Department of Watermanagement - Delta management	Department of Urban Watermanagement

An initial study towards the added value of an integral calculation of the urban and surface water system in order to reduce the impact of urban flooding in Stellendam

Daniëlle Marcella Coster

Thesis

[13-06-2021]

Supervisors and committee members:

Lennard Stigter [1]

Jasper van den Heuvel [2]

[1]Department of Urban Watermanagement, Waterfeit Adviseurs, Roosendaal 4701, The Netherlands

[2]Department of Watermanagement, HZ University of Applied Sciences, Middelburg 4382, The Netherlands

Table of Contents

Chapter 1 – **Introduction**

Almost half of the Netherlands is located below sea level and more than half of the population are concentrated in heavily urbanized areas. By continuous draining and pumping, the ground level in these areas has subsided under the mean sea level. These areas manage water levels artificially by installing water storage capacity and pumping capacity in a so-called polder system. Climate change, sea level rise, population growth and ongoing urbanization result in increased vulnerability of the low-lying areas in the Netherlands because it will result in increased flooding frequency, increased damage, and the possibility of increased use of water, energy and other resources (De Graaf, van de Giesen, & van de Ven, 2007).

An important consequence of climate change is the increase in the intensity and frequency of precipitation. Rainfall is transported from cities through sewer systems. During extreme rainfall, a small part is discharged to water treatment plants and the rest is discharged to the urban surface water system or stored in (overflow) facilities. Today, surface water systems and sewerage systems are often still viewed as stand-alone systems. By disregarding the interaction between sewage and surface water, the risks of flooding can be underestimated. Also, measures taken in one of the two systems may not have the desired effect if the coupled system is unable to handle the changing amount of water. High surface water levels can obstruct the outflow of water from the sewer system or lead to the inflow of surface water into the sewer system. Sewerage has traditionally been designed for the discharge of water, surface water systems for the storage of water. Short-term rainfall events with a high precipitation intensity are therefore decisive for sewerage and long-term precipitation events with large precipitation volumes for surface water. In order to take effective measures to combat flooding, it is necessary to use integrated surface water sewerage models in which both systems can be tested in conjunction with their own characteristic loadings. Having such an integrated model will lead to a better cost-benefit analysis of measures to be taken; and in some cases lead to savings (TKI Deltatechnologie, sd).

This thesis is part of the graduation research conducted at Waterfeit Adviseurs in Roosendaal. Waterfeit Adviseurs is a consultancy company specialized in solving complex (urban) water matters. Waterfeit is active in both the technical and policy field of urban water management. At Waterfeit, consultancy is provided for sewer designs and water management plans. In addition, the company offers policy and process guidance and they conduct climate stress tests focused on adaptive measures regarding urban water.

1.1 Problem statement

Stellendam (image 1) is a Dutch village positioned in a polder located in the municipality of Goeree-Overflakkee, South Holland. Due to its location in the delta, Goeree-Overflakkee will suffer the consequences of climate change stronger than others parts of the Netherlands (Advies, Stresstest Goeree-Overflakkee, 2018). Due to a rise in sea levels, the flood defences and areas outside the dykes are going to be more vulnerable, salt will intrude further into the polder and the water quality will decline.

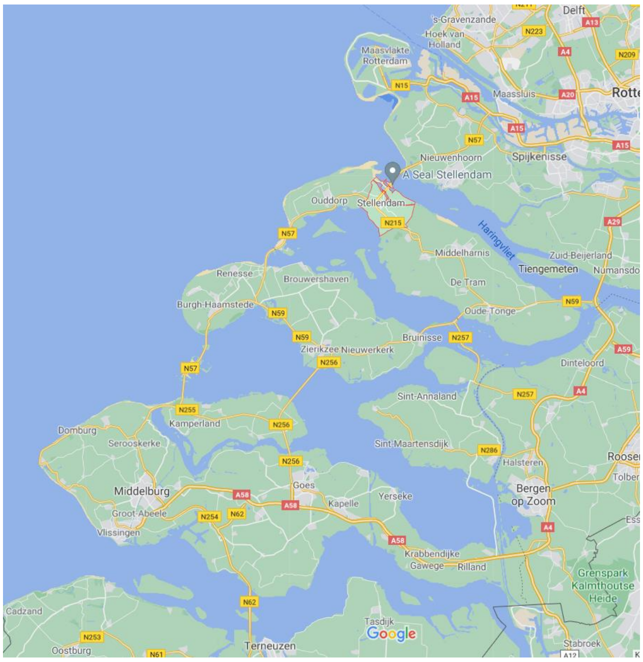


Figure 1: Location of Stellendam. Retrieved from: Google Maps.

In the past, the urban area of Stellendam has had to deal with heavy rainfall twice in a period of 15 years. In September 1998, a rainfall amount of more than 100 millimeters spread over the area and in October 2013 a similar amount occurred in a time period of 24 hours. Normally, around 80 millimeter of precipitation falls throughout the entire month of October (Nu.nl, 2013). In both situations, the intense rainfall led to local flooding. On October 13 2013, the fire department was called out several times to provide assistance for flooding. The sewers' pumps could not handle the large amounts of water, resulting in flooded streets and water flowing into houses and basements, and even the sinking of a dike slope. There was a layer of water in at least a hundred homes in the entire region of Goeree-Overflakkee (Rijnmond, 2013). Image 1 and 2 give an impression of flooding in the urban area of Stellendam at 13 October 2013. Due to the abundant rainfall the Waterboard Hollandse Delta has set up two polders as a water storage area. The surplus water was discharged via emergency pumps to the water storage in the Volgerland and Koudenhoek polders at the head of the region Goeree-Overflakkee (Nu.nl, 2013). The Waterboard Hollandse Delta estimates the costs of the extra measures against flooding on the islands of South Holland at 1 to 2 million euros (Trouw, 2013). Farmers of the region also experienced nuisance due to this event: much of the land on which crops were grown has been flooded (Flakkee Nieuws, sd). The damage to the farmers is estimated between 50,000 and 150,000 euros (Schellart, 2013). The calamity resulted in extra hours of employees, the hiring of third parties, increased use of pumping stations and unplanned (repair) work leading to total costs incurred in the week from 13 to 18 October to an amount of € 699,439 for the Waterboard Hollandse Delta (M.L.Bakker, 2014).

In order to reduce urban flooding for the inhabitants of Stellendam in the future during such a precipitation event, the idea has been put forward by the Waterboard Hollandse Delta to compartmentalize the drainage area in situations of extreme rainfall with two calamity weirs. However, there is uncertainty about the effectiveness of the weirs during such extreme precipitation amounts due to the lack of an urban and surface water system model in which the influence on the urban area can be simulated.

Figure 2: Flooding in the urban area of Stellendam. Retrieved from: Trouw, 2021

Figure 3: Flooding in the urban area of Stellendam. Retrieved from: roon.zideo.nl, 2021

1.2 Focus of study

This research analyses the functionality of calamity weirs with regard to limiting flooding in the urban area of Stellendam during an extreme precipitation event similar to the event of October 2013. In addition to this, it is scrutinized which optimizations can be made in the water system to reduce urban flooding for Stellendam. Finally, this research focuses on the added value of integral modelling of an urban and surface water system model and the development of the hydraulic modelling program D-HYDRO.

1.2.1 Objective

The objective of this research is to determine the functionality of suggested calamity weirs by the Waterboard Hollandse Delta and recommending various optimizations in the water system which will limit the amount and duration of water on the streets in the urban area of Stellendam during a heavy amount of precipitation. Hydraulic models will be used to simulate real-time data from the event of October 2013 which has caused a lot of inconvenience in Stellendam. In addition to this, this study will commit a part to the understanding of the added value of using an integral hydraulic model of the urban and surface water system as part of a TKI study with the Waterboard Hollandse Delta, Deltares, the municipality of Goeree-Overflakkee and Waterfeit Adviseurs as project partners. Finally, this study contributes to the development of a new hydraulic modelling program called D-HYDRO.

1.2.2 Research questions

The following main question is leading in this research: *what is the influence of calamity weirs and what optimizations are recommended in the system in order to limit the locations where water flows above ground level and the duration of water above ground level causing urban flooding in the area of Stellendam, during a similar event of October 2013?*

To answer this question, the research is divided into five sub questions:

- *What is the duration and corresponding total amount of precipitation that led to flooding in the urban area of Stellendam in October 2013?*
- *How will the hydraulic models be constructed in order to simulate the locations and duration of water above ground level resulting in flooding in the urban area of Stellendam during an similar event of October 2013?*
- *Does the use of an integrated urban and surface water system model lead to different results regarding the duration and locations of water above groundlevel compared to a separate urban sewage system model in the urban area of Stellendam during an similar event of October 2013?*
- *What is the influence of calamity weirs on the locations and duration of water above ground level in the urban area of Stellendam during a similar event of October 2013?*
- *What optimizations in the system can be applied in order to reduce the locations and duration of water above ground level in the urban area of Stellendam during a similar event of October 2013?*

During this research, the project area comprises only the core of the urban area of Stellendam. The so-called Havenhoofd located in the port area is not included in this study.

Chapter 2 – **Literature Research**

This chapter of the report provides insight in the theoretical background of the research. First, the influence of climate change on the urban area of Stellendam with regard to flooding is being elaborated. Then, more information is being provided regarding the precipitation event of October 2013. Subsequently, the different model concepts are elaborated from which a hydraulic model can be constructed. Additionally, more information is given about the program with which the models are constructed. Finally, an explanation is given about the implementation of the relevant calamity weirs.

2.1 Climate change

The Netherlands has a moderate maritime climate with relatively mild winters, mild summers and rainfall throughout the year. This is caused by the influence of the North Sea which plays a major role in the climate of the Netherlands. In total there is an average of about 800 to 900 millimeters of precipitation on an annual basis. During extremely dry years, this can locally remain below 500 millimeters, in very wet years the amount of precipitation can rise to 1000 millimeters (Klimaatinfo, sd). However, the climate is changing: the temperature on earth is rising due to the increase of greenhouse gases in the air (Rijksoverheid, sd). The KNMI regularly draws up new climate scenarios for the Netherlands. They form the basis for research into the effects of climate change and adaptation to that change. The KNMI climate scenarios are based on the same sources as from the IPCC, the International Panel for Climate Change. The most recent are the KNMI'14 scenarios. These scenarios show the change around 2050 and 2085 compared to the climate in the period of 1981-2010. The four KNMI'14 scenarios together describe the corners within which climate change in the Netherlands is likely to occur:

- WH: strong temperature rise (warm), high value change in air flows
- WL: strong temperature rise (warm), low value change in air flows
- GH: moderate temperature rise, high value change air currents
- GL: moderate temperature rise, low value of air flow change (Kennisportaal Klimaatadaptatie, sd)

The main consequences of climate change for the Netherlands are:

- increase in extreme weather events: more heavy precipitation event, more heat waves;
- an increased risk of flooding: the rivers and sewer systems are no longer able to drain the water properly during heavy rainfall;
- milder winters;
- wetter periods in the spring, autumn and winter;
- drier and hotter summers, increase in amount of tropical days (Milieucentraal, sd).

In this research, the influence of climate change with regard to increasing rainfall intensity plays a major role. The increasing heat and droughts are not being discussed further.

As a low-lying, the province in which Stellendam is located, South Holland, is extra vulnerable to climate change (Provincie Zuid-Holland, sd). In South-Holland, the area Goeree-Overflakkee is bordered on the west side by the North Sea. In the urban areas such as Stellendam, water runs off roofs and streets when it rains into the sewage system. Precipitation in gardens and lawns is often being infiltrated into the ground. Most urban areas are just a little higher than the surrounding rural area, and can drain water fairly easily via the existing waterways. Some areas are located in between dyke bodies or have little open water within the buildings: a heavy amount of precipitation causes local flooding at these locations. Additionally, in low-lying areas streets and neighborhoods in the larger urban areas are flooded by heavy rainfall. The rural area is large and extensive. In case of prolonged precipitation low parts are fragile. The amount of storage and drainage of water is limited by the surface water and the capacity of pumping stations that pump the water from the area into the surrounding surface water.

Although longer periods without precipitation will occur more often, when it rains, the intensity of the showers in the summer is heavier. In the most conservative scenario (1 ° C temperature rise), the increase in extreme precipitation will be 5.5–14% in 2050. In the scenario with higher temperature, (+2 ° C) the increase is 12-25% in 2050. By 2085 there will be an increase in extreme rainfall of 45%. In an unchanged situation, the risk of nuisance and damage due to precipitation on Goeree-Overflakkee will increase (Advies, Stresstest Goeree-Overflakkee, 2018).

In all scenarios, the amount of precipitation increases in winter (3% -17% in 2050 to 30% in 2085). Also the number of days with more than 10 mm rainfall increases. There is also an increase in the ten-day rainfall sum (sum of the amount of rainfall in ten days). The existing system of sewers and waterways can expected to handle the increase in precipitation manhole. The effects on rural areas may be greater. The accessibility of plots in the winter months may become less. Depending on the wax, there is a greater chance of reduced yields. In the current situation, the cores often discharge indefinitely into the rural area. As long as there is enough space in the rural area for the processing of water there are no problems with one increase in winter precipitation. (Advies, Stresstest Goeree-Overflakkee, 2018).

2.2 October event Stellendam

October 2013 was a wet month with an average of 110 millimeters of rain across the entire country where the normal amounts are about 83 millimeters. A large part of the monthly sum fell on the weekend of Friday 11 to Sunday 13 October. The KNMI issued a code orange (warning for extreme weather) for Zeeland, South Holland and Utrecht because of large amounts of precipitation (75 millimeters in 24 hours) and the associated risk of flooding. Most of the precipitation occurred between Saturday evening and Sunday evening in South Holland: over 120 mm in some places. The highest precipitation sum of October was measured in the south-west of the country, where locally about 225 mm occurred. In De Bilt, the precipitation sum came out at 161 mm. October 2013 is therefore one of the five wettest October months in De Bilt in over a hundred years.

Image 4 and 5 show the amount of precipitation in 24 hours for 13 and 14 October 2013 for the Netherlands. In image 4 it can be seen that in Goeree-Overflakkee 120 millimeters precipitation occurred in 24 hours, in image 5 this is 40 millimeters in 24 hours. The figures show that most precipitation fell in the west of Goeree-Overflakkee in the period October 12 08:00 to October 13 08:00.

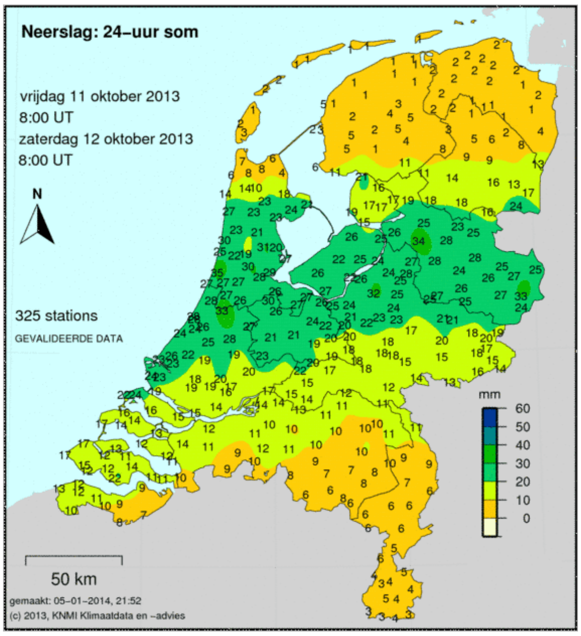


Figure 4: Precipitation amounts from the KNMI ground stations from 08:00 to 08:00 for October 14, 2013. Retrieved from: 59939603-Waterschap-hollandse-delta

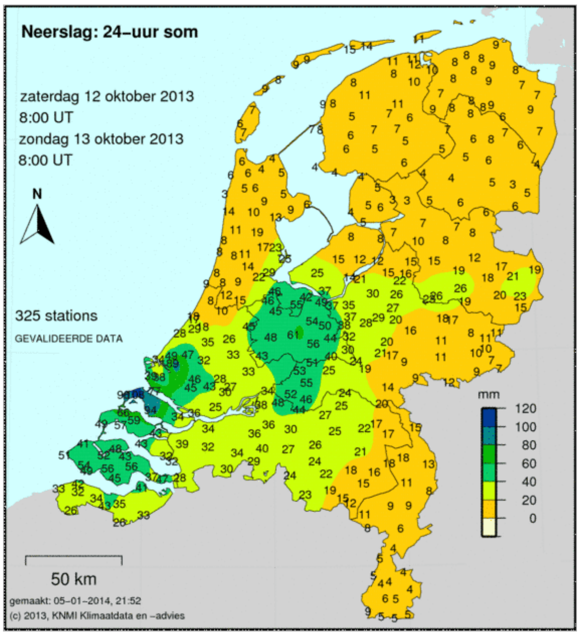


Figure 5: Precipitation amounts from the KNMI ground stations from 08:00 to 08:00 for October 13, 2013. Retrieved from: 59939603-Waterschap-hollandse-delta

In the period from 12 to 15 October 2013, a low-pressure area which remained in the vicinity of the Netherlands, brought a large amount of precipitation in the west of the management area of the Waterboard Hollandse Delta. As a result, the water level in the surface water rose sharply, with an exceedance of more than 1 meter above the target level in some places on Goeree-Overflakkee and Voorne-Putten. Based on the KNMI statistics, the amount of precipitation that fell on 13 October 2013 in Goeree-Overflakkee occurs less often than once every 1000 years as can be seen in table 1 (M.L.Bakker, 2014).

Table 1: Maximum precipitation of the KNMI ground stations and their repetition times based on the KNMI statistics. Retrieved from: 59939603-Waterschap-hollandse-delta

KNMI-station	24-uursom (mm)	herhalingstijd (jaar)	4-daagse som (mm)	Herhalingstijd (jaar)
Goedereede	130	>1000	180	>1000
Ouddorp	113	>1000	156	>1000
Dirksland	122	>1000	152	>1000
Den Bommel	66	22	87	9
Nieuw Helvoet	104	450	134	300
Oostvoorne	68	25	113	66
Brielle	68	25	105	38

The Waterboard Hollandse Delta shared data for this research with the precipitation statistics for Stellendam specifically. This can be found in table 2, where the amount of precipitation per day and cumulatively is determined. This indicates that a total amount of precipitation of 152.63 millimeters occurred in 144 hours, with the peak of the event on October 13. This table also shows the recurrence time (the amount of precipitation that is exceeded once every so many years) for associated amount of precipitation in years. A probability of 1 percent per year corresponds to a recurrence period of 100 years (KNMI, sd). From this table it can be read that for October 13 2013, during the peak of the event, a recurrence period of 200 years applies.

Table 2: Measured precipitation in Stellendam per day and cumulative in millimeters with associated recurrence time in years. Retrieved from Waterboard Hollandse Delta

Datum	mm per dag	mm cumulatief	uren cumulatief	T=x herhalingstijd in jaar (Regio R, Jaarstatistiek 2019)	T=x herhalingstijd in jaar (Regio R, Jaarstatistiek 2019)
10-10-2013 10:00	6,43	6,43	24	<0,5	Kleiner dan T=0,5
11-10-2013 10:00	12,78	19,21	48	<0,5	Kleiner dan T=0,5
12-10-2013 10:00	17,95	37,16	72	<0,5	Kleiner dan T=0,5
13-10-2013 10:00	84,96	122,12	96	T>50 - T<100	Groter dan T=50 en kleiner dan T=100
14-10-2013 10:00	23,43	145,55	120	T=200	Ongeveer T=200
15-10-2013 10:00	7,08	152,63	144	T=200	Ongeveer T=200

This conclusion is based on the precipitation statistics for extreme precipitation events in the Netherlands, delivered by STOWA (Stichting Toegepast Onderzoek Waterbeheer). They published a report with basic statistics for extreme precipitation in the Netherlands. An overview of the rainfall quantities in millimeters at different recurrence times and rainfall durations between 10 minutes and 8 days can be found in table 3. From this it can be read that an amount of precipitation of 145.55 millimeters in 120 hours corresponds approximately to a T = 200 recurrence time.

Table 3: Basis statistics for the year; rainfall quantities (in mm) at different recurrence times and rainfall durations between 10 minutes and 8 days. Retrieved from: (STOWA, 2019)

	Neerslagduur										
T [jaar]	10 min	30 min	60 min	2 uur	4 uur	8 uur	12 uur	24 uur	2 dagen	4 dagen	8 dagen
0.5	8.1	10.4	12.6	15.3	18.6	22.2	24.6	30.4	38.6	50.4	68.3
1	10.2	13.5	16.2	19.5	23.4	27.7	30.5	36.8	46.0	59.3	79.4
2	12.2	16.6	20.0	24.0	28.4	33.4	36.5	43.8	54.0	68.6	90.5
5	15.1	21.2	25.8	30.7	35.9	41.7	45.2	54.2	65.5	81.4	105.1
10	17.5	25.3	31.0	36.8	42.8	49.1	52.9	63.0	74.9	91.6	116.1
20	20.3	30.2	37.2	44.2	51.1	58.0	61.9	72.6	85.0	102.1	127.0
25	21.3	32.0	39.5	46.9	54.1	61.2	65.2	75.9	88.5	105.6	130.5
50	24.7	38.2	47.7	56.5	64.8	72.5	76.6	86.9	99.5	116.6	141.5
100	28.7	45.8	57.7	68.4	78.0	86.2	90.2	98.9	111.4	128.1	152.3
200	33.4	55.0	70.0	81.3	88.7	95.0	98.1	112.1	124.2	140.0	163.2
250	35.0	58.4	74.5	86.5	93.9	100.0	102.9	116.7	128.5	143.9	166.7
500	40.8	70.4	90.7	105.0	112.2	117.5	119.6	131.7	142.5	156.4	177.5
1000	47.6	84.9	110.6	127.6	134.4	138.3	139.2	148.2	157.5	169.4	188.3

The Administrative Agreement on Water (2003) contains administrative agreements between the national government, provinces, municipalities, water boards and the drinking water sector aimed at tackling the water tasking for the Netherlands in the 21st century (M.L.Bakker, 2014). As an obligation under the Water Act, the province has included standards with regard to water quantity. The province of South Holland has translated the rules from the Water Act into a Water Ordinance for the Province of South Holland. The water regulation for the Waterboard Hollandse Delta applies here. The water regulation Waterboard Hollandse Delta establishes frameworks for protection against regional flooding:

1. With a view to the storage and drainage capacity for which regional waters must be designed, the standard for the area of a municipality (within built-up areas) is an average probability of flooding of:
    a. 1/100 per year for buildings other than glasshouse horticulture;
    b. 1/50 per year for greenhouse horticulture;
    c. 1/10 per year for the rest of the area.
2. With a view to the storage and drainage capacity for which the regional waters must be designed, the standard for the area of a municipality (outside the built-up area) is an average flood probability of:
    a. 1/100 per year for main infrastructure;
    b. 1/50 per year for glasshouse horticulture and high-quality agriculture and horticulture;
    c. 1/25 per year for arable farming;
    d. 1/10 per year for grassland

Compared to the strictest standard of 1/100 per year the repetition time of this event for Goeree-Overflakkee is therefore more than a factor of 10 smaller than this strictest standard (M.L.Bakker, 2014).

