Using Tygron to assess the extent of hindrance due to stormwater in Olst

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Witteveen + Bos

Preface

In front of you is the final report of my Bachelor Thesis, *"Using Tygron to assess the extent of hindrance due to stormwater in Olst".* This research was carried out within the "Stedelijk waterbeheer en Klimaatadaptatie" group of Witteveen+Bos in Utrecht. I hope that the outcome of my thesis will contribute to the answer where Tygron can be used within Witteveen+Bos.

I would like to express special thanks to my supervisor at Witteveen+Bos, Daniël van den Heuvel, for all his help and valuable feedback during my entire graduation period. With the, sometimes, critical questions Daniël helped with looking from different perspectives at Tygron. His experience in the hydrological world gave great insides into the plausibility of the (in between) results. I thank my internal supervisor at University of Twente, Maarten Krol, for the bi-weekly hour meetings. Maarten his time, flexibility in the ever-changing findings and also keeping me on track for the writing of the eventual report, were precious to me. Lastly, I want to thank the "Stedelijk waterbeheer en Klimaatadaptatie" group, they showed me what it is like to work in a consultancy and engineering firm and what it is to be part of a team which is working on all kinds of different projects. The weekly meetings, the chats during the lunch walks and the possibility to pop-by colleagues whenever I had a question, contributed to this research.

Lastly, I want to thank Witteveen+Bos for the opportunity for carrying out my Bachelor's Thesis in their organisation.

Hopefully, you will enjoy reading my thesis as much as I did investigating and write it.

Maarten Verboom
Enschede, July 7, 2022

Summary

This study looks at the predictive power of Tygron in assessing the extent of hindrance due to stormwater in villages in the Netherlands. This was done by carrying out a sensitivity analysis on different parameters. The results were used to construct a base model which was able to predict the extent of hindrance due to stormwater in Olst. These results were compared with validated results simulated via the software InfoWorks to assess the predictive power of Tygron.

Firstly, the schematization of Tygron was investigated. The schematization of the sewer system has some major simplifications. The largest is that water can enter the sewer system at a lower location than it can overflow. Also, the sewer system is schematized as a point-based construction, with this the sewer system in Tygron has no bottlenecks inside the network while this is often the case in reality. With the schematization known, a sensitivity analysis was carried out. The results of Tygron were checked if they were sensitive to the following parameters; the grid size, initial groundwater depth, pump capacity per sewer area, storage capacity of the sewer system, the capacity of the sewer overflow and the height of the sewer overflow. During the sensitivity analysis, it became clear that the results of Tygron are not sensitive for the grid size when set finer than 1x1m, and the initial groundwater depth. The results are sensitive to the other parameters, especially the overflow height combined with maximum overflow discharge for larger rain events. When the open water reaches the sewer overflow height, the overflow will stop discharging water. In reality, the pressure behind the overflow is important, this is not taken into account in the schematization of Tygron. Therefore, to have an overflow discharge, it is recommended to set the overflow height one meter above ground level.

Secondly, the water hindrance as simulated by Tygron was assessed. The water hindrance extent in Olst, according to Tygron simulations, is large for heavy rain events when looking at the average water level per street section. When comparing the maximum simulated water levels, almost every street experiences water hindrance. Even for the smallest simulated rain event in this research (Bui08) on 114 of the 117 streets, water hindrance occur.

Thirdly, a result comparison was done between the results obtained by Tygron and InfoWorks for three rain events. The parameters for the compared Tygron were set on values which were close to reality or adapt for the simplifications and schematization of the Tygron model. The overall performance between Tygron and InfoWorks is not well. There is much more water in Tygron compared with InfoWorks for all rain events. When taking a closer look at where the maxima water levels are simulated, similar results can be seen between Tygron and InfoWorks. When taking the highest 10% simulated water levels, 60% is simulated in the same location.

For assessing the extent of hindrance due to stormwater in Olst, Tygron is not considered to give the same water volumes as InfoWorks. However, Tygron simulates the maximum water levels in similar locations as InfoWorks. Tygron is therefore recommended to be used for quick scans, but not for detailed assessments of the extent of hindrance due to stormwater.

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1. Introduction

1.1 Background

Over the past decades, precipitation has increased in intensity due to climate change (Tabari, 2020). Next to that, cities across the Netherlands have expanded and thus, more pavement was introduced. Paved surfaces strongly increase the amount and speed of stormwater runoff. This makes cities more vulnerable to problems caused by more extensive rain events.

However, not only in cities increasing precipitation has caused hindrance but also in villages, the water hindrance due to stormwater can cause serious problems. In Olst (a village in the municipality Olst-Wijhe, Netherlands) on the 12th of July 2019, due to a heavy storm (circa 40 mm precipitation in total), multiple streets got flooded as can be seen in Figure 1. The storm that hit Olst was very local, in the rest of the province Overijssel the storm did not cause any significant hindrance (Hulman, 2019a). This example shows that heavy precipitation can have an impact on a very small area.

Figure 1: De Jan Hooglandstraat in Olst (Hulman, 2019b).

Cities and villages need to adapt to the possibility that there can occur a (local) heavy rain event that can cause hindrance due to stormwater. The municipality Olst-Wijhe requested a cost-benefit analysis for different measures to reduce the chance and impact of water hindrance in Olst. Therefore the municipality took the initiative to set up the masterplan rainwater for Olst. The master plan included also measures to prevent large damage due to water hindrance in the future (Witteveen+Bos, 2021).

1.2 Current state of the art

To assess the risks and to locate the problems that can arise from rain events, computerized hydrologic models are used. The model that was used to set the master plan of Olst was created in the software program InfoWorks ICM. This model is calibrated well for assessing hydraulic performance in a Dutch urban context. InfoWorks is a hydraulic model based on nodes and conduits, the manholes and sewer pipes in a sewer system. Water on the surface is simulated according to the shallow water equations (Innovyze, 2014).

In the past few years, more integrated approach-oriented models were developed. These integrated models can simulate a scenario with output on multiple disciplines. So instead of only being able to do a water hindrance analysis, the model can do a heat stress test or simulate how much nitrogen deposition there will be from implementing a certain measurement.

One example of such an integrated approach-oriented model is Tygron. This model promotes itself to be able to be deployed more widely.

1.3 Research gap

However, it is currently not known what the predictive power of Tygron is in water simulation compared with a single approach-oriented model such as InfoWorks. The predictive power of Tygron in water simulation is investigated in this research.

1.4 Research Objective

This study will mainly focus on the simulation of hindrance due to stormwater in villages. This will be done via investigating and modelling the hydrological model of a case study in Tygron after which it will be compared with obtained data via modelling in InfoWorks and obtained data via a questionnaire. Therefore the research objective of this study is:

"To evaluate the pros and cons of Tygron for assessing the hindrance due to stormwater compared with data established by modelling in InfoWorks ICM"

The pros and cons of Tygron are considered to be the possibilities that there are available in Tygron for modelling the hindrance of stormwater as well as finding the bottlenecks (streets/intersections) where water is collected.

Hindrance due to stormwater is considered to be, in terms of modelling, when there is at least 5 cm of water against a building. This is measured from the ground level of the property. In terms of measured data, hindrance due to stormwater is considered to be the opinion of the inhabitants. The 5 cm of water against a building is based on estimations in "WaterSchadeSchatter" (STOWA, 2015). Stormwater hindrance is not only causing direct damage to buildings but also indirect (financial) damage due to for example roads and/or rail tracks that cannot be used (Slager & Wagenaar, 2017). Also, indirect damage can occur due to the overflow of the sewer system, such as pollution of the surface water and unpleasant odour (André et al., 2020).

Data established by modelling in InfoWorks ICM is considered to be the data of two maps that were created in InfoWorks of all buildings in Olst that should have water hindrance after a 60 mm/h rain event and a so-called "Herwijnen-bui", which is a 94 mm rain event in 70 minutes. A large part of the research will be constructing the model and simulating at least these two rain events.

1.5 Research questions

To achieve the research objective, the main question was established. The main question of this research will be:

"*To what extent is Tygron capable of simulating stormwater hindrance in villages in the Netherlands?"*

To answer the main question, four different sub-questions were made. It is interesting to know whether certain parameters in Tygron have a significant influence on the model and its prediction as a whole. Parameters which are sensitive to the result should be chosen carefully, parameters less sensitive to the result may be left behind and further research may not be needed for low influencing parameters. Therefore the first sub-question is:

1. *"Which schematization parameterization choices are relevant for implementing an area in Tygron?"*

It will be checked in a sensitivity analysis whether certain parameters have a large influence on the outcomes of the model, this will be explained in the Method. The outcomes of this research q

As mentioned before, this research is about stormwater and the hindrance that can occur due to that. First, it is important to see what relevant output can be generated in Tygron. For this research, a case study will be carried out. The parameters tested in the sensitivity analysis were used to make an estimation for the parameters used in the case study. This case study will be carried out on Olst, a village in Olst-Wijhe, the Netherlands. This results in the following sub-question:

2. *"What is the extent of water hindrance in Olst in Tygron simulations?"*

With the created prediction of Tygron, the data can be compared with existing data. This was done in the following sub-question:

3. *"What are the differences in performance when simulating rain events in Tygron and InfoWorks?"*

2. Theoretical Framework

The theoretical framework consists of the Tygron water module, which is an implementation of a 2D grid-based shallow water model which is on its own based on the numerical approached 2D Saint Venant equations (Tygron, 2021e) (Horváth et al., 2014). Each calculation in the model relies on data, which has multiple sources and is relying on a different theory. In this section, attention will be given to parameters that are specific for the schematisation and parameterisation for water hindrance. Lastly, attention will be given to the approaches of model intercomparisons between the Tygron model with InfoWorks ICM.

2.1 2D grid calculations

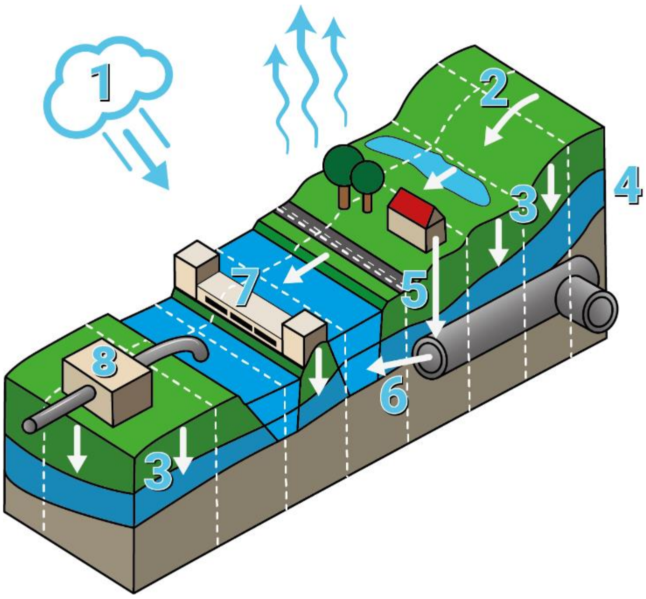
Tygron models are using a 2D grid for calculations where the 3D world is stored in. In Tygron, vector information, such as areas/real estate records/neighbourhoods, are first rasterized. After that, the model carries out the calculations based on the rasterized data (Tygron, 2021e).

The grid size consists of equally sized square cells with possible sizes per cell ranging from 0.25 m^2 to 100 m^2. Switching to a smaller grid size increases the accuracy but significantly affects the calculation time (Hessel, 2005). Reducing the cell size from 2 m^2 to 1 m^2 increases the calculation time by more than the square of change that you would expect (2/1 = 2 times higher resolution, 2^2 = 4 times longer calculation time). This is because next to the increasing number of cells, the time step for each calculation is shortened as well. The shortening is there since water is not allowed to skip a cell and therefore the timesteps are shortened to prevent this from happening.

2.2 Water flows in Tygron

In the water module of Tygron, the calculations are carried out in a closed bounded two-dimensional water system. Per simulation step (around 14 steps per second on 1 m^2 grid size) the slope, groundwater and current water level and these hydraulic relations/interactions between the different cells are important. Due to the boundary conditions of the model, some connections with the outer world need to be made. These connections are the sewer pump, which removes water from the system. And connections between the surface water inside and outside the simulated area. This is explained in the following section.

Tygron is built out of a lot of different sub-models as can be seen in Figure 2 there are multiple water flows streaming in a 2D grid.



1. Rainfall/Evaporation
2. Surface flow
3. Infiltration
4. Groundwater flow
5. Sewer inflow
6. Sewer overflow
7. Structure flow
8. Outflow (e.g. pumping)

Figure 2: Water flows in the Tygron model (Tygron, 2021e).

1. First, there is rainfall and evaporation. The model is capable of simulating a precipitation pattern, with a fluctuating precipitation rate. However, precipitation is a uniform spread rain event for the whole area the same. It cannot deviate as is happening in the real world. Important to notice is that there is no precipitation simulation on the two outer grid rings of the project area (Tygron, 2021d). To prevent the influence of this a large enough project area should be chosen. Water can also evaporate, in Tygron multiple periods of evaporation can be defined. Since we are only interested in the modelling of water hindrance during and right after the rain event, there is one evaporation rate which is depending on the presence of surface water, vegetation, elevation, groundwater and the water storage of plant roots (Tygron, 2021b). The plant roots can let the water evaporate out of the soil.
2. When the rainwater hits the surface it will flow to the lowest point. This is according to the shallow water model. The surface is based on the digital terrain model (AHN3), which follows the slope of the landscape. This model is combined with the digital surface model, which also includes the height of buildings (AHN, 2016). With the 2D Saint Venant equations, the eventual flow speed is determined by the surface conditions and the slope.
3. The water can infiltrate the groundwater in Tygron in two ways, infiltration from the surface to the unsaturated zone and infiltration from the unsaturated zone to the saturated zone. The boundary between these two layers is estimated at the groundwater level. The infiltration from surface water to the unsaturated zone is limited to the lowest infiltration speed which is a characteristic of the ground surface (Tygron, 2021a). Based on the surface elevation and the groundwater table, the water in the underground can also exfiltrate out of the ground back onto the surface.
4. The groundwater flow is determined by the level of the groundwater. The water will flow to the lowest point. The groundwater level is calculated per grid cell and influenced by the water storage capacity of the soil. The default initial groundwater prequel is estimated at one meter below the surface as standard value(Tygron, 2022a).
5. See Sewer system, Section 2.3.
6. See Sewer system, Section 2.3.

7. The structure flow is determined by the size of the overflows and their direction/orientation towards the surface water.
8. Water can leave the system via the pumps in the sewer, see Section 2.3, or via the construction type inlet. The inlet is the connection between the water inside the model and the world outside the model. This feature in the model can be used to simulate water leaving or entering the model via channels and creeks at the boundaries of the research area.

With all the water flows combined, the height of the water on the surface can be estimated.

2.3 Sewer system

The sewer system can consist of one or multiple sewer areas (see the yellow area in Figure 3). Each sewer area is connected to one overflow and has a certain storage. Since it is not possible to connect multiple sewer overflows to one sewer area, in the schematization either multiple overflows can be combined into one larger one or the sewer area should be split into smaller areas. The sewer is not simulated as pipes but as a bucket. The capacity of this bucket is the area of all sewered cells (see the orange area in Figure 3) multiplied by a parameter for the depth (in mm). This gives the storage capacity (Tygron, 2020a). The water can flow in the sewer (the "bucket") according to a set of parameters.

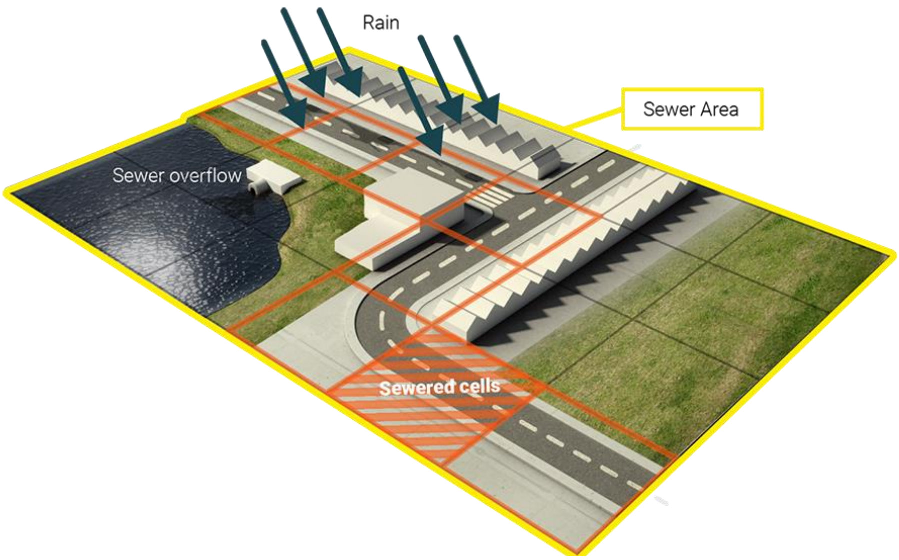


Figure 3: Sewage system (Tygron, 2020a)

The inflow (number 5 in Figure 2) of a certain sewer area (see the yellow area in Figure 3) is determined by whether there is water on the surface of a sewered grid cell. Also, precipitation landing on buildings with a (stormwater) connection to the sewer system can enter the sewage system. Not all types of buildings are connected to the sewer system. In Appendix C, the type of buildings/pavement that are connected to the sewer system can be seen. The inflow is stopped when the capacity of the sewer system of that specific sewer area is reached. When the capacity is reached, the inflow is limited to the outflow of the sewer system. The water is taken from all the sewered cells at the same rate. When space in the sewer system is limited to a very small volume, the cells in which water can enter the sewer system are chosen randomly. There is no difference made between high or low elevation or type of underground, besides that it must be a sewered cells (Tygron, 2021e).

Water can leave the sewer system (number 6 in Figure 2) in two ways, pumps and overflow. The pumping capacity (m^3/s) can be set as the characteristics of the pump located in the sewer area. Water that leaves the sewer system via this way disappears from the model. The other possible outflow occurs when the sewer water passes a certain percentage of the storage capacity in the sewer area. This sewer overflow threshold is a changeable parameter and when the sewer storage has reached that percentage, the sewer overflow will release water into the open water (see Figure 4) at its maximum overflow capacity. When the open water reaches the sewer overflow height, the overflow will stop discharging water. The overflow only discharges the sewage water from inside the sewer area at a location inside the sewer area. The sewer overflow capacity (in m^3/s) is a parameter that limits the possible overflow.

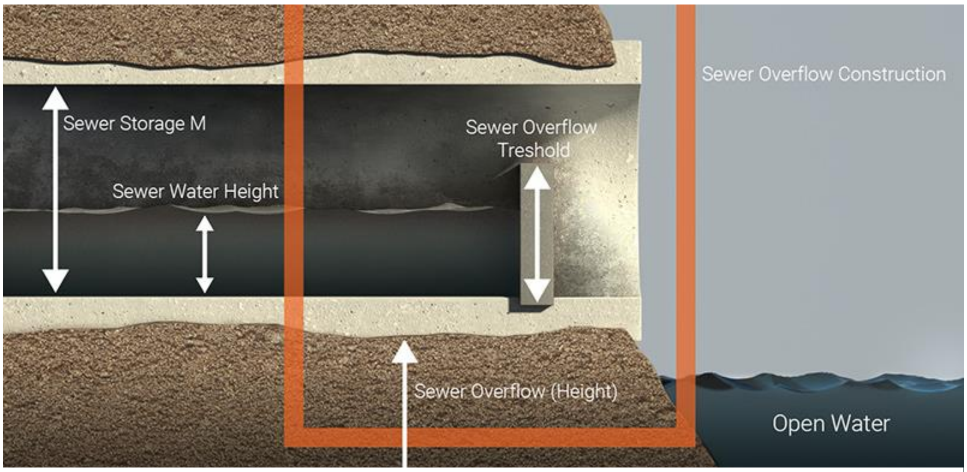


Figure 4: Sewer Overflow (Tygron, 2020b)

The sewer system itself is schematized as a point-based construction where the level of the sewer is not taken into account. After water enters the sewer system, it is unknown where the water is coming from and especially from which height the water enters the sewer system. This results in that water can enter the sewer at a lower level than where it overflows. This schematisation also causes that water is instantly stored in the sewer and can instantly leave the sewer via the pump or overflow (Tygron, 2022c).

