x
2226	28,62	x
2250	34,44	x
2248_uit	27,41	27,91
2216	27,41	27,91
RWZI	27,41	27,91

Figure 28: Outfall boundary conditions on right side of the study area

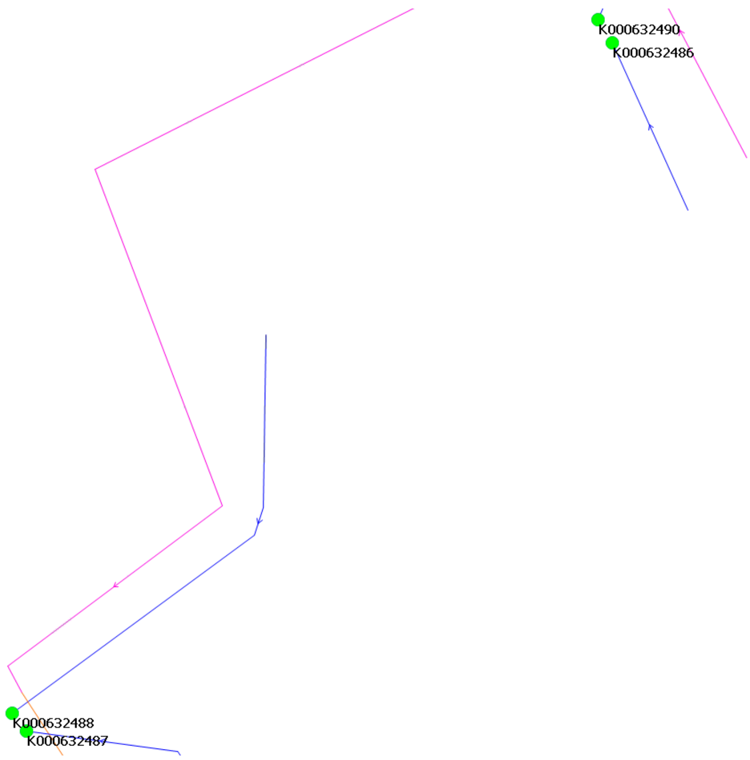


Figure 29: Outfall boundary conditions zoomed at node K000632486

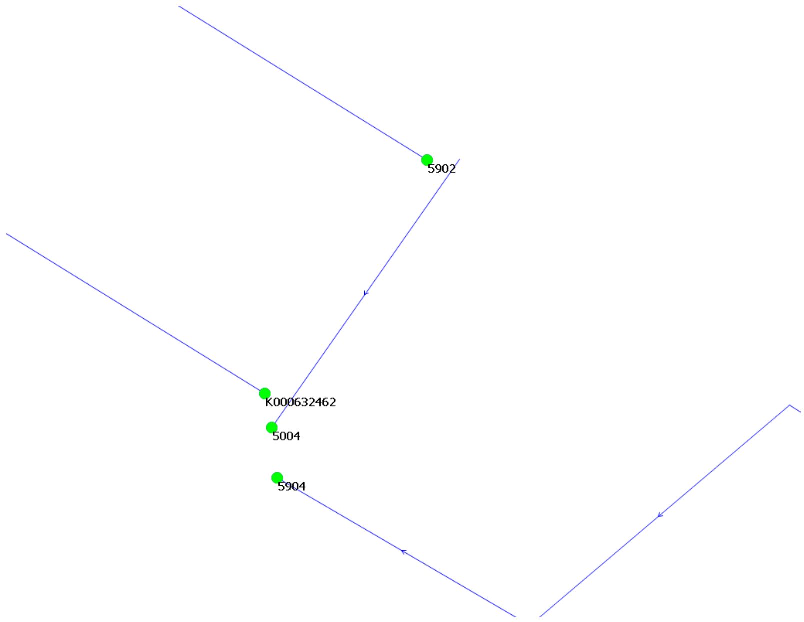


Figure 30: Outfall boundary conditions zoomed at node K000632462

Table 12: Outfall boundary conditions right part of the study area

Node ID	Watercourse level (mTaw	Maximum level (mTaw)
K000113223	44,286	x
K000146849	34,34	x
K000146860	36,1	36,43
K000632462	34,61	34,962
K000632470	31,699	x
K000632471	34,81	x
K000632472	34,514	x
K000632473	40,48	40,668
K000632474	39,76	39,866
K000632477	38,629	x
K000632481	36,56	36,928
K000632482	35,39	36
K000632483	35,39	35,913
K000632486	33,656	33,756
K000632487	33,378	33,662
K000632488	33,378	33,662
K000632490	33,656	33,662
K000632493	34,88	x
K000652120	31,812	32,054
K000703632	39,504	39,504
5004	34,88	35,222
6085	37,471	37,809
6063	39,858	39,958
6070	40,539	40,639
6100	38,384	38,656
5902	34,61	34,967
5904	34,88	35,222