2.3 Urban flooding

Urban flooding is the accumulation of floodwaters that result when the inflow of storm water exceeds the capacity of a drainage system to infiltrate water into the soil or to carry it away (Framing the Challenge of Urban Flooding in the United States, 2019). Storm sewer inlets drain water from the street system and convey the flow through subsurface pipes to discharge points at downstream locations. A combination of transmission systems—channels, streets, and pipes—conveys precipitation falling on the city to its outfall locations in larger streams or to the coast. Floodwaters accumulating in larger streams can overwhelm the capacity of the stream channel and inundate surrounding areas, particularly in downstream areas. Smaller, chronic floods can also occur in older cities with combined sewer systems carrying both storm water and wastewater. These systems can become surcharged during storms, causing sewer backups in homes and discharge of untreated wastewater into streams. Aging and inadequate drainage infrastructure and failing pipe systems create additional flooding problems (Framing the Challenge of Urban Flooding in the United States, 2019). An overview of the sewer system of Stellendam can be seen in Appendix I.

2.4 Hydraulic modelling

A hydraulic or hydrodynamic model is a simplified mathematical description of the hydraulic processes in a particular geographic and geometric context (Stichting RIONED, 2019). For most modelling issues, specific modelling software is being used to build the model and calculate (simulate) it. During this research, multiple models are being used in order to gain insight into flooding in extreme rainfall situations. Specifically, it concerns insight into the locations where water on the street or flooding occurs and how water flows over ground level at these locations. Flooding is the situation in which water on the street leads to urban flooding or damage in or to buildings or public infrastructure (Stichting RIONED, 2019).

2.4.1 Model concepts

Per model part, schematisations are possible that can have zero, one, two or three spatial dimensions (0D, 1D, 2D or 3D) (Stichting RIONED, 2019). Figure 7 provides a simplified schematic representation of the dimensions for a model. The most suitable model is the simplest model that is able to describe the relevant processes manhole enough. The distinction in the characterization lies in the way in which the following model parts are schematized:

- the precipitation discharge process;
- the infrastructure of the urban water system (sewerage, infiltration facility);
- flow over ground level;
- connection to the surface water system.

Figure 6 shows schematically the aforementioned defining elements for a model concept. The flow over ground level and the connection to the surface water system are the central model concepts in this research.

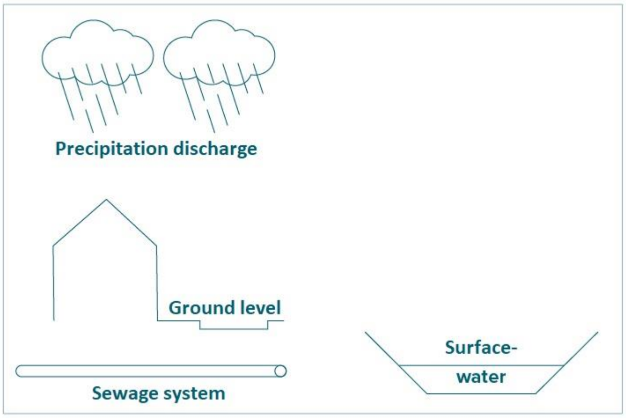


Figure 6: Schematic representation of the defining parts of a model concept

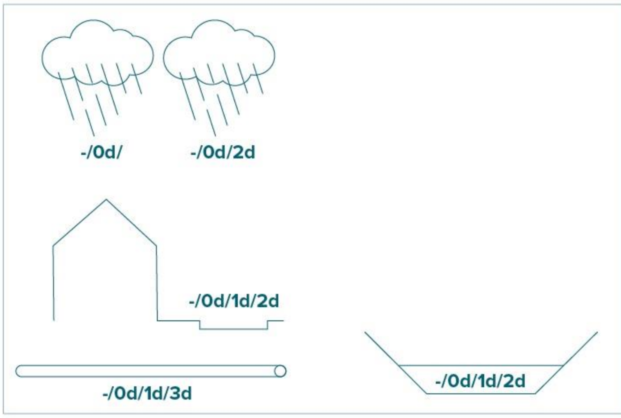


Figure 7: A simplified schematic representation of the possible dimensions for a model

2.4.1.1 Schematisation of flow over ground level (water on the street)

If the storage and discharge capacity of the sewer system is insufficient during extreme rainfall intensities, water will end up in the street and the discharge over the surface will play an important role in water transport. When the storage of the surface water system is inadequate in extreme rainfall situations, there is inundation and water also ends up at ground level. Water in the street can cause urban flooding and damage. That is why it is important to gain insight into the locations where water on the street or flooding occurs, the height of the water levels and the associated damage. Calculating water on the street, transport over ground level and flooding goes further in a model-based manner than the hydraulic calculation of a sewer or water system model. For water on the street and flooding, a sewerage model with flow over ground level is used.

The sewerage model shows the parts of a sewer system as nodes and connections. Inspection manholes are knots. Nodes can also represent a reservoir in which the hydraulic head is negligible, for example a mountain settling basin. A connection is an element with uniform hydraulic properties, to which you can assign a flow rate and hydraulic displacement. For example, a sewer, overflow threshold, pumping station with pressure pipe or passage. Figure 8 shows a schematic representation of a sewerage model without surface water and flow over ground level.

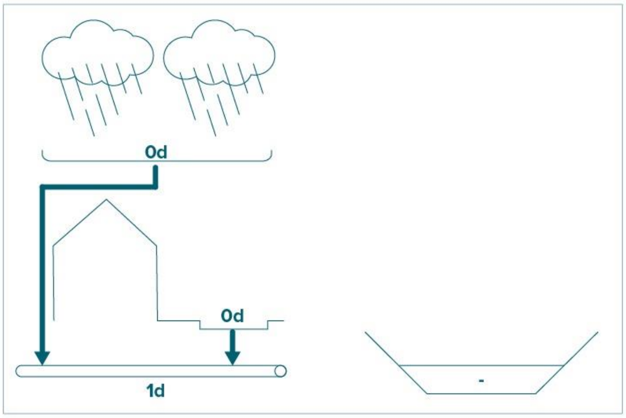


Figure 8: A simplified schematic representation of a sewerage model without surface water and flow over ground level

Water on the street is simplified schematized as a quantity of water in a storage room on top of a sewer manhole. This is a 0D approach. This approach does give an impression of the occurrence of water at ground level, but not a reliable determination of the location and quantity. For this, 1D flow profiles over the ground level or a 2D run-off model based on a digital terrain model are used. These model concepts are schematically represented in figure 9.

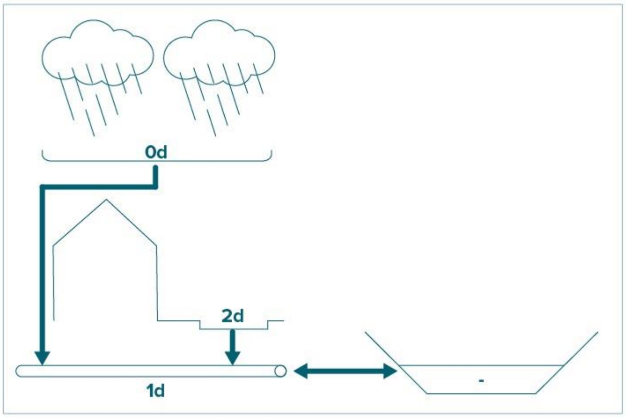


Figure 9: A simplified schematic representation of the sewerage model with flow over ground level without surface water

2.4.1.2 Schematisation of the connection to the surface water system

If the sewer system or infiltration system is connected to a surface water system, there are various options for schematizing this surface water system: 0D if only the storage in the surface water is included, 1D if the flow in the longitudinal direction of the surface water is also schematized and 2D if the flow in the horizontal plane is schematized. If there is little interaction between the sewerage or infiltration facility and the surface water system, there is also the option not to model the surface water system.

A sewerage model with ground level flow is often used to simulate extreme amounts of precipitation. During such events, interaction with the surface water quickly occurs and it is obvious to link the sewerage model with flow over ground level with a 0D, 1D or 2D surface water model. Which type of surface water model is chosen follows from the characteristics of the surface water:
- If the system that has to be modelled does not influence the outside water level of the surface water system, the outside water level is placed on the model as a precondition;
- A city pond or a canal / polder system with a pumped discharge can be part of the 2D ground level model (the water surface is considered as ground level) or schematized separately as a 0D reservoir with a pump. This is schematically represented in figure 10;
- A canal / polder system in which separate segments are coupled with flow or water level limiting structures, such as tight culverts or weirs, can be modelled as connected 0D reservoirs with empirically determined relationships between flow rate and water level (Q-H relationships) of the intermediate connections. This is schematically represented in figure 11;
- Flowing systems such as streams and rivers are modelled as a 1D model of the regional water system with accompanying parameters. This is schematically represented in figure 12.

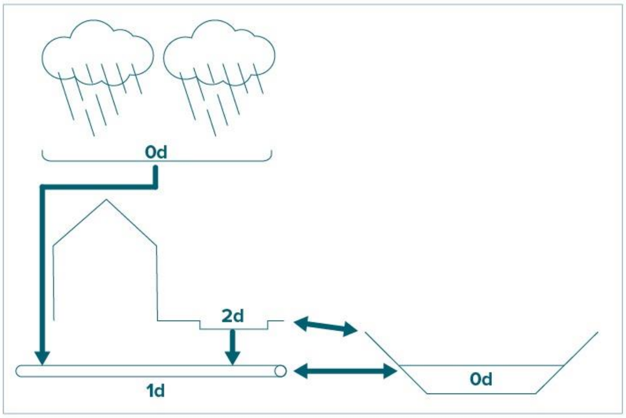


Figure 10: A simplified schematic representation of the sewerage model with flow over ground level and connection with surface water as a 0D reservoir

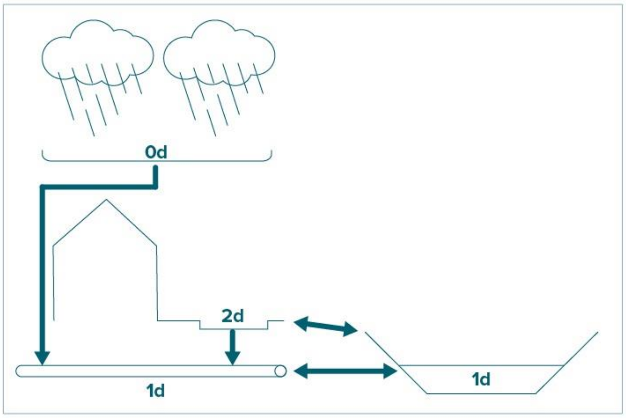


Figure 11: A simplified schematic representation of the sewerage model with flow over ground level and connection with surface water as a 1D flow profile

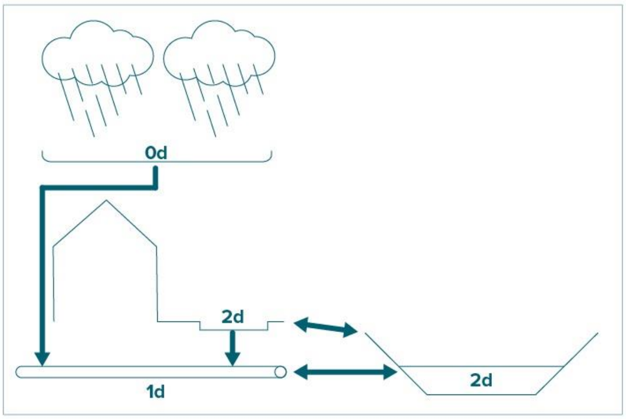


Figure 12: A simplified schematic representation of the sewerage model with flow over ground level and connection with surface water as 2D flow model

2.5 D-HYDRO

The D-HYDRO Suite is the successor to Delft3D 4.01 Suite, SIMONA (WAQUA, TRIWAQ), Duflow and SOBEK2 2. D-HYDRO create suite simulations of storm surges, hurricanes, tsunamis, detailed flows and water levels, waves, sediment transport and morphology, water quality and ecology. Moreover, it can simulate the interaction between these processes. The software package has been developed for professionals and non-specialists, ranging from consultants, technicians and contractors to policymakers and administrators involved in design, implementation and management. During this research the following versions are used: D-HYDRO Suite 1D2D (Beta) (0.9.7.51931) and (09.9.52575).

The core of the D-HYDRO package is the D-Flow Flexible Mesh module (D-Flow FM) with which one-dimensional, two-dimensional and three-dimensional hydrodynamic simulations can be made on unstructured grids. D-Flow FM is the successor to Delft3D-FLOW, WAQUA, TRIWAQ, Duflow and SOBEK2-FLOW and the result of five years of research by Deltares, the Ministry of Infrastructure and the Environment, the Ministry of Economic Affairs, Agriculture and Innovations, STOWA and Dutch engineering firms (Deltares, 2015).

To increase innovation, the national government has set up the Top Consortia Knowledge and Innovation (TKI). Representatives of companies, science and the government work together to support innovation and share knowledge. This research is part of the TKI D-HYDRO Urban-Rural project, in which experts and innovative entrepreneurs increase knowledge in the field of water, delta and maritime technology.

2.6 Calamity Weirs

A calamity is the commonly used indication of a (natural) disaster or an unexpected event that can cause serious damage (Wikipedia, 2016). In order to be prepared, governments have contingency plans which describe what to do in the event of a calamity.
An unexpected event can lead to serious damage if it includes:
- Failure of infrastructure (transport and storage, communication, control systems, energy, drinking water, water management);
- Failure of special facilities (in the field of care, management and control, enforcement);
- Uncontrolled behavior of large sections of the population.

An example of a calamity which is important in this research is a flood.

A weir is a fixed or movable dam between 2 waters. If the water level rises above a certain height, the weir will overflow or the doors will open. This keeps the water at the desired level (Rijkswaterstaat, sd). Some weirs have a position and therefore one fixed level; then it is called a threshold. Movable weirs usually have a minimum and a maximum level (Waterschap Rijn en IJssel, 2013). The water board determines what the water level should be in the most important canals, rivers and ditches. This is written down in a water level decision, a decision in which the water board sets the water levels within a specific area (often one or more polders) for 10 years (Waterschap Noorderzijlvest, sd). In situations where there is a high risk of flooding, the choice can be made to discharge the water via the adjustable weirs.

The Waterboard Hollandse Delta has made the design and locations for the calamity weirs available by means of a memo. A detailed elaboration can be found in Appendix II.

Chapter 3 – **Methodology**

In this chapter the required research strategy is provided to obtain the corresponding outcome presented in the introduction. The methodology is divided into two parts, the first part describing the construction, initialisation and validation of the hydraulic models with associated functions in D-HYDRO. The second part of the methodology focuses on the implementation of calamity weirs and optimizations of the water system in order to reduce flooding in the urban area of Stellendam. All results are generated on a laptop provided by Waterfeit.

3.1 Hydraulic models

To reduce urban flooding caused by a heavy precipitation event hydraulic models are used to simulate the event of October 2013. The models are used to calculate the locations and duration of water in the street and to test the influence of calamity weirs and additional optimizations in the water system. In addition to this, the hydraulic models will also be used to determine the added value of an integral calculation of the urban and surface water system. In total, three hydraulic models will be constructed:

- a 1D urban model with the sewer system and associated structures of the urban area of Stellendam
- a 1D rural model of the surface water and associated structures
- a combined 1D urban-rural model

The 1D calculations provide insight into the locations where water is located above ground level in combination with the duration of the water on the street. The link with the 2D ground level can be used to analyse so-called bottlenecks. An elevation model is made based on the AHN3 (Algemeen Hoogtebestand Nederland) in QGIS where the height of the ground level, buildings and surface water are reconstructed. The elevation model will normally only be used in 2D calculations. However, this study only simulates 1D calculation results and the link with ground level is not included. This trade-off was made because calculating the measures takes a lot of time, and with 2D ground level this will increase even further. Additionally, the results in this research can be obtained with using only 1D calculations to test measures and to analyse whether the locations and duration of water above ground level are decreasing. Finally, the D-HYDRO program is still under development and this trade-off minimizes unexpected delays in research.

3.1.1 Model initialisation

During this study, the influence of a specific precipitation event on the water system in Stellendam is calculated using the previously mentioned hydraulic models. In order to simulate the most reliable results, the models are initialized using a RestartFile. A RestartFile is a file that can be added to a model where an initial water level is set based on a previous calculation. The RestartFile which will be used for the models in this research is created by filling the water system (sewage system and surface water system) completely, with an initial water level of 0.15 and letting this system stabilize by calculating 7 days without precipitation. In the last time step of this calculation, the water level in the system no longer decreases but remains constant. When this situation is reached, the water levels of the last time step are used as the starting value to calculate the desired precipitation event. This prevents the system from immediately filling up at the start of the calculations, which paints an unrealistic picture of the actual situation.

3.1.2 Urban model validation

For the 1D urban model, an existing model has been supplied from the municipality of Goeree-Overflakkee, which has been constructed in SOBEK2. Additionally, a GWSW format (Urban Water Data Dictionary) is constructed by Waterfeit with a special data structure describing the system of Stellendam in the field of urban water management. First of all, the existing model will be analysed using visual inspection via QGIS. It is examined whether the model is still relevant and whether any adjustments are necessary. In order to start simulating with the model in D-HYDRO, there are two ways to import the existing data: via the SOBEK2 importer and via the GWSW importer. When using the SOBEK2 importer, the existing SOBEK2 model is directly loaded into D-HYDRO. When using the GWSW importer, the various CSV files that make up the GWSW are loaded into D-HYDRO, creating a model. Subsequently, it is decided to construct the model via the GWSW importer of D-HYDRO, with the reason that the SOBEK2 importer was not yet available for the urban model.

A validation was performed to check the conversion of SOBEK2 to D-HYDRO. Calculations in SOBEK2 and D-HYDRO can be expected to yield comparable results. To validate the model, first a stationary precipitation event is used in which 40 liters per second per hectare fall over a period of 12 hours. This equates to an amount of 1.2 millimeters per five minutes. An average temperature of 18.2 degrees and a standard evaporation value of 0.16 is used. Calculations are based on an empty system where initial outside water levels are given at the places where in reality water discharges into the surface water. The initial outside water levels are assigned to the model by so-called 'boundary nodes', the values that are entered come from the Waterboard Hollandse Delta. Summer or winter outside water levels can be used for the initial water levels, with the winter level being higher. The values that are assigned are the summer water levels because the central precipitation event of this research takes place in October. The stationary rainfall provides insight into the water flow of the system, on which the model can be validated by comparing these results with the SOBEK2 urban model. Constant precipitation intensity leads over time to an unchanging discharge situation, making it well suited for checking the water balance.

When the stationary flows match the models of SOBEK2 and D-HYDRO, the dynamic system behavior will be analysed. This will be done by comparing the water balance of the urban systems calculated from D-HYDRO and SOBEK2 and the calculated water levels per manhole. A variable rainfall intensity event 8 is used for the validation. This is a standardized test precipitation event that is widely used in the Netherlands to test the hydraulic functioning of sewer systems. At event 8, a rainfall of 2 hours is calculated with a total amount of rainfall of 19.8 millimeters with a time step of 5 minutes. The same values for initial water level, evaporation and temperature as for the 40 l / s / ha event are also used in this calculation. Figure 13 shows the hydrogram of event 8 with the amount of precipitation per time step.

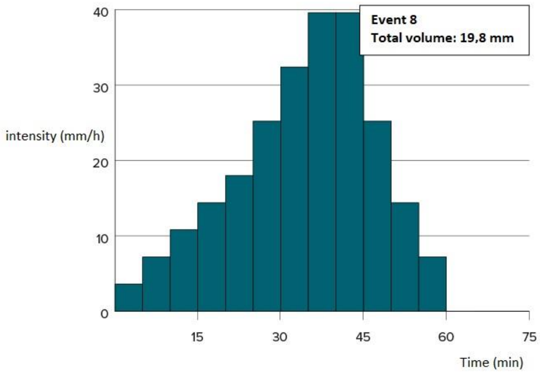


Figure 13: Hydrogram of event 8 with the amount of precipitation in mm/h per time step in minutes

The comparison will be made using a supplied PYHTON script from Waterfeit. This script provides two graphs of the entire system in the urban area, showing the difference in the water level between SOBEK2 and D-HYDRO per manhole and the time shift differences of the emptying behavior of the system. In consultation with Waterfeit a difference of 5 centimeters or less on the peak of the calculated water levels is most desirable. This consideration has been taken to prevent too much time being lost in the fine grinding of the models. The results provide an overview of the discharge of the overflows in D-HYDRO and SOBEK2 for the 40 l / s / ha event, two graphs with the difference in the maximum calculated water level between D-HYDRO and SOBEK2 for both events, a table with the difference in water balance between D-HYDRO and SOBEK2 for event 8, and a graph showing the difference in emptying behavior for the last time step of event 40 l / s / ha between D-HYDRO and SOBEK2.

3.1.2.1 Urban model October event

When the urban model has been validated, the relevant event of October 2013 is simulated and the calculated water levels are analysed for water above ground level locations and durations. The available data derives from the Waterboard Hollandse Delta. A RestartFile is used to initialize the system correctly. Figure 14 shows the input values for the precipitation, with the peak of this event occurring on October 13 at 10:00:00. At this moment there is an amount of precipitation of 12.14 millimeters in one hour. The total amount of precipitation is 159.39 millimeters, with the calculation starting on 09-10-2013 23:00:00 and ending on 18-10-2013 00:00:00 with a time step of one hour. These input values have been used in order to simulate the run-up to the event as realistically as possible. This timestep of one hour is sufficient for calculating surface water systems, a higher resolution is desirable for the sewage system. Because the calculations are based on a resolution of one hour, high precipitation intensities within this hour are not known and the amount of flooding from sewers is underestimated. However, this resolution is sufficient for the interaction between sewerage system and surface water. This urban model is used to make the comparison with the integral model to analyse whether the results match and which model best simulates reality. As a result, two manholes are plotted from the Voorstraat with the calculated water levels. The location of these manholes can be found in Appendix III. The location at the Voorstraat is being analysed because information has been obtained from the municipality that water occurred above ground level at these locations.