The following schematisations show the path water can take towards the sewer system and with that the overflow. Notice that the location where the water can enter the sewer system can be located lower than where the water leaves the sewer system.

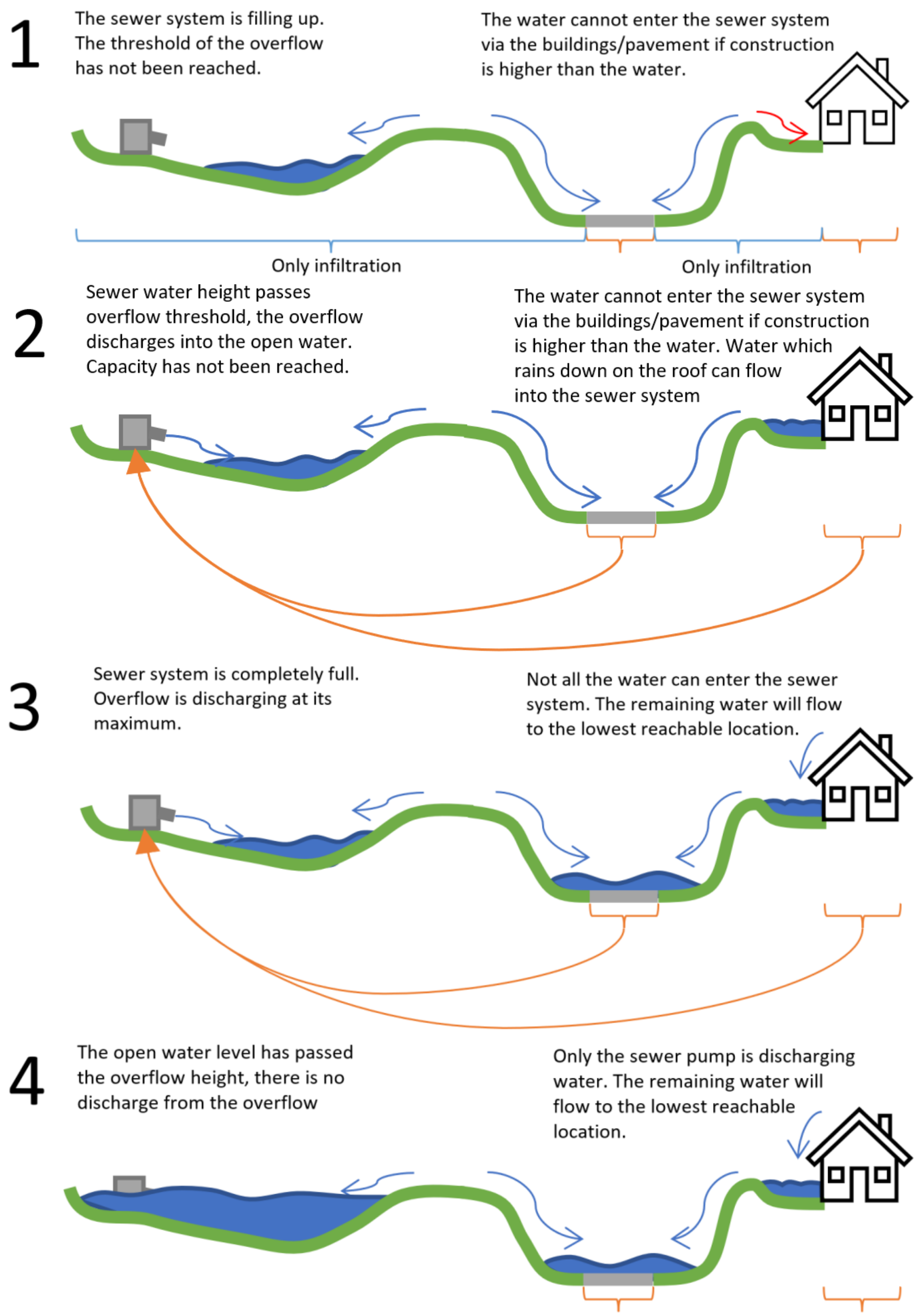


Figure 5: Schematisations of which path the water takes towards the sewer system and overflow

2.4 Differences with InfoWorks

InfoWorks takes a different approach, the InfoWorks model is not using the bucket model as explained in the previous sections. The InfoWorks model simulates the sewer system as a conduit-based model, which means that it consists of points (sewerage manholes) and lines (sewer pipes). This is often considered more accurate than a bucket model (Rioned, 2009). With this, InfoWorks takes into account that the sewer system can have bottlenecks underground, the maximum discharge is through the smallest pipe. In Tygron the location of inflow is partly taken into account. It is based on the sewered cells and not on the location of the manholes whereas this is the case in InfoWorks. Next to that, the location of where the discharge from the sewer system is, is not taken into account in Tygron. Only the overflow location is used, whereas in InfoWorks this is the case for the overflow as the pump capacity. The time needed for a droplet of water to flow through the sewer system is taken into account in InfoWorks, whereas this is not the case in Tygron. In the schematization, water can travel with the speed of light in the sewer system of Tygron. Lastly in Tygron, when the sewage system is filled up above a threshold volume will instantaneously have outflows at one designated overflow location; it will never overflow via manholes or storm drains.

2.5 Origin of the used data

The model makes use of multiple sources of self-loaded (open) data. In the Table below the different sources, the application inside the model and the accuracy, if relevant, of the data is shown. There are more datasets used, and information about road use intensities. Since these are not relevant for assessing the rainwater plan of Olst, these are not included in the following table.

Table 1: Origin of the used data

Data	*Application*	*Spatial resolution*	*Source*
Elevation profile	Height profile of Olst	0.5 m^2	(AHN, 2016)
BGT	Dataset with roads, water and street objects		(PDOK & Kadaster, 2022a)
BRP	Information with crop fields, grasslands, etc.	Per field	(PDOK & EZK, 2022)
BRO	Soil type	On average[1] 25 m^2	(PDOK & BZK, 2022)
BRK	Cadastral data	Per building	(PDOK & Kadaster, 2022b)
Water dataset	Rivers canals etc.		(RWS, 2022)
IMWA	Water system constructions such as culverts		(hetWaterschapshuis, 2020)

[1] It differs per region how many soil samples were taken. Only 0.002% of the Netherlands was sampled and therefore the scale is 1:50000 or 25 square meters

3. Research Methodology

To carry out this research, a methodology was made which consists of four steps. By taking these four steps the sub-questions and main question were answered.

The four steps are:

1. Building a base model
2. Carrying out a sensitivity analysis on the parameters in Tygron
3. Carrying out a performance evaluation between Tygron and InfoWorks
4. Concluding and answering main research question

3.1 Base model

The first step is getting a grip on Tygron and its underlying parameters. The goal of this step was to achieve a certain basic understanding of the different parameters while building a model that can be used for the next steps.

The performances of Tygron and the comparison with InfoWorks were carried out on a case study of Olst. Olst is, as explained in the Background, a village in the Netherlands which has experienced water hindrance for a longer period. This village was chosen for this research due because it already had been assessed with InfoWorks. Furthermore, the case area was not covering a complete city which would make it a complex system, while Olst is being an urban area. The project area is of workable size of 2500 m width and 4500 m wide, it fits in the maximum area Tygron can handle (10 km x 10 km in the version which is available at Witteveen+Bos) (Tygron, n.d.).

As explained in Section 2.1, the calculation time is strongly influenced by the grid size. The grid size was set at 1 m^2 resolution while testing and constructing the model. When calculating the results the accuracy was increased to 0.5 m^2, the finest grid size of the AHN3 profile (AHN, 2016). This is not the most coarse grid size data of the input data, see also Section 2.5, however, since the elevation data has more impact on the data compared with other datasets, the grid size of 0.5 m^2 was chosen. Nevertheless, differences in grid sizes were compared in the sensitivity analysis, as can be seen in the results in Section 4. The option to increase the elevation model around water streams was set at 0.5 m^2 for all simulations, this improves the flow throughput in very small channels and creeks (Tygron, 2022b).

Next to the base data, which can be seen in the Theoretical Framework Section 2.5, the water overlay Configuration Wizard was filled in. For this, the following settings were implemented. The settings used for the case area can be seen in the following table.

Table 2: Changeable rainwater overlay parameters in the Configuration Wizard

Configuration Wizard	Used for	Data (with the source if known)
Weather	Simulating the precipitation	Different types of dynamic rain events (see Appendix A)
Water areas	Setting the surface water levels	Was set on importing the fixed water levels (WDOD, 2021)
Groundwater	Setting the groundwater	Will be tested by carying out the sensitivity analysis
Sewers	Setting the data for the sewer system, such as the area, storage capacity and pumping capacity	The present sewer areas and their characteristics (see Appendix E)
Constructions Weirs, Culverts, Pumps	Creating water connections within the model	The constructions of the weirs, culverts and pumps were corrected. This so it can be used in Tygron (see Appendix B)
Constructions Sewer overflows	The connection between the sewer system and the surface water	The location of the overflow
Hydrologic coefficients	Setting the infiltration, runoff, evaporation	This data is already present in the model due to the known landscape characteristics (AHN, BRK, etc.) the default values of the Tygron model
Output overlays	The different output overlays can be chosen	-

Sewer area and pump capacities

The sewer system, for the theory, see Section 2.3, is implemented in the Tygron model as follows: First, the types of sewer systems located in the case area were defined. Since there is a part of Olst where there is only a wastewater sewer (see black lines in Figure 6a), this area is not included in the sewer area since the precipitation in this area will not enter the sewer since there is no separated sewer system for rainwater. In Tygron it is only possible to have a sewer overflow and a sewer pump at the same location giving its capacity for the region in which it is located. There is in the whole case study area only one main pump, pumping the water out of the whole area. Since the Boskamp and Olst Zuid areas are pumping their water towards the main pump area (Olst en Den Nul), these areas could be separated (Witteveen+Bos, 2022). When water reaches a pump in the Tygron model, it leaves the model. Water cannot transfer from one to another sewer area, a part of the main pump is in reality being used to pump sewer water away from the Boskamp and Olst Zuid areas. Therefore, additions were made to the pumping capacities to take into account that the water is in reality transported between sewer areas, this can be seen in the table on the next page. These pumps limited the number of sewer areas to three and therefore there it was decided to create the sewer areas as shown in Figure 6b.

Table 3: Pump capacities used in Tygron model, real pump capacity

Pump	**Real pump capacity** (Witteveen+Bos, 2022)	**In reality this pump includes these areas as well**	**Pump capacity in Tygron**
Olst en Den Nul (main pump)	0.192 m^3/s	Olst Zuid and Boskamp	0.146 m^3/s
Olst Zuid	0.048 m^3/s	Boskamp	0.028 m^3/s
Boskamp	0.018 m^3/s	-	0.018 m^3/s

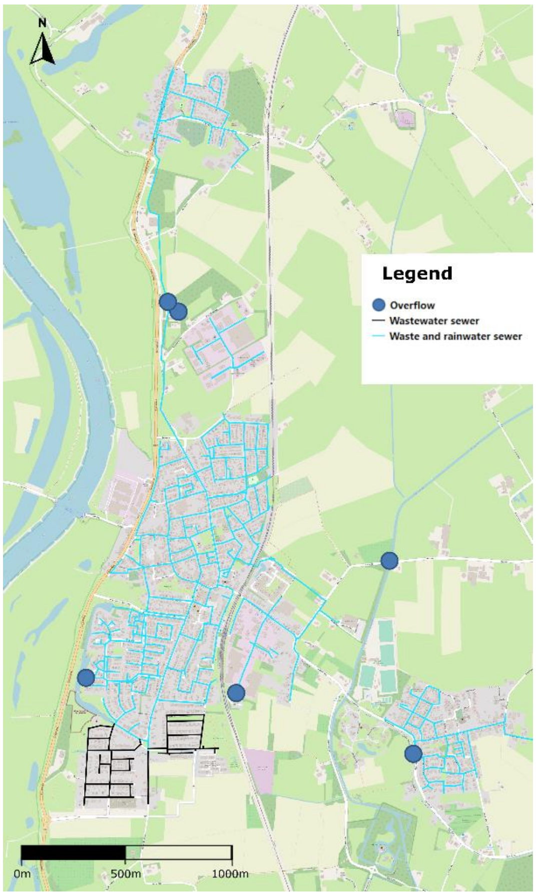


Figure 6a: All overflows and type of sewer

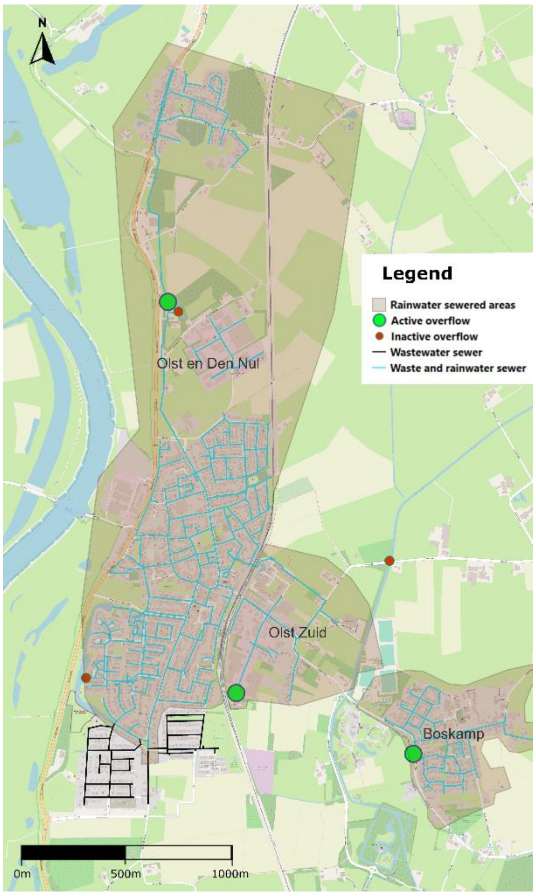


Figure 6b: Sewer areas with active overflows

Figure 6: Sewer system as implemented in Tygron model

Sewer overflow capacity

Since not all sewer overflows are active, there can only be one sewer overflow per sewer area, it was decided to combine the overflow capacity of the remaining sewer overflows. Since the overflow capacity of the sewer overflows is unknown an estimation was made. As a limitation, the maximum flow rate possible through the sewer pipes in front of the overflow was chosen. The maximum flow through a pipe was estimated with the use of the Chézy equation (Allaby, 2008) (see Appendix F).

The maximum flow through a pipe was estimated for 14 pipes which are ending at the sewer overflows. The discharge capacity for the model inactive overflows, were added to the main overflow per area. For calculation details and the dimensions of the pipes, see Appendix F. The overflow capacities as implemented can be seen in the following table.

Table 4: Maximum overflow discharge per sewer area

Area	Total maximum discharge (m^3/s)
Olst en Den Nul	5.08
Olst Zuid	2.02
Boskamp	5.25

Sewer storage

The dimensions of the sewer pipes are known as well as the storage capacity of the extra salvage basin in Boskamp, with this a total storage capacity per sewer area can be calculated (WDOD, 2021). For the storage capacity, the rainwater, as well as the combined sewer pipes (in blue in Figure 6a), were used. Next to the storage in the pipes, the area Boskamp has an extra storage facility. This storage facility can store 430m^3 of stormwater. Since the storage of the sewer system in Tygron is schematized as a bucket with an area of the connected sewered cells (see Section 2.3), the area of the sewered cells had to be determined in order to derive the bucket height. According to Tygron, not all of the 69 area- and building types are connected to the sewer system, for example, agricultural fields are not connected and neither are sidewalks. The complete list of which type of area is connected can be found in Appendix C. This results in the sewered cells (raster data) within the sewered areas as can be seen in Figure 7. Areas/buildings such as sidewalks, closed pavement or cycle paths are often sewered in the real world. However, in Tygron these types of constructions are not sewered. This could cause a difference compared with InfoWorks where there is looked where the sewer manholes are located. The height of the bucket is determined by the area the storage is divided. By giving more constructions a sewer connection, the total sewer storage does not change, the area it is divided by and with that the height of the bucket does.

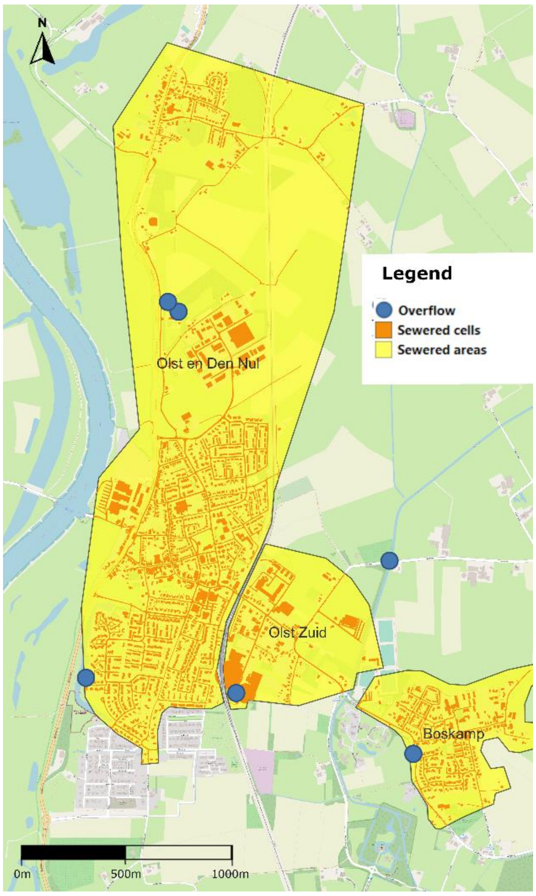


Figure 7: Sewered cells within sewer area

According to the equation, $Height\ bucket = \frac{Volume\ sewer\ system}{Area\ sewered\ buildings}$, the height of the bucket can then be determined. The sewered cells within each sewer area can be seen in the above figure. The storage height of each sewer system can be seen in Table 5.

Table 5: Sewer storage calculation

Sewer area	Volume sewer	Area sewered cells	Sewer storage height
Olst en Den Nul	4270 m^3	399.9×10^3 m^2	10.68 mm
Olst Zuid	368 m^3	79.3×10^3 m^2	4.64 mm
Boskamp	430 m^3 [1]	71.8×10^3 m^2	6.00 mm

[1] In Boskamp a storm storage of 223 is present, this extra salvage basin is already included in the 430 m^3

3.2 Sensitivity analysis on parameters in Tygron

After the fixed parameters were set, the model can be assessed on its sensitivity to the remaining changeable parameters.