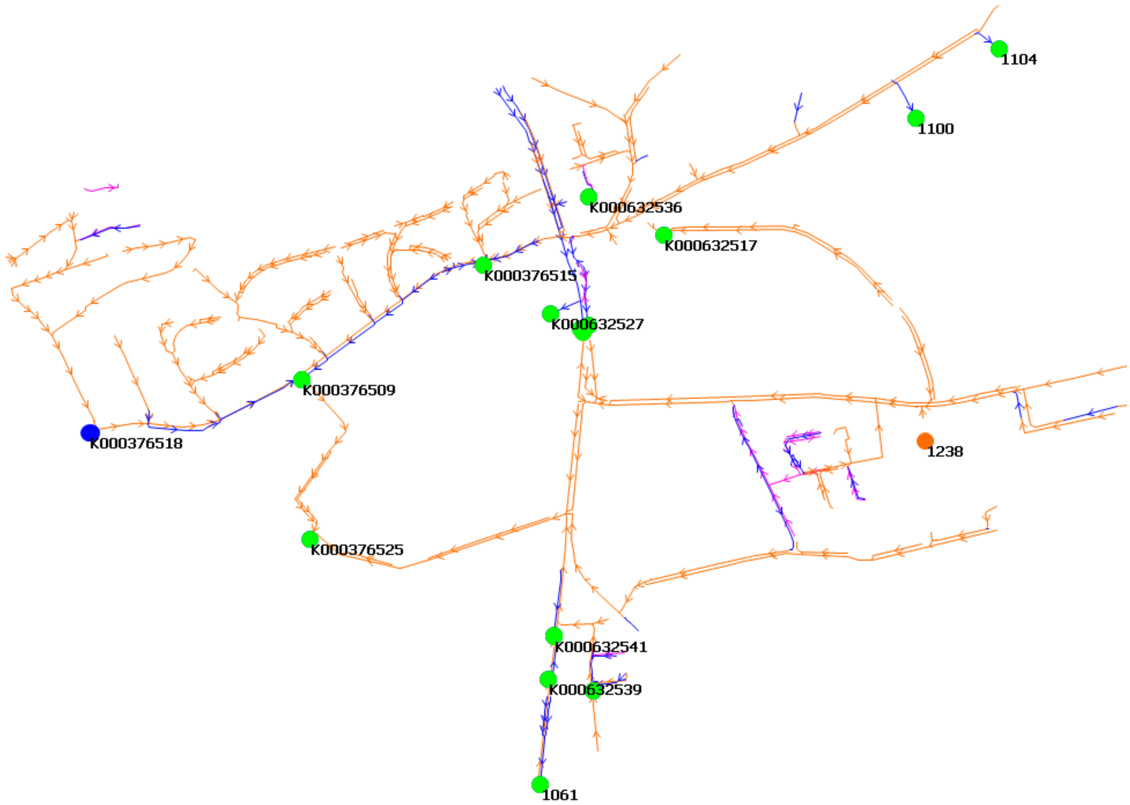


Figure 31: Outfall boundary conditions on bottom side of the study area

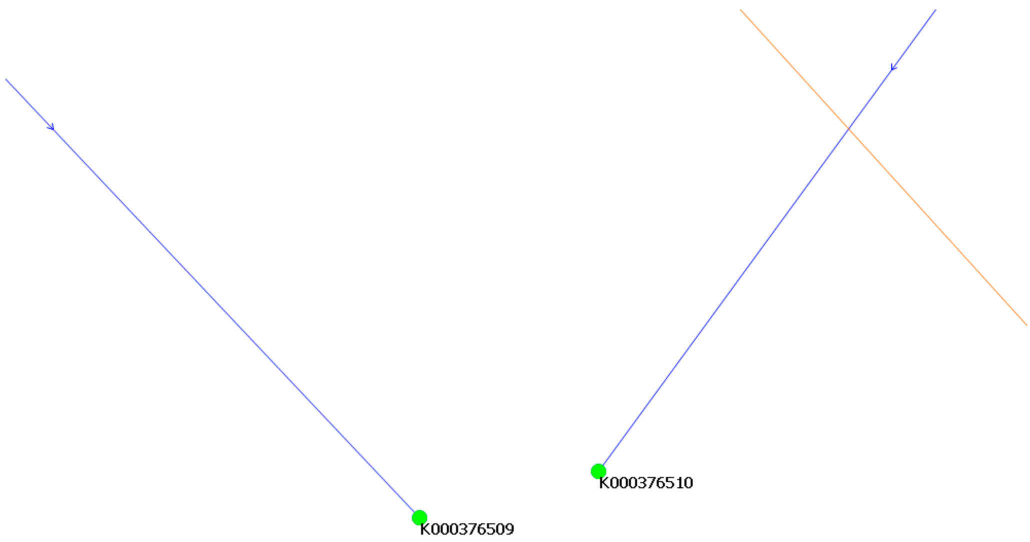


Figure 32: Outfall boundary conditions zoomed at node K000376509

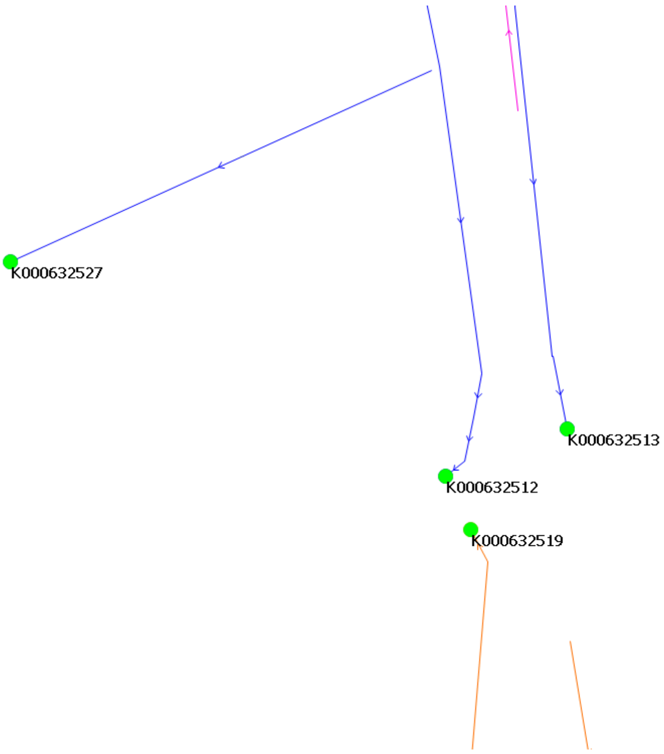


Figure 33: Outfall boundary conditions zoomed at node K000632527

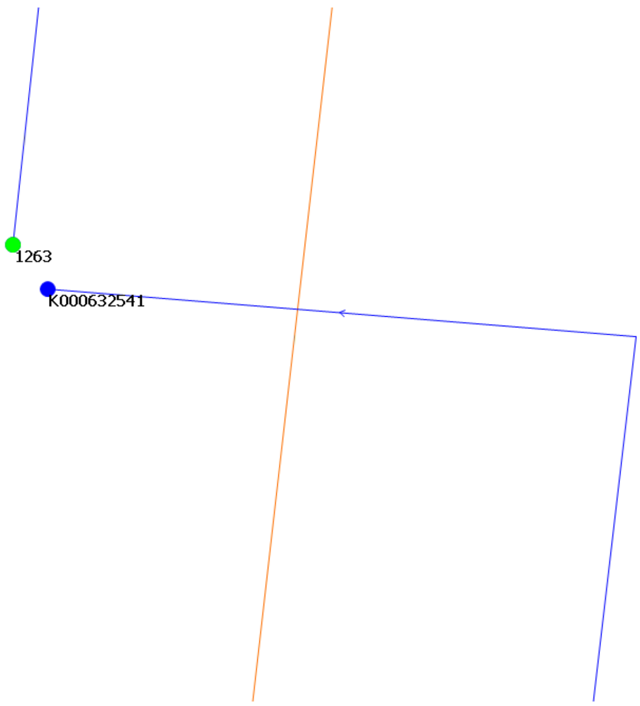


Figure 34: Outfall boundary conditions zoomed at node K000632541

Table 13: Outfall boundary conditions bottom part of the study area

Node ID	Watercourse level (mTaw)	Maximum level (mTaw)
K000376509	29,21	29,413
K000376510	29,21	29,443
K000376515	30,17	30,232
K000376525	27,7	28,279
K000632512	29,52	29,808
K000632513	29,52	29,808
K000632517	29,72	30,202
K000632519	29,52	29,808
K000632527	29,52	29,808
K000632536	31,44	31,852
K000632539	30,05	x
K000632541	29,9	30,258
K000632546	30,431	30,466
1061	29,66	29,897
1100	30,72	30,903
1104	31,31	x
1263	30,15	30,258