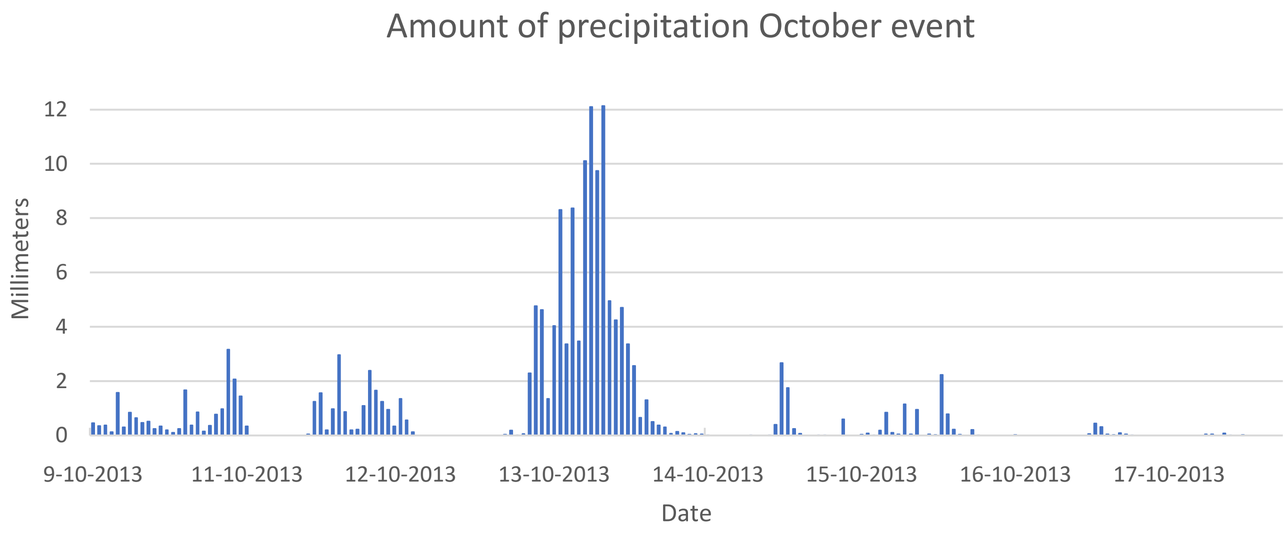


Figure 14: Hydrogram of the amount of precipitation in millimeters for the October event

3.1.3 Rural model validation

For the rural model, an existing SOBEK2 model has been supplied from the Waterboard Hollandse Delta. First of all, the existing model will be analysed using visual inspection via QGIS and Google Maps. It is examined whether the waterways and structures in the model are also present in the actual situation. This is done by going through the available data of surface water bodies and structures from the Waterboard Hollandse Delta and noting any deviations. If anything is unclear, the Waterboard will be contacted. These adjustments will be made in the existing SOBEK2 model to keep the comparison and actual situation as reliable as possible. When any adjustments have been made in the SOBEK2 model, it is imported via the SOBEK2 importer in D-HYDRO. The 1D rural model will be initialised using a RestartFile. An overview of the surface water system network can be seen in Appendix IIII.

To validate the rural model a precipitation event is being used where an amount of 50 millimeters spread over 2 days where the entire 50 millimeters occurs on the first day. This equates to an amount of 0.173611 per 5 minutes for 24 hours. The calculation time is therefore 2 days with a time step of one minute. Calculations are based on an initial water level of zero, which means that the water level in relation to NAP is zero. The precipitation amount is used to analyse the processing of the surface water system and to notice differences between the results in D-HYDRO and SOBEK2. The choice of the precipitation event was decided in consultation with Waterfeit. A surface water system is sensitive to long-term precipitation with large total precipitation amounts because it reacts slowly to precipitation and has a lot of storage. An event with less rainfall is therefore irrelevant to look at. The RealTimeControl module will also be developed for the calculations in this model. This means that there are orifices, weirs and pumps in the model which have controllers to regulate the capacity or crest levels. Because D-HYDRO has not yet further developed the RTC module for pumping stations, the switch-on and switch-off levels of the pumping stations are manually adjusted to the SOBEK2 model.

The rural model is not calculated with the precipitation event of October because this research is mainly aimed at urban flooding in Stellendam.

The results show a graph with the comparison of the calculated water levels by D-HYDRO and SOBEK2 for the precipitation event 50 millimeters. Based on these results, it is assessed whether the model can be used to generate reliable results in combination with the urban model.

3.1.4 Combined urban-rural model

In the combined urban-rural model, the validated 1D urban and rural models are linked together in D-HYDRO. This model best represents a simulation of the actual situation and is therefore the most complete model. A small change has been made to this model at the final pumping station of Stellendam (12464 GM, Appendix IIII). At this pumping station, the water level decreases too quickly in one calculation time step, causing a instability. For that reason, a so-called three-pump pumping station has been implemented in this model in consultation with Waterfeit. Two extra pumps are added where the switch-on and switch-off levels are adjusted and the total pump capacity is being divided over the three pumps. The three pumps turn off one after the other. When the water level approaches the deflection level, only one of the pumps is still running. This one pump cannot pump the water level far below the deflection level, which decreases the instability.

This is implemented as follows:

- Pump_1D_1
  Capacity: 0.955 m³/s
  Switch-on level: -0.84
  Switch-off level: -0.96
- Pump_1D_2
  Capacity: 0.955 m³/s
  Switch-on level: -0.79
  Switch-off level: -0.91
- Final pumping station 12464GM
  Capacity: 0.955 m³/s
  Switch-on level: -0.89
  Switch-off level: -1.01

The 1D combined rural and urban model will be used to simulate the amount and duration of water on the street during the precipitation event of October 2013. The same data and input values are used as with the 1D urban model in which the October event is also calculated. The result will be a map constructed in QGIS with the amount and location of water on the street in the urban area of Stellendam at the peak of the event at time step 13 October 10:00:00. The combined 1D urban-rural model will also be used to test the operation and influence of calamity weirs during the aforementioned precipitation event. Finally, the combined model will be used to calculate optimizations in the water system and compare the results with the 1D urban model during the precipitation event of October 2013 to determine the added value of the integral model.

3.2 Optimizations of the water system

A large part of this research is devoted to making the hydraulic models and simulate the influence of calamity weirs in order to reduce the impact of flooding in the urban area of Stellendam. Additionally, this part of the report described which model optimizations are possible to cause less urban flooding during a precipitation event similar to October 2013. The implementing of the calamity weirs is too presented in this part of the report. Four types of model optimizations are described, which have been submitted in consultation with the Waterboard Hollandse Delta, the municipality of Goeree-Overflakkee and Waterfeit. All calculations related to the optimization of the water system will be done using the validated 1D urban - rural model.

3.2.1 Calamity weirs

The Waterboard Hollandse Delta has put forward the idea of realizing two calamity weirs that can be used in the future to adequately retain excess water in the upstream areas. A more detailed explanation with the reasoning and locations of the weirs can be found in Appendix II. The dimensions of weir 45651ST are shown in Figure 15, the dimensions of weir 45652ST are shown in Figure 16. The weirs are constructed at the proposed locations in D-HYDRO using RealTimeControllers with a LookUpTable. This means that the water level is measured at a measuring station close to each weir, and the crest level of the weir will be automatically regulated based on the measured water level.

Stuw Langeweg - 45651ST

Eindresultaat & Aanbeveling:	Klepstand maximaal	-0,23	(m NAP)
	Klepstand minimaal	-1,95	(m NAP)
	Verstelhoogte klepstand	1,72	(m)
	Overstortbreedte	3,00	(m)
	Overstortende straal	0,49	(m NAP)

Figure 15: Dimensions of calamity weir 45651ST

Stuw Eendrachtsdijk - 45652ST

Eindresultaat & Aanbeveling:	Klepstand maximaal	-0,11	(m NAP)
	Klepstand minimaal	-1,60	(m NAP)
	Verstelhoogte klepstand	1,49	(m)
	Kruinbreedte	2,00	(m)
	Overstortende straal	0,37	(m NAP)

Figure 16: Dimensions of calamity weir 45652ST

The results contain an overview graph made with a script written by Waterfeit in PYTHON showing the difference in calculated water levels between the reference model without calamity weirs and the model in which the calamity weirs have been added.

3.2.2 Increase of pump capacity

Stellendam contains multiple pumping stations, the locations of these pumps can be found in Appendix I and III. The pumping station which pumps out excess water from the surface water (12464GM, Appendix IIII) currently has a capacity of 10,320 m³ per hour, converted 172 m³ per minute. This will be increased to 250 m³ per minute based on the advice of the Waterboard Hollandse Delta. Because a three-pump pumping station has been realized in this model, the two fictitious pumps now have a capacity of 3438 m³ / h per pump. 2500 m³ / h is added to this, this becomes 5938 m³ / h. The capacity will be 1.649 m³/s per pump. The final pumping station remains at 0.955 m³/h to prevent the return of the aforementioned instability. By increasing the pumping capacity, more excess water can be pumped out of the surface system. It is to be expected and desired that less inundation therefore occurs in the urban area.

The results show an overview graph made with a script written by Waterfeit in PYTHON showing the difference in calculated water levels between the reference model without adjusted pump capacity and the model in which the pump capacity have been increased.

3.2.3 Retaining water upstream

The urban area of Stellendam is located downstream, allowing the surface water to flow naturally to this location which causes urban flooding in times of heavy precipitation. By arranging the upstream water level in such a way that the excess water is more retained at this location, less water will flow towards the urban area of Stellendam and the desired situation is that the urban flooding will be reduced. An exploratory calculation is made to analyse whether water storage upstream results in lower water levels in the urban area of Stellendam. The crest width of the 28 weirs in the surface water system are made 10% of the original width to create more backwater upstream, so that less water flows towards the Stellendam core. This exploratory calculation is made to see whether this way of optimizing the water system is worth researching further and whether it provides the desired effect.

The results show an overview graph made with a script written by Waterfeit in PYTHON showing the difference in calculated water levels between the reference model without the adjusted weirs and the model in which the width of the weirs have been decreased.

3.2.4 Flap valves

A flap valve consists of a plate with a hinge at the top and is often made of polyethylene and / or stainless steel to prevent deterioration by the relatively acidic environment. Some check valves are mounted at a slight angle to ensure that the valve closes under gravity. Flap valves in a sewer system must be checked regularly because dirt can get between the valve and the stop and prevent the valve from closing. (Wikipedia, 2020).

The influence of the flap valves on reducing the locations and duration of street water in the Stellendam urban area are calculated, as mentioned earlier, using the 1D urban - rural model. This is implemented in the model by changing the flow direction of the internal overflow at the locations where the connection with surface water and a combined sewage pipeline is located. As a result, outflow from surface water is not possible if the surface water level is higher than the sewage system water level. With storm water sewage pipes, the water is being discharged directly onto the surface water, and an orifice is placed where the flow direction can be changed. In this case, the orifice serves as the sewage check valve. This is applied at every location where the sewage system is linked to the surface water, which amounts to the implementation of a total of 12 flap valves. The result is an overview graph showing the differences in the calculated water levels per manhole between the model with the flap valves and the reference model without the flap valves.

Chapter 4 – **Results**

This chapter presents the findings obtained during this research. This concerns the calculation results of the models mentioned in the chapter Methodology, and the measures that have been established with the aid of literature research. In addition, it also contains results related to the validation comparison of the models between SOBEK2 and D-HYDRO to perform a reliability analysis. The calculation results are manifested by maps produced in QGIS, the results of the comparison analysis between SOBEK2 and D-HYDRO are visible with graphs created in PYTHON.

4.1 Hydraulic models

This part of the results focuses on the results obtained from D-HYDRO in the manner described in the chapter 'Methodology'. A distinction is made between the results of the urban area in which only the sewer system has been modelled, the rural area in which only the surface water has been modelled, and a linked model in which both systems are connections and calculations are made with the relevant precipitation October event that is leading in this research. Overview graphs are also shown for each model, showing the differences in water levels between SOBEK2 and D-HYDRO. Based on these graphs, it was assessed whether the D-HYDRO model generates reliable results.

4.1.1 Urban model validation

The urban model has been validated with two events: both with a stationary situation and with a variable rainfall intensity. Table 1 shows the flow rates at the overflows in a stationary situation, at the last time step of the 40 liter / second / ha precipitation event calculation. The values are in m^3 / s and the differences between D-HYDRO and SOBEK can be read in the table 4.

Table 4: Flow rates through overflows in D-HYDRO and SOBEK in m³ / s at time step 12:00:00 with stationary event 40l / s / ha

Overflow ID		Flow rate m³/s		Deviation	
D-HYDRO	SOBEK2	D-HYDRO	SOBEK2	m³/s	%
OVS6	37488-37488U	0.141	0.134	0.008	5.8%
OVS1	32279-32279U	0.096	0.097	-0.001	-1.0%
OVS9	H32320-H32320U	0.275	0.269	0.006	2.3%
OVS8	37473-37473U	0.110	0.114	-0.004	-3.3%
OVS7	35403-35403U	0.357	0.351	0.006	1.7%
OVS4	31312-31312U	0.123	0.128	-0.004	-3.4%
OVS3	31159-31159I	0.076	0.074	0.002	2.8%
OVS5	31350-31350U	0.029	0.032	-0.002	-6.9%
OVS10	P303I-P303	0.375	0.366	0.009	2.4%
Total		1.583	1.563	0.019	1.2%

From this table it can be deduced that the system behavior at the overflows usually corresponds between D-HYDRO and SOBEK, with a maximum deviation of approximately 0.002 m³ / s and 6.9% at OVS5.

The maximum calculated water levels of both models have been compared for all manholes in the urban system. Figure 12 shows the calculated differences in water levels between D-HYDRO and SOBEK2. At the grey points the difference is less than 5 centimeters, at the orange points the maximum calculated water level in D-HYDRO is 5-10 centimeters higher than in SOBEK2, at the light blue points the water levels calculated in D-HYDRO are 5-10 centimeters lower than in SOBEK2. The x-axis and y-axis show the coordinates of the manholes. The core of Stellendam is relevant for this study, the areas that are located outside the coordinates (61750, 426500) are not taken into account.

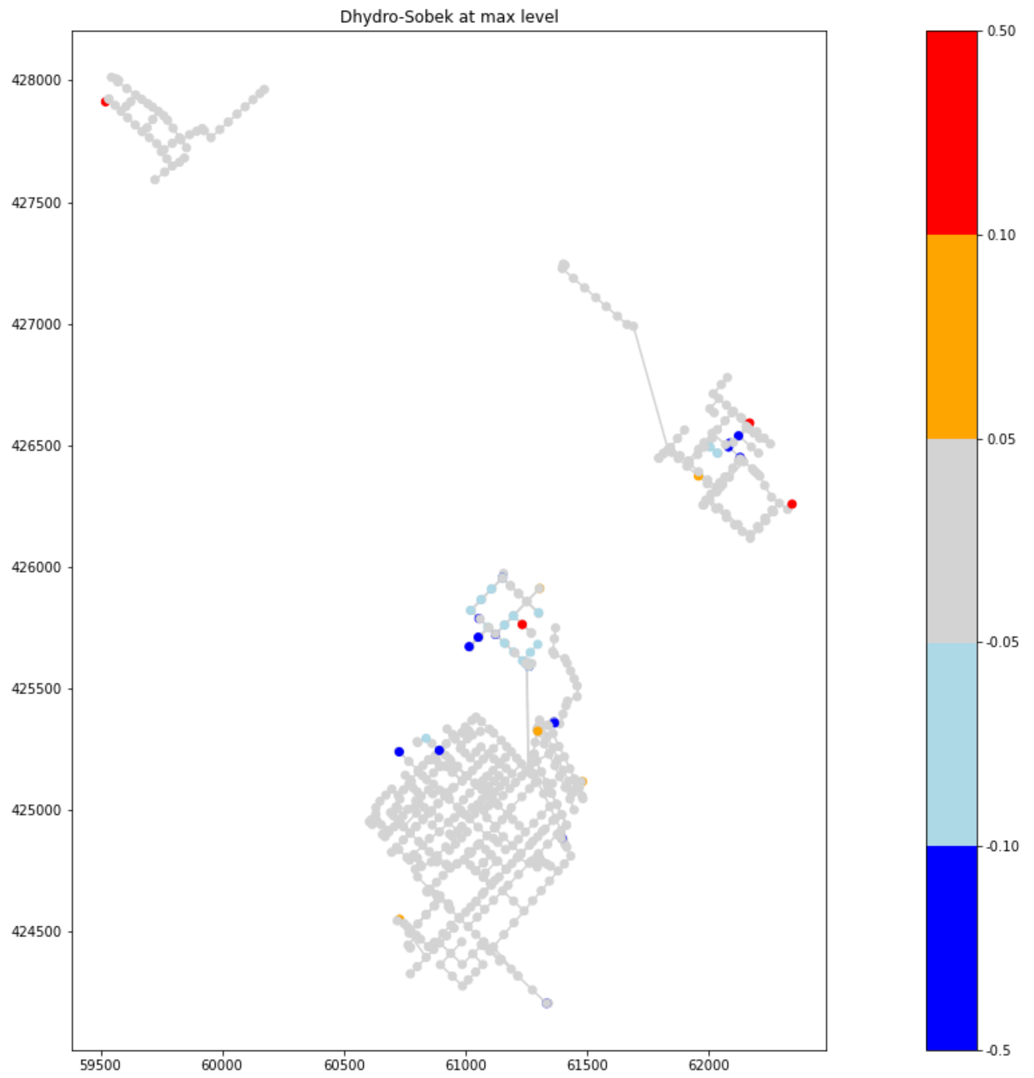


Figure 17: The difference in maximum calculated water level between D-HYDRO and SOBEK for a 40 liter / second / ha event

As can be seen in figure 17, there are 6 dark blue points where D-HYDRO calculates a higher value for the water level and there is one dark red point where SOBEK2 calculates a higher water level. The darker blue points are the so-called boundary nodes. It is known that differences occur here because a compartment in the form of a manhole is constructed at the boundary in D-HYDRO, which creates a possibility for storage. At SOBEK2, the boundary is a discharge point without a compartment and the water is simply out of the system immediately. The differences at the boundaries can probably be reduced by further model optimisations. However, the effect on the total calculations is limited, especially because the link with the rural model is made on these points. Therefore, further model optimization is not performed.

The calculated water levels in D-HYDRO and SOBEK2 have also been compared at the last time step of the 12-hour event of 40 liters / second / ha. This provides insight into the reliability of D-HYDRO with regard to the underutilisation of the system. The results can be seen in figure 18: the x-axis and y-axis show the coordinates of the manholes, the deviations are visible with the use of a continuous colour scale in which the deviations are shown in centimeters. The figure shows that there is hardly any difference in the calculated water levels between D-HYDRO and SOBEK2 for the last time step of a stationary precipitation event.

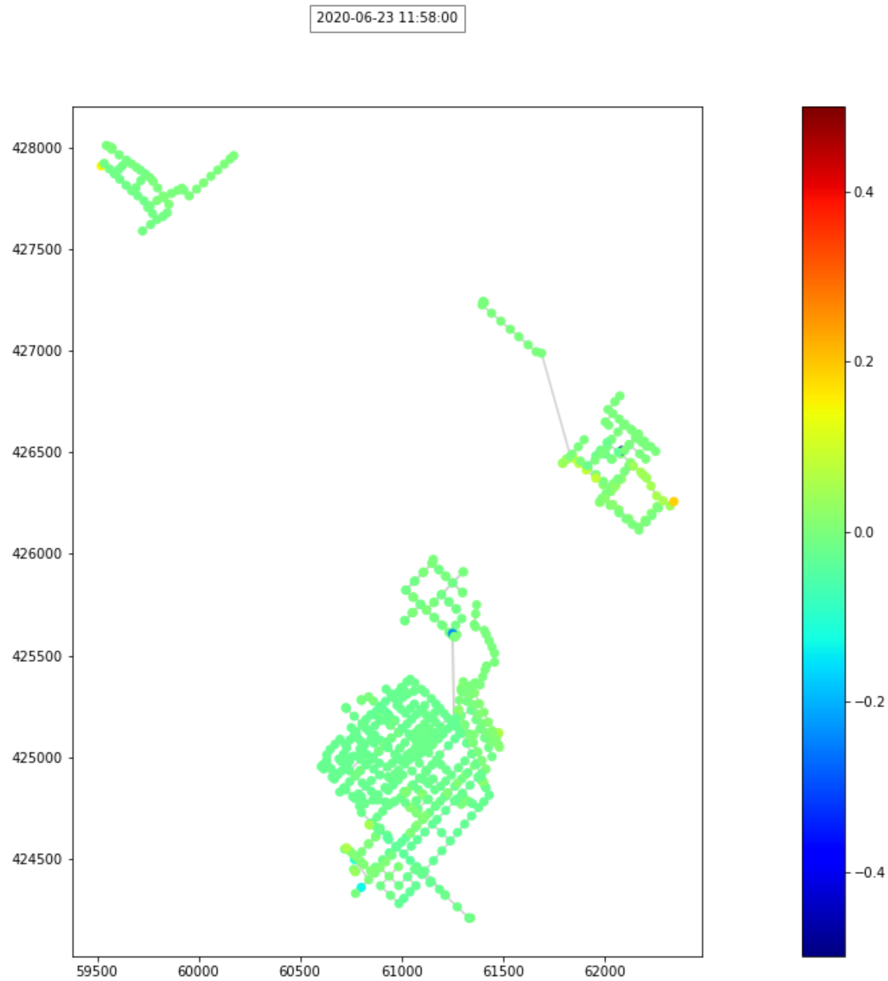


Figure 18: The difference in maximum water level between D-HYDRO and SOBEK for a 40 liter / second / ha event at the last time step of the 12 hour calculation time

Based on these tables and graphs, it is concluded that the model is efficient enough in terms of stationary system behavior to generate reliable results.

To analyse whether the dynamic system behavior of D-HYDRO corresponds with SOBEK2 the variable precipitation intensity was calculated. At this event the incoming and outgoing water volumes in m³ are being compared, as can be seen in table 5. It can be observed that the largest deviation is in the influx of the boundaries, which can be explained because SOBEK2 does not count the aforementioned storage at the boundaries which D-HYDRO does.

Table 5: The incoming and outgoing water volumes in D-HYDRO and SOBEK in m³ with the corresponding difference between the models

	D-HYDRO	DIFFERENCE D-HYDRO - SOBEK	SOBEK
Water balance boundaries in m³	309	95	214
Water balance boundaries out m³	9482	37	9445
Water balance laterals in m³	9595	-3	9598
Water balance laterals out m³	0	0	0

Additionally, the maximum calculated water levels of both models have been compared for all manholes in the urban system. Figure 19 shows the calculated differences in water levels between D-HYDRO and SOBEK2. At the grey points the difference is less than 5 centimeters, at the orange points the maximum calculated water level in D-HYDRO is 5-10 centimeters higher than in SOBEK2, at the light blue points the water levels calculated in D-HYDRO are 5-10 centimeters lower than in SOBEK2. The x-axis and y-axis show the coordinates of the manholes.