Challenged parameters and analysis

The parameters which are considered to have a rough estimated standard value or where it is expected that the results of the model are sensitive for are the:

- Grid size
- Initial groundwater depth
- Pump capacity per sewer area
- Storage capacity of the sewer system
- Capacity of the sewer overflow
- Height of the sewer overflow

For the changed parameters, different values were used. In the table on the next page, the tested parameter and the settings for that specific parameter can be seen per run. Next to parameters that can be changed, two different rain events were used in the sensitivity analysis. These rainevents were Bui08 and historical rain event Herwijnen (see Appendix A). Bui08 is often used in the design phase of the sewer system, as one of the larger rain events, sewer systems should be able to accommodate without causing hindrance (van Luijtelaar, 2020). The Herwijnen rain event was used since it is an intense rain event which will cause, in reality, with certainty for water hindrance and therefore is suitable to compare stormwater hindrance(van Luijtelaar, 2020).

Table 6: Runs for the sensitivity analysis and the set parameters

Run	Name of the run	Rainevent[1]	Grid size (mxm)	Groundwater depth (m)	Sewer storage capacity[2]	Sewer pump capacity[3] (m^3/s)	Sewer overflow height[4]	Sewer overflow discharge (m^3/s)	Number of overflows[5]
1	Bui08_025m2	Bui08	0.25x0.25	1	Area_Pump	Based on real	Original	1	3
2	Bui08_05m2	Bui08	0.5x0.5	1	Area_Pump	Based on real	Original	1	3
3	Bui08_1m2	Bui08	1x1	1	Area_Pump	Based on real	Original	1	3
4	Bui08_2m2	Bui08	2x2	1	Area_Pump	Based on real	Original	1	3
5	Bui08_5m2	Bui08	5x5	1	Area_Pump	Based on real	Original	1	3
6	Base_Pumps	Bui08	1x1	1	Area_Pump	Based on real	Original	1	3
7	Bui08_GW_D_0m_Pumps	Bui08	1x1	0	Area_Pump	Based on real	Original	1	3
8	Bui08_GW_D_10m_Pumps	Bui08	1x1	10	Area_Pump	Based on real	Original	1	3
9	Bui08_GW_D_100m_Pumps	Bui08	1x1	100	Area_Pump	Based on real	Original	1	3
10	Bui08_SW_Q_null	Bui08	1x1	1	DIM_BK_AREASW	0	Original	1	5
11	Bui08_SW_Q_0032	Bui08	1x1	1	DIM_BK_AREASW	0.032	Original	1	5
12	Bui08_SW_Q_025	Bui08	1x1	1	DIM_BK_AREASW	0.25	Original	1	5
13	Bui08_SW_Q_050	Bui08	1x1	1	DIM_BK_AREASW	0.5	Original	1	5
14	Bui08_SW_Q_100	Bui08	1x1	1	DIM_BK_AREASW	0.5	Original	1	5
15	Bui08_SW_Q_150	Bui08	1x1	1	DIM_BK_AREASW	1.5	Original	1	5
16	Bui08_SW_Q_200	Bui08	1x1	1	DIM_BK_AREASW	2	Original	1	5
17	Bui08_ST_Null_Pumps	Bui08	1x1	1	Null	Based on real	Original	1	3
18	Bui08_ST_AgeBased_Pumps	Bui08	1x1	1	Area_Pump_Age	Based on real	Original	1	3
19	Bui08_Base_Pumps	Bui08	1x1	1	Area_Pump	Based on real	Original	1	3
20	Bui08_ST_Null	Bui08	1x1	1	Null	Based on real	Original	1	5
21	Bui08_SW_ST_Age	Bui08	1x1	1	AGEBASED	1	Original	1	5
22	Bui08_ST_DimBK	Bui08	1x1	1	DIM_BK_AREASW	Based on real	Original	1	5
23	Herwi_SO_Q_0_Pumps	Herwijnen	1x1	1	Area_Pump	Based on real	Original	0	3
24	Herwi_SO_Q_1_Pumps	Herwijnen	1x1	1	Area_Pump	Based on real	Original	1	3
25	Herwi_SO_Q_10_Pumps	Herwijnen	1x1	1	Area_Pump	Based on real	Original	10	3
26	Herwi_SO_Q_10_H_Groundlevel_Pum	Herwijnen	1x1	1	Area_Pump	Based on real	Ground level	10	3
27	Herwi_h1mhoger	Herwijnen	1x1	1	Area_Pump_20mm	Based on real	Original+1 m	1	3
28	Herwi_o_10_h_maaiveld	Herwijnen	1x1	1	Area_Pump_20mm	Based on real	Ground level	10	3
29	Herwi_H10m	Herwijnen	1x1	1	Area_Pump_20mm	Based on real	10 m	10	3
30	Herwi_20mm	Herwijnen	1x1	1	Area_Pump_20mm	Based on real	Original	1	3
31	Herwi_o_1_h_maaiveld	Herwijnen	1x1	1	Area_Pump_20mm	Based on real	Ground level	1	3

[1] The rain events, their duration and intensity can be seen in Appendix A

[2] There are six different sewer storages used for the runs. The storage capacity can be seen in Appendix E

[3] Sewer pump discharge, based on real means the calculated discharge as can be seen in Table 3

[4] Sewer overflow height original is the height of the sewer overflow as it is in the real world, ground level is the ground level around the sewer overflow

[5] The number of overflows is not the same for every run, the locations can be seen in Appendix E

The output of Tygron exists out of 7 maps with the water level given per cell (with a certain grid size) at a certain moment in time (a timeframe). With a grid size of 1x1 meter, in total 10,667,500 water levels are known. The time steps are at:

- 0 seconds, to check whether there is no additional water on the surface at the start of the simulation
- 1200 seconds (20 minutes), the start point of the Herwijnen rain event
- 2400 seconds (40 minutes), end of the first peak in the Herwijnen rain event
- 3600 seconds (60 minutes), at this point the 60 mm and Bui08 rain event stops
- 5400 seconds (1h 30 minutes), at the end of the Herwijnen rain event main peaks
- 7200 seconds (2 hours), in between measurement point for the 60mm and Bui08 rain event
- 10800 seconds (3 hours), end of the simulation. All rain events have stopped since it is expected that there will not occur new maximum water level. Also, three hours limits the computing time of Tygron.

Next to the map per timeframe, a map with the maximum water level per grid cell that occurs during the 3 hour simulation is generated.

Sample areas

This research focuses on stormwater hindrance. An increased water level in ditches and creeks is not considered as hindrance, as long as surface water does not goes beyond the bank, as they are intended for extra storage during rain events. Therefore all water bodies were clipped out of the comparison as well as the grass fields/agriculture (see Figure 8a). The models Tygron and InfoWorks are taking a different approach in the way they model the sewer system, see Section 2.4. Next to that, the output generated by Tygron and InfoWorks is different, raster data and vector data respectively. Therefore, comparing the data per grid cell could cause significant differences while at the same time the overall performance could be a good estimation. Next to a volumetric difference, it is interesting to see where in the study area the differences between Tygron and InfoWorks occur. Therefore, a comparison on street level is considered to be the scale (see Figure 8b). In total 117 street sections were made, ranging from the smallest section (the Kneu) of 202 m^2 to the largest (de Meente) of 99,500 m^2.

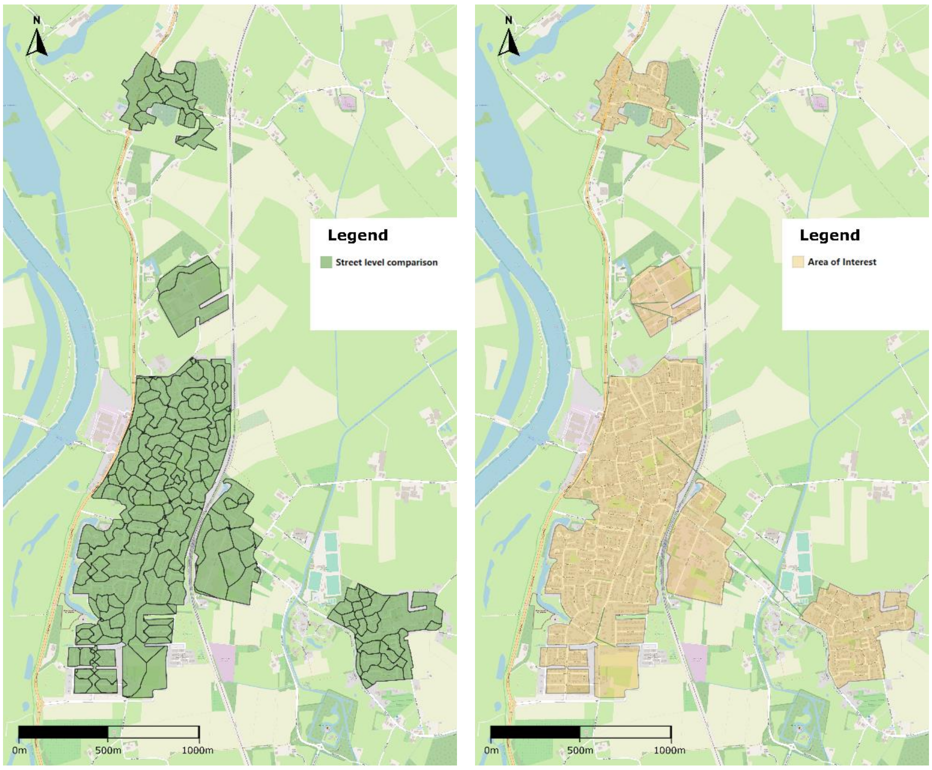


Figure 8. Area of interest *Figure 8b. Street level based, created by Thiessen polygons*

Figure 8: Area of interest and street level map

The 8 maps are summarised in the street sections map, shown in Figure 8. This results in:

0. Initial map at t=0, the volume of water (0-sum) and average water level per street.
1. Initial map at t=1200s, the volume of water (1-sum) and average water level per street.
2. Initial map at t=2400s, the volume of water (2-sum) and average water level per street.
3. Initial map at t=3600s, the volume of water (3-sum) and average water level per street.
4. Initial map at t=5400s, the volume of water (4-sum) and average water level per street.
5. Initial map at t=7200s, the volume of water (5-sum) and average water level per street.
6. Initial map at t=10800s, the volume of water (6-sum) and average water level per street.
7. The maximum sum (max-sum) and maximum average water level (max-mean) during one run per street. And, the maximum water level simulated in a section (max-max) during one run.

The comparison between the runs, with different parameters, was done by comparing the max-mean (the average water level in a section based on the maximum water level map). The results of these comparisons can be seen in the Results (Section 4.2).

Model performance evaluation

To assess for which parameters the model is sensitive, two different methods were used: the Nash Sutcliffe model efficiency score (NSE) and the Volumetric Efficiency (VE). The reason for this is that the VE-value is less influenced by large outliers compared with the NSE (Criss & Winston, 2008). The NSE-score was used to check whether there are large outliers. These are expected to occur since the goal of this step is to find the sensitive parameters and the model parameters were changed in a broad range. However, it could be that a parameter has a large influence on a small area while having almost no impact on the average result. Therefore the VE-value was determined as well.

The Nash Sutcliffe model efficiency score was used (Nash et al., 1970). The NSE value can be calculated using the following equation:

$$NSE = 1 - \frac{\sum_{i=i}^{n}\left(H_{MP,i} - H_{MB,i}\right)^2}{\sum_{i=i}^{n}\left(H_{MB,i} - \overline{H_{MB,\iota}}\right)^2}$$

In which:
$H_{MP,i}$ is the simulated average maximum (max-mean) water height on the surface in street section i in the model with a changed parameter
$H_{MB,i}$ is the simulated average maximum (max-mean) water height in street section i in the base model
$\overline{H_{MB,\iota}}$ is the average maximum water level in the whole case study area

A NSE-value of one means that the changed parameter has no influence on the model outcomes, whereas a value close to zero means that the model parameter is strongly influencing the model outcome. Negative values are possible and indicate that the model outcome is extremely influenced by the parameters (Bennett et al., 2013).

Next to the NSE-value, the volumetric efficiency (VE) is calculated, the VE-value represents the fractional volumetric mismatch. The VE-value can be calculated with the following equation:

$$VE = 1 - \frac{\sum_{i=1}^{n}\left|V_{MP,i} - V_{MB,i}\right|}{\sum_{i=1}^{n} V_{MB,i}}$$

Where:
$V_{MP,i}$ is the volume of water on the surface according to the model with the changed parameter in street section i
$V_{MB,i}$ is the volume of water on the surface according to the base model in street section i.

VE-value equal to one means that there is no difference caused by the parameter.

With this, answer was given to the first research question, *"Which schematization parameterization choices are relevant for implementing an area in Tygron?"*.

With this answer, the parameters could be chosen to form a model which can be compared with InfoWorks.

3.3 Performance evaluation between Tygron and InfoWorks

With the results of the sensitivity analysis on the parameters of the Water module in Tygron, see Section 4.2, a comparison with InfoWorks was made. The overall performance was assessed in terms of the total volume of water on the surface and on a smaller scale. First, the method for the overall performance will be explained.

Based on the conclusion drawn in Section 5.1, the following parameters were considered to be sensitive for the results: sewer pump capacity, the sewer overflow capacity combined with the sewer overflow height.

Used data InfoWorks

As mentioned in Section 3.1, one of the reasons that the study area Olst was chosen, was that there had already been done a cost-benefit analysis for different measures. For this cost-benefit analysis, an InfoWorks model was created for Olst and was validated (Witteveen+Bos, 2021). The model was recalculated with three different rain events for this research. These rain events were Bui08, historical rain event Herwijnen and 60 mm of precipitation in 60 minutes, henceforth called rain event 60mm (see Appendix A).

The output of InfoWorks were data maps (one per rain event) which consisted of polygons (1.3 million polygons for this project), for practical reasons these maps were converted to raster data maps. These maps were summarised per street section, see Figure 8b. This results in the maximum volume (max-sum) and maximum water level measured during one simulation run per street section (max-max). Data on the development of water level over time was not available for this research so a comparison to the timesteps in the simulations of Tygron was not possible.

Used data Tygron

For Tygron, the same three rain events were used for InfoWorks. For the parameters assessed in the sensitivity analysis, values were chosen.

The parameter grid size was chosen to be 1x1 m, this is due to the sensitivity analysis shows that the outcome is not sensitive for a finer grid size while calculation time increases exponentially. Next to this, the sensitivity analysis showed that the initial groundwater depth has no influence for this project area. Therefore, the standard suggested value of Tygron was used (1m). The conceptual model as well as the results of the sensitivity analysis show that the sewer pump capacity has a direct correlation with the water on the surface. The pump capacity was chosen to be as realistic as possible since the outcome could also be influenced by the overflow parameters. For the exact sewer pump capacity per sewer area, see Table 3.

As will be mentioned in Conclusion Section 5.1, the overflow parameters had to be chosen carefully since the outcome of the model is sensitive for these parameters. The overflow discharge capacity was calculated based on the dimensions of the sewer pipes and the Chézy equation (see Appendix F). The sensitivity analysis showed that the overflow discharge is often limited due to that the overflow is flooded. Therefore, the overflow height was set on the ground level at its location plus one meter.

In the following table the different parameters and their values can be seen.

Table 7: Runs for the performance comparison between Tygron and InfoWorks

Run	**Name of the run**	**Rainevent[1]**	**Grid size (mxm)**	**Groundwater depth (m)**	**Sewer storage capacity[2]**
62	Bui08_so_all_correct_h_maai_1	Bui08	1	1	Area_Pump
63	60mm_so_all_correct_h_maai_1	60mm	1	1	Area_Pump
64	Herwi_so_all_correct_h_maai_1	Herwi	1	1	Area_Pump

Run	**Sewer pump capacity[3] (m^3/s)**	**Sewer overflow height[4]**	**Sewer overflow discharge (m^3/s)**	**Number of overflows[5]**
62	Based on real	Ground level +1m	All	3
63	Based on real	Ground level +1m	All	3
64	Based on real	Ground level +1m	All	3

[1] The rain events, their duration and intensity can be seen in Appendix A
[2] There are six different sewer storages used for the runs. The storage capacity can be seen in Appendix E
[3] Sewer pump discharge, based on real means the calculated discharge as can be seen in Table 3
[4] Sewer overflow height original is the height of the sewer overflow as it is in the real world, ground level is the ground level around the sewer overflow
[5] The number of overflows is not the same for every run, the locations can be seen in Appendix E

The 8 maps with data output of Tygron, were converted in the same way as the data of the sensitivity analysis, see page 16.

Overall performance evaluation between Tygron and InfoWorks

The overall differences were evaluated with the Volumetric Efficiency. This is since this method is relatively less affected by large outliers compared with for example the Nash Sutcliffe model efficiency score (Bennett et al., 2013).

The Volumetric Efficiency (VE) represents the fractional volumetric mismatch. The VE-value can be calculated with the following equation:

$$VE = 1 - \frac{\sum_{i=1}^{n} \left| V_{MP,i} - V_{MB,i} \right|}{\sum_{i=1}^{n} V_{MB,i}}$$

Where:
$V_{MP,i}$ is the volume of water on the surface according to the Tygron model in street section i
$V_{MB,i}$ is the volume of water on the surface according to the InfoWorks model in street section i.

VE-value equal to one means that there is no difference between Tygron and InfoWorks.

Street level performance evaluation between Tygron and InfoWorks

At street level, the model was evaluated by comparing the water levels per simulation and checking whether there were large differences, in both percentage and absolute difference. These differences were visualised on a scale map based on the sections as seen in Figure 8b.

Last but not least, there was looked between where the top 5, 10 and 15% highest water levels on the surface were simulated according to the two models. These numbers were chosen due to when looking at the 20%, or more, highest water levels on the surface water, the InfoWorks model includes zero values since less than 20% of the surface was flooded. Therefore, percentages larger than 15% would not give accurate results. This comparison was carried out on the sample areas as can be seen in Figure 8a. With this method, it was checked whether on the same locations bottlenecks occur in the different models.

With these methods, the overall and street level performance evaluation an answer was formulated to the second research question, *“What are the differences in performance when simulating rain events in Tygron and InfoWorks?”*.

3.4 Concluding and answering research question

The last step of this research is the concluding step. In this step, an answer will be formulated to the main research question, “*To what extent is Tygron capable of simulating rainwater hindrance in Olst?”*. This was done in the Conclusion of this research, see Section 5. Discussion points and recommendations were worked out in respectively Section 6 and Section 7.

4. Results

4.1 Building a base model

The model that was built in Section 3.1 can be used to simulate rain events in the area of Olst. The model itself was not finalised in this stage, that was done on the information gathered during step 2, as explained in Section 3.2.

In the following figure, an impression of the model can be seen.