F.2 Inflow boundary conditions

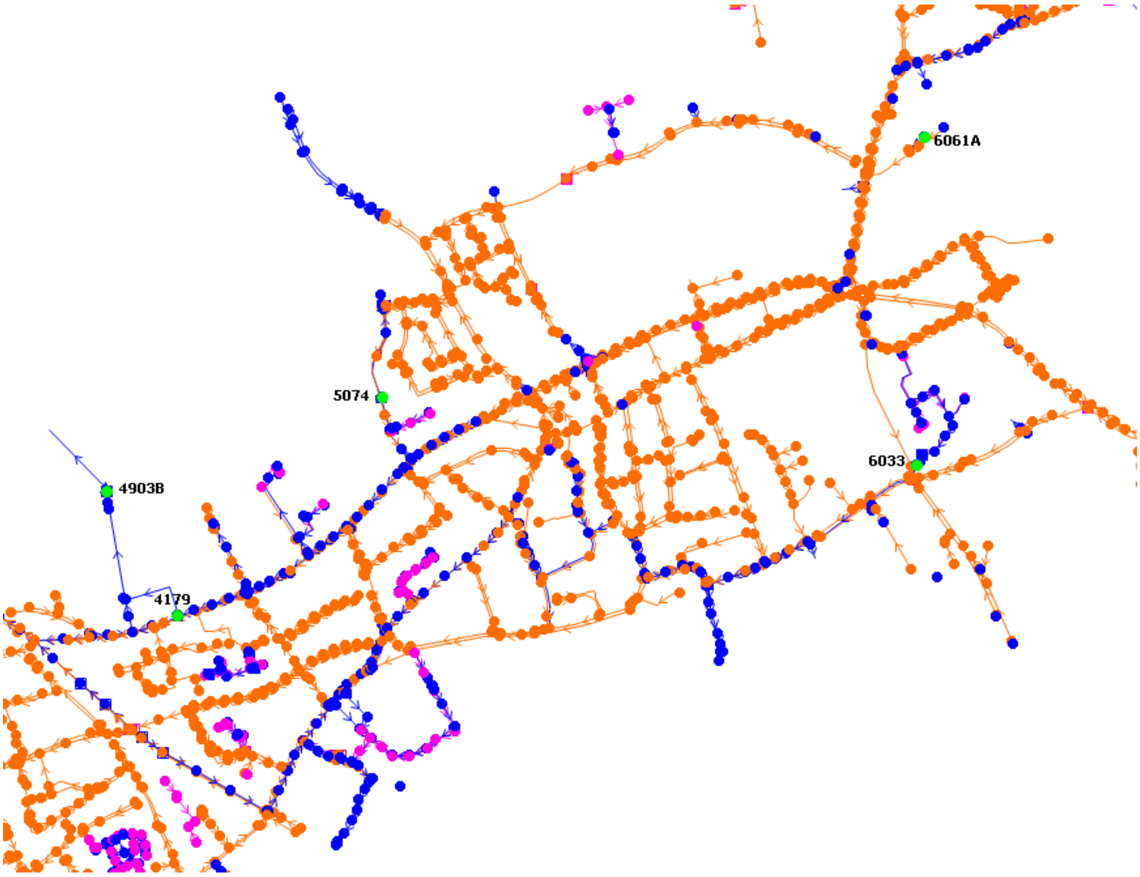


Figure 35: Inflow boundary conditions in the study area

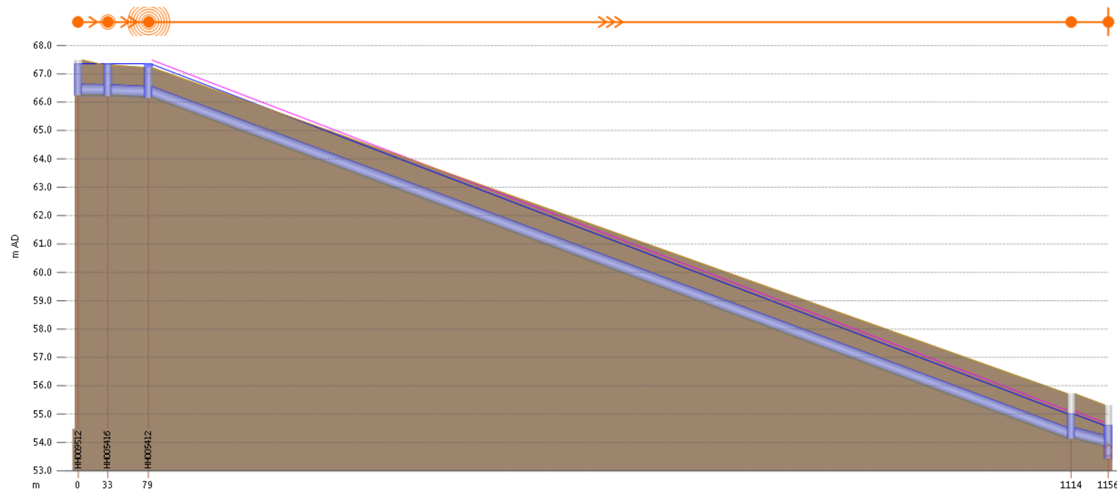
Table 14: Inflow boundary conditions in the study area

Number	Node ID	Location	Inflow (m3/s)
1	5074	Kerkebosstraat	0,011
2	4903B	Waterstraat	0,088
3	4179	Bieststraat	0,007
4	6061A	't Wiek	0,020
5	6033	Echelbeek	0,440

G Validation results (return period = 2 years)

Kolderstraat:

Figure 36: View of Kolderstraat



Link	-	-	HH005412.1	-
length (m)	33.0	45.6	1035.2	41.8
Shape ID	CIRC	CIRC	CIRC	CIRC
width (mm)	400	400	400	400
height (mm)	400	400	400	400
us inv (m AD)	-	66.214	66.149	54.122
ds inv (m AD)	-	66.159	54.122	53.850
grad (m/m)	-	0.00121	0.01162	-
pfc (m3/s)	0.042	0.067	0.209	0.157
US flow (m3/s)	-	0.05094	0.24671	-
Node	-	HH005412	HH002760	-
ground (m AD)	-	67.219	55.722	-

Figure 37: Height profile of Kolderstraat

Mommestraat:

Figure 38: View of Mommestraat

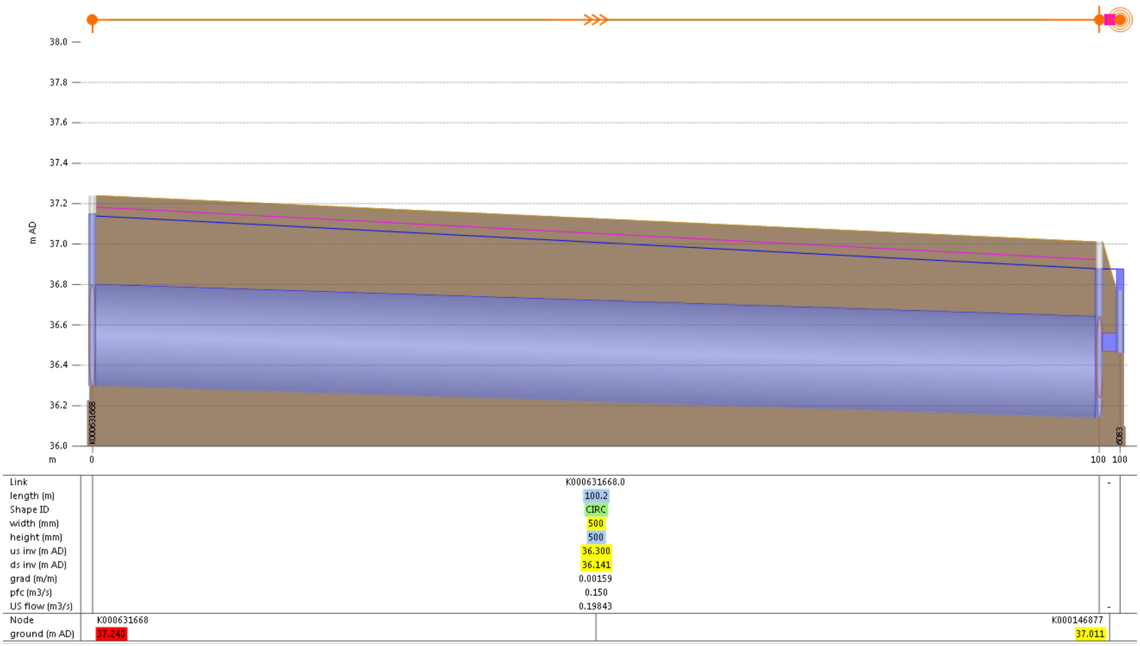


Figure 39: Height profile of Mommestraat

't Wiek:

Figure 40: View of 't Wiek

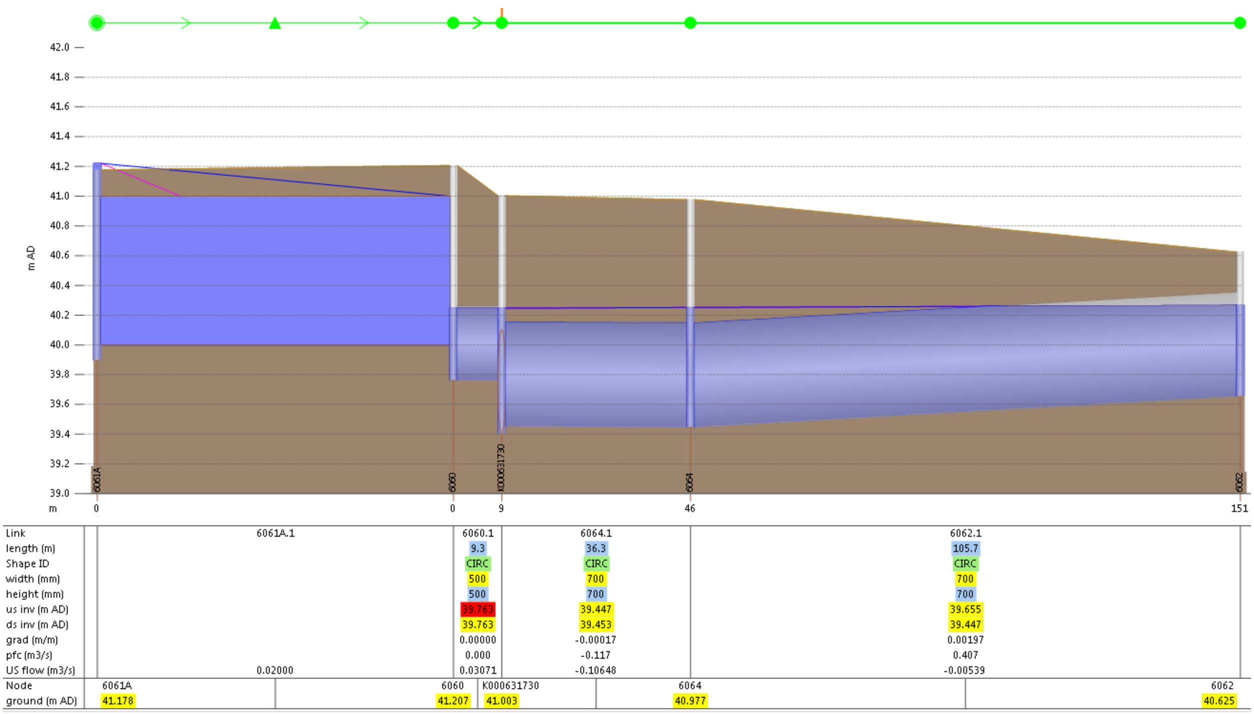


Figure 41: Height profile of 't Wiek

Boektlaan:

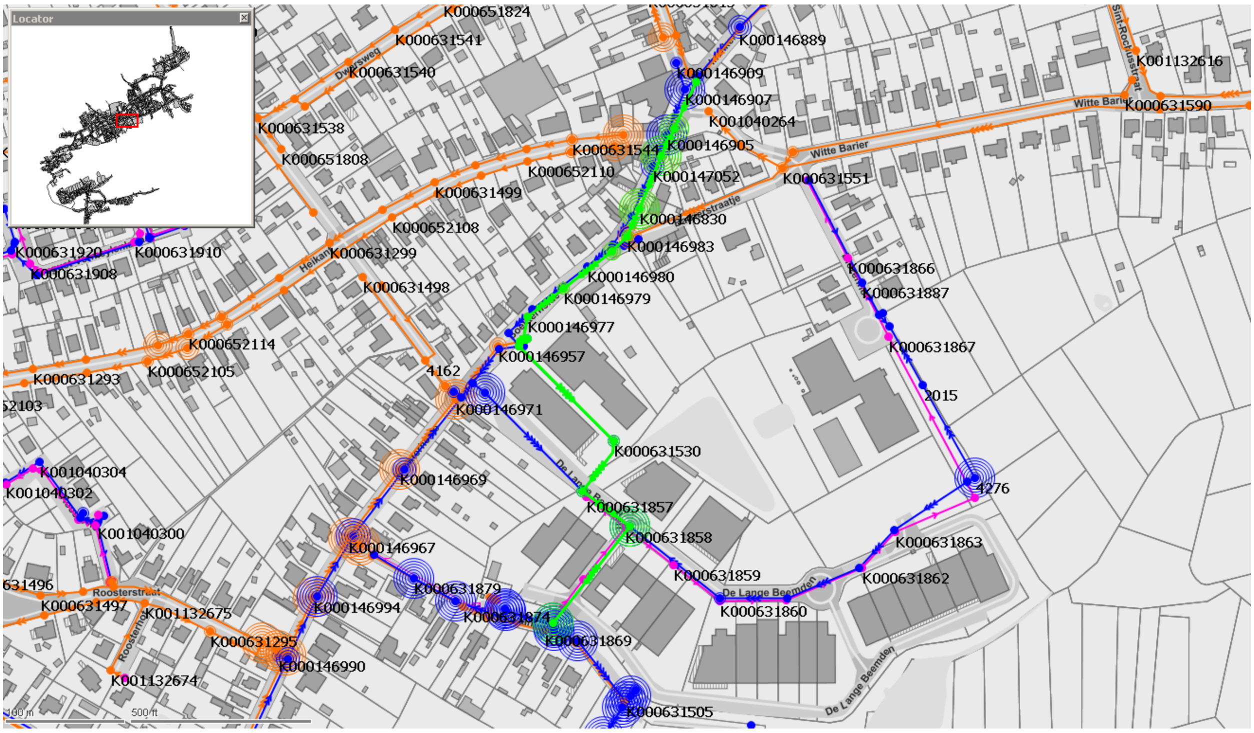
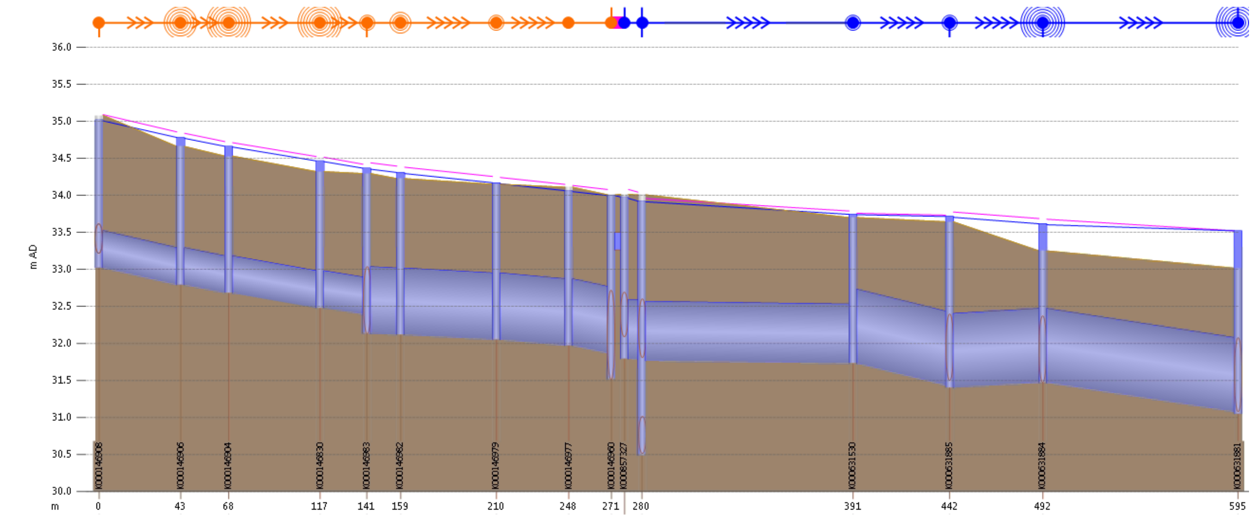