Three manholes indicate a higher water level in D-HYDRO than in SOBEK2. This difference is caused by a instability (spike), after which the model stabilizes and the calculated water levels match. An example of a node where this happens is plotted in figure 20. As can be seen in this figure there is a difference in the spike, however the model stabilizes after a few time steps after which the water level corresponds between D-HYDRO and SOBEK2 .

The manholes where SOBEK2 calculates a higher water level than D-HYDRO are mainly the boundaries in the model, which was also mentioned earlier for the 40 l / s / ha event. An example of a node where this occurs is plotted in figure 21, where it can be clearly seen that SOBEK maintains a constant water level. The other manholes where the water level in D-HYDRO is calculated higher than in SOBEK2 are located behind a weir, where the system fills with surface water through the boundaries. An example of a node in which this occurs is plotted in figure 22.

Because the differences are minimal and the larger differences can be explained, this model is validated as reliable enough in consultation with Waterfeit to make the integrated model. This has been confirmed by means of a memorandum by the municipality of Goeree-Overflakkee and Deltares.

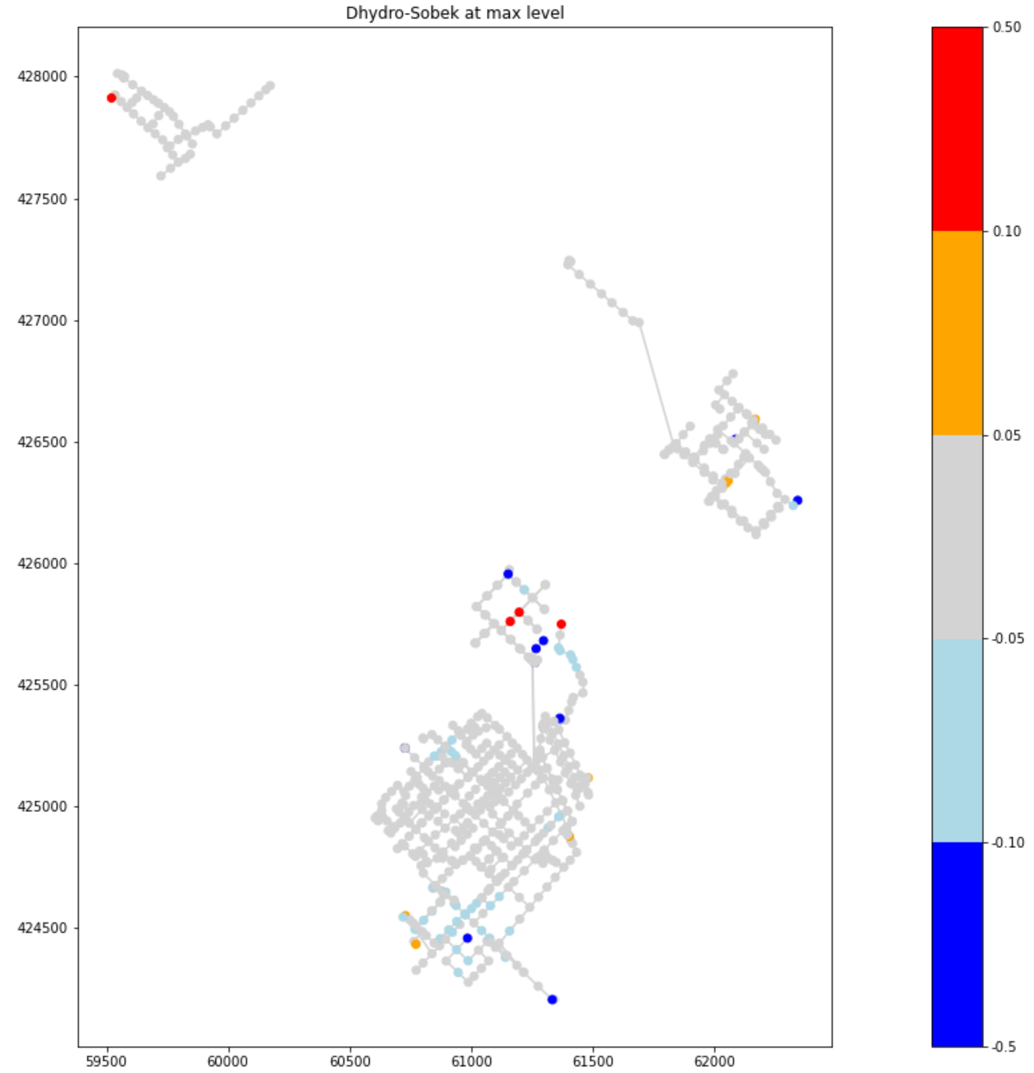


Figure 19: The difference in maximum water level between D-HYDRO and SOBEK for event 8

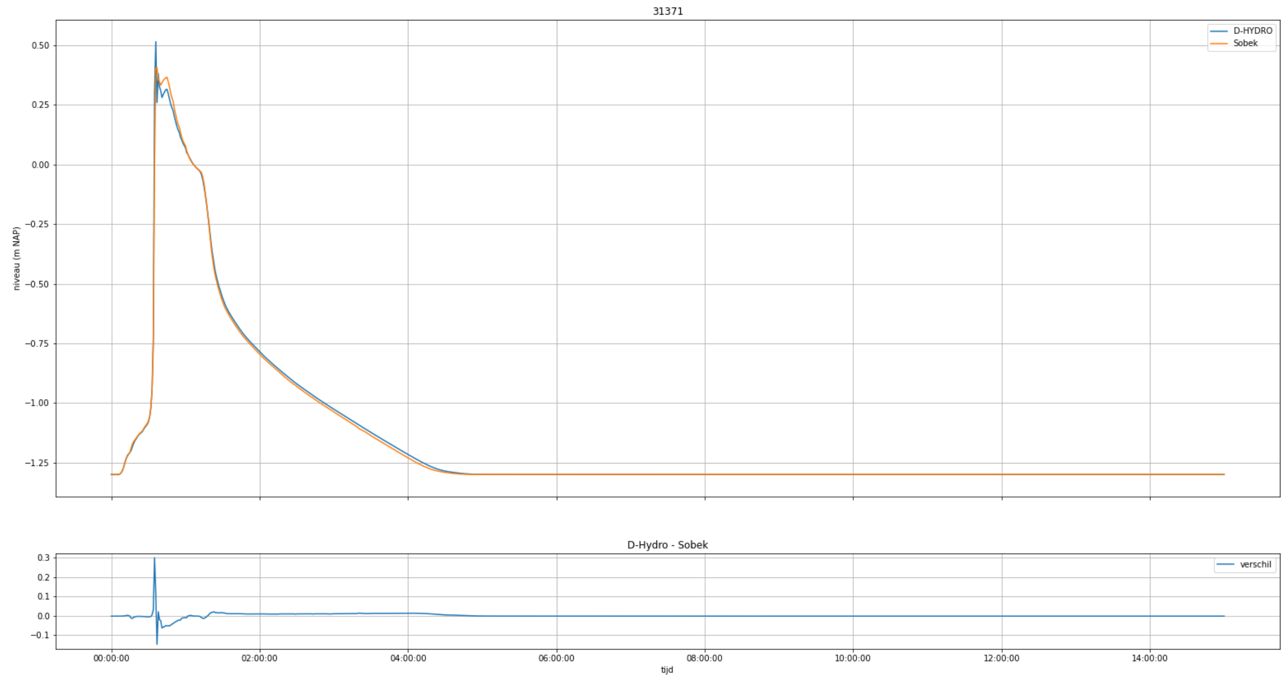


Figure 20: : The difference in maximum water level between D-HYDRO and SOBEK2 for node 31371

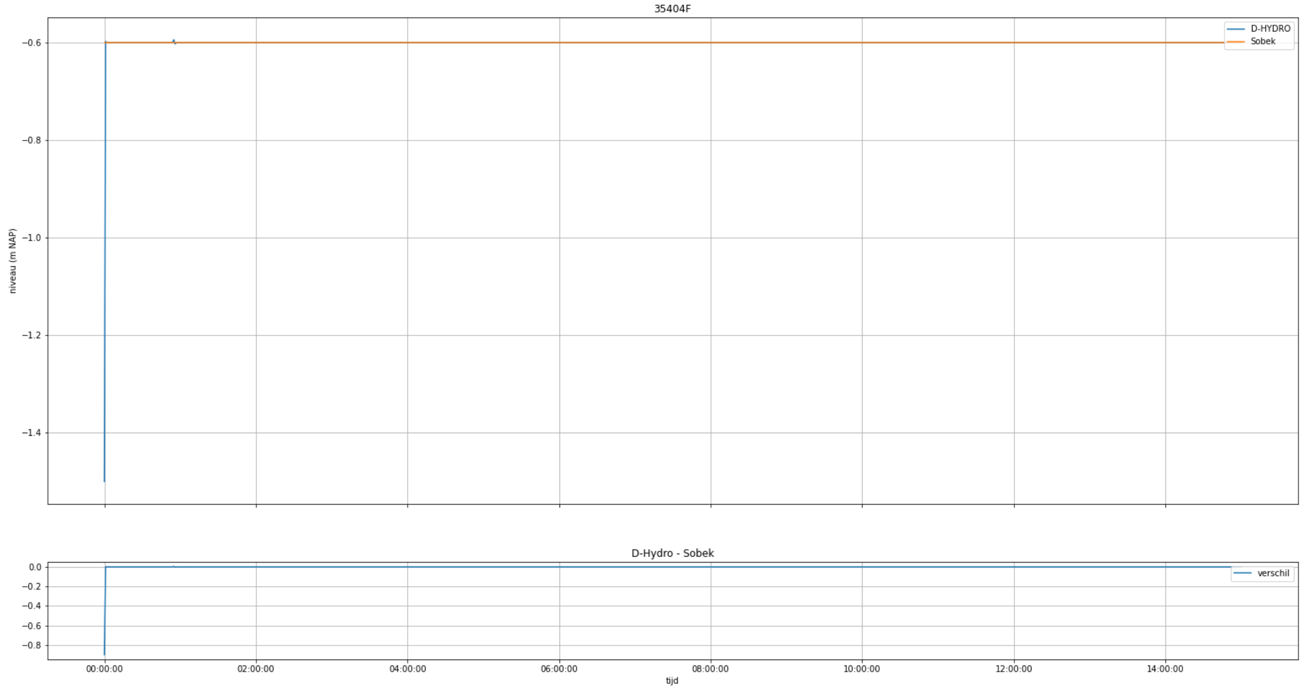


Figure 21: The difference in maximum water level between D-HYDRO and SOBEK2 for boundary node 35404F

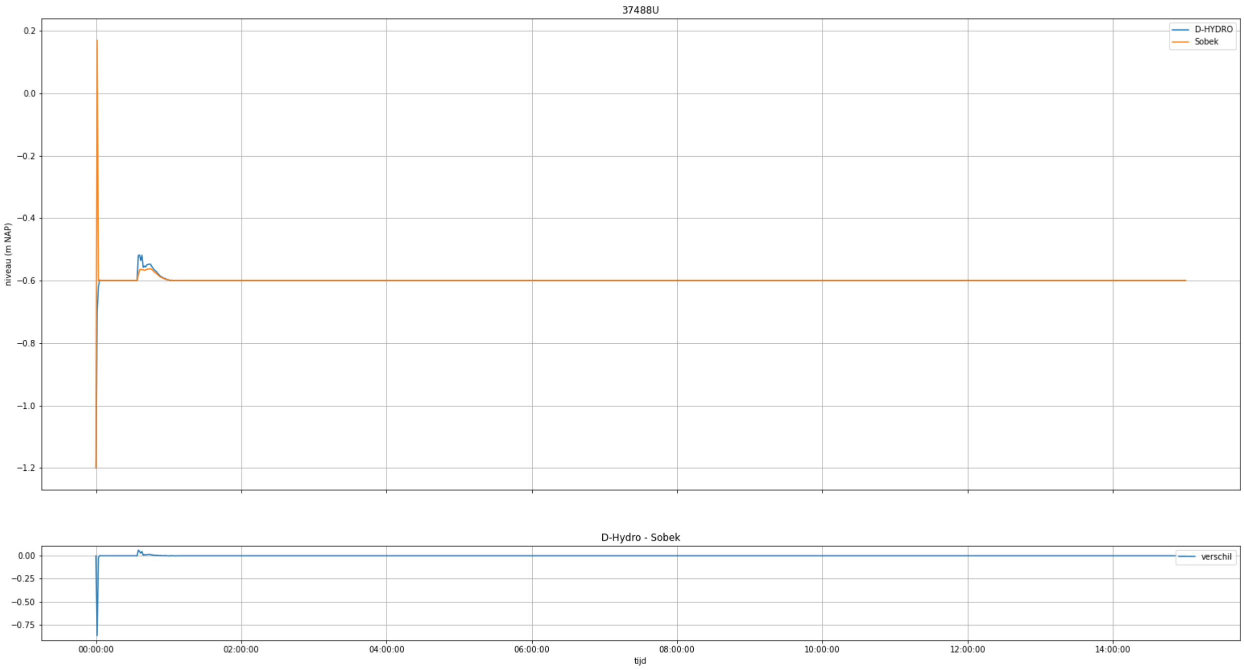


Figure 22: The difference in the calculated water levels between D-HYDRO and SOBEK2 for node 37488U

4.1.1.1 Urban model October event

After the model validation, the October 2013 event was calculated with the urban model and the calculated water levels have been analysed. In this model no water above ground level is calculated, which indicates that during the October 2013 event there will be no water on the street when only simulating the sewer system. Figure 23 shows the calculated water levels of manhole 031336 located in the Voorstraat (see Appendix III) in meters NAP. The maximum calculated water level is -0.83 meters NAP, the surface level is 0.38 meters NAP. This means that when more than 0.45 meters NAP water is calculated, water occurs on the street. Figure 23 visualises that this is not the case. The same situation applies to figure 24, where manhole 031044 is plotted (see Appendix III). At this manhole, the surface level is 0.45 NAP, and the maximum calculated water level is -0.09 m NAP. This would indeed mean that no water would occur in the street, which does not correspond to the actual situation.

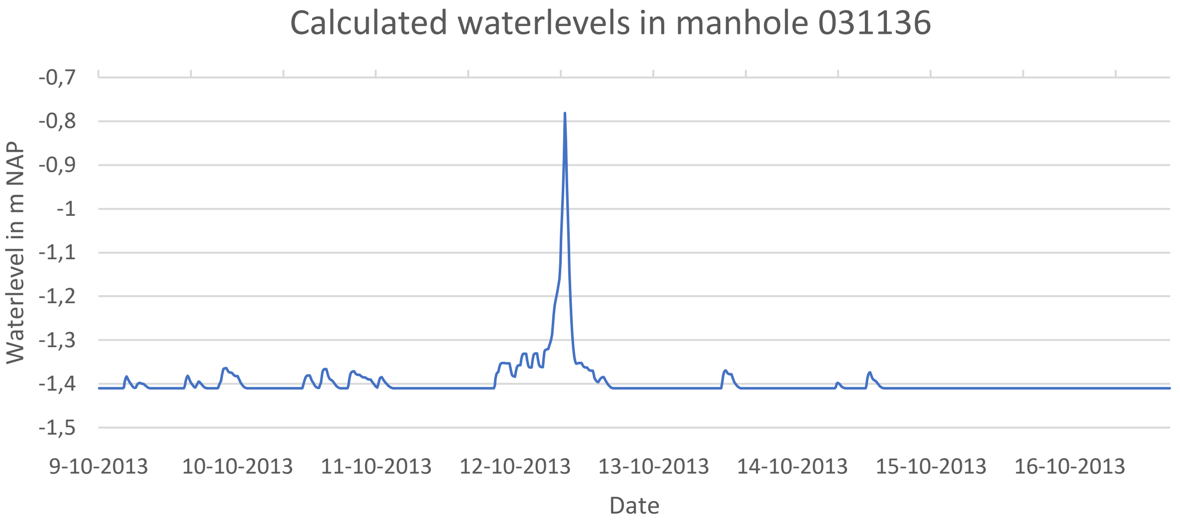


Figure 23: The water level in meters NAP of manhole 031136 during the event of October

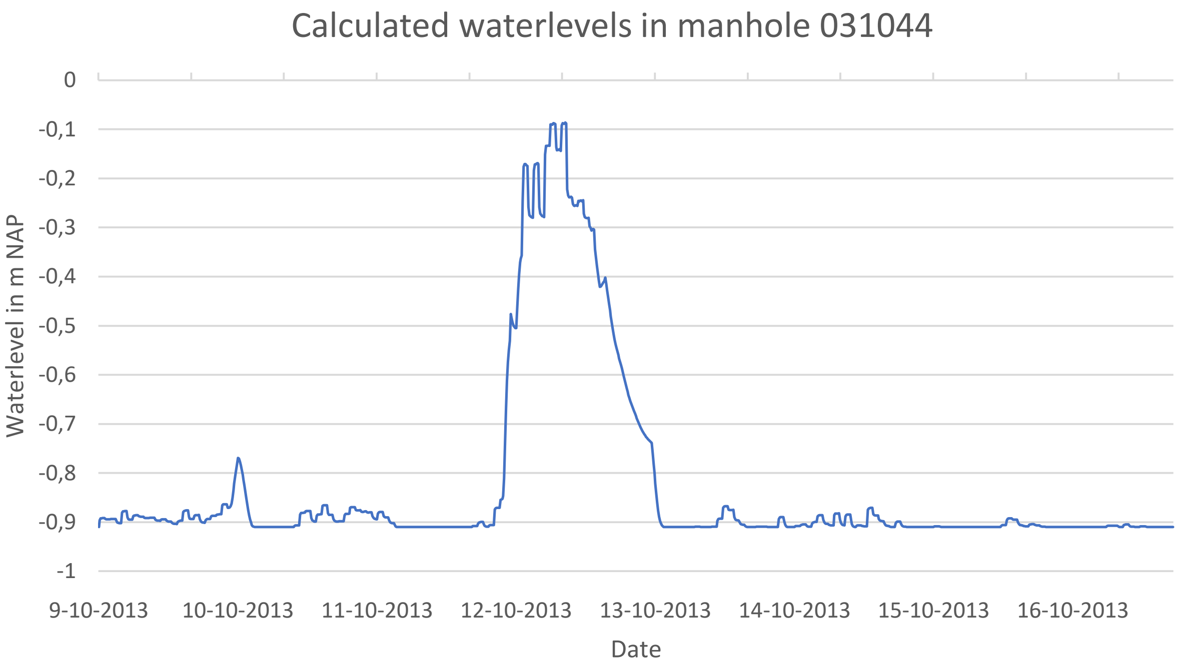


Figure 24: The water level in meters NAP of manhole 031044 during the event of October

4.1.2 Rural model

The rural model has been validated with an event in which 50 millimeters of precipitation is calculated in which this amount occurs entirely in 24 hours and no precipitation occurs for the next two days.

Figure 25 shows the calculated differences in water levels between D-HYDRO and SOBEK2 for the 50 millimeter event. At the grey points the difference is less than 5 centimeters, at the orange points the maximum calculated water level in D-HYDRO is 5-10 centimeters higher than in SOBEK2, at the light blue points the water levels calculated in D-HYDRO are 5-10 centimeters lower than in SOBEK2. The x-axis and y-axis show the coordinates of the nodes. Two areas stand out which are coloured red. The one node that is coloured red is a boundary node, which causes a deviation due to the difference in storage between D-HYDRO and SOBEK2 as discussed earlier in the urban results. The differences in the larger area where D-HYDRO calculates a higher water level and the nodes are coloured red seem to be due to a control-driven weir. In D-HYDRO the crest level is -0.27505 meters and in SOBEK2 the crest level is 0.43 meters. Because the area is relatively small and the direction of the water flow is not towards the urban area, the deviation is not considered relevant.

Where the nodes are coloured light blue (62000,425000) seems to be due to the influence of pumping station 12464GM, which has an instability in D-HYDRO. The switch-on level of this pump is set at -0.54 meters, the switch-off level is set at -0.66 meters. This means that the pump starts pumping when the water level at the pump is -0.54 meters, and the pump switches off when the water level is -0.66 meters. However, the pumping station in D-HYDRO does not pump off at the set switch-off level, as can be seen in figure 26. Here the calculated water level is plotted for the node located in front of the pump, which clearly shows that the pump switches off at -0.78 meters NAP. At the end of the calculation, at time step 21:00:00, this figure also shows an instability in the form of the fluctuating calculated water levels in D-HYDRO. After making a so-called side view in D-HYDRO, where the water level can be seen over an entire watercourse, it has been observed that the water level is influenced by this instability. In consultation with the Waterboard Hollandse Delta, it was decided that this model is efficient enough to make the link with the urban system and generate reliable results. The instability will be reduced in the integral urban – rural model.

Figure 25: The difference in the calculated maximum water level between D-HYDRO and SOBEK2 for the event with 50 millimeter precipitation

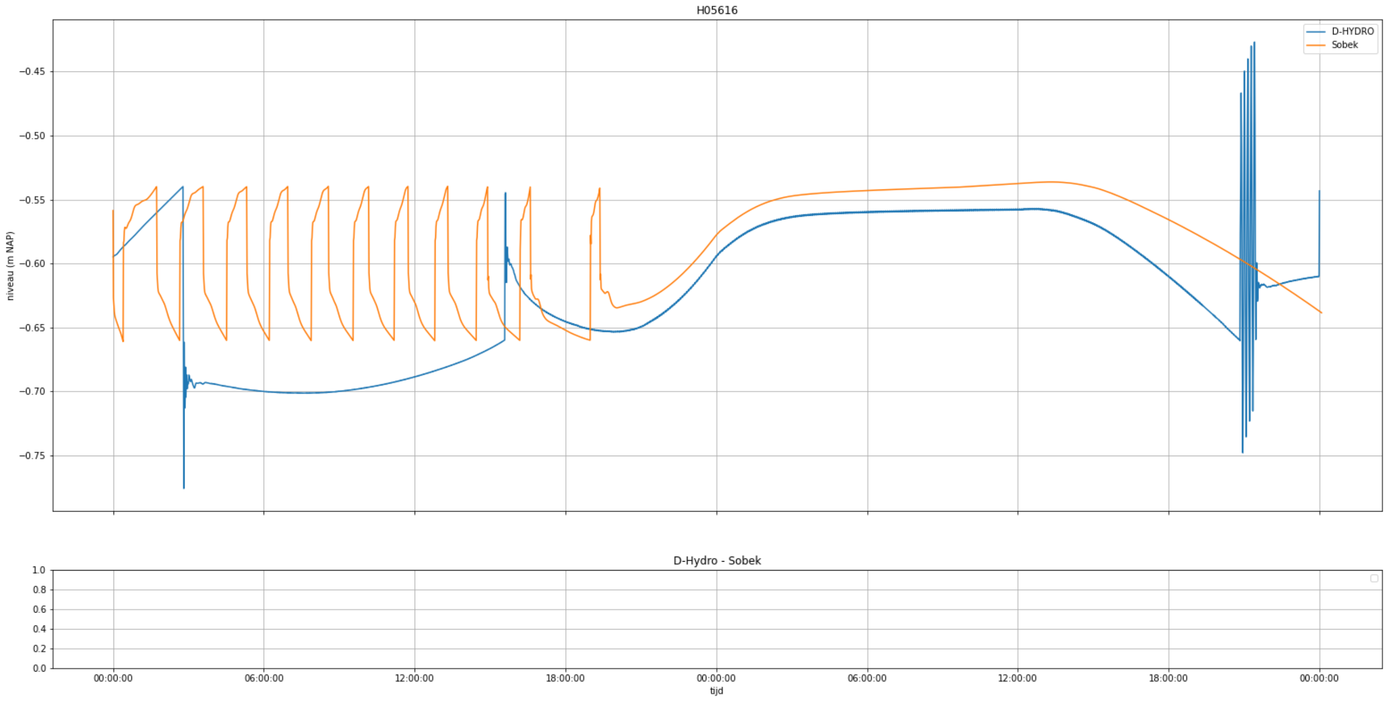


Figure 26: The difference in the calculated water levels between D-HYDRO and SOBEK2 for node H05616

4.1.3 Combined urban – rural model

The combined urban - rural model has been created by linking the validated urban and rural model to each other, resulting in one integral model. This model was used to calculate the October 2013 event and to analyse the added value of the connection with the surface water. This model has additionally been used for calculating aforementioned optimizations of the water system. Appendix V shows an overview map with the result of the calculated street water locations at time step 13 October 10:00:00. Most of the amount of water is calculated in the Voorstraat, which corresponds to the actual situation and the feedback from the municipality. There is a clear difference in the result compared to the urban model, where the integral calculations are more in line with the actual situation.