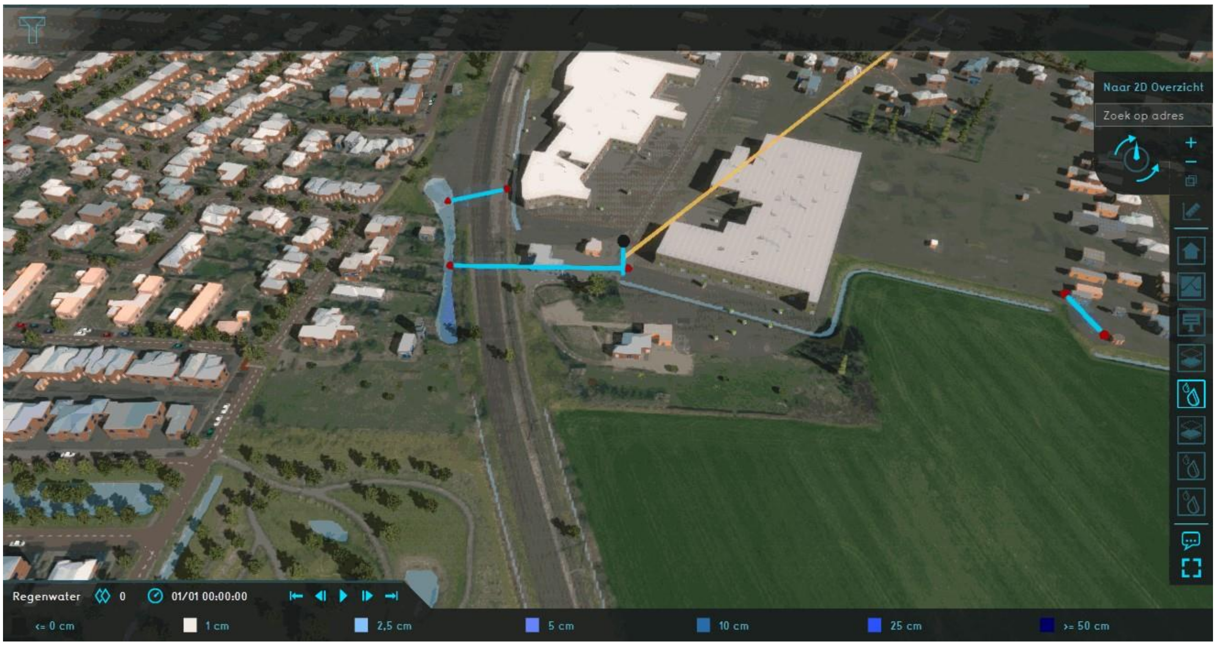


Figure 9: Ambiance of Olst in Tygron, near overflow Olst Zuid

The Olst Zuid overflow can be seen as well as the, for modelling reasons, corrected culvert as explained in Appendix B.

4.2 Characteristics of the Tygron model

After creating the Olst model in Tygron as the closest to reality, using the information provided in Table 2. After small corrections, as explained in the methodology, the sensitivity analysis could be carried out. As mentioned in the methodology, the following parameters were investigated.

- Grid size
- Initial groundwater depth
- Pump capacity per sewer area
- Storage capacity of sewer system
- Capacity of the sewer overflow
- Height of the sewer overflow

4.2.1 Grid size

In the Table below the different grid sizes can be seen and their calculation time as well as their NSE- and VE-value (where the observed data is the base level).

Table 8: NSE- and VE-value for grid size parameter

Run	**1**	**2**	**3**	**4**	**5**
Grid size	0.25x0.25 m	0.5x0.5 m	1x1 m	2x2 m	5x5 m
Calculation time	8 hours[1]	13 minutes	5 minutes	2 minutes	3 seconds
NSE-value	0.989	0.983	-	0.950	0.751
VE-value	0.939	0.921	-	0.857	0.732

[1] Since the expected running time was longer than one hour, Tygron switches to a slower server for long taking simulation runs. Therefore, the running time increases enormously.

As can be seen in the table above, is that changing the grid size has an influence on the outcome. However, reducing the grid size smaller than 1x1m does not change the NSE- and VE- value much. The calculation time, however, is increasing enormously when reducing the grid size. This is partly due to the switching of the calculation CPU.

In the following figure the maximum average water level on the surface can be seen.

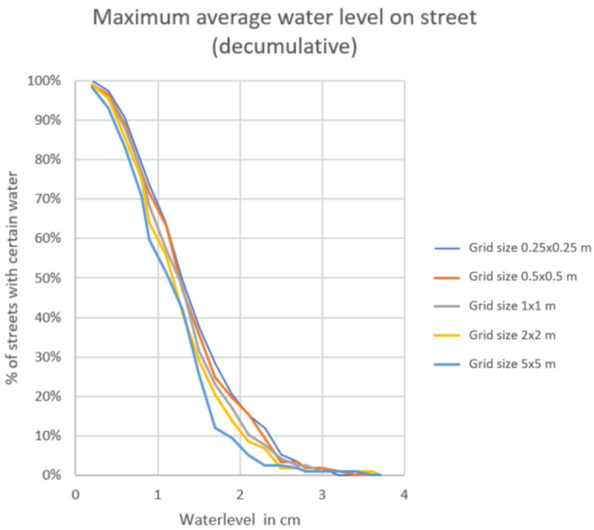


Figure 10a. Maximum average water level on surface

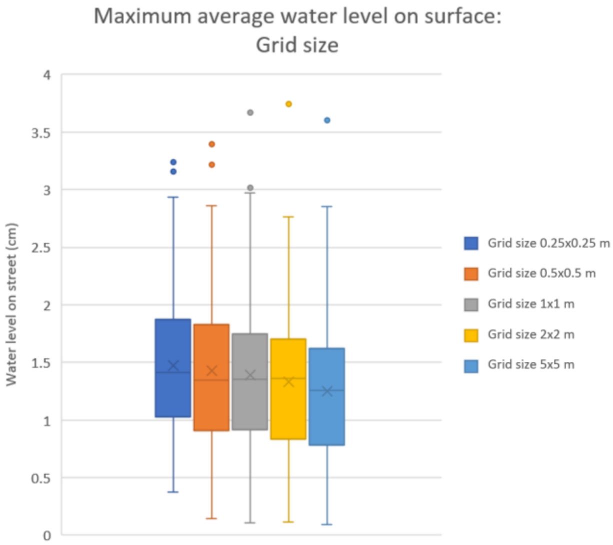


Figure 10b. The maximum average water level on the surface

Figure 10: Results of sensitivity analysis grid size, average

It can be seen that the coarser the grid size gets, on average slightly more water is present on the surface. In the following graphs, the maximum water level in a run per section can be seen.

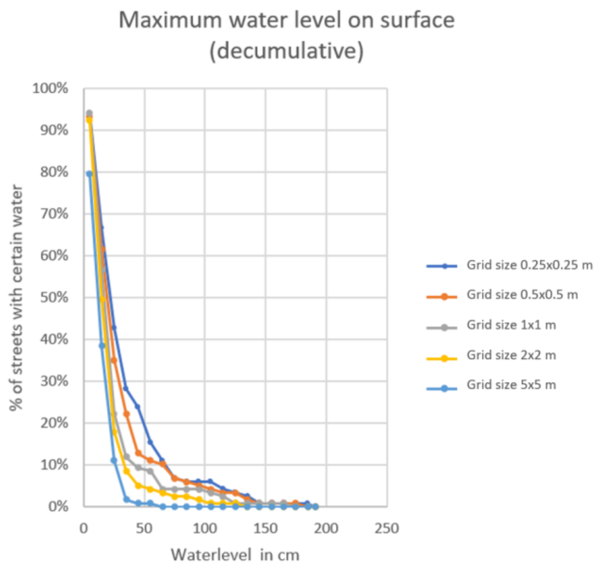


Figure 11a. Maximum water level on surface

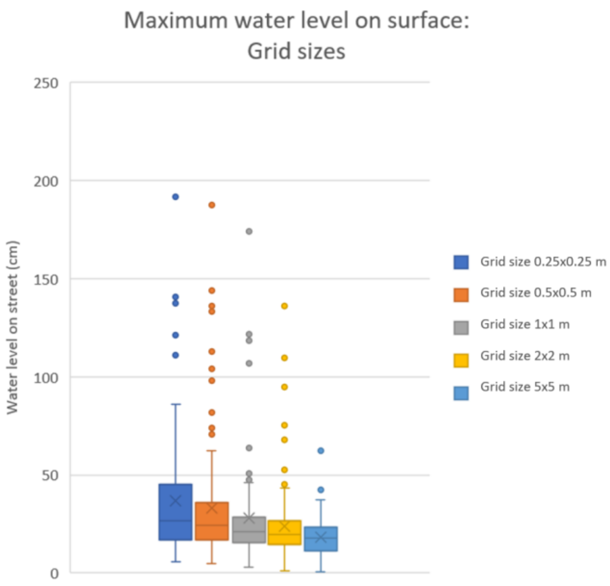


Figure 11b. The maximum water level on the surface

Figure 11: Results of sensitivity analysis grid size, maximum

What can be seen is that the variation in the maximum water levels in a section is larger when looking at a finer grid size as can be seen in Figure 11b. What can be seen in Figure 11a, is that the maximum water level found in the simulation with a grid size of 5x5m sticks at 62.5 cm whereas the finer grid size of 0.25x0.25m finds a maximum water level on the surface of 191.8 cm.

This also explains the lowest NSE-value for the coarsest grid size. At the same time, all grid sizes are performing quite well for the Volumetric Efficiency.

4.2.2 Initial groundwater depth

The different initial groundwater depths per simulation run can be seen in the table below. For the comparison, an initial depth of 1 meter (the standard value of Tygron) was chosen, which is run 6.

Table 9: NSE- and VE-value for initial groundwater depth parameter

Run	**6**	**7**	**8**	**9**
Initial groundwater depth (in m)	1	0	10	100
NSE-value	-	1.000	1.000	1.000
VE-value	-	1.000	1.000	0.999

The NSE values are all 1.000, and the same accounts for nearly all the volumetric differences. This means that there is no difference in the outcome when changing the initial groundwater depth. This means that the initial groundwater depth has no influence on the results. It was expected that there would not have been much difference in an initial groundwater depth of 10 or 100 meters. It can be the case that in three hours of simulation, water makes the transfer from 0 to the 10 meters depth, not to mention that the transfer from 0 to 100 meters is even larger. This will be further discussed in the Discussion (see Section 6.1).

In Appendix G.1 the boxplot made from the measurements of the average maximum water level in every section can be seen as well as the decumulated maximum water level on the surface.

4.2.3 Pump capacity per sewer area

The values for the changed parameter pump capacity per pump can be seen in the table below. As base, a pump capacity of 1 m^3/s was chosen.

Table 10: NSE- and VE-value for pump capacity parameter

Run	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Pump capacity (in m^3/s)	0	0.032	0.25	0.5	1	1.5	2.0
NSE-value	0.770	0.782	0.858	0.926	-	0.865	0.371
VE-value	0.195	0.234	0.463	0.665	-	0.737	0.570

This shows that the pump capacity has a large influence on the outcome. Therefore, extra attention should be given to the pump capacity parameter.

In the following figure, the maximum average water level can be seen. At the y-axis of the left figure, the percentage of the street sections with a certain water level can be seen.

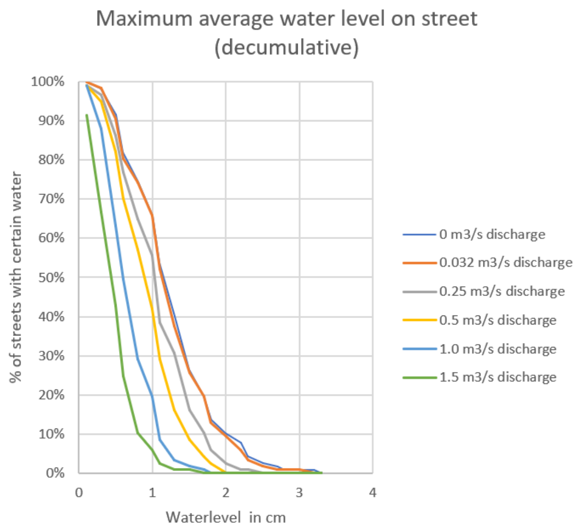


Figure 12a. Maximum average water level on surface

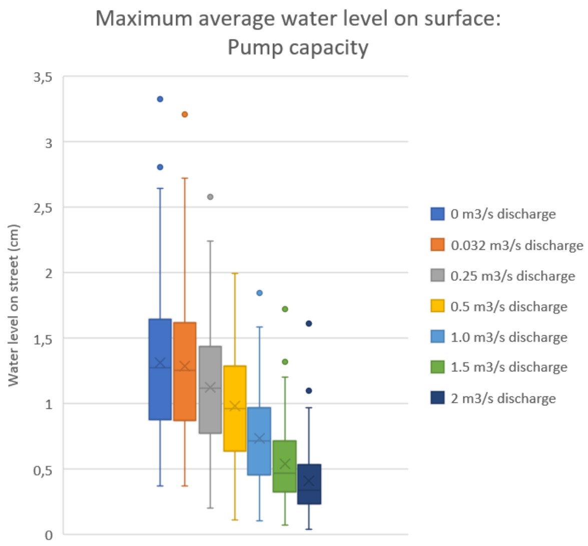


Figure 12b. The maximum average water level on the

Figure 12: Results of sensitivity analysis parameter pump capacity

As can be seen in the graphs in Figure 12 is that the water on the surface is decreasing when there is more capacity per pump. This can also be seen in the average water level on the surface over time in the following figure.

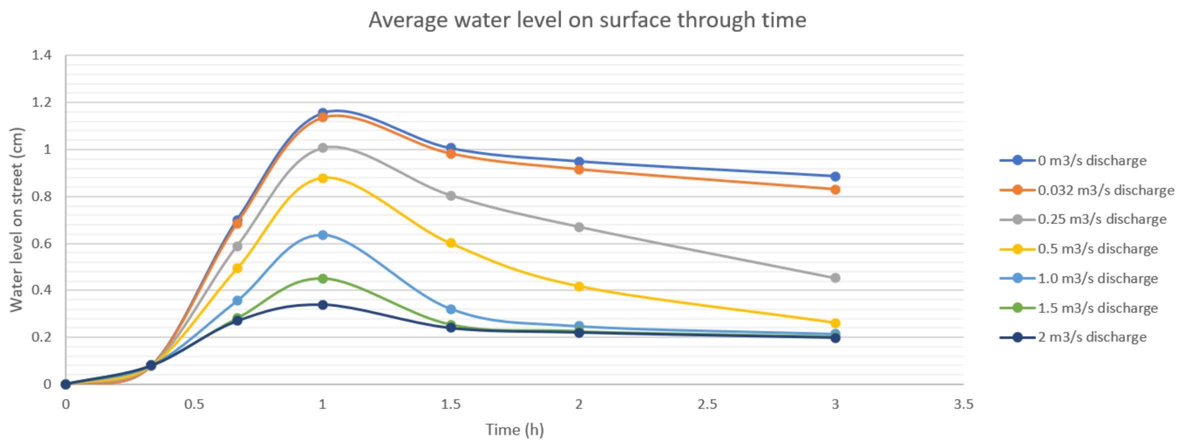


Figure 13: Average water level on surface through time for changing pump capacity parameter

There is a certain amount of water that will last till the end of the simulation run. Around 20 mm of water is on average present on the surface after three hours when there is a 1 m^3/s or higher discharge from the pumps (see Figure 13). This is water that cannot reach the sewer sewered cells and therefore cannot be pumped away. In Appendix G.3, the water level can be seen on the sewered cells.

In the following graph, simulations 0.032 m^3/s, 0.25 m^3/s and 2 m^3/s were run again but with a simulation span of 30 hours.

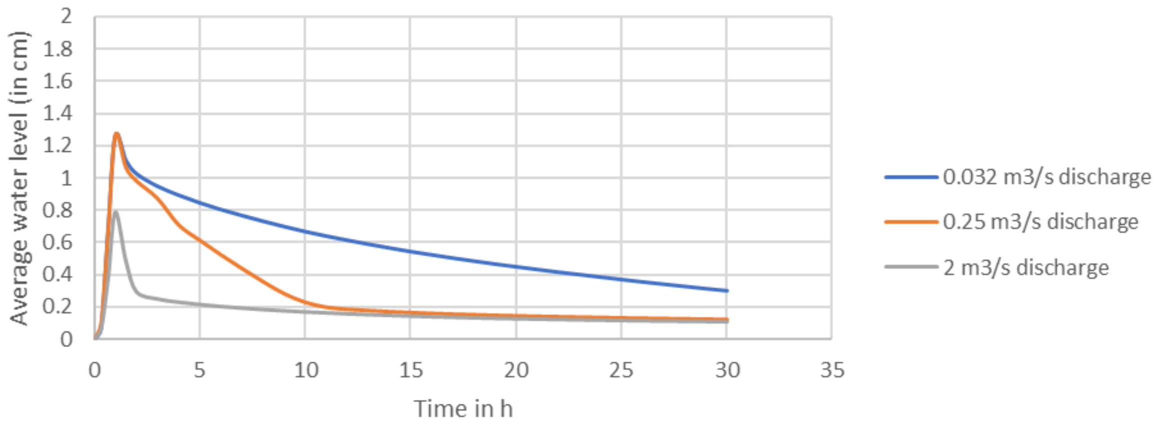


Figure 14: 30 hours run for average water level on the surface through time for changing pump capacity parameter

The average water level in the pump capacity of 0.25 m^3/s simulation, is around 11 hours at the same level as the 2 m^3/s simulation. After 11 hours, the average water level on the surface at the 0.25 m^3/s simulation is slowly decreasing at the same rate as the 2 m^3/s simulation. This concludes that there is indeed water on the surface which cannot reach the sewered cells (see also Appendix G.3).

4.2.4 Storage capacity of sewer system

In contrast with the grid size and the groundwater depth, the storage capacity of the sewer system can be influenced in two ways. Changing the area of the sewer system or changing the bucket height (multiplied by the area that forms the storage volume) of the sewer system. For modelling reasons some other parameters had to be changed as well, the complete model settings can be seen in Appendix D.

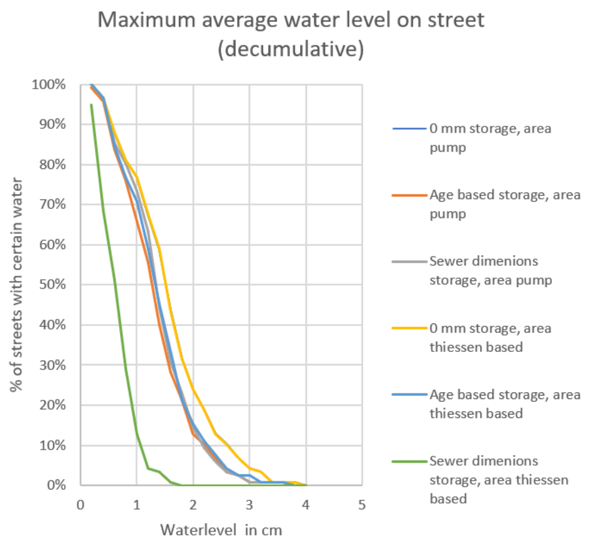
Table 11: NSE- and VE-value for sewer storage parameter

Run	**17**	**18**	**19**	**20**	**21**	**22**
Sewer area[1]	Pumps Based	Pumps Based	Pumps Based	Thiessen Based	Thiessen Based	Thiessen Based
Bucket height[]	0 mm	Age Based	Sewer Based	0 mm	Age Based	Sewer Based
NSE-value	0.981	0.984	-	0.981	0.951	0.981
VE-value	0.865	0.935	-	0.865	0.907	0.501

[1] The two sewer area maps as well as the sewer storage heights can be seen in Appendix E.

The NSE-value keeps close to one, whereas the VE-value really differs per run. It can be seen that changing the storage capacity of the sewer system can really influence the outcome of the model.

In the following figure, the maximum average water level can be seen. At the y-axis of the left figure the percentage of the streets with a certain water level can be seen.