Figure 42: View of Boektlaan



Link	K000146908.1	-	K000146904.1	-	-	K000146982.1	K000146979.1	-	-	-	K000146959.9	K000631530.8	K000631885.1	K000631884.1
length (m)	43.1	25.4	48.3	24.7	17.9	50.5	38.3	22.5		9.2	111.5	51.0	49.4	103.1
Shape ID	CIRC	CIRC	CIRC	CIRC	CIRC	CIRC	CIRC	CIRC		-	CIRC	CIRC	CIRC	CIRC
width (mm)	500	500	500	500	900	900	900	900		-	800	1000	1000	1000
height (mm)	500	500	500	500	900	900	900	900		-	800	1000	1000	1000
us inv (m AD)	33.020	32.790	32.680	32.480	32.134	32.116	32.050	31.970		-	31.766	31.729	31.403	31.470
ds inv (m AD)	32.790	32.680	32.480	32.394	32.116	32.050	31.970	31.867		-	31.729	31.433	31.470	31.077
grad (m/m)	0.00534	0.00434	0.00414	0.00348	-	0.00131	0.00209	0.00457		-	0.00033	0.00580	-0.00136	0.00381
pfc (m3/s)	0.277	0.249	0.243	0.223	0.564	0.643	0.814	1.206		-	0.236	1.793	-0.865	1.453
US flow (m3/s)	0.28173	0.26109	0.24236	0.24868	-	0.89376	0.89547	0.90248	-	-	0.50404	0.50977	0.99943	1.04920

Node	-	-	K000146904	K000146830	-	-	K000146979	-	-		K000146959	K000631530	K000631885	K000631884	K000631881
ground (m AD)	-	34.660	34.530	34.320	-	34.226	34.150	34.110	-		34.006	33.700	33.643	33.250	33.017

Figure 43: Height profile of Boektlaan

H Results of bottlenecks (return period = 2 years)

Stationsstraat:

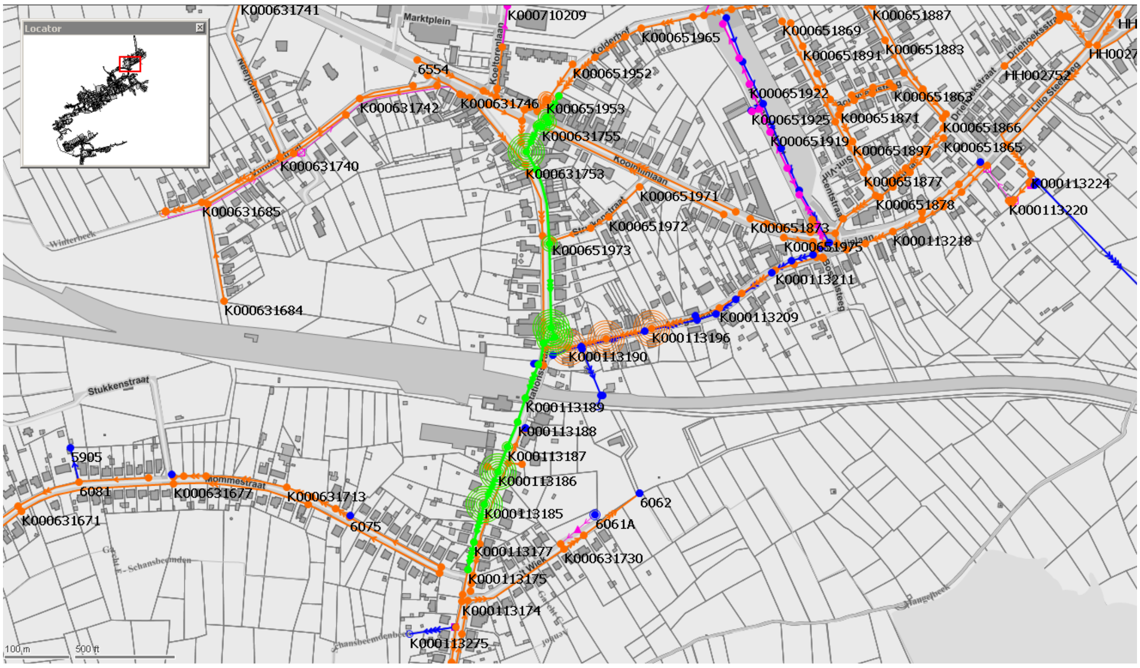


Figure 44: View of Stationsstraat

Langstraat:

Figure 45: View of Langstraat

Nieuwstraat:

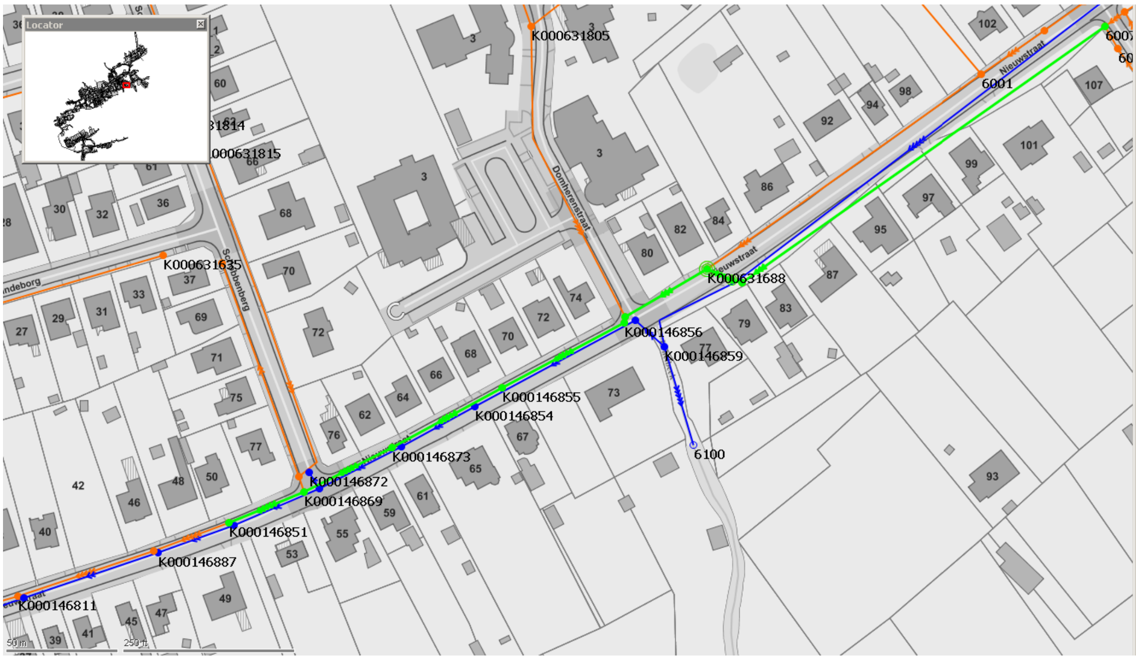


Figure 46: View of Nieuwstraat

Ambachtlaan:

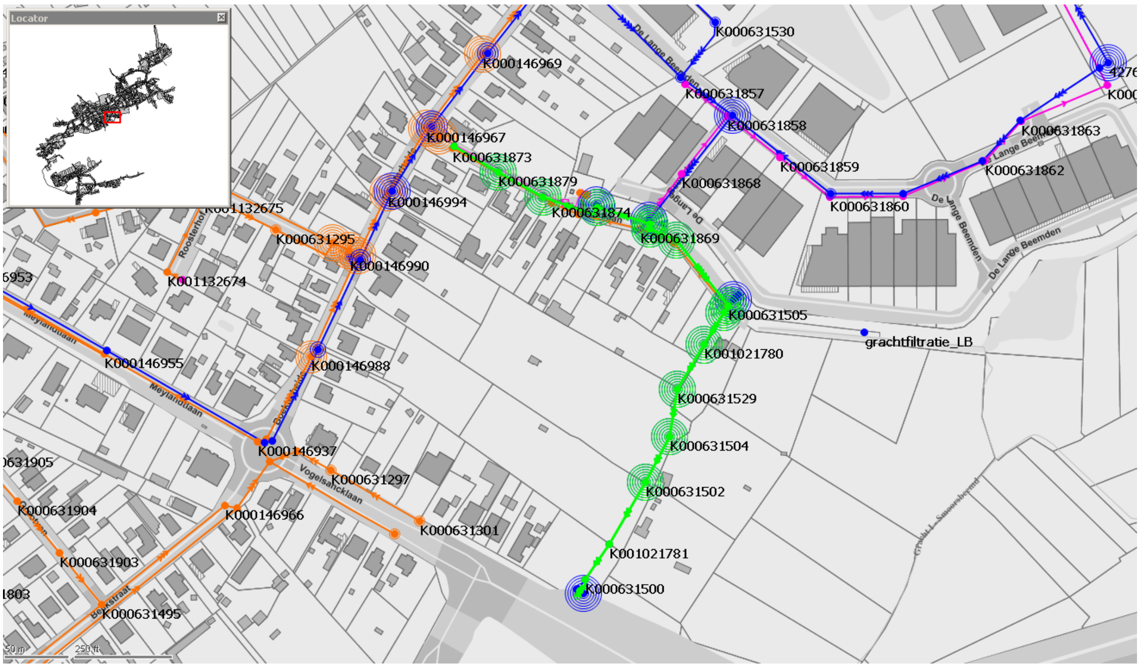


Figure 47: View of Ambachtlaan

Kerkstraat:

Figure 48: View of Kerkstraat