The calculated water level for manhole 031044 in meters is shown in figure 27. The first three days of the water levels is the same as in figure 24, but when the amount of precipitation increases there is a difference in the calculated amount of water between the urban model and the combined model. Here it can clearly be seen that water rises above the surface level of the manhole, which is at the aforementioned 0.45 meters NAP. The same applies for manhole 031136, as can be seen in figure 28 where the calculated water levels in meters NAP occur above the surface level of 0.38 after about 4 days. There is water on the street for about two days, which is a long time.

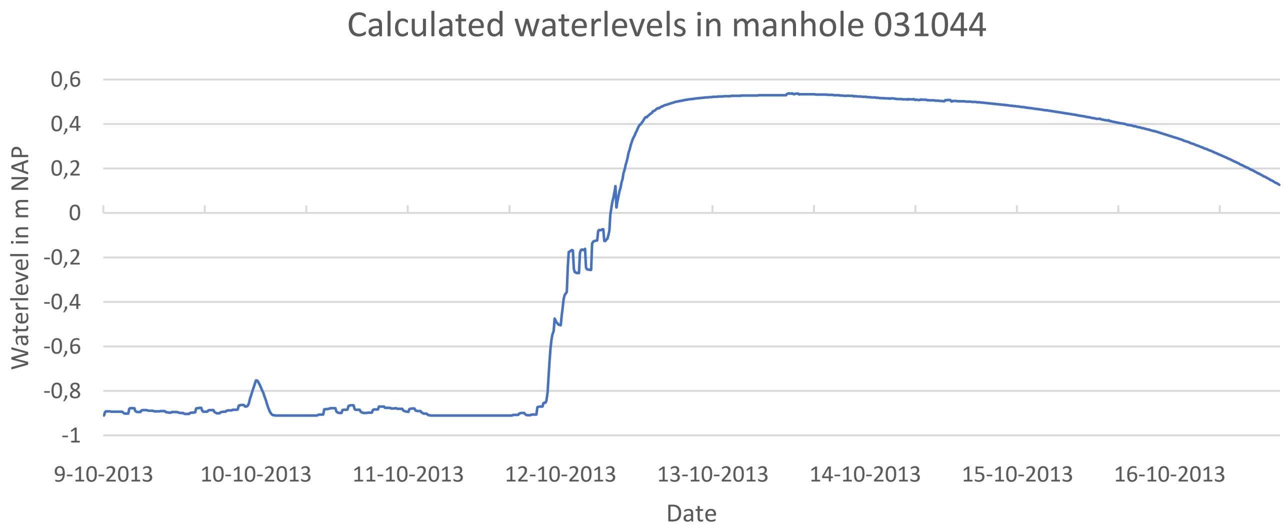


Figure 27: The calculated water level in meters of manhole 031044 during the event of October 2013 with the integral urban – rural model

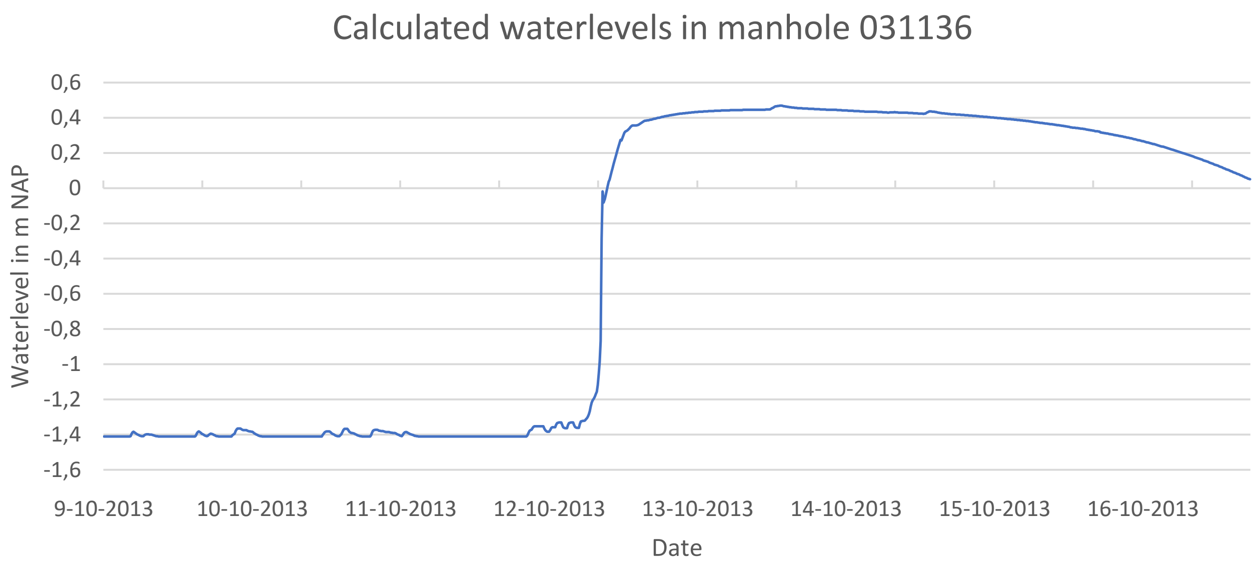


Figure 28: The calculated water level in meters of manhole 031044 during the event of October 2013 with the integral urban – rural model

If we then look at a node in the surface water system, we see a similar picture in figure 29 as in figure 27. This means that there is an influence of the surface water in the sewer system. This is also the node that gave the aforementioned instability, due to the influence of the three-pump pumping station the instability has been removed.

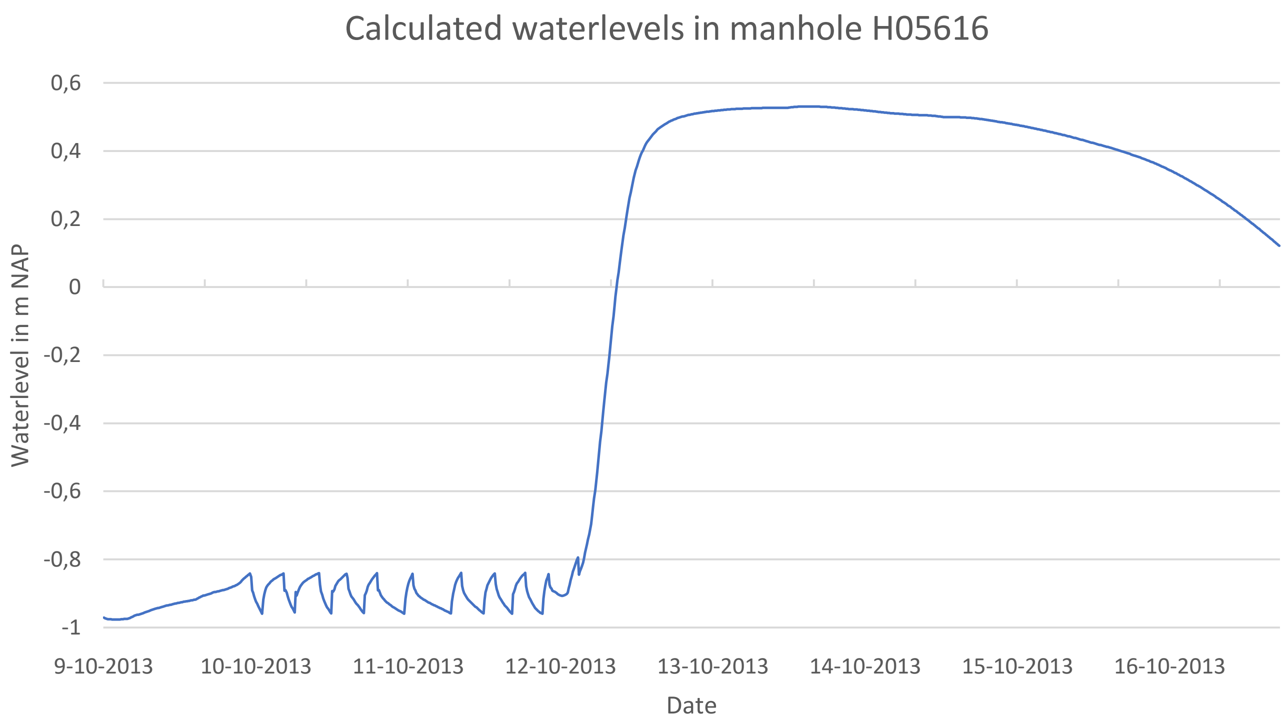


Figure 29: The calculated water level in meters of node H05616 during the event of October 2013 with the integral urban – rural model

It can therefore be stated that there is a difference between the calculated water levels with the urban model and the integral model, whereby the integral model not only better simulates the actual situation but also shows that the surface water affects the sewer system.

4.2 Optimizations of the water system

4.2.1 Calamity weirs

The Waterboard Hollandse Delta has put forward the idea of realizing two calamity weirs that can be used in the future to adequately retain excess water in the upstream areas. The proposed calamity weirs have been implemented in the integral sewage surface water model and the functionality has been analysed on the basis of the precipitation event of October 2013. It was investigated whether the calamity weirs have the desired effect, reducing water levels in the urban area and resulting in less flooding.

The overview figure 23 shows the difference in calculated water level in meters per manhole of the reference model and the model with the calamity weirs at 13 October 2013 10:00:00. The x and y axis show the x and y coordinates of the manholes, the legend shows the calculated difference in meters. If the model with the calamity weirs calculates a higher water level of 0.4 meters, the manholes will be red. If the reference model without the calamity weirs calculates a higher water level of 0.4 meters, the manholes will be green. As can be observed is that the calculated water level in the south of the urban area (61000,424500) has decreased to a minimal extent, less than 10 centimeters. Minimal difference can be seen in the other locations of the urban area, from which it can be concluded that the calamity weirs have little effect here.

Figure 30: The difference in the calculated maximum water level between the reference model and the model with calamity weirs at time step 13-10-2013 10:00:00

To analyse how long the water remains above ground level and what the waterdepth at these location is, two manholes from the Voorstraat (Appendix III) are plotted which can be found in figure 30 and 31. These figures show the calculated water level in m NAP of a manhole for the reference model without calamity weirs (orange) and with calamity weirs (blue). The dotted line shows the ground level. These figures show that the amount of water decreased to minimum value, which at manhole 31029 ensures that no water flows above ground level. The amount of water and duration above ground level for manhole 31136 is barely decreased.

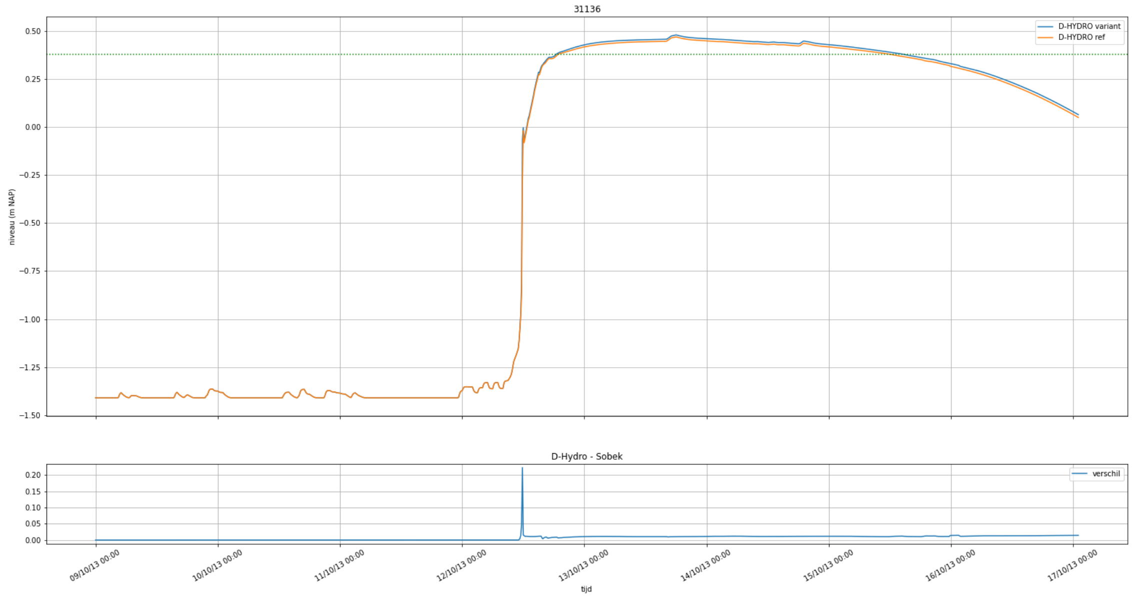


Figure 31: The water levels in m NAP for manhole 31136 calculated by the reference model and the model with calamity weirs during the precipitation event of October 2013

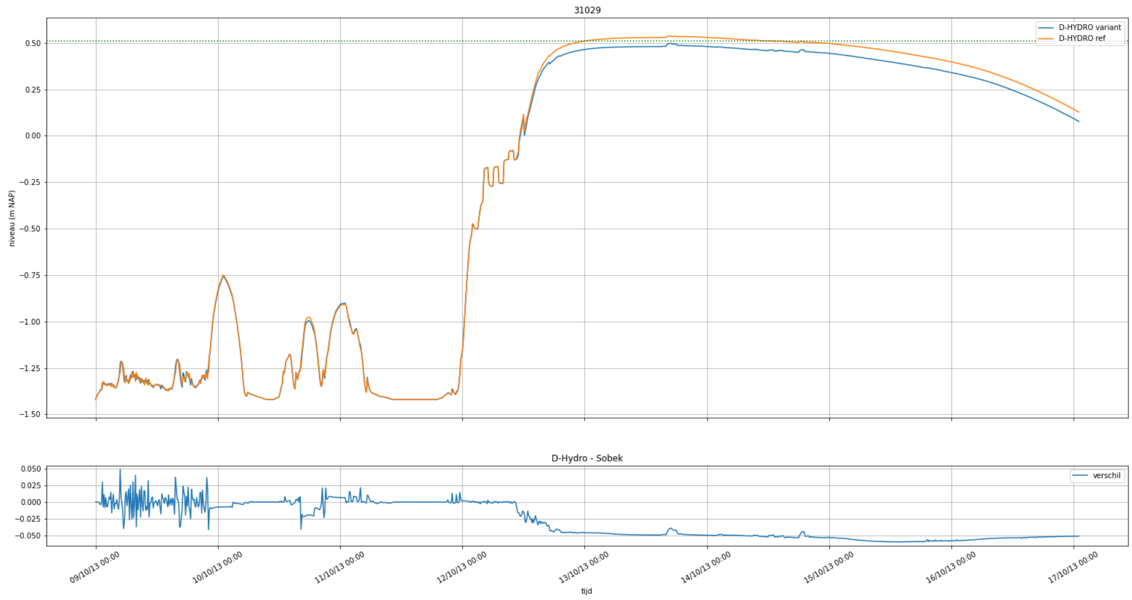


Figure 32: The water levels in m NAP for manhole 31029 calculated by the reference model and the model with calamity weirs during the precipitation event of October 2013

As an exploratory calculation, the crest levels of the weirs are raised 30 centimeters further. If the crest level increases, more water will be retained upstream so that less flows to the urban area of Stellendam. The 30 centimeters are in consultation with Waterfeit and only based on an exploratory calculation to analyse whether the design of the weirs should be further investigated. The same calculation has been executed as with the proposed calamity weirs, the result can be seen in figure 32. This figure shows the calculated water level in meters per manhole of the reference model and the model with the adjusted calamity weirs at 13 October 2013 10:00:00. As can be seen, a lower water level is calculated for the adjusted calamity weirs compared to the proposed calamity weirs.

Figure 33: The difference in the calculated maximum water level between the reference model and the model with adjusted calamity weirs at time step 13-10-2013 10:00:00

To analyse how long the water remains above ground level and what the waterdepth at this location is, manhole 31029 from the Voorstraat is plotted which can be found in figure 33. As can be seen, the calculated water level is a lot less in comparison with the proposed calamity weirs of the Waterboard in figure 31. It can be concluded that the proposed calamity weirs of the Waterboard provide insufficient results and that it is advised to analyse whether the design needs to be adjusted.

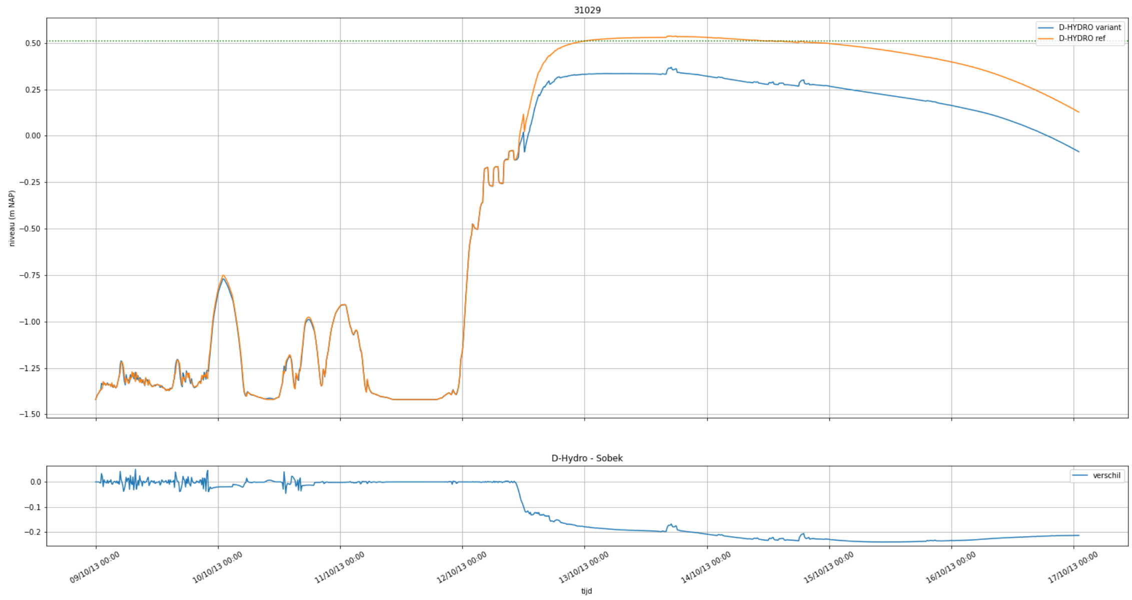


Figure 34: The water levels in m NAP for manhole 31029 calculated by the reference model and the model with the adjusted calamity weirs during the precipitation event of October 2013

4.2.2 Increase of pump capacity

The final pumping station of Stellendam, 12464GM which can be seen in Appendix IIII, which pumps out excess water from the surface water currently has a capacity of 10,320 m³ per hour converted 172 m³ per minute. This will be increased to 250 m³ per minute based on the advice of the Waterboard Hollandse Delta. It has been analysed whether the increase in pumping capacity of the final pumping station have the desired effect, reducing water levels in the urban area and resulting in less urban flooding.

Figure 34 shows the difference in calculated water level in meters per manhole of the reference model and the model with the calamity weirs at 13 October 2013 10:00:00. The x and y axis show the x and y coordinates of the manholes, the legend shows the calculated difference in meters. If the model with the adjusted pumping capacity calculates a higher water level of 0.4 meters, the manholes will be red. If the reference model without the adjusted pumping capacity calculates a higher water level of 0.4 meters, the manholes will be green. What can be observed from this figure is that with an adjusted pump capacity, approximately 20 centimeters less water is calculated in the urban area.

Figure 35: The difference in the calculated maximum water level between the reference model and the model with adjusted pumping capacity at time step 13-10-2013 10:00:00

In order to determine whether this affects the amount and duration of water above ground level in the urban area, two manholes are plotted from the Voorstraat which can be seen in figure 35 and 36 (Appendix III). To repeat, these manholes are plotted because it has been indicated from the municipality that urban flooding is experienced at this location with such amount of precipitation. These figures show the calculated water level in m NAP of a manhole for the reference model without adjusted pumping capacity (orange) and with adjusted pumping capacity (blue). The dotted line visualises the ground level. From both figures it can be perceieved that the reference model calculates about two days of water above ground level. In figure 36 there is about 20 centimeters of water above ground level, in figure 35 this is about 5 centimeters. In both figures it is visualised that the model in which the pump capacity is adjusted, there is no longer any water above ground level calculated. These figures additionally show that the calculated water level in the manholes decrease considerably faster due to the increased pumping capacity.