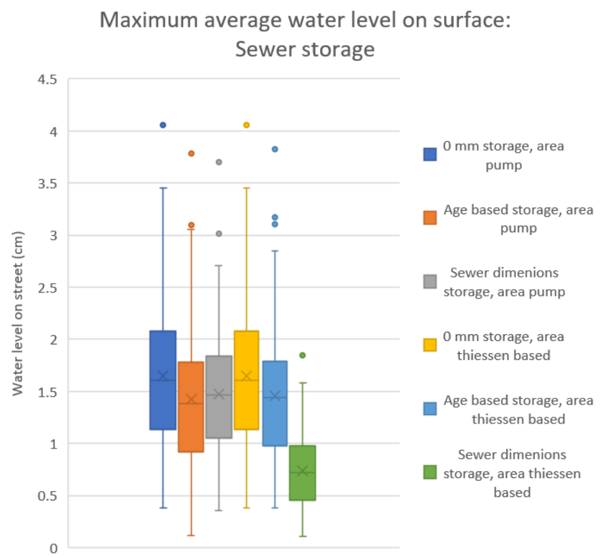


Figure 15a. Maximum average water level on surface *Figure 15b. The maximum average water level on the*

Figure 15: Results of sensitivity analysis parameter sewer storage

As can be seen in Figure 15a, there can be seen no difference between the results of the 0mm storage with a sewer area made with Thiessen and the 0mm storage with a sewer area based on the pumps. In Figure 16, this difference is also not visible through time (lines are on top of each other). Furthermore, it can be seen that the storage based on sewer storage in a Thiessen based sewer area has a lower water level on the surface. This can be explained that the sample areas for the Thiessen based and pump based sewer systems are not the same, the Thiessen based has larger sample areas.

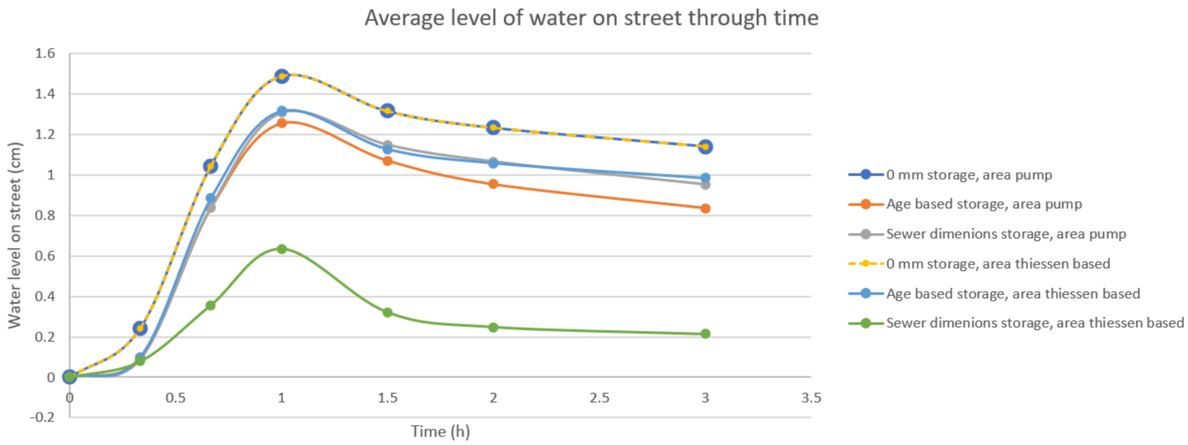


Figure 16: Average water level on surface through time for sewer storage parameter

The pumping discharge was zero when there was no storage possible, as can be seen in Figure 16. This indicates that when there is no storage available, the pumps cannot work. Due to that, it also does not matter how many pumps there are available when the storage equals zero.

4.2.5 Capacity of the sewer overflow

Next to the pump capacity, the sewer overflow also has an overflow capacity. Since this gets into use when the sewer pumps are used at full capacity and the sewer system is completely filled, which was not the case yet with a Bui08. Therefore, a heavier rain event (the historical rain event Herwijnen) was chosen as described in the Research Methodology on page 14. In the following table the NSE- and VE-values can be seen for the different overflow capacities. The initial/base overflow capacity is 1m^3/s.

Table 12: NSE- and VE-value for sewer overflow maximum discharge parameter

Run	**23**	**24**	**25**	**26**
Sewer overflow capacity (in m^3/s)	0	1	10	10
Height overflow	Original	Original	Original	Ground level
NSE-value	1.000	-	0.999	0.998
VE-value	1.000	-	1.000	0.994

As can be seen in Table 12 is that, according to the NSE- and VE-value, model outcomes are not sensitive to changing the sewer overflow capacity. However, adjusting the sewer overflow height to the ground level (in Dutch: maaiveld), there is a slight change visible.

In Appendix G.2 the boxplot made from the measurements of the average maximum water level in every section can be seen as well as the decumulated maximum water level on the surface.

In the following graph the measured overflow per overflow can be seen, as well as it location.

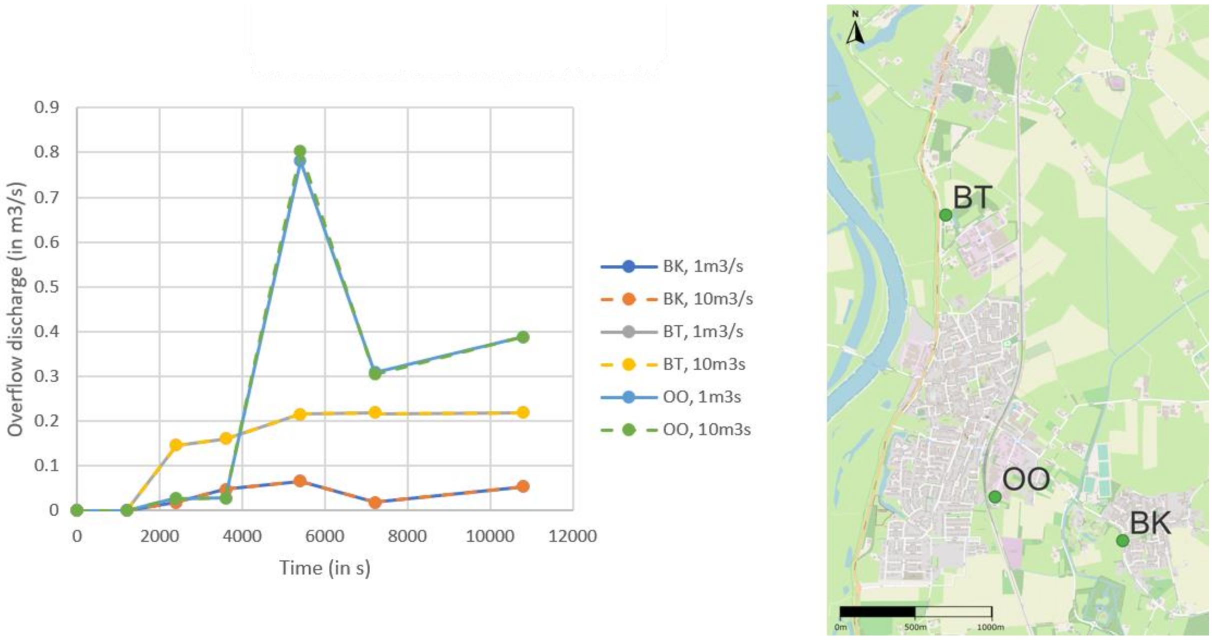


Figure 17: Simulated discharge per overflow with different set maxima for the overflow capacity

According to the simulations, the sewer outflow is bouncing into a limit which is much lower than the settled maximum. Increasing the capacity of the sewer overflow above 0.8 m^3/s alone has no influence that this maximum discharge is reached. In the following section, an answer will be given on why there is a limit on the discharge which is lower than the set maximum discharge.

4.2.6 Sewer overflow height

The overflow height has also an influence on the sewer overflow. If the height is below the water level around the overflow, there is no discharge (see Figure 5). This can explain why the discharge in Figure 17 is limited at 0.8 m^3/s and not to the set maxima.

In the following runs, there was looked at whether the height has an influence on the sewer overflow discharge and with that, the outcome of the model. Run 30 was used as base model for the comparison.

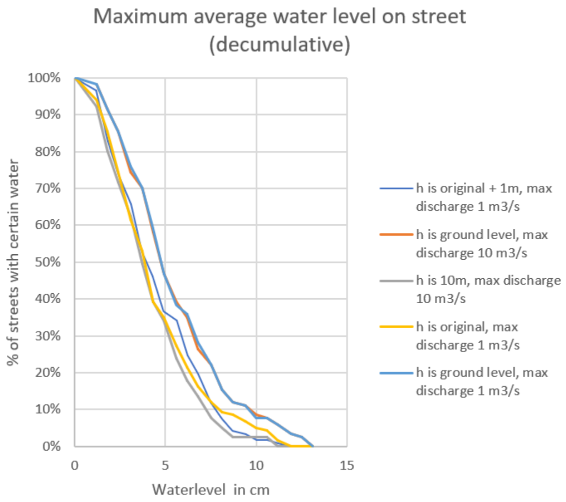
Table 13: NSE- and VE-value for sewer overflow height and maximum discharge parameter

Run	**27**	**28**	**29**	**30**	**31**
Sewer overflow capacity (in m^3/s)	1	10	10	1	1
Height overflow[1]	Original +1m	Ground level	10 m	Original	Ground level
NSE-value	0.639	0.873	0.394	-	0.866
VE-value	0.770	0.996	0.697	-	0.982

[1] For the heights in m per overflow, see Appendix E.

As can be seen in the table above, is that the water levels in the sections are strongly influenced by the different overflow heights.

In the following figure, the maximum average water level per street section can be seen as well as the variation of the maximum average water level.



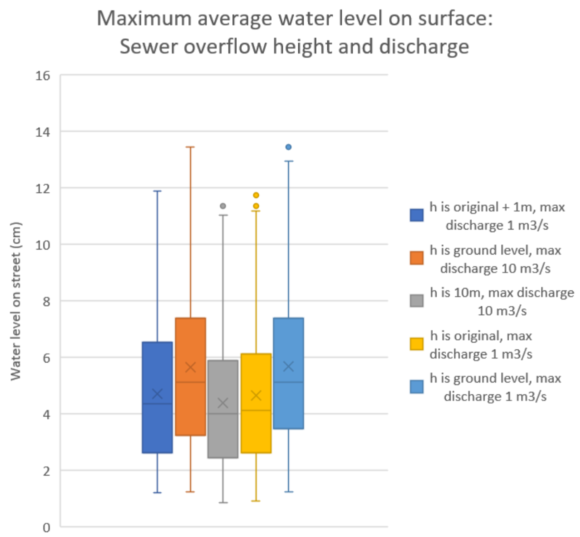


Figure 18a. The maximum average water level on the surface Figure 18b. The maximum average water level on the surface
Figure 18: Results of sensitivity analysis parameter sewer overflow height and discharge

Figure 18 shows that there is almost no difference between the two simulations with the same ground level heights while having different set maximum discharges. There can differences be seen between the runs and the variation are quite large. It can be seen that when the height is set at a point relatively high above the surface (10m or original with an additional meter), the water level does not reach the same maximum water level per section over time and drops even more, see Appendix G.4. This can also be seen in the discharges of the sewer overflow, in the following graph the discharges for all overflows combined through time can be seen.

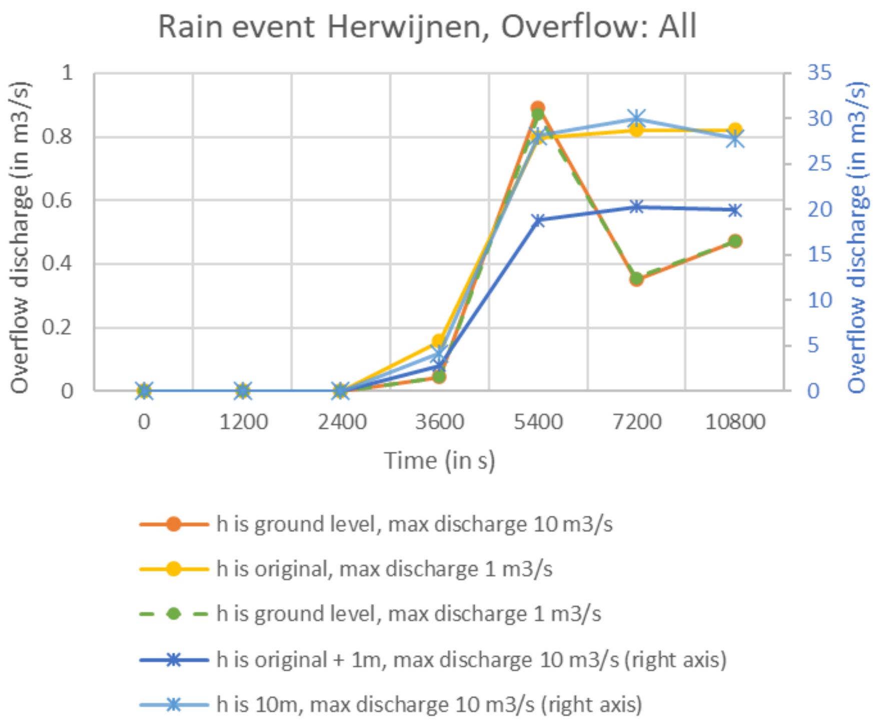


Figure 19: Overflow discharge of all overflows combined through time for different overflow heights and discharges

The above graph shows that the overflow in the run where the overflow height is set on 10 meters, can have a sewer overflow discharge of 10 m^3/s (there are three overflows so the total maximum discharge is 30 m^3/s).

Changing the overflow discharge has only an influence on the results as in combination the overflow height is also adjusted or is originally at a point relatively high above the surface.

4.2.7 Extra findings during sensitivity analysis

During the simulations for the sensitivity analysis, an extra investigation was put on where the water settled. As can be seen in Figure 13, a certain minimum level of water is at the end of the simulation. Since the sewer system was not full during these runs, it was questioned where the water did go.

Therefore, four different simulations were carried do diagnose the destination of the water flows. For these runs, different amounts of storage were used. The other parameters were set on the default values (see Appendix D for all values). The calculated storage (Area_Pump) is based on the dimensions of the sewer system as calculated in Table 5 on page 14. The storage of 20mm, means that there is enough storage to fit the whole Bui08 in the sewer system without making use of the sewer pump and/or overflow, for the parameters of this storage in Tygron see Appendix E.

Table 14: Water level on certain surface types for four different simulations

Run	45	44	46	29
Rain event	Bui08	Bui08	Herwijnen	Herwijnen
Sewer storge	Calculated storage (Area_Pump)	20mm	Calculated storage (Area_Pump)	20mm
Sewered area (including roads and buildings)	1.48 cm	0.02 cm	5.15 cm	3.62 cm
Construction, not sewered (sidewalks, etc.)	1.59 cm	0.79 cm	6.86 cm	5.09 cm
Open area (gardens etc.)	1.34 cm	0.77 cm	6.54 cm	4.82 cm
Agricultural fields	1.56 cm	1.47 cm	9.32 cm	8.14 cm
Neighbourhood	Average water level on the road			
Boskamp	2.73 cm	0.00 cm	8.34 cm	6.58 cm
Olst Zuid	2.28 cm	0.00 cm	6.66 cm	3.74 cm
Olst en Den Nul	3.55 cm	0.00 cm	13.39 cm	9.42 cm

The calculated storage is not enough to keep the roads free of water, both for the Bui08 and Herwijnen. The storage of 20mm, however, shows that there is enough capacity in the sewer system to have no water on the roads at Bui08. This is in line with the expectations since Bui08 should be able to fit completely in the sewer system. Despite that there is enough space in the sewer system for Bui08, still, some water ends in other types of areas and constructions. The water cannot flow towards sewered cells in the model.

4.3 Performance evaluation between the base-schematization in Tygron and InfoWorks

The performance evaluation between Tygron and InfoWorks is carried out in two steps. As described in Section 3.3, the first step of the performance evaluation is the overall performance evaluation and the second step is the street level performance evaluation.

4.3.1 Overall performance evaluation between Tygron and InfoWorks

For the overall performance evaluation, the Volumetric Efficiency was calculated as explained in Section 3.3. The VE-value per rain event is:

- For Bui08, the VE-value is -15.6
- For 60mm, the VE-value is -2.5
- For Herwijnen, the VE-value is -1.1

This means that there is an enormous difference between the volume of water on the surface. A negative VE-value means that there is more water on the surface in Tygron compared with InfoWorks. When looking at the overall performance per neighbourhood, large differences can be seen in the water on the surface.

Table 15: Volumetric differences between Tygron and InfoWorks per neighbourhood

Rain event	Bui08	60mm	Herwijnen
Total simulated volume Tygron (in m^3)	12,651	46,756	79,434
Total simulated volume InfoWorks (in m^3)	720	10,609	26,416
Total volumetric difference (in m^3)	11,931	36,147	53,019
Total volumetric difference (in percentage)	1657%	341%	201%
Volumetric difference in Olst en Den Nul (in %)	2196%	354%	207%
Volumetric difference in Olst Oost (in %)	1702%	532%	434%
Volumetric difference in Boskamp (in %)	334%	76%	28%

The Tygron model has in almost every neighbourhood more water on the surface at all rain events. Only at the two large rain events, 60mm and Herwijnen, there is less water on the surface in neighbourhood Boskamp compared with InfoWorks.

Table 16: Volume of water on the surface in neighbourhood Boskamp

Rain event	Bui08	60mm	Herwijnen
InfoWorks	184 m^3	1054 m^3	3148 m^3
Tygron	614 m^3	805 m^3	870 m^3

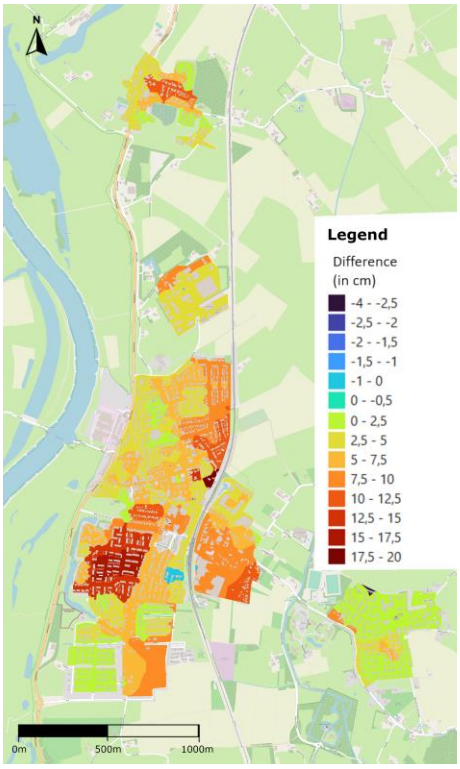
This can also be seen in the next section. An explanation for this could be that the overflow for the Boskamp area (5.25 m^3/s) is high compared with the other overflows (5.08 m^3/s for Olst en Den Nul and 2.02 m^3/s for Olst Zuid), see Appendix F.

The overall performance of Tygron, compared with InfoWorks is not satisfactory.

4.3.2 Street level performance evaluation between Tygron and InfoWorks

For the street level performance evaluation, there was looked at the different street sections.

In the following maps the absolute difference in centimetres can be seen, for the Herwijnen (left map) and Bui08 (right map) rain event, between the Tygron and InfoWorks models. Note that these are the absolute differences in the average water level on the surface per street section between Tygron and Infoworks.