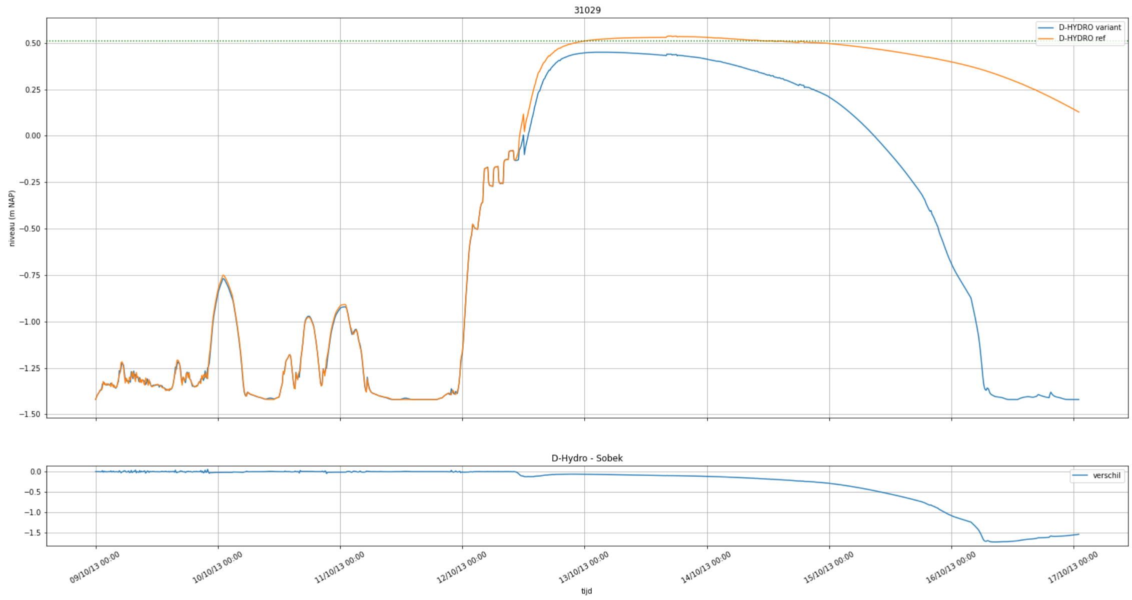


Figure 36: The water levels in m NAP for manhole 31029 calculated by the reference model and the model with the adjusted pumping capacity during the precipitation event of October 2013

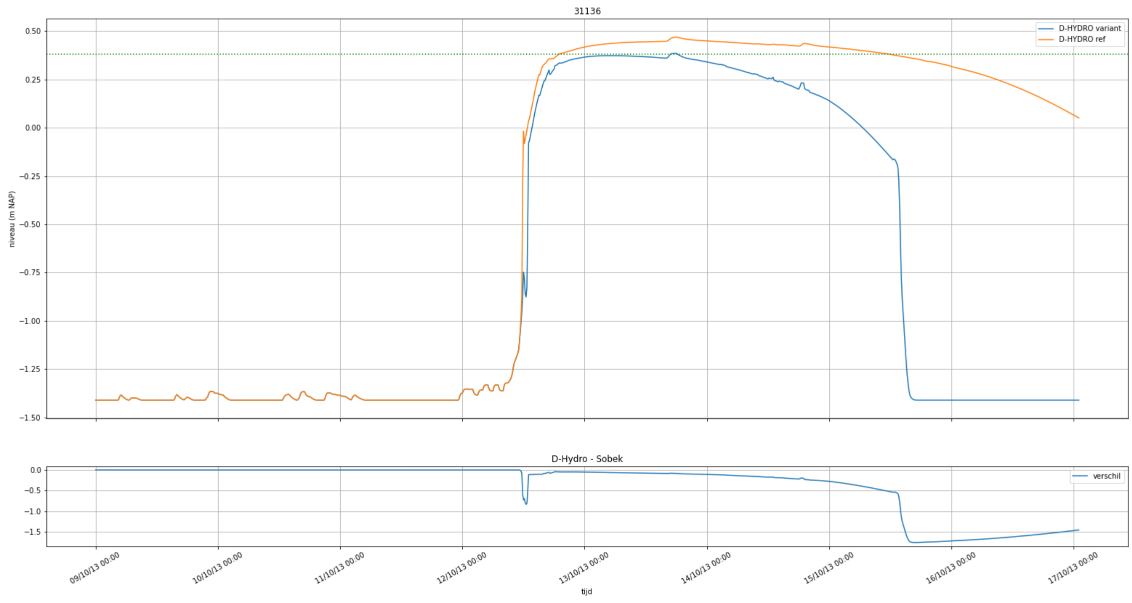


Figure 37: The water levels in m NAP for manhole 31136 calculated by the reference model and the model with the adjusted pumping capacity during the precipitation event of October 2013

4.2.3 Retaining water upstream

The urban area of Stellendam is located downstream, allowing the surface water to flow naturally to this location which causes urban flooding in times of heavy precipitation. An exploratory calculation is made to analyse whether water storage upstream results in lower water levels in the urban area of Stellendam. This has been simulated by adjusting the crest width of the 28 weirs in the surface water system to 10% of the original width to create more backwater upstream, so that less water flows towards the Stellendam core. The result of this calculation can be found in figure 38, which shows the difference in calculated water level in meters per manhole of the reference model and the model with the adjusted weirs at 13 October 2013 10:00:00.

Figure 38: The difference in the calculated maximum water level between the reference model and the model with adjusted weirs at time step 13-10-2013 10:00:00

The x and y axis show the x and y coordinates of the manholes, the legend shows the calculated difference in meters. If the model with the adjusted weirs calculates a higher water level of 0.4 meters, the manholes will be red. If the reference model without the adjusted weirs calculates a higher water level of 0.4 meters, the manholes will be green. What can be observed from this figure is that when creating more storage upstream, approximately 15 centimeters less water is calculated in the urban area of Stellendam. The red and orange nodes in the surface water system visualize a higher calculated water level due to the influence of the adjusted weirs, which is a explainable and desirable outcome. This is because the water is retained more at these locations, causing the water level to rise here but resulting in lower water levels at the urban area of Stellendam.

In order to determine whether this affects the amount and duration of water above ground level in the urban area, two manholes are plotted from the Voorstraat which can be seen in figure 39 and 40.

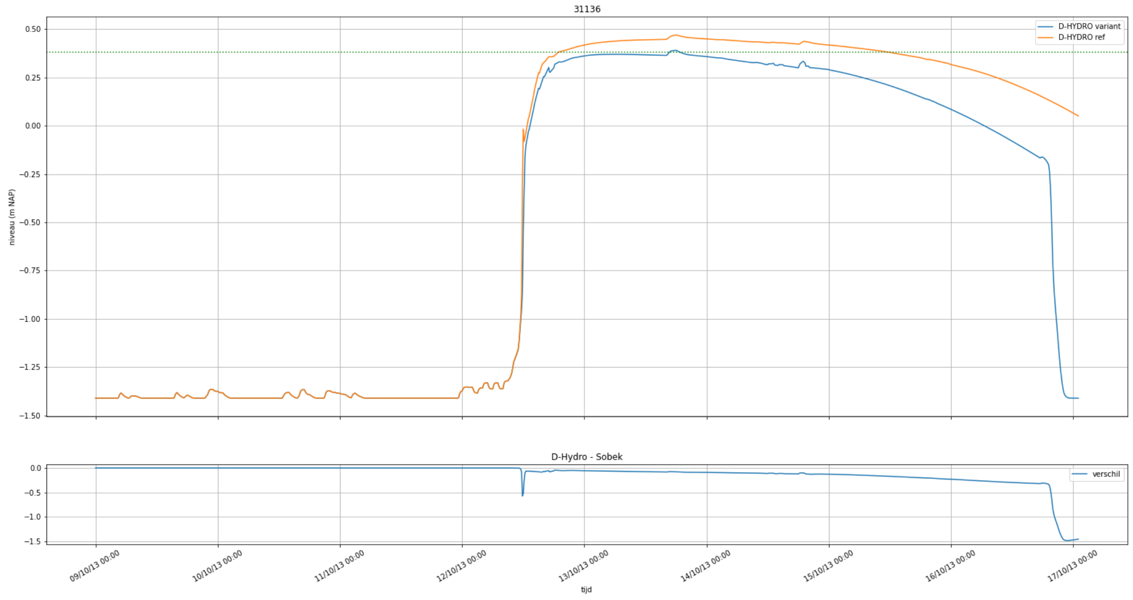


Figure 39: The water levels in m NAP for manhole 31136 calculated by the reference model and the model with the adjusted weirs during the precipitation event of October 2013

Figure 39 shows the calculated water level in m NAP of manhole 31136 for the reference model without adjusted weirs (orange) and with adjusted weirs (blue). The dotted line visualises the ground level. From this figure it can be perceieved that the reference model calculates approximately 20 centimeters for about two days of water above ground level. This figure visualises that the model in which the weirs are adjusted, there is no longer any water above ground level calculated. Additionally to this, the calculated water level in the manholes drops considerably faster with the model with the adjusted weirs in comparison to the reference model.

Figure 40 gives approximately the same desired result as figure 39: less water is calculated in the model with the adjusted weirs, so that the amount of water above ground level (in this case 5 centimeters) decreases to no water above ground level. Also, the duration of the high water levels in the sewer system is significantly reduced due to the model optimization by retaining more water upstream.

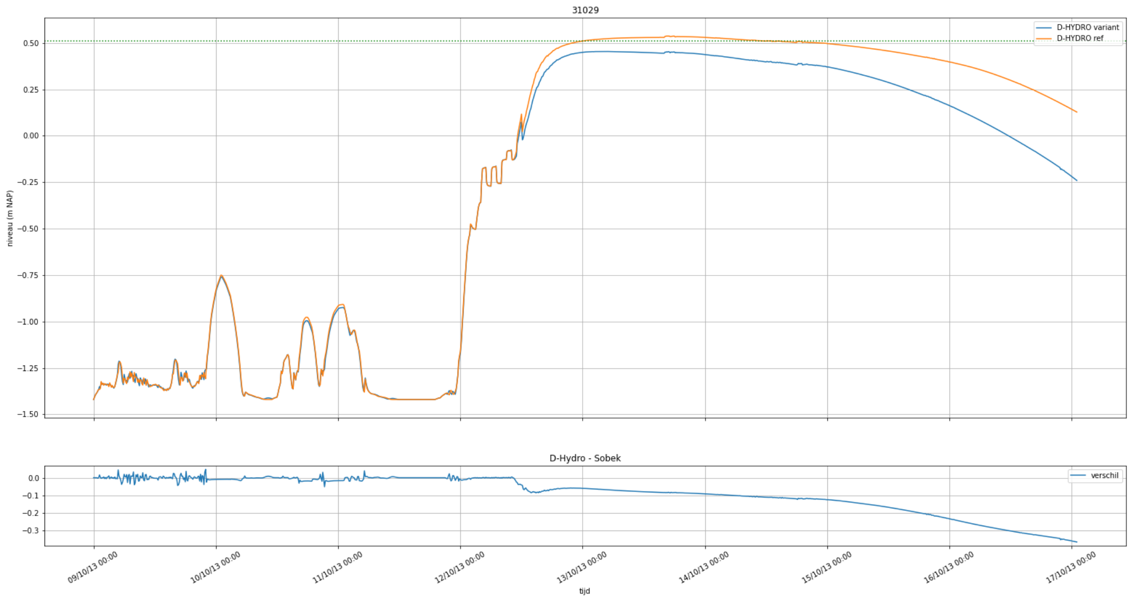


Figure 40: The water levels in m NAP for manhole 31029 calculated by the reference model and the model with the adjusted weirs during the precipitation event of October 2013

In order to confirm this assumption that the water level upstream of the surface water system will be higher due to the adjusted weirs, a node located upstream of the surface water system has been plotted in figure 41.

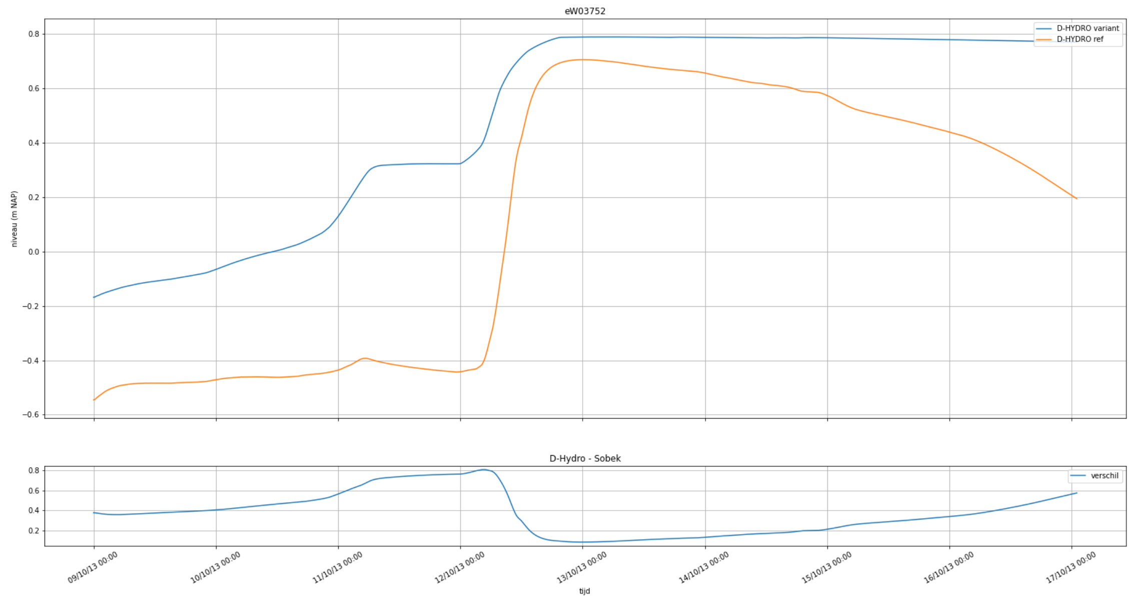


Figure 41: The water levels in m NAP for node eW03752 calculated by the reference model and the model with the adjusted weirs during the precipitation event of October 2013

In this figure, the blue line is above the orange line which indicates that the model with the adjusted weirs indeed ensures that more water is retained upstream compared to the results without adjusted weirs.

4.2.4 Flap valves

To prevent water from the surface system from flowing back into the sewer system causing it to become overloaded and overflowing, 12 check valves in the sewer system have been implemented in the integral urban surface water model. Subsequently, the event of 13 October was calculated and it was analysed whether the amount of locations and duration of water above ground level has decreased. The overview graph 42 shows the difference in calculated water level in meters per manhole of the reference model and the model with the flap valves at 13 October 2013 10:00:00. The x and y axis show the x and y coordinates of the manholes, the legend shows the calculated difference in meters. If the model with the flap valves calculates a higher water level of 0.4 meters, the manholes will be red. If the reference model without the flap valves calculates a higher water level of 0.4 meters, the manholes will be green. As can be clearly seen in the overview graph, the calculated water level in the urban area of Stellendam with the flap valves is a lot lower, which is the desired result. The points coloured red in the graph are nodes of the surface water. It is to be expected and realistic that a higher water level is calculated here because less water flows into the sewer and therefore remains in the surface water.

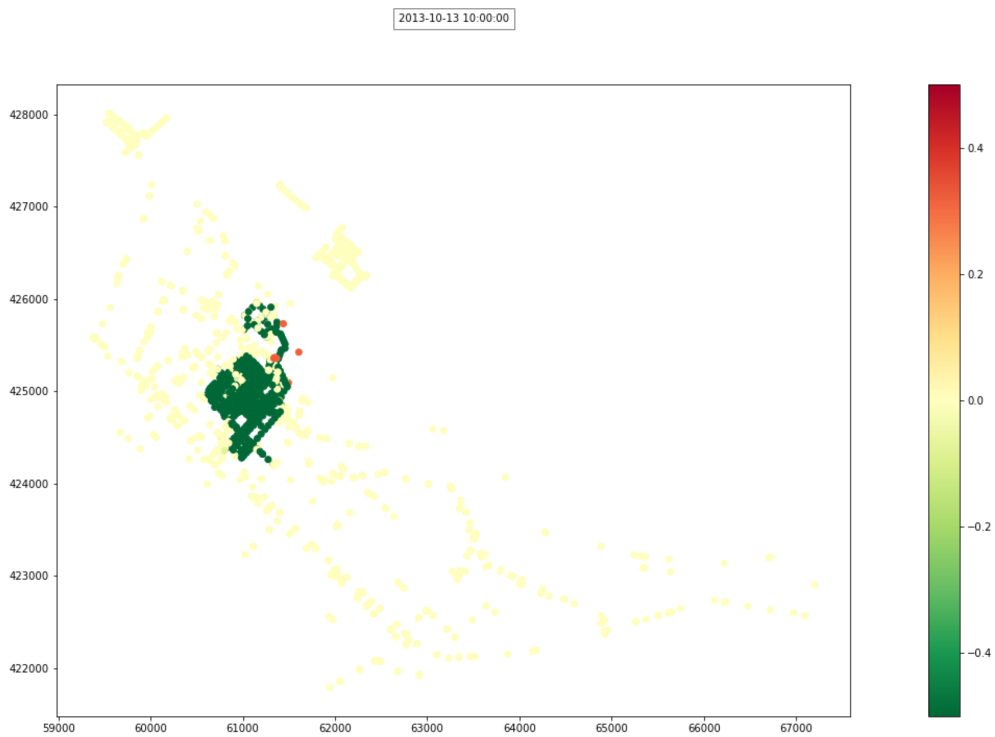


Figure 42: The difference in the calculated maximum water level between the reference model and the model with flap valves at time step 13-10-2013 10:00:00

To analyse how long the water remains above ground level and what the waterdepth at these location is, two manholes from the Voorstraat are plotted which can be found in 44 and 45. These figures show the calculated water level in m NAP of a manhole for the reference model without flap valves (orange) and with flap valves (blue). The dotted line shows the ground level. These figures show that the amount of water has decreased to such an extent that no water comes above ground level. It can also be seen that the water level drops very quickly, in contrast to the reference model without flap valves where the water remains on the street for about two days.

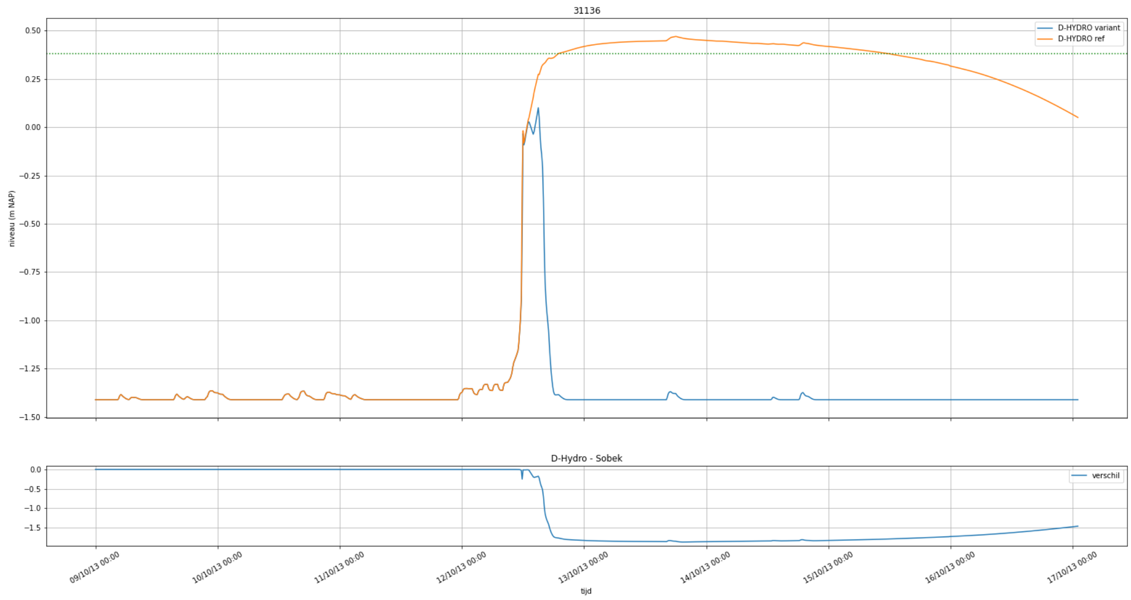


Figure 43: The water levels in m NAP for manhole 31136 calculated by the reference model and the model with flap valves during the precipitation event of October 2013

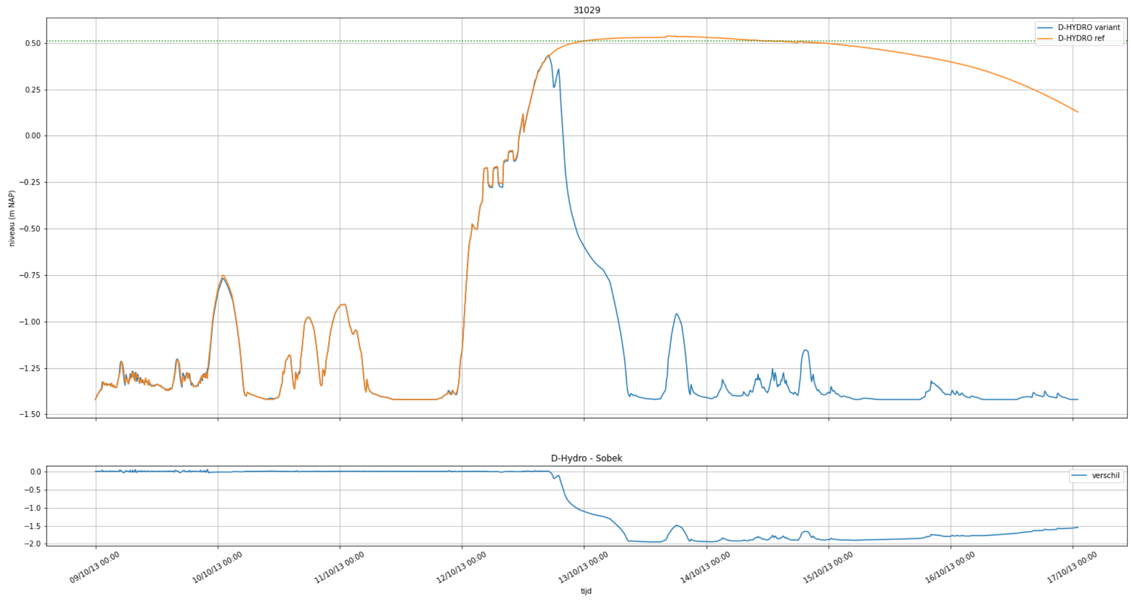


Figure 44: The water levels in m NAP for manhole 31029 calculated by the reference model and the model with Flap valves during the precipitation event of October 2013

To make an estimation of the costs when this optimization is implemented as a measure, information was requested from the municipality of Goeree-Overflakkee. It has been suggested to assume an average price of €3,500 excluding BTW per sewage check valve. It is advised to realize a total of 12 check valves, which corresponds to a total price of €42,000. The construction will be a day's work for 2 mechanics (16 hours x € 75) = €1,200. The delivery costs including accessories and associated mounting materials are estimated at around €2,300, bringing the total costs to an amount of €45,500. When choosing stainless steel fasteners and HDPE valves, maintenance costs are minimal. It is estimated that these need to be renewed approximately after 30 years.

Chapter 5 – **Discussion**

This research has contributed to reducing urban flooding in Stellendam during a severe precipitation event, using a simulation of October 2013. A large part is devoted to making hydraulic models to simulate this event and to test measures. However, the reliability of a model study can always be a point of discussion because the real situation can never be hundred percent correctly simulated. However, the use of a hydraulic model when analyzing a precipitation event certainly has added value compared to carrying out literature research alone.