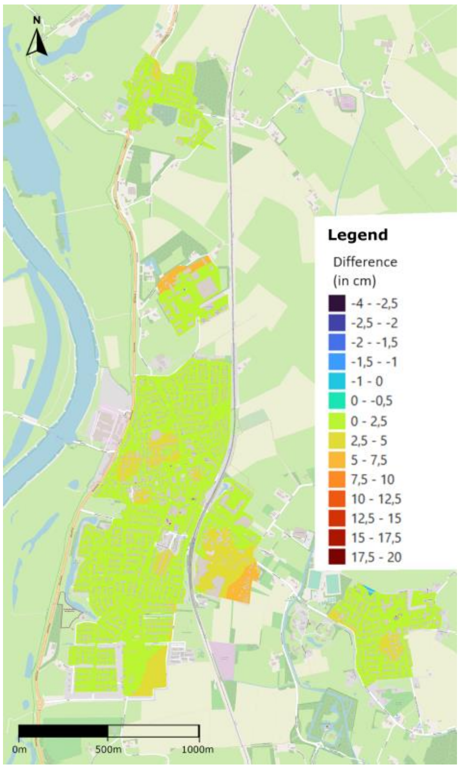


Figure 20a: Rain event Herwijnen *Figure 20b: Rain event Bui08*

Figure 20: Absolute difference between Tygron and InfoWorks (Tygron – InfoWorks)

In Bui08, there is only one street section where there is less water in the Tygron model compared with the InfoWorks model. The street section Anemoonstraat has 0.8 cm less water on the surface in Tygron compared with InfoWorks.

In the Herwijnen simulation, the absolute difference is in a range of -3.3 cm (Anemoonstraat) and +17.3 cm (J.W. Dumonstraat) between the water on the surface in Tygron compared with InfoWorks.

In general, it can be seen that in almost every section (with two exceptions), the average water level is almost always higher in Tygron compared with InfoWorks.

In the following graph, the maximum water levels can be seen for the three rain events and per model.

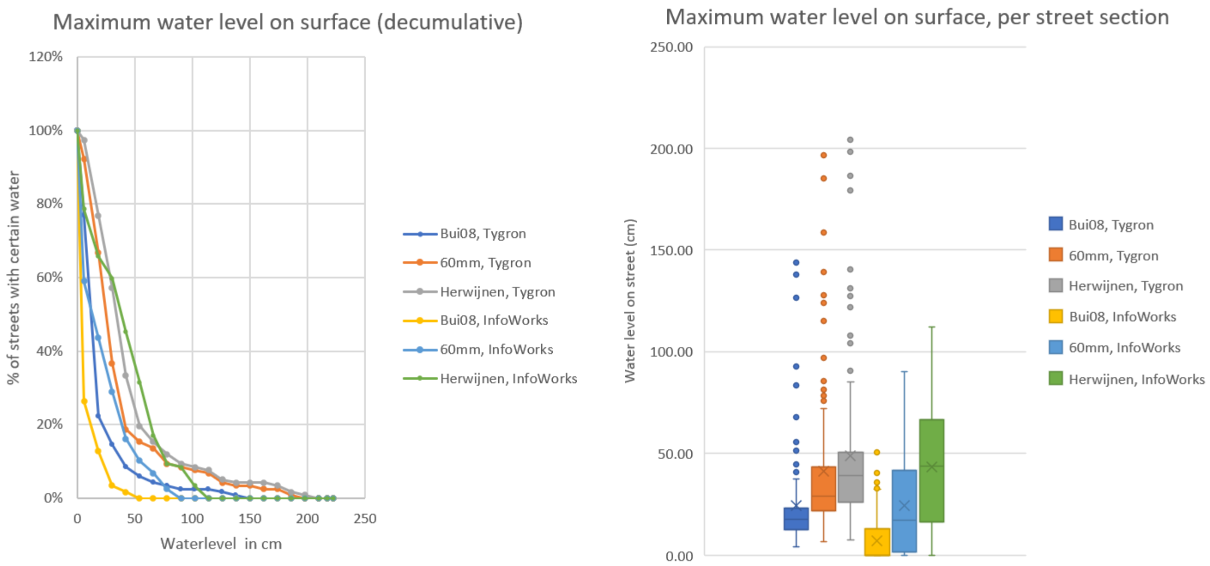


Figure 21a: Maximum water level on surface *Figure 21b: The maximum water level on the surface, variance*
Figure 21: Maximum water level for three rain events and two models

As can be seen, except for the outliers in Tygron, the variation in the InfoWorks model is larger then in Tygron. On average, the maximum simulated water level is lower in InfoWorks compared with Tygron. In Appendix 0 it can be seen that the percentual difference for Bui08 and Herwijnen are similar. If there is 70% more water in Tygron compared with InfoWorks, during Bui08, than this is also the case in the Herwijnen rain event.

In the following figures, the maximum water levels can be seen per grid cell (1x1 m) for both models with the rain event Herwijnen.

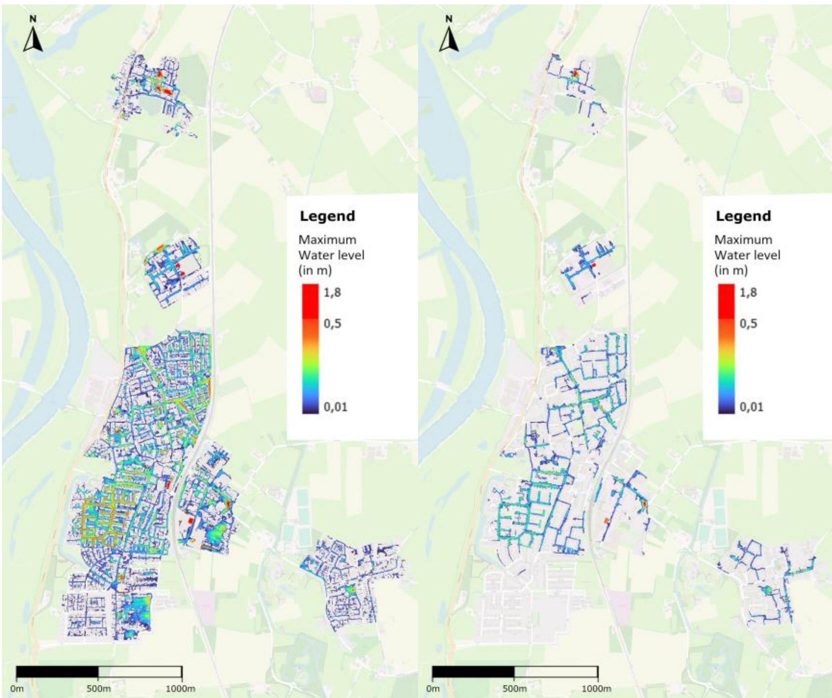


Figure 22a: Tygron *Figure 22b: InfoWorks*
Figure 22: Water levels per grid cell, Herwijnen rain event

The maximum water levels are in Tygron higher than in InfoWorks with the same rain event Herwijnen. However, the locations where the bottlenecks occur look similar. Therefore, in the following figure the top 10% of the water levels can be seen for both models. The colours indicate whether the maximum water level is simulated in Tygron, in InfoWorks or in both models.

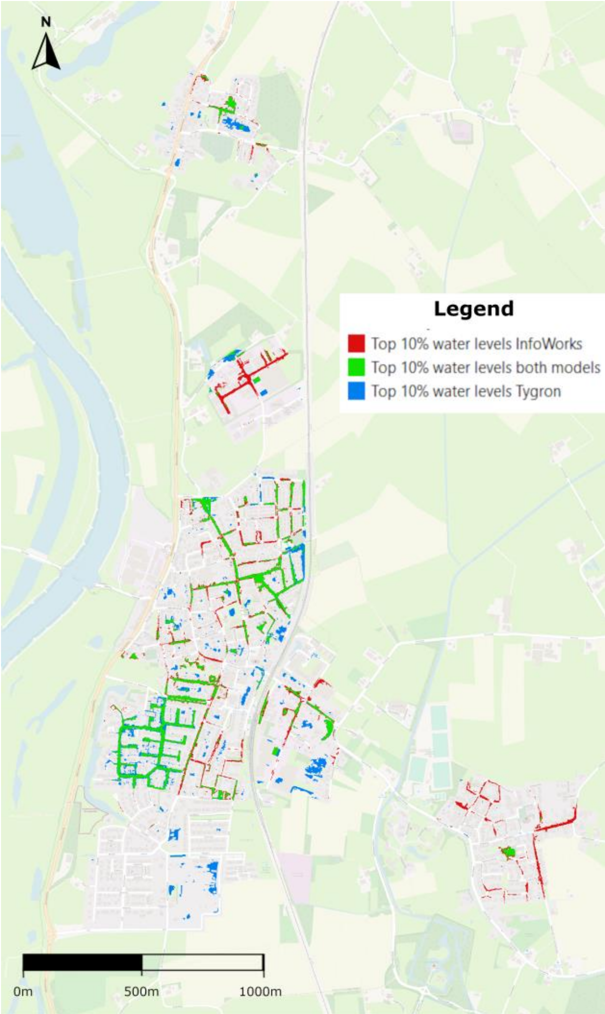


Figure 23: 10% highest water levels in Tygron and InfoWorks for Herwijnen rain event

Both models show that the highest water levels occur on similar places in neighbourhood Olst en Den Nul. For the 10% highest water levels, both models predict 70% at the same location within Olst en Den Nul. The other areas were simulated not that well with 37% for Olst Zuid and only 17% for Boskamp. Similar results were achieved for the highest 5 and 15% (see Appendix H.2). In the following table, the results per neighbourhood can be seen for the highest 10%.

Table 17: Highest 10% water levels per neighbourhood

	Olst Zuid	*Olst en Den Nul*	*Boskamp*	*Total*
Highest 10% water levels InfoWorks	38.4%	40.3%	69.2%	40.2%
Highest 10% water levels both models	36.8%	70.3%	16.5%	59.8%
Highest 10% water levels Tygron	63.1%	47.3%	2.3%	40.2%

This shows that Tygron makes a medium-well prediction for the location where the highest water levels occur and therefore where the bottlenecks are located.

5. Conclusion

In this Section, the answer to the research sub-questions is formulated. This is done in the same order as the questions were formulated.

5.1 Characteristics of the Tygron model

In the results, six different parameters were investigated. The different runs showed that the following parameters influence the outcome of the Tygron model. The conclusions in this part are drawn from the results of the sensitivity analysis. In the following table the NSE-values can be seen.

Table 18: NSE- and VE-values sensitivity analysis

Runs Grid size	**1**	**2**	**3**	**4**	**5**		
NSE-value	0.989	0.983	-	0.95	0.751		
VE-value	0.939	0.921	-	0.857	0.732		
Runs Initial groundwater depth	**6**	**7**	**8**	**9**			
NSE-value	-	1	1	1			
VE-value	-	1	1	0.999			
Runs pump capacity	**10**	**11**	**12**	**13**	**14**	**15**	**16**
NSE-value	0.77	0.782	0.858	0.926	-	0.865	0.371
VE-value	0.195	0.234	0.463	0.665	-	0.737	0.57
Runs Sewer storage	**17**	**18**	**19**	**20**	**21**	**22**	
NSE-value	0.981	0.984	-	0.981	0.951	0.981	
VE-value	0.865	0.935	-	0.865	0.907	0.501	
Runs Sewer overflow capacity	**23**	**24**	**25**	**26**			
NSE-value	1	-	0.999	0.998			
VE-value	1	-	1	0.994			
Runs Sewer overflow height	**27**	**28**	**29**	**30**	**31**		
NSE-value	0.639	0.873	0.394	-	0.866		
VE-value	0.77	0.996	0.697	-	0.982		

The grid size has a limited effect on the outcome of the model, however, the calculation time increases exponentially (from 5 minutes with a grid size 1x1 m to 8 hours with a grid size of 0.25x0.25 m). The small influence on the result can be explained due to that at the smallest grid size, 0.25x0.25 m, the data used does not differ compared with 0.5x0.5 grid size (see Table 1) since that is the smallest size on which data is available. Only the calculation steps and simulated water flows are smaller and should therefore give a more accurate result. The coarser the grid size is set, to 5x5m, the larger the outcome difference becomes. This is logical since the time step is increased next to that all input data is averaged as for example the elevation.

The outcome of the Tygron model is not sensitive to the initial groundwater depth parameter. Increasing or decreasing from the initial value Tygron provides, 1m, does almost give no difference in the maximum water levels at the surface. This was not expected and will be discussed in the Discussion (see Section 6.1).

According to the conceptual model, the pump capacity has a direct correlation with the water on the sewered cells. The higher the pump capacity, the more water can be transported taken by the sewer system and does not stay on the surface. The results show this correlation as well, the larger the pump capacity, the lower the water on the surface. The model outcomes are sensitive to the parameter pump capacity.

The results of the Tygron model are sensitive to the storage capacity of the sewer system. This can not only be seen in the results (see Section 4.2.4), but can also be explained by the conceptual way of modelling Tygron uses. The water can directly enter the sewer system when it is on a sewered cell and is only limited by the storage of the sewer system. Increasing the storage of the sewer system directly lowers the water level on the sewered buildings/areas (see Section 4.2.7, page 31).

As mentioned in the Results (see Section 4.2.5 and 4.2.6), the outcome of Tygron are only sensitive to the overflow capacity when there is enough height difference between the overflow and the surface. This can be explained by the conceptual model of Tygron (see Figure 5), the overflow has no discharge when the (water level on the) surface is higher than the overflow height, the point where the overflow can discharge. The outcome of the model is sensitive to the overflow capacity, however, this is only when the overflow can discharge the amount of water. This can be limited by the sewer overflow height. Setting the height of the sewer overflow is therefore just as important as choosing the capacity.

To summarise, *"Which schematization parameterization choices are relevant for implementing an area in Tygron?"*. The answer is that the results of Tygron are sensitive to the following parameters:

- The pump capacity of the sewer system
- The storage capacity of the sewer system
- The sewer overflow capacity combined with the sewer overflow height.

Based on the findings in the results and the conclusion, the parameters for the Tygron model, which will be used to answer the other research questions, were set. See Section 3.3 for the chosen values and the reasoning.

5.2 Water hindrance in Olst in Tygron simulations

The second research question was, *"What is the extent of water hindrance in Olst in Tygron simulations?"*.

The water hindrance extent in Olst, according to Tygron simulations, is large for rain events 60mm and Herwijnen when looking at the average water level per street section.

Table 19: (Average per street section) water level on surface in Olst in Tygron simulations

Rain event	Average (in cm)	Min (in cm)	Max (in cm)	Median (in cm)
Bui08	0.78	0.09	2.94	0.93
60mm	2.88	0.27	8.34	3.03
Herwijnen	4.90	1.01	16.98	4.95

Tygron simulates in Olst a minimum of 1 cm of water on the surface in a street section with a Herwijnen rain event. Also for the moderate rain event Bui08, water ends up on the surface.

When looking at the maximum simulated water levels in Tygron, water hindrance even occurs in 114 of the 117 street sections for Bui08 (a maximum water level of higher than 5cm).

5.3 Performance evaluation between Tygron and InfoWorks

The overall performance of Tygron compared with InfoWorks is not considered to be good. The schematization of Tygron was simulated with the values as close as possible to reality with adjustments made for the unrealistic events that could occur as described in the method. The Volumetric Efficiency yields negative results for all tested rain events, meaning that there is more water on the surface in

Tygron than in InfoWorks. There is 16.6 times more water simulated in the Tygron model for Bui08, 3.4 times more for 60mm rain event and 2 times more for the Herwijnen rain event.

At street level, Tygron and InfoWorks show similar results. On average, Tygron simulates more water on the surface in all street sections, two sections excluding. When comparing the highest maxima, the locations where this water level is simulated look similar. The Tygron model simulates 60%, of the 10% highest water levels in the same location as InfoWorks does. This shows that the model gives a moderate prediction of the location of the water hindrance. The performance of Tygron in simulating the highest water level in the same location as InfoWorks does, differs a lot per neighbourhood (17% in Boskamp, 37% in Olst Zuid and 70% in Olst en Den Nul).

As mentioned in the theoretical framework, Tygron and InfoWorks take a different approach when simulating rainwater events. It was described that especially the sewer system, is simplified in the Tygron model and the results showed that differences in the outcomes of the models occur.

This concludes the answer to the second research question, *"What are the differences in performance when simulating rain events in Tygron and InfoWorks?"*.

5.4 Main research question

The answer to the main research question, "*To what extent is Tygron capable of simulating stormwater hindrance in villages in the Netherlands?",* is based on all the findings, results and conclusions.

Tygron is not well capable of simulating the amount of hindrance due to stormwater in villages, however, Tygron is quite well in simulating the locations where the hindrance could occur.

6. Discussion

To assess the extent of hindrance due to stormwater in Olst, in this research, Tygron was used. The results of Tygron were tested on whether they are sensitive to different parameters. Furthermore, the schematisation of the Tygron model was compared with InfoWorks as well as that the results of both models were compared.

6.1 Sensitivity analysis

In the sensitivity analysis, most outcomes could be explained via the conceptual modelling of Tygron. However, the initial groundwater depth did give an unexpected outcome. It was expected that by setting the initial groundwater depth at 0 meters (ground level), no water could infiltrate and would cause higher water levels. Making the NSE- and VE-value lower than 1. This did not occur, the water levels on the surface changed minimally. The exact reason for this is unknown, it can be explained that the initial groundwater depth is increased or decreased towards the water levels in creeks and ponds in the case area before the rainwater is possible to infiltrate. However, this should not happen at the speed which is occurring in the simulations (Tygron, 2021a).

6.2 Schematisation of the sewer system

For the schematisation of the sewer system, Tygron makes multiple simplifications.

Firstly, water entering the sewer system is schematised differently in Tygron and InfoWorks. In InfoWorks, water flows to the closest manhole (Thiessen based). This is not limited by barriers that can lay in between the rain water and the manhole (such as a creek/wall). In Tygron, water will flow according to the elevation profile on the surface and can only enter the sewer system if it ends on a sewered cell. It does not matter where the droplet is located on the sewered cell for entering the sewer system. Both schematisations for entering the sewer system are different from reality in their own way.

The schematisation of the sewer system in Tygron (point-based construction) results in that when water has entered the sewer system in Tygron, it is unknown where the water came from. This simplification of reality results in that water can overflow at a higher location than the water did enter the sewer system. This can result in the discharge of the overflow can be entering the sewer system again via the sewered cells. Since there are multiple sewered constructions around the overflows, this phenomenon could have occurred although the sewer overflows were relocated at a small distance from the original location.

Thirdly, in the schematisation of the sewer system in Tygron, the water can only enter the sewer system via sewered cells. It is determined by Tygron whether a construction/area is connected to the sewer system. It can be discussed whether, for example, sidewalks and parking spots are sewered or not. The outcome could be different if other cells are sewered. However, since the total storage will be the same, large differences are not expected.

Lastly, in reality, water can enter the sewer system in higher elevated areas while water cannot enter the sewer system in lower elevated areas due to that the lower located sewer system is already full. In reality, water can come out of the manholes in these lower elevated areas. Water cannot overflow via manholes in Tygron. Water that would, in reality, flow from high elevated areas to lower elevated areas via the sewer system, will not end up in lower elevated areas due to the simplifications made in Tygron. Therefore, decreased water levels may be seen in low elevated areas whereas increased water levels may be seen in high elevated areas. This is in contradiction with InfoWorks where the elevation of the sewer system is taken into account. In InfoWorks, the water can flow back to the surface via manholes.

7. Recommendations

7.1 Practical recommendations for cases where Tygron is used

Tygron is not capable of doing a complete detailed water assessment for villages in the Netherlands, however, Tygron has shown that, compared with InfoWorks, it can predict the location of where water hindrance can occur. Therefore, it is recommended to use Tygron for the following purpose.

Tygron can be used to do a quick scan to check where the largest bottlenecks occur.

It is recommended to set the sewer overflow height at surface level plus one meter. This is not as it would be in reality, however, the results of this research show that the discharge of the overflow can be limited extremely by the surface level whereas a certain overflow is expected. Increasing the overflow height prevents this and lets the sewer overflow discharge at its maximum given rate

7.2 Usage of Tygron for Witteveen+Bos

Tygron promotes itself to have the predictive power to do multiple assessments in the same software. This research shows that Tygron is not capable of doing a complete assessment of the extent of hindrance due to stormwater. In this section, the cases where Tygron has shown to have predictive and can be used will be discussed as well as cases where the predictive power of Tygron falls short and should not be used.

This research shows that Tygron can be used for quick scans to assess the location of water hindrance. Tygron shows similar results in the location of where high water levels are simulated compared with InfoWorks.

However, since the sewer system is simulated as a point-based bucket model in Tygron, Tygron cannot be used for making a design for the sewer pipes and or their dimensions. This is since, the model cannot take into account; the slope, the dimensions or the location of the sewer pipes/manholes. Furthermore, based on this research, it is not possible to design the complete storage capacity of the sewer system in Tygron. This due to that the sewer system is influenced by many parameters. Next to that, the schematisation of the sewer system shows that the sewer pump starts pumping directly when water enters the sewer system, independently of its location.

7.3 Recommendations for further research

Most of the Tygron simulations were carried out on sewer areas which were determined by the location of the sewer pumps. The final assessment of hindrance due to stormwater in Olst and the comparison between results of Tygron and InfoWorks were carried out on this pump location based sewer areas. However, since there were multiple sewer overflows, their location could also have been used as the basis for the sewer areas (see Appendix E for the sewer maps). As shown in the sensitivity analysis, the results are sensitive to which sewer area is used. This could be because of the area of the overflow based sewer system is larger. However, further research on the sewer area should be done to make sure if it really change the conceptual modelling of Tygron or whether it is due to change is size.

For steeper elevation areas, this research focussed on an area with a rather flat sloped elevation, it is interesting to see whether implementing sewer overflows of high elevated areas can be placed in lower elevated areas. This would simulate the overflow of manholes in low areas. The potential of this research would be that it can be checked whether Tygron can be used in areas with more elevation differences.

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Appendices

A. Rain events

For the rain events multiple rain events were used. In the following Table their intensities over time can be seen.

Table 20: Rain event and their intensities over time (RIONED, 2019).

Time (s)	Bui08 (mm)	Herwijnen (mm)	60mm (mm)
300	0.3	0	50
600	0.6	0	50
900	0.9	0	50
1200	1.2	0	50
1500	1.5	2.05	50
1800	2.1	2.05	50
2100	2.7	9.75	50
2400	3.3	9.75	50
2700	3.3	6.25	50
3000	2.1	6.25	50
3300	1.2	10.1	50
3600	0.6	10.1	50
3900	0	11.35	0
4200	0	11.35	0
4500	0	5	0
4800	0	5	0
5100	0	1.8	0
5400	0	1.8	0
5700	0	0.1	0
6000	0	0.1	0
6300	0	0.05	0
6600	0	0.05	0
6900	0	0.1	0
7200	0	0.1	0
7500	0	0.05	0
7800	0	0.05	0
8100	0	0	0
8400	0	0	0
8700	0	0.1	0
9000	0	0.1	0
9300	0	0.05	0
9600	0	0.05	0
9900	0	0.05	0
10200	0	0.05	0
10500	0	0	0
10800	0	0	0

B. Corrected constructions

The location and radius of the weirs and culverts are known (WDOD, 2021). However, they need small adjustmenst before Tygron can use them for calculations. Culverts in Tygron can olny consist out of straigth lines. Every angle would be seen if it was the end or begin fo a culvert. The advice of Tygron is that the culvert is redrawn, while keeping it radius of the original data . In the following figure an example of a redrawing can be seen.

Figure 24: In orange, the location of the real culvert. In green, the simulated culvert.

As can be seen, the original culvert was replaced by two straight culverts. The depicts the water across a barrier via the following way.

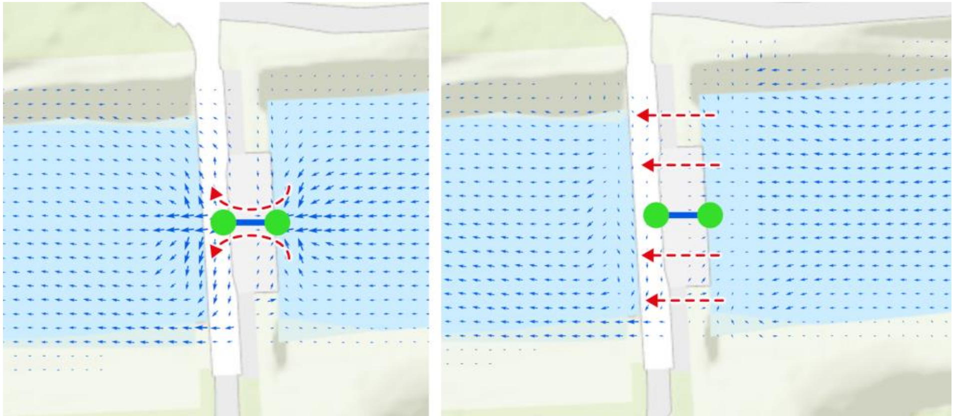


Figure 25: Depiction how water is transferred *via a culvert in Tygron* (Tygron, 2020c).

C. Sewered cells

The following 69 types of buildings/pavement are located in the Tygron model according to the cadastral information (PDOK & Kadaster, 2022b).

Table 21: All types of buildings/areas and whether they are sewered or not

Sewered	Function	Sewered	Function	Sewered	Function
No	Afvalbak	No	Pijp voor gevaarlijke stoffen	Yes	Klassieke middenklasse woning
No	Akkerbouwgewassen	No	Riooloverstort	Yes	Klinkerwegen
No	Bedrijventerrein	No	Schuur	Yes	Loodsen
No	Braakliggend terrein	No	Spoorlijn	Yes	Luxe appartementen
No	Duiker	No	Stadsbankje	Yes	Middenklasse woning
No	Fietsenrek	No	Standaard loofbomen	Yes	Moderne villa
No	Fietsersbrug	No	Standaard naaldbomen	Yes	Monumentaal pand
No	Fietspaden	No	Standaard tuin	Yes	Naoorlogse luxe appartementen
No	Fruitbomen	No	Stoep	Yes	Naoorlogse middenklasse woning
No	Gesloten verharding	No	Straatbrug	Yes	Naoorlogse sociale woningbouw
No	Graanvelden	No	Stuw	Yes	Naoorlogse villa
No	Grasland	No	Tuinbouw	Yes	Oud gebouw
No	Half verharde stadsruimte	No	Verharde loopbrug	Yes	Oude loodsen
No	Hoofdweg brug	No	Verkeersbord	Yes	Oude middenklasse woning
No	Hoogspanningsmast (klassiek)	No	Voetgangerspad	Yes	Oude villa
No	Houten hek	No	Windmolen (klassiek)	Yes	Overige functie
No	Maisvelden	No	Woonwagen	Yes	Religieus gebouw
No	Muur	Yes	Hedendaags onderwijsgebouw	Yes	Restaurant
No	Ondergrondse installatie voor gevaarlijke stoffen	Yes	Hoofdweg	Yes	Sociale woningbouw
No	Ondergrondse opslag met gevaarlijke stoffen	Yes	Installatie met gevaarlijke stoffen	Yes	Sportcentrum
No	Ondergrondse parkeergarage	Yes	Kantoren	Yes	Wegen
No	Open stadsruimte	Yes	Klasieke sociale woningbouw	Yes	Winkels
No	Parkeergelegenheid	Yes	Klassiek kantoor	Yes	Ziekenhuis

D. Input for Tygron models

In the table below the different parameters can be seen for every simulation run, the name of the file is shown as the field name.

Table 22: Parameters in the water overlay Configuration Wizard which differ per simulation run

Run	Name of the run	Rainevent[1]	Grid size (mxm)	Groundwater depth (m)	Sewer storage capacity[2]	Sewer pump capacity[3] (m^3/s)	Sewer overflow height[4]	Sewer overflow discharge (m^3/s)	Number of overflows[5]
1	Bui08_025m2	Bui08	0.25x0.25	1	Area_Pump	Based on real	Original	1	3
2	Bui08_05m2	Bui08	0.5x0.5	1	Area_Pump	Based on real	Original	1	3
3	Bui08_1m2	Bui08	1x1	1	Area_Pump	Based on real	Original	1	3
4	Bui08_2m2	Bui08	2x2	1	Area_Pump	Based on real	Original	1	3
5	Bui08_5m2	Bui08	5x5	1	Area_Pump	Based on real	Original	1	3
6	Base_Pumps	Bui08	1	1	Area_Pump	Based on real	Original	1	3
7	Bui08_GW_D_0m_Pumps	Bui08	1	0	Area_Pump	Based on real	Original	1	3
8	Bui08_GW_D_100m_Pumps	Bui08	1	100	Area_Pump	Based on real	Original	1	3
9	Bui08_GW_D_10m_Pumps	Bui08	1	10	Area_Pump	Based on real	Original	1	3
10	Bui08_GW_D_1m	Bui08	1	1	DIM_BK_AREASW	1	Original	1	5
11	Bui08_SW_Q_0032	Bui08	1	1	DIM_BK_AREASW	0.032	Original	1	5
12	Bui08_SW_Q_025	Bui08	1	1	DIM_BK_AREASW	0.25	Original	1	5
13	Bui08_SW_Q_050	Bui08	1	1	DIM_BK_AREASW	0.5	Original	1	5
14	Bui08_SW_Q_150	Bui08	1	1	DIM_BK_AREASW	1.5	Original	1	5
15	Bui08_SW_Q_200	Bui08	1	1	DIM_BK_AREASW	2	Original	1	5
16	Bui08_SW_Q_null	Bui08	1	1	DIM_BK_AREASW	0	Original	1	5
17	Bui08_SW_ST_Age	Bui08	1	1	AGEBASED	1	Original	1	5
18	Bui08_ST_Null_Pumps	Bui08	1	1	Null	Based on real	Original	1	3
19	Bui08_ST_AgeBased_Pumps	Bui08	1	1	Area_Pump_Age	Based on real	Original	1	3
20	Bui08_Base_Pumps	Bui08	1	1	Area_Pump	Based on real	Original	1	3
21	Bui08_ST_Null	Bui08	1	1	Null	Based on real	Original	1	5
22	Bui08_ST_DimBK	Bui08	1	1	DIM_BK_AREASW	Based on real	Original	1	5
23	Herwi_Base_Pumps	Herwi	1	1	Area_Pump	Based on real	Original	1	3
24	Herwi_SO_Q_0_Pumps	Herwi	1	1	Area_Pump	Based on real	Original	0	3
25	Herwi_SO_Q_10_Pumps	Herwi	1	1	Area_Pump	Based on real	Original	10	3
26	Herwi_SO_Q_10_H_Groundlevel_Pum	Herwi	1	1	Area_Pump	10	Grond niveau	10	3
27	Herwi_h1mhoger	Herwi	1	1	Area_Pump_20mm	Based on real	Original+1	1	3
28	Herwi_H10m	Herwi	1	1	Area_Pump_20mm	Based on real	10	10	3
29	Herwi_20mm	Herwi	1	1	Area_Pump_20mm	Based on real	Original	1	3
30	Herwi_o_1_h_maaiveld	Herwi	1	1	Area_Pump_20mm	Based on real	Maaiveld	1	3
31	Herwi_o_10_h_maaiveld	Herwi	1	1	Area_Pump_20mm	Based on real	Maaiveld	10	3
32	Bui08_GW_D_0m	Bui08	1	0	DIM_BK_AREASW	1	Original	1	5

Run	Name of the run	Rainevent[1]	Grid size (mxm)	Groundwater depth (m)	Sewer storage capacity[2]	Sewer pump capacity[3] (m^3/s)	Sewer overflow height[4]	Sewer overflow discharge (m^3/s)	Number of overflows[5]
33	Bui08_GW_D_100m	Bui08	1	100	DIM_BK_AREASW	1	Original	1	5
34	Bui08_GW_D_10m	Bui08	1	10	DIM_BK_AREASW	1	Original	1	5
35	Bui08_SW_Q_Pumps	Bui08	1	1	Area_Pump	Based on real	Original	1	3
36	Herwi_GW_D_0m	Herwi	1	0	DIM_BK_AREASW	1	Original	1	5
37	Herwi_GW_D_10m	Herwi	1	10	DIM_BK_AREASW	1	Original	1	5
38	Herwi_GW_D_10m	Herwi	1	10	DIM_BK_AREASW	1	Original	1	5
39	bui08_h1mhoger	bui08	1	1	Area_Pump_20mm	Based on real	Original+1	1	3
40	Bui60mm_h1mhoger	Bui60	1	1	Area_Pump_20mm	Based on real	Original+1	1	3
41	bui08_h10m	bui08	1	1	Area_Pump_20mm	Based on real	10	10	3
42	bui60mm_h10m	bui60	1	1	Area_Pump_20mm	Based on real	10	10	3
43	60mm_20mm	60mm_	1	1	Area_Pump_20mm	Based on real	Original	1	3
44	Bui08_20mm	Bui08	1	1	Area_Pump_20mm	Based on real	Original	1	3
45	BaseBui08	BaseB	1	1	Area_Pump	Based on real	Original	1	3
46	BaseHerwijnen	BaseH	1	1	Area_Pump	Based on real	Original	1	3
47	BaseBui60mm	BaseB	1	1	Area_Pump	Based on real	Original	1	3
48	60mm_o_10_h_maaiveld	60mm_	1	1	Area_Pump_20mm	Based on real	Maaiveld	10	3
49	60mm_oq_calc_h_maaiveld	60mm_	1	1	Area_Pump_20mm	Based on real	Maaiveld	Calc	3
50	bui08_o_10_h_maaiveld	bui08	1	1	Area_Pump_20mm	Based on real	Maaiveld	10	3
51	bui08_oq_calc_h_maaiveld	bui08	1	1	Area_Pump_20mm	Based on real	Maaiveld	Calc	3
52	Herwi_oq_calc_h_maaiveld	Herwi	1	1	Area_Pump_20mm	Based on real	Maaiveld	Calc	3
53	Herwi_oq_all_h_maai_1_st_calc	Herwi	1	1	Area_Pump	Based on real	Maaiveld+1	All	3
54	Bui08_oq_all_h_maai_1_st_calc	Bui08	1	1	Area_Pump	Based on real	Maaiveld+1	All	3
55	60mm_oq_all_h_maai_1_st_calc	60mm_	1	1	Area_Pump	Based on real	Maaiveld+1	All	3
56	60mm_oq_all_h10_st_calc	60mm_	1	1	Area_Pump	Based on real	10	All	3
57	Bui08_oq_all_h10_st_calc	Bui08	1	1	Area_Pump	Based on real	10	All	3
58	Herwi_oq_all_h10_st_calc	Herwi	1	1	Area_Pump	Based on real	10	All	3
59	Bui08_so_all_correct_h_10	Bui08	1	1	Area_Pump	Based on real	10	All	3
60	60mm_so_all_correct_h_10	60mm_	1	1	Area_Pump	Based on real	10	All	3
61	Herwi_so_all_correct_h_10	Herwi	1	1	Area_Pump	Based on real	10	All	3
62	Bui08_so_all_correct_h_maai_1	Bui08	1	1	Area_Pump	Based on real	Ground level	All	3
63	60mm_so_all_correct_h_maai_1	60mm_	1	1	Area_Pump	Based on real	Ground level	All	3
64	Herwi_so_all_correct_h_maai_1	Herwi	1	1	Area_Pump	Based on real	Ground level	All	3

[1] The rain events, their duration and intensity can be seen in Appendix A
[2] There are six different sewer storages used for the runs. The storage capacity can be seen in Appendix E
[3] Sewer pump discharge, based on real means the calculated discharge as can be seen in Table 3
[4] Sewer overflow height original is the height of the sewer overflow as it is in the real world, ground level is the ground level around the sewer overflow
[5] The number of overflows is not the same for every run, the locations can be seen in Appendix E

E. Sewer storages

There are multiple options for the sewer storages. They are based on the height of the bucket as well as on the area of the bucket. For this research two different maps for the area were used. These can be seen in the following figures

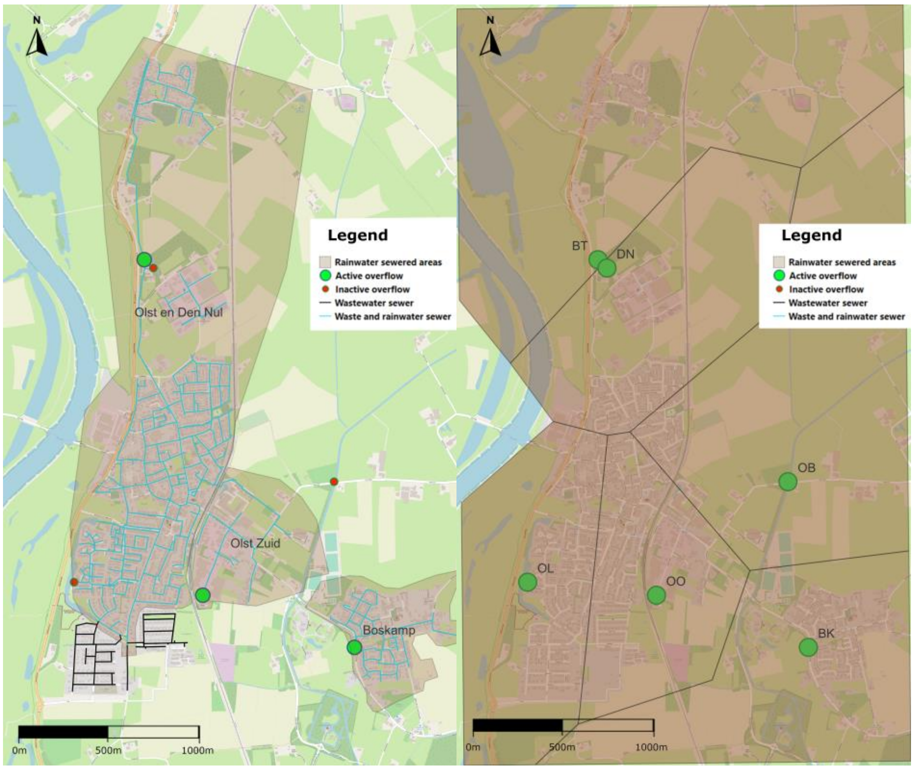


Figure 26a. Based on in summation active pumps *Figure 26b. Based on Thiessen*
Figure 26: Sewer areas

In the following Table, the different storages (in mm) can be seen as well for the map shown in Figure 26a.