Another point of discussion of this research is the program with which the simulations are made: D-HYDRO. During this research, the program is still under construction and this research therefore contributes to the development of D-HYDRO. However, any instabilities or limitations of the program must be taken into account because a Beta version has been used.

The next point of discussion is the fact that the precipitation data of the relevant October precipitation event has been made available in a time step of one hour. This is sufficient for calculating surface water systems, a higher resolution is desirable for the sewage system. Because the calculations are based on a resolution of one hour, high precipitation intensities within this hour are not known and the amount of flooding from sewers is underestimated. However, this resolution is sufficient for the interaction between sewerage system and surface water.

Additionally, the time in which this research takes place is a minor point of discussion. This has reduced the time available for model validation, such as the instability of the Stellendam pumping station. The reliability of the results has been validated by adding a three-pump pumping station, which has eliminated the instability but the root cause has not been identified.

Finally, this research focuses mainly on an extreme precipitation event similar to October 2013, in which research has shown that this caused urban flooding in Stellendam. However, it is an event where research has shown that it is a T = 200 event and compared to the strictest standard of 1/100 per year the repetition time of this event for Goeree-Overflakkee is therefore more than a factor of 10 smaller than this strictest standard. It is therefore a point of discussion whether the water system should be designed for this, or whether flooding is accepted during such an event, although it is desirable that the nuisance for residents is of course as little as possible.

Chapter 6 – **Conclusion**

October 13 2013 is a day that the residents of Stellendam will not soon forget. There was so much rainfall in a short period of time through which the water flowed into the basements of homes and stores. This research contributes to the prevention of such situations by testing optimizations of the water system that greatly reduce the amount of locations and duration of water located in the streets. During this research, the following main question was leading: *what is the influence of calamity weirs and what optimizations are recommended in the system in order to limit the locations where water flows above ground level and the duration of water above ground level causing urban flooding in the area of Stellendam, during a similar event of October 2013?*

This research also provides clarity about the cause of such urban flooding: the inundation from the surface water and the backflow through the pipes. This has already been a suspicion of the municipality of Goeree-Overflakkee and the Waterboard Hollandse Delta but it has never been confirmed because the use of integrated models is a new concept. The same applies to the operation of the proposed calamity weirs: the concept was on the table, but there is no model in which the surface water and sewage system are linked so that the operation of the weirs can be tested. Until now: thanks to this research, there is an urban and surface water system model available to calculate optimizations in the water system and convert them into implementable measures. Additionally due to this research, installing flap valves is a good solution to prevent surface water from flowing back into the sewage system. Furthermore, the functionality of the proposed calamity weirs has been calculated which has shown that they do not sufficiently help to prevent flooding in the urban area of Stellendam. By adjusting the setpoints of the weirs, less water flows to the urban area of Stellendam but not yet enough to decrease the amount of water above ground level to reduce urban flooding. It is therefore advised to reconsider the design of the calamity weirs. It was also researched whether the current water system can be optimized by retaining more water upstream. The conclusion is that this can help reduce flooding in the urban area of Stellendam, and it is recommended that a follow-up study be conducted into the possibilities of redesigning the proposed weirs so that less water is admitted downstream. Finally, increasing the pump capacity at the pumping station of the surface water system is a possibility for optimization whereby less water ends up on the street and the duration of the water on the street is greatly reduced.

Also, during this research the added value of setting up an integral urban and surface water model in comparison with a model in which only the sewer system is modelled has been analysed. The results clearly show that the integral model generates the most realistic outcomes and can therefore be defined as the most reliable. This indicates that integrated water management has added value for the optimization of the surface water and sewage system. The two systems should no longer be approached independently of each other, but as one water system. This also stimulates more cooperation between municipalities, water boards and consultancy agencies.

Finally, this research contributed to the development of D-HYDRO and analysed the reliability of the results calculated by comparing them with a well-known and used reference program: SOBEK2. The results show that the calculations between D-HYDRO and SOBEK2 show minimal deviations, which is explainable because SOBEK2 is throughout the years optimized through multiple users. However, these deviations are so small that the conclusion is that D-HYDRO can be used to generate reliable results.

Chapter 7 – **Recommendations**

This study only simulates 1D calculation results and the link with ground level is not included. This trade-off was made because calculating the measures takes a lot of time, and with 2D ground level this will increase even further. Additionally, the results in this research can be obtained with using only 1D calculations to test possible optimalizations of the water system and to analyse whether the locations and duration of water above ground level are decreasing. Finally, the D-HYDRO program is still under development and this trade-off minimizes unexpected delays in research. For a follow-up study, it is recommended to also generate 1D / 2D results to analyse where the water that ends up on ground level flows to. To be more specific, generating 1D / 2D results on the locations where the flap valves have been implemented is a recommendation for further research. In this way it can be analysed whether water still flows into the manholes via ground level and the functioning of the valves is therefore reduced. It is also advisable to perform a calculation with a different precipitation event to analyse the effectivity of the flap valves during an amount of precipitation that occurs more often. Additionally, 1D / 2D calculations also provide a better picture of the inundation from surface water.

Another recommendation is to optimize the water system by retaining more water upstream. This will have an effect on reducing flooding in the urban area of Stellendam, but will probably cause more flooding in the countryside. The advice is therefore a follow-up study in which it can be investigated in which places water can be efficiently retained upstream without this affecting the agriculture in the area. It is also recommended that a follow-up study be conducted into the possibilities of redesigning the proposed weirs so that less water is admitted downstream.

Furthermore, this research focuses mainly on an extreme precipitation event similar to October 2013, in which research has shown that this caused urban flooding in Stellendam. It is also recommended to analyse the added value of an integral model for other precipitation amounts.

The final recommendation is to additionally research other options for further optimalization of the water system, such as storing water upstream in the polder. The water is then first stored before it is naturally discharged in smaller amounts downstream to the urban area. Because in the polder mainly agricultural land is available, an analysis must first be carried out in order to determine whether water storage upstream is possible and at which locations water can be efficiently stored.

Chapter 8 - **References**

Advies, R. W. (2018). *Stresstest Goeree-Overflakkee.* 16: Oktober.

Advies, R. W. (2018). *Stresstest Goeree-Overflakkee.*

de Bruijn, K., Slager, K., Piek, R., Riedstra, D., & Slomp, R. (2018). *Leidraad voor het maken van overstromingssimulaties.* Deltares.

De Graaf, R., van de Giesen, N., & van de Ven, F. (2007). *Alternative water management options to reduce vulnerability for climate change in the Netherlands.* Springer. Opgehaald van file:///C:/Users/Danielle/AppData/Local/Packages/microsoft.windowscommunicationsapps_8wekyb3d8bbwe/LocalState/Files/S0/2196/Attachments/Graaf2007_Article_AlternativeWaterManagementOpti[7529].pdf

Deltares. (2015). *D-HYDRO Suite.*

Flakkee Nieuws. (sd). *Grote overlast door noodweer op Goeree-Overflakkee*. Opgehaald van Flakkeenieuws.nl: https://flakkeenieuws.nl/nieuws/grote-overlast-door-noodweer-op-goeree-overflakkee/6257

Framing the Challenge of Urban Flooding in the United States. (2019). In E. a. National Academies of Sciences, *Framing the Challenge of Urban Flooding in the United States.* Washington DC: National Academies Press.

Kennisportaal Klimaatadaptatie. (sd). *Klimaatadaptatienederland.nl*. Opgehaald van Klimaatscenario's: https://klimaatadaptatienederland.nl/hulpmiddelen/overzicht/klimaatscenario/

Klimaatinfo. (sd). *Het klimaat in Nederland*. Opgehaald van Klimaatinfo.nl: https://klimaatinfo.nl/klimaat/nederland/

KNMI. (2013, November 1). *Oktober 2013*. Opgehaald van KNMI.nl: https://www.knmi.nl/nederland-nu/klimatologie/maand-en-seizoensoverzichten/2013/oktober

KNMI. (sd). *Oktober 2013*. Opgehaald van KNMI.nl: https://www.knmi.nl/nederland-nu/klimatologie/maand-en-seizoensoverzichten/2013/oktober#:~:text=Oktober%202013%20was%20een%20natte,en%20met%20zondag%2013%20oktober.

KNMI. (sd). *Uitleg over extreme neerslag* . Opgehaald van KNMI.nl: https://www.knmi.nl/kennis-en-datacentrum/uitleg/extreme-neerslag

M.L.Bakker. (2014). *Evaluatierapport Wateroverlast Oktober 2013.* Waterschap Hollandse Delta.

Milieucentraal. (sd). *Wat is klimaatverandering?* . Opgehaald van Mileucentraal.nl: https://www.milieucentraal.nl/klimaat-en-aarde/klimaatverandering/wat-is-klimaatverandering/#:~:text=Ook%20in%20Nederland%20wordt%20het,water%20niet%20meer%20goed%20afvoeren.

Nu.nl. (2013, Oktober 13). *Veel overlast door aanhoudende regen*. Opgehaald van Nu.nl: https://www.nu.nl/binnenland/3600587/veel-overlast-aanhoudende-regen.html

Provincie Zuid-Holland. (sd). *Klimaat*. Opgehaald van zuid-holland.nl: https://www.zuid-holland.nl/onderwerpen/klimaat/

Rijksoverheid. (sd). *Klimaatverandering*. Opgehaald van Rijksoverheid.nl: https://www.rijksoverheid.nl/onderwerpen/klimaatverandering

Rijkswaterstaat. (sd). *Dammen, sluizen en stuwen*. Opgehaald van Rijkswaterstaat.nl: https://www.rijkswaterstaat.nl/water/waterbeheer/bescherming-tegen-het-water/waterkeringen/dammen-sluizen-en-stuwen.aspx

Rijnmond. (2013, Oktober 13). *Hoosbuien teisteren Goeree-Overflakkee*. Opgehaald van Rijnmond.nl: https://www.rijnmond.nl/nieuws/107897/Hoosbuien-teisteren-Goeree-Overflakkee

Schellart, M. (2013, Oktober 26). *Schade Delta loopt in miljoenen*. Opgehaald van Nieuweoogst.nl: https://www.nieuweoogst.nl/nieuws/2013/10/26/schade-in-delta-loopt-in-miljoenen

Stichting RIONED. (2019, November 1). *Modelleren hydraulisch functioneren*. Opgehaald van Riool.net: https://www.riool.net/modelleren-hydraulisch-functioneren

Stichting RIONED. (2019, November 1). *Numerieke benadering van de stromingsvergelijkingen*. Opgehaald van riool.net: https://www.riool.net/numerieke-benadering-van-de-stromingsvergelijkingen

Stichting RIONED. (2019, November 1). *Stap II. Modelconcept selecteren*. Opgehaald van riool.net: https://www.riool.net/stap-ii.-modelconcept-selecteren

STOWA. (2019). *NEERSLAGSTATISTIEKEN EN REEKSEN VOOR HET WATERBEHEER 2019.*

TKI Deltatechnologie. (sd). *DEL106 – 11204353-001 D-HYDRO, Urban-Rural*. Opgehaald van https://www.tkideltatechnologie.nl/project/del106-11204353-001-d-hydro-urban-rural/

Trouw. (2013, Oktober 17). *Wateroverlast Zuid-Holland kost ruim miljoen*. Opgehaald van Trouw.nl: https://www.trouw.nl/nieuws/wateroverlast-zuid-holland-kost-ruim-miljoen~bd22cfb5/?referrer=https%3A%2F%2Fwww.google.nl%2F

Waterschap Noorderzijlvest. (sd). *Stuwen*. Opgehaald van Noorderzijlvest.nl: https://www.noorderzijlvest.nl/ons-werk/beheer-onderhoud/beheer-bouwwerken/stuwen/

Waterschap Rijn en IJssel. (2013, Juli 5). *Stuwen*. Opgehaald van wrij.nl: https://www.wrij.nl/thema/kennis-informatie/waterthema'-0/waterpeilbeheer/stuwen/

Wikipedia. (2016, November 25). *Calamiteit*. Opgehaald van Wikipedia: https://nl.wikipedia.org/wiki/Calamiteit

Wikipedia. (2020, Januari). *Terugslagventiel*. Opgehaald van Wikipedia: https://nl.wikipedia.org/wiki/Terugslagventiel

Appendix I - **Urban Network Stellendam**

Appendix II - **Memo Waterboard Hollandse Delta calamity weirs**

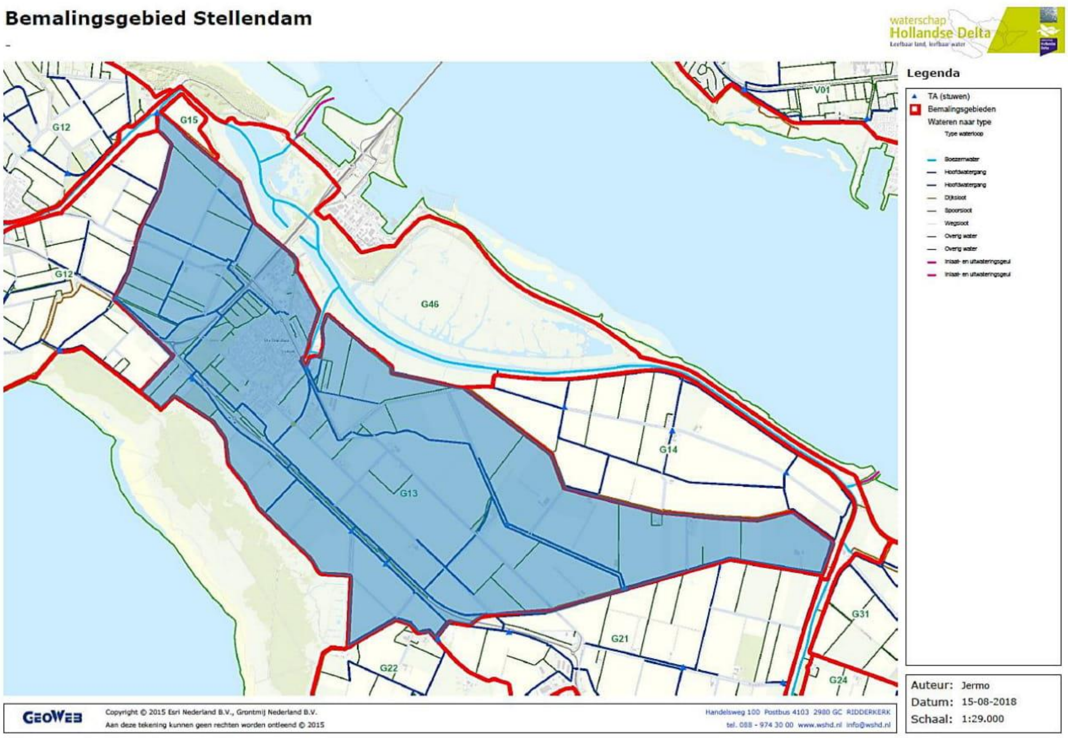
DATUM	16-08-2018	VAN	[redacted]
AAN	[redacted]	AFSCHRIFT AAN	[redacted]
BETREFT	Klepbreedte calamiteitenstuwen Stellendam		

waterschap Hollandse Delta

MEMO

1 Vraag

Gevraagd wordt naar de benodigde klepbreedte voor 2 nog te realiseren calamiteitenstuwen (45652ST en 45651ST). De stuwen kunnen in de toekomst worden ingezet om het overtollige water in de bovenstroomse gebieden adequaat vast te houden. De calamiteitenstuwen komen in bemalingsgebied G13 Stellendam (oppervlakte is 1437 [ha]). In figuur 1 is het bemalingsgebied G13 gearceerd in het blauw.



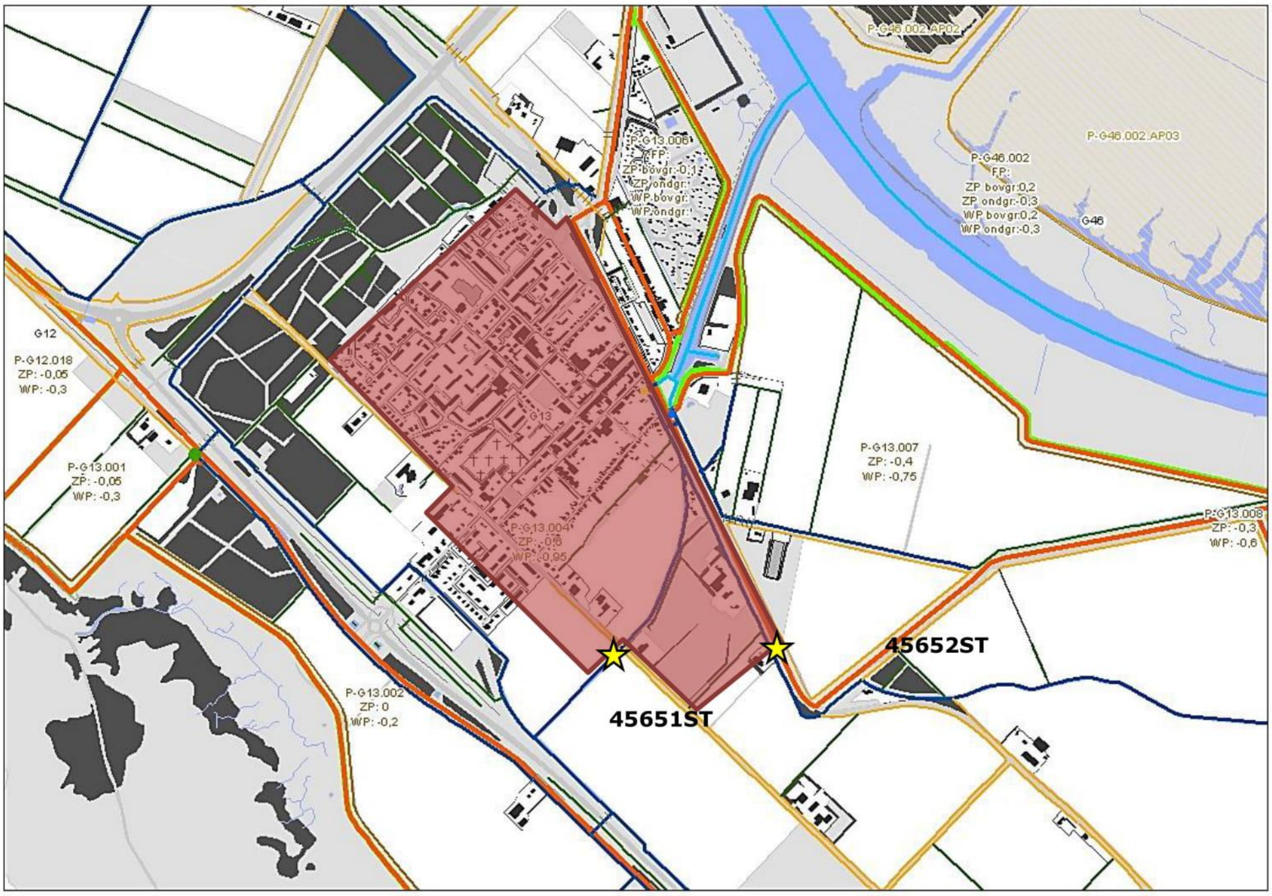
Figuur 1 - weergave afvoerend oppervlakte naar gemaal Stellendam.

2 Hydrologische gegevens

2.1 Locatie

Door het opzetten van de calamiteitenstuwen kan het overtollige water vanuit het landelijk deel van het peilgebied G13.004 worden vastgehouden tot het kritisch maaiveld <u>minus kritische straal.</u> Tegelijkertijd kan het water conform de ontwerp-afvoernorm naar het Stellendam afgevoerd worden.

Door de realisatie van de calamiteitenstuwen wordt tijdelijk (bij optrekken stuw) een peilscheiding gecreëerd. Deze stuwen scheiden, tezame met een nog aan te leggen zanddam, bij calamiteiten het peilgebied G13.004 in 2 delen. In figuur 2 is in het rood weergegeven welk deel van G13.004 gescheiden wordt van het overige peilgebied. In het rood gearceerde gebied bevindt zich het gemaal Stellendam (12464GM). De locatie van de stuwen is aangeduid m.b.v. de sterren. Het rode gebied doet niet mee in de afvoer via de stuwen. Dit gebied is ca. 10 [ha], wat insignificant is t.o.v. het overig gebied en daarom wordt dit gegeven verwaarloosd in deze analyse.



Figuur 2 - Aanduiding peilscheiding in G13.004 – tijdens calamiteiten. Zie bijlage 1 voor de precieze locatie van de stuwen.

2.2 Capaciteit calamiteitenstuwen

De capaciteit die de calamiteitenstuwen dienen te hebben, wordt gelijk gesteld aan de gemaalcapaciteit van Stellendam minus de capaciteit van 30189GM. In de nieuwe situatie wordt de capaciteit van gemaal Stellendam 172,4 [m³/min] → staat gelijk aan 2 [l/s/ha]. De capaciteit van 30189GM is niet bekend. Er wordt geschat dat deze 83 [ha] (peilgebied G13.007) * 1,5 [l/s/ha] → geeft 8 [m³/min]. De benodigde totaal capaciteit van de 2 calamiteitenstuwen is dan ca. 165 [m³/min] → 2,75 [m³/sec].

-

2.3 Verdeelsleutel

Via de twee hoofdwatergangen (H13660 en H32974) waarin de stuwen zijn gepland, wordt al het water vanaf bovenstrooms G13 afgevoerd naar gemaal Stellendam. Het natte oppervlakte van deze watergangen bij zomerpeil (hoger dan winterpraktijkpeil) wordt gebruikt om de verdeelsleutel voor de afvoersituatie voor de gebruiken. Dit is een arbitraire doch realistische aanname voor de waterstand tijdens calamiteit. Er is gekeken naar het dichtstbijzijnde ideomaprofiel en daarbij is uitgegaan van een schone watergang (geen bagger). Waterlijn is meegenomen om de ruimtelijke inpasbaarheid van de overstortbreedte mee te nemen.

- H13660 - Natte oppervlakte ≈ 4,5 [m²];
  Waterlijn ≈ 6 [m];
- H32974 - Natte oppervlakte is ≈ 11,5 [m²];
  Waterlijn ≈ 9 [m].

De verdeelsleutel o.b.v. het natte oppervlakte wordt 70 [%] over 45651ST (stuw Langeweg) en 30 [%] over 45652ST (stuw Eendrachtsdijk). Dit leidt tot een ontwerpdebiet van 1,92 [m³/sec] voor 45651ST en 0,83 [m³/sec] voor 45652ST.

3 Dimensies calamiteitenstuwen

Het kritisch maaiveld in G13.004 is +0,26 [m NAP]. Het is niet achterhaalbaar of dit het kritisch maaiveld is bovenstrooms van de calamiteitenstuwen.

Bij het bepalen van de overstortende straal is het beleid om uit te gaan van het laagst vigerend peil: in dit geval praktijkwinterpeil. Zie paragraaf 3.1.

3.1 Advies bij praktijkwinterpeil

De overstortende stralen van de stuwen mogen maximaal $^1/_4$ zijn van de benedenstroomse waterhoogte. Uitgaande van een schone watergang (geen bagger) en winterpeil geeft dit:

- H13660 - Waterhoogte 0,95 [m];
  - Maximale overstortende straal 0,24 [m] 45651ST;
- H32974 - Waterhoogte 0,65 [m];
  - Maximale overstortende straal 0,16 [m] 45652ST.

Op basis van de hierboven gestelde randvoorwaarden, wordt de volgende dimensionering verkregen:

<u>Stuw Langeweg - 45651ST</u>

	Eindresultaat & Aanbeveling:	Klepstand maximaal	0,02	(m NAP)
		Klepstand minimaal	-1,95	(m NAP)
		Verstelhoogte klepstand	1,97	(m)
		Overstortbreedte	8,73	(m)
		Overstortende straal	0,24	(m NAP)

<u>Stuw Eendrachtsdijk - 45652ST</u>

	Eindresultaat & Aanbeveling:	Klepstand maximaal	0,10	(m NAP)
		Klepstand minimaal	-1,60	(m NAP)
		Verstelhoogte klepstand	1,70	(m)
		Kruinbreedte	6,94	(m)
		Overstortende straal	0,16	(m NAP)

<u>Conclusie:</u> De dimensionering van de stuw Eendrachtsdijk is niet inpasbaar indien bij het bepalen van de overstortende straal rekening wordt gehouden met praktijkwinterpeil. Sleutelen aan de overdeelfactor is geen mogelijkheid. Wat wel een mogelijkheid is, is om niet uit te gaan van praktijkwinterpeil, maar van praktijkzomerpeil – zie paragraaf 3.2.

3.2 Advies bij praktijkzomerpeil

In deze situatie is het uitgangspunt dat er bij een calamiteit minimaal een peilstijging tot aan zomerpeil wordt gerealiseerd bij gemaal Stellendam. Dit betreft een peilstijging van 0,3

-

[m]. Deze peilstijging vindt plaats voor aanvang van het optrekken van de calamiteitenstuwen.

Praktijkzomerpeil is -0,60 [m NAP]. Hieruit volgt:

- H13660 - Waterhoogte 1,30 [m];
  - Maximale overstortende straal 0,32 [m] 45651ST;
- H32974 - Waterhoogte 1,00 [m];
  - Maximale overstortende straal 0,25 [m] 45652ST.

De resultaten bij deze randvoorwaarden zijn:

Stuw Langeweg - 45651ST

Eindresultaat & Aanbeveling:	Klepstand maximaal	-0,06	(m NAP)
	Klepstand minimaal	-1,95	(m NAP)
	Verstelhoogte klepstand	1,89	(m)
	Overstortbreedte	5,67	(m)
	Overstortende straal	0,32	(m NAP)

Stuw Eendrachtsdijk - 45652ST

Eindresultaat & Aanbeveling:	Klepstand maximaal	0,01	(m NAP)
	Klepstand minimaal	-1,60	(m NAP)
	Verstelhoogte klepstand	1,61	(m)
	Kruinbreedte	3,55	(m)
	Overstortende straal	0,25	(m NAP)

Conclusie: Bovenstaande dimensies zijn theoretisch inpasbaar.

3.3 Advies bij praktijkzomerpeil + versterking waterbodem

Indien benedenstrooms de waterbodem wordt versterkt, kan gekozen worden voor een nog grotere overstortende straal. Dit betreft een afwijking van algemeen beleid zoals gesteld in *'Nota toetsingskaders en beleidsregels voor het watersysteem 2014'*. De versterking van de waterbodem dient uitspoeling (cq. ongewenste morfologie) te voorkomen.

Hieronder zijn de resultaten opgenomen van een situatie waarbij de overstort breedte van de stuwen als volgt is bepaald:

- Stuw Langeweg 456521ST - Overstortbreedte van 3 [m];
- Stuw Eendrachtsdijk 456522ST - Overstortbreedte van 2 [m].

Stuw Langeweg - 45651ST

Eindresultaat & Aanbeveling:	Klepstand maximaal	-0,23	(m NAP)
	Klepstand minimaal	-1,95	(m NAP)
	Verstelhoogte klepstand	1,72	(m)
	Overstortbreedte	3,00	(m)
	Overstortende straal	0,49	(m NAP)

De hieruit voortkomende overstortende straal ≈40 [%] van de benedenstroomse waterdiepte (>0,25 [%]).

Stuw Eendrachtsdijk - 45652ST

Eindresultaat & Aanbeveling:	Klepstand maximaal	-0,11	(m NAP)
	Klepstand minimaal	-1,60	(m NAP)
	Verstelhoogte klepstand	1,49	(m)
	Kruinbreedte	2,00	(m)
	Overstortende straal	0,37	(m NAP)

De hieruit voortkomende overstortende straal ≈40 [%] van de benedenstroomse waterdiepte (>0,25 [%])

-

4 Conclusies

De volgende op- en aanmerkingen worden meegegeven op het plan om tijdens calamiteiten peilgebied G13.004 te scheiden in 2 aparte gebieden.

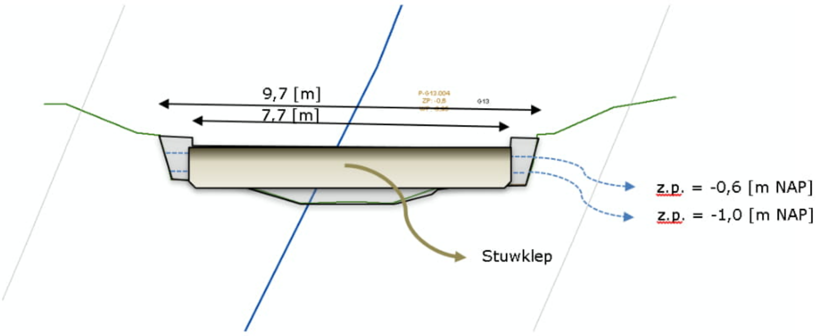
- **Onderhoud**
  - De calamiteitenstuwen liggen bij normaal bedrijf gestreken. Door morfologische en ecologische omstandigheden stapelt bagger en sediment zich op de gestreken calamiteitenschuiven. Het benodigde frequente onderhoud leidt tot hogere kosten. De werking van de calamiteitenschuiven is niet gegarandeerd, indien deze niet frequent worden onderhouden en getest.
- **Effectiviteit**
  - De effectiviteit van deze maatregel is hydrologisch niet in kaart gebracht. Het is niet gekwantificeerd welke opgave er behaalt dient te worden benedenstrooms van de calamiteiten stuwen en hoe de komst van deze calamiteitenstuwen invulling geeft aan het behalen van de opgave;
  - Het is tevens niet bepaald wat deze calamiteitenstuwen bovenstrooms teweeg brengen. Door water vast te houden in het systeem, vindt er mogelijk afwenteling plaats van wateroverlast bij gemaal Stellendam naar wateroverlast elders in het gebied.
- **Complexiteit**
  - De inpassing van deze calamiteitenschuiven, en overige systeemaanpassingen die benodigd zijn om het water bovenstrooms vast te houden, maken het waterbeheer (onnodig) complex(er). Vanuit de watersysteem toetsing 2011 is geen waterbergingsopgave in kaart gebracht. De vraag is dan ook of dit gecompliceerde plan nut en noodzaak heeft.
- **Afwijken beleid**
  - Om de stuwen ruimtelijk inpasbaar en financieel haalbaar te maken, is afwijking van het beleid nodig.

5 Advies

Op basis van de resultaten in hoofdstuk 3 en de hierboven opgesomde conclusies, kan een keuze worden voorgelegd aan de opdrachtgever over het verdere verloop van de geplande werkzaamheden.

-

5.1 Illustratie stuw Langeweg – 45651ST



Bijlage 1 – Geadviseerde ligging stuwen

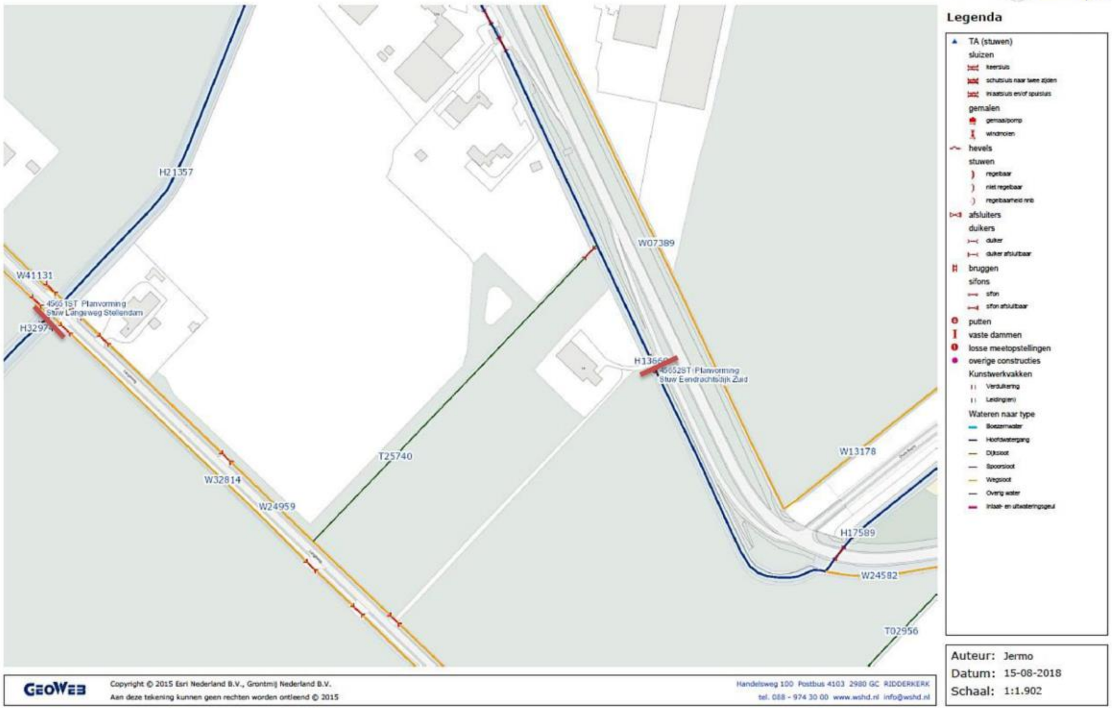
In figuur 3 is de huidige ligging van de geplande stuwen weergegeven met de rode streep.
Echter wordt de locatie bij de ster aanbevolen, om ervoor te zorgen dat de calamiteitenstuwen daadwerkelijk peil regulerend zijn.

Dit, omdat bij de oude locatie er nog een mogelijke waterroute is, namelijk via de overige watergangen T02965 naar W24959 en T25740. Voor het opstuwen effect is het niet erg dat de 2 calamiteitenstuwen niet daadwerkelijk een peilscheiding bewerkstelligen. Maar wat hydrologisch gezien absoluut niet gewenst is, is dat deze overige watergangen de hoofd-afvoerstromen worden. Door de kleine dimensionering van de watergang en duiker, worden hier ongewenst hoge stroomsnelheden voorzien.

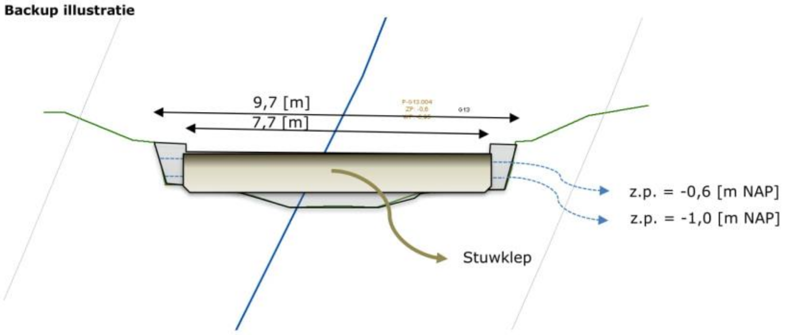
PAGINA 8 van 10

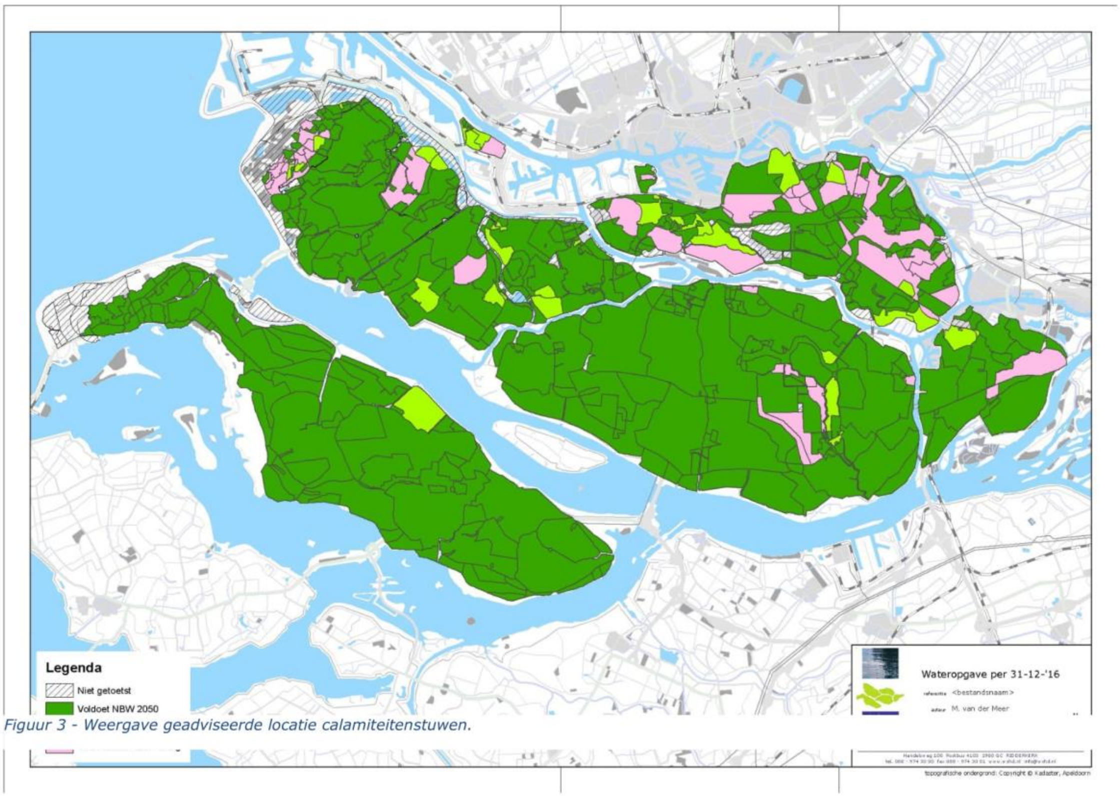
Initiele ligging stuwen

-



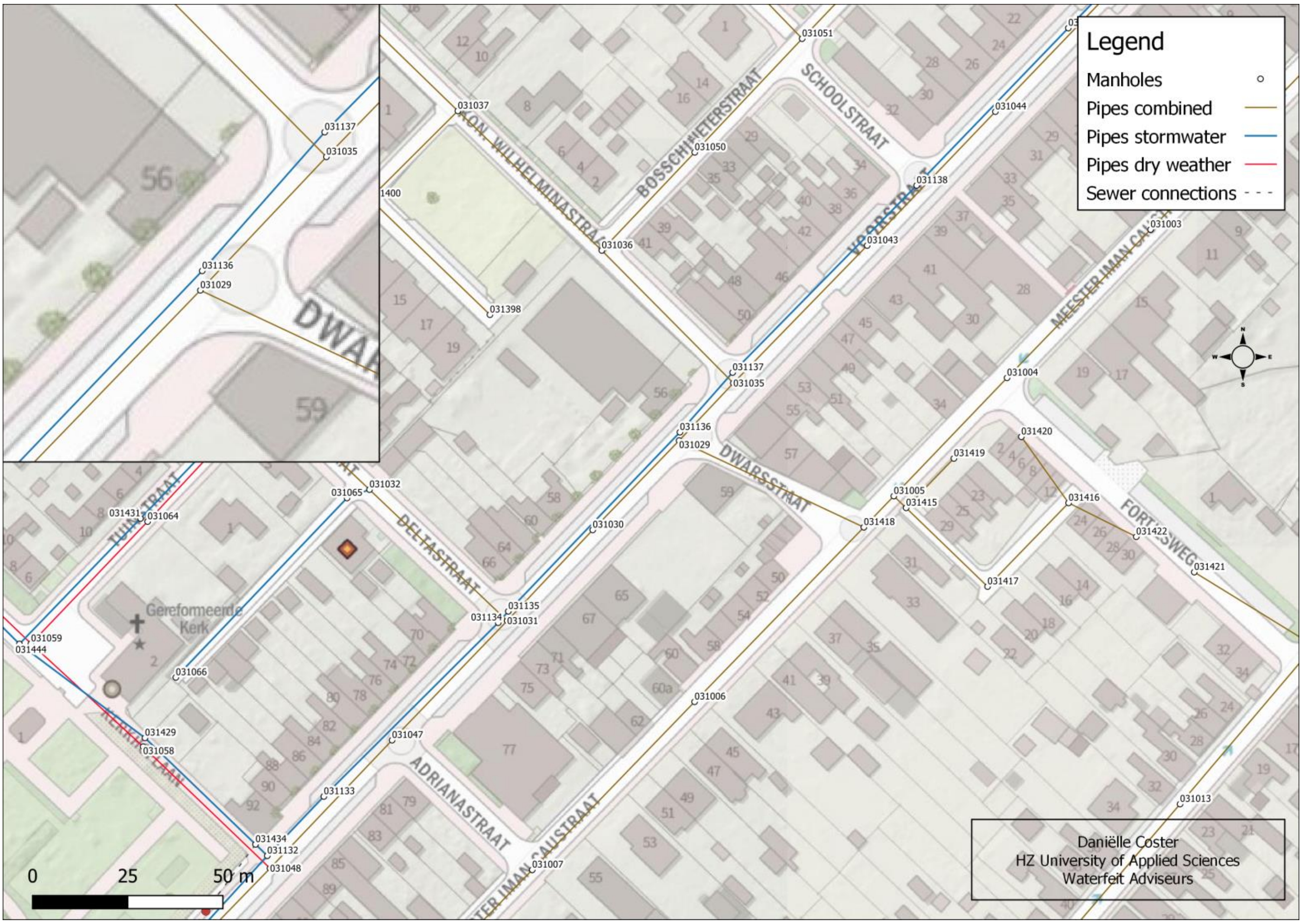
Backup illustratie



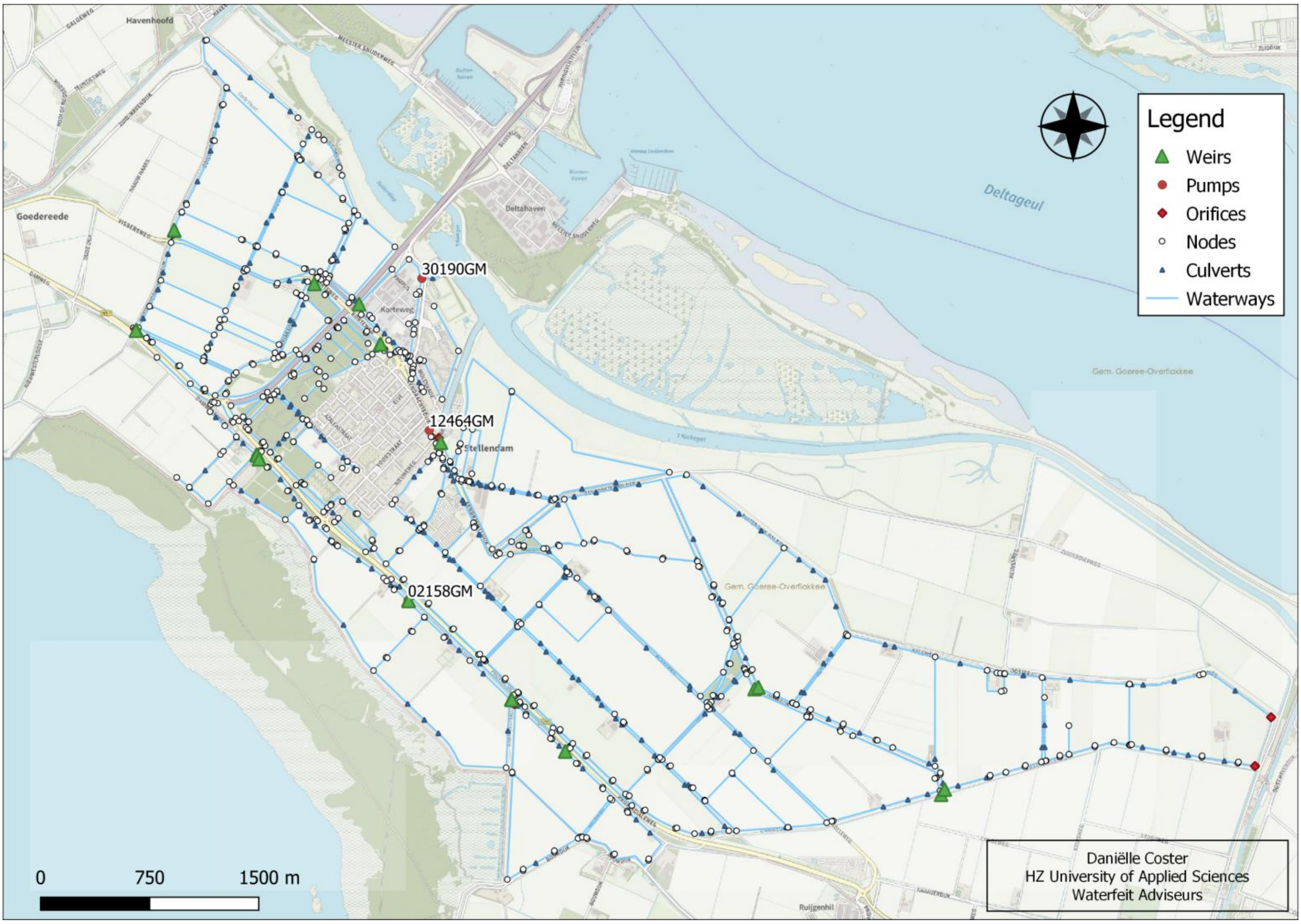


Figuur 3 - Weergave geadviseerde locatie calamiteitenstuwen.

Appendix III – **Manholes Voorstraat**



Appendix IIII - **Surface water system network**



Appendix V – **Waterdepth above ground level integral model 13 October 10:00:00**