Table 23: Sewer storage for area based on pumps

Storage	Runs	Boskamp (in mm)	Olst en Den Nul (in mm)	Olst Zuid (in mm)
Null	18	0	0	0
Storage age based (in mm)	19	3.8	3.565	4
Area_Pump (in mm)	1, 2, 3, 4, 5, 6, 7, 8, 9, 20, 23, 24, 25, 26, 35, 45, 46, 47, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64	6.00	10.68	4.64
Area_Pump_20mm (in mm)	27, 28, 29, 30, 31, 39, 40, 41, 42, 43, 44, 48, 49, 50, 51, 52	107.8	107.8	138.0

For Area_Pump_20mm, a calculation was made. The base assumption for these runs was that the whole Bui08 should fit in the sewer system, whithout the pumps being used. Since the sewer storage is the height of the bucket, the total amount of water from Bui08 should be multiplied by the total sewered area devided by the sewered cells. The following table shows this calculation.

For Age based, according to the automatic settings of Tygron, neighbourhoods before 1965 have storage of 0.7 mm and after 1965 have 4 mm of storage (Tygron, 2021c). Since the construction date of the sewer pipes was known, the estimated sewer storage based on age could be calculated.

Table 24: Calculation of storage Area_Pump_20mm

Neighbourhood	Area wijk (m^2)	Area Sewered (m^2)	Height (mm)
Boskamp	398764	71836	107.8288
Olst en Den Nul	439977	79250	107.8429
Olst Zuid	2839875	399855	137.9614

In the following table, the storages can be seen for the areas based on Thiessen (see Figure 26b)

Table 25: Sewer storage for area based on Thiessen

Storage	**Run**	**BK (in mm)**	**BT (in mm)**	**DN (in mm)**	**OB (in mm)**	**OL (in mm)**	**OO (in mm)**
Null	21	0	0	0	0	0	0
Storage age based (in mm)	17	3.8	3.273	3.863	3.808	3.314	4
Dim_BK_AREASW (in mm)	10, 11, 12, 13, 14, 15, 16, 22, 32, 33, 34, 36, 37, 38	5.973	12.82	8.042	11.464	7.177	9.46

F. Maximum overflow capacity based on Chézy equation

As explained in the Methodology (see page 11), the maximum overflow was determined by the limit set by the Chézy equation:

$V = C\sqrt{R_h i}$ where:
V is the velocity of the water through a channel/pipe $(m\ s^{-1})$
C is the Chézy coefficient $(m^{1/2}\ s^{-1})$, which is $C = 18\log(12R/k)$
R_h is the hydraulic radius (m)
i the hydraulic gradient $(-)$ which is the slope of the pipe $(\Delta h/L)$
Δh is the height difference between the beginning and the end of the conduit (m)
L is the length of the conduit (m)
k is the Nikuradse rougness coefficient (m)

The hydraulic radius is A/P where A is the cross sectional area of the flow and P is the wetted perimeter of this cross section. It is assumed that the maximum flow through the pipe means that the pipe is also completely filled. Therefore the cross sectional area (A) is equal to the cross section of the pipe and the wetted perimeter (P) is equal to the radius of the pipe. Due to this:

$$R = \frac{A}{P} = \frac{\pi r^2}{2\pi r} = \frac{r}{2} = \frac{d}{4}.$$

The maximum discharge can be calculated by multiplying the velocity with the area of the pipe:

$$Q = A\,V = 2\,\pi\,r\,18\log\left(\frac{12\frac{d}{4}}{k}\right)\sqrt{\frac{d}{4}\frac{\Delta h}{L}} = 18\,\pi\frac{d}{2}\log\left(\frac{3d}{k}\right)\sqrt{d\frac{|h_1-h_2|}{L}}$$

$Q = 9\,\pi\,d\log\left(\frac{3d}{k}\right)\sqrt{d\,\frac{|h_1-h_2|}{L}}$ where:
d is the diameter of the pipe (m)
k is the wallroughness of the pipe, 0.002 (m)
h_1 and h_2 the height of respecitvely the start and the end of the pipe (m)
L is the length of the tube (m)

In the following Table the different dimensions of the 14 sewer pipes can be seen (WDOD, 2021).

Table 26: Dimensions of different sewer pipes can be seen used to calculate the maximum possible discharge

Connection or in front of sewer overflow	Pipe label	d (m)	h1 (m)	h2 (m)	L (m)	Q (m^3/s)
BT	644	1	0.52	0.62	61.45	3.62
BT	2932	1	0.45	0.4	49.13	2.86
OO	516	0.4	2.62	2.53	19.63	0.54
OO	515	0.4	2.53	2.46	25	0.42
BK	294	1	1.6	1.63	8.77	5.25
OL	436	0.5	2.25	2.14	36.85	0.79
OL	435	0.6	1.55	1.5	2.86	3.08
OL	434	0.5	2.02	2.15	45.71	0.77
OB	491	0.4	2	1.87	285.16	0.17
OB	492	0.4	1.72	1.68	195.65	0.11
DN	276	1	0.55	0.4	102.81	3.43
BT	643	1	0.68	0.62	57.6	2.90
DN	274	0.7	0.57	0.54	106.25	0.59
DN	275	0.7	0.75	0.57	111.25	1.41

This results in the average maximum discharge based on two or more pipes per overflow:

Table 27: Discharge per sewer overflow, the average of the pipes in Table 26

Overflow	Area	Maximum discharge (m^3/s)
BT	Olst en Den Nul	3.13
OO	Olst Zuid	0.48
BK	Boskamp	5.25
OL	Olst Zuid	1.54
OB	Olst en Den Nul	0.14
DN	Olst en Den Nul	1.81

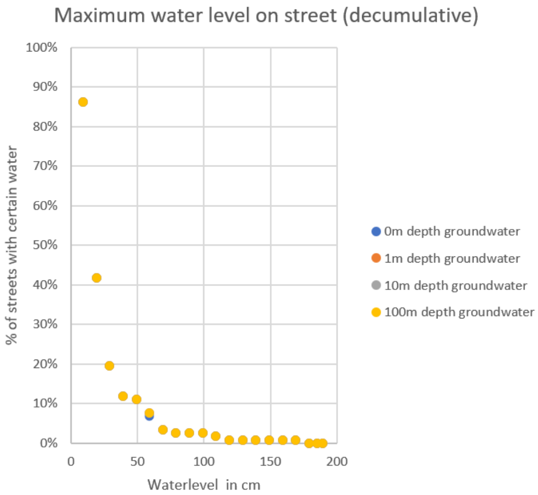
Resulting in the maximum discharge per sewer area:

Table 28: Maximum overflow discharge per sewer area, the sum of the pipes in Table 27

Area	Total maximum discharge (m^3/s)
Olst en Den Nul	5.08
Olst Zuid	2.02
Boskamp	5.25

G. Results sensitivity analysis

G.1. Initial groundwater depth



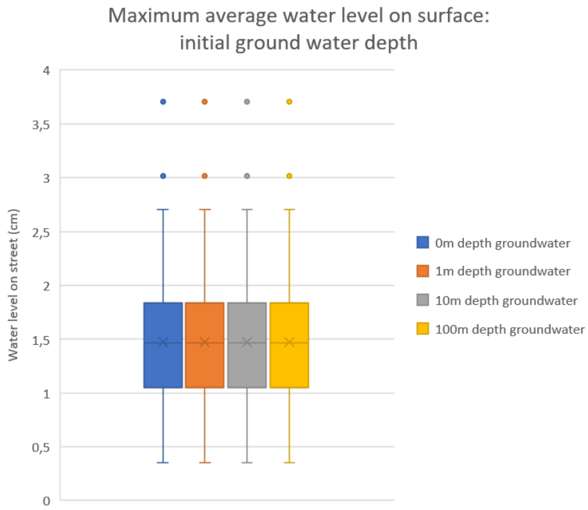
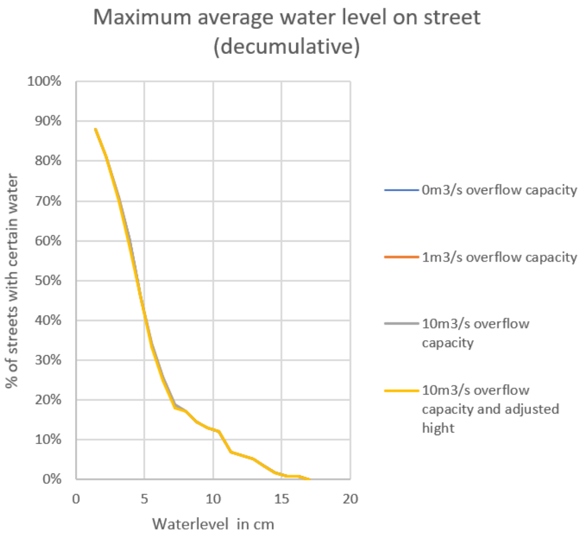


Figure 27a. Maximum water level on surface *Figure 27b. The maximum average water level on the surface*

Figure 27: Results sensitivity analysis initial groundwater depth

G.2. Sewer overflow capacity



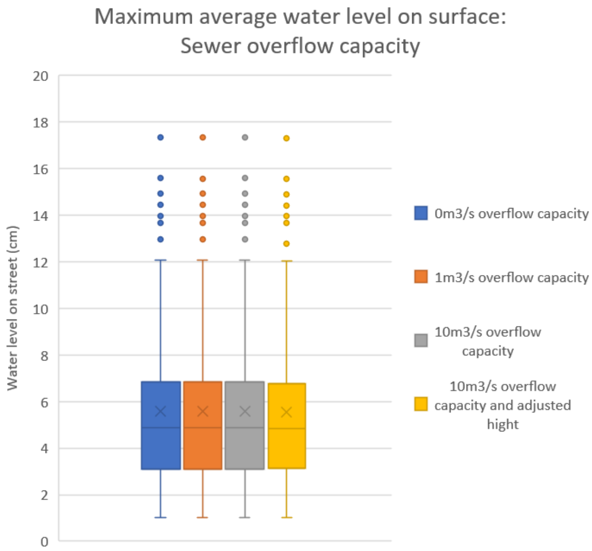
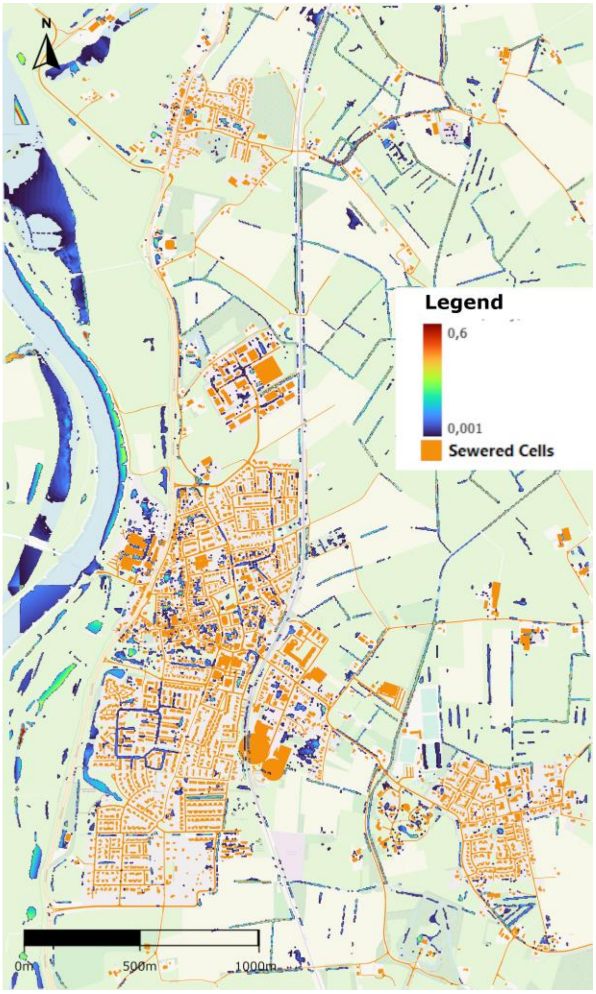


Figure 28a. Maximum average water level on surface *Figure 28b. The maximum average water level on*

Figure 28: Results sensitivity analysis sewer overflow capacity

G.3. Pump capacity

Part of the water cannot reach the sewer system as mentioned in Section 4.2.3. In the following images the water level can be seen as well as the location.



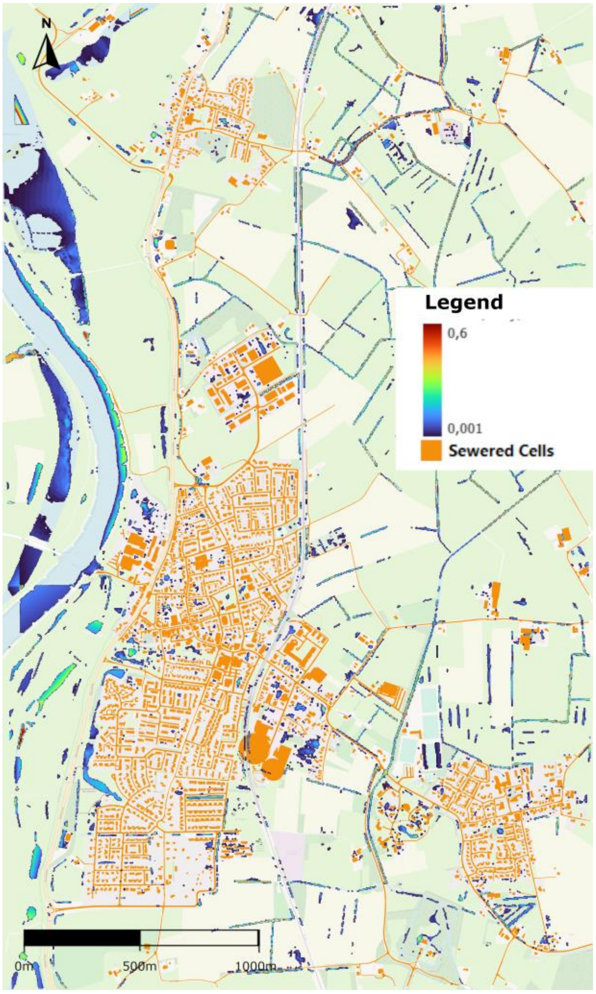


Figure 29a. Pump capacity of 0.032 m3/s *Figure 29b. Pump capacity of 0.25 m3/s*

Figure 29: Water levels can be seen after a 30 hour simulation run for Bui08

As can be seen is that there is almost no water present on the sewered cells after 30 hours when the pump capacity is 0.25 m^3/s compared with quite some water on the sewered cells after 30 hours in the 0.032 m^3/s simulation.

G.4. Sewer overflow height

In the following graph, the water level on the surface per street section can be seen through time. Per simulation the water overflow height and the discharge is changing.

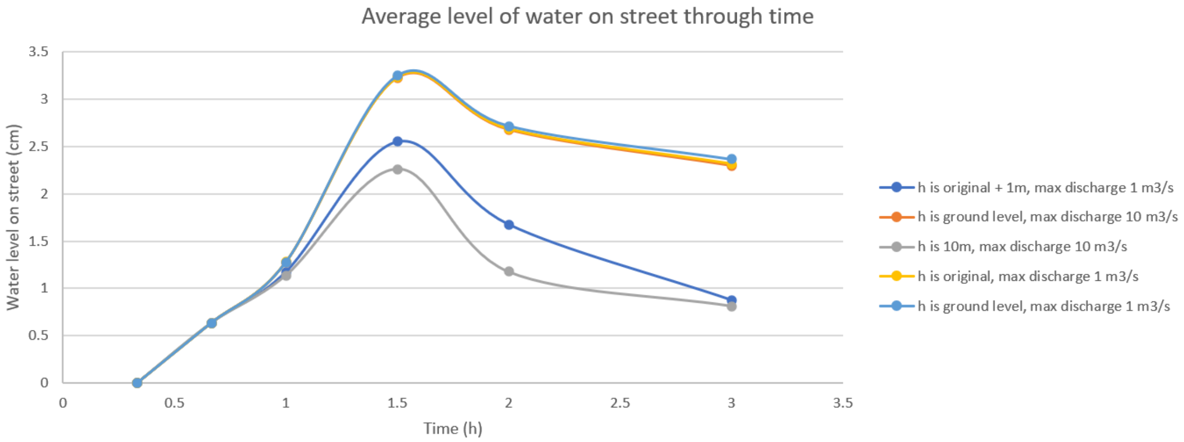


Figure 30: Average water level on surface through time for sewer overflow height and discharge parameter

In the above graph, can be seen that when the height is set at a point relatively high above the surface, the water level does not reach the same maximum and drops even more.

H. Results performance evaluation between Tygron and InfoWorks

The performance evaluation between Tygron and InfoWorks is carried out in two steps. As described in Section 3.3, the first step of the performance evaluation is the overall performance evaluation and the second step is the street level performance evaluation.Street level performance evaluation between Tygron and InfoWorks

In the following maps, the percentual difference between Tygron and InfoWorks for the rain events Herwijnen and the Bui08 can be seen. Note that these are the maximum simulated water levels within the section. A street section has no colour when the maximum water level is lower than 1 mm in the InfoWorks model.

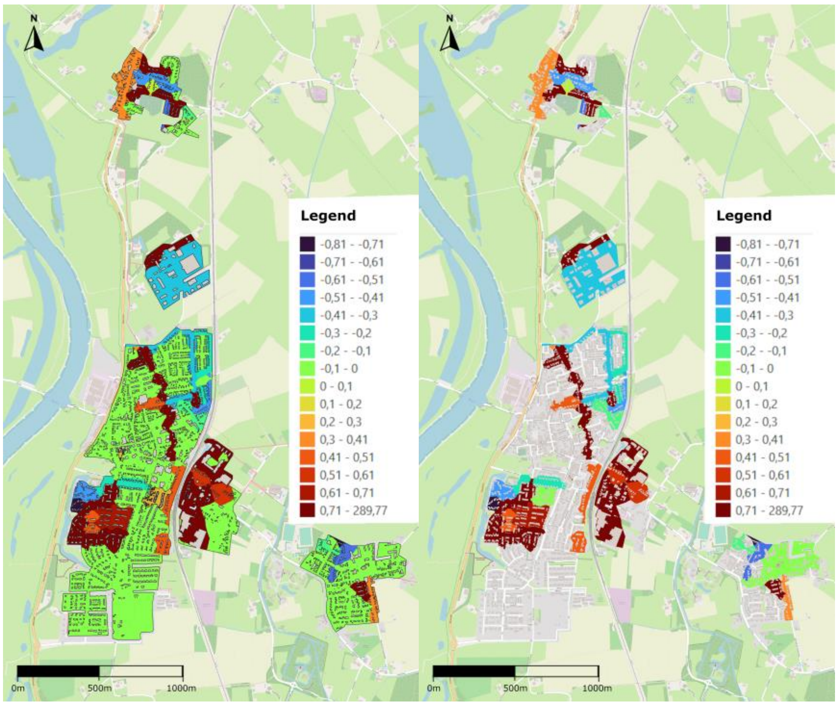


Figure 31a: Rain event Herwijnen *Figure 31b: Rain event Bui08*

Figure 31: Percentual difference between Tygron and InfoWorks for the maximum water level measured in the area

For most areas in neighbourhood Olst en Den Nul and Boskamp the percentual difference is between 0 and -10% in the Herwijnen simulation. This is not an extreme large difference. For both Herwijnen and Bui08, it can be seen that the difference is in the same range for the same section.

H.2. Highest water levels measured in Tygron and InfoWorks

In the two following figures the location can be seen of the highest 5% and 15% water leves. The figures indicate whether the water level was simulated in Tygron, InfoWorks or that it was the highest water level in both models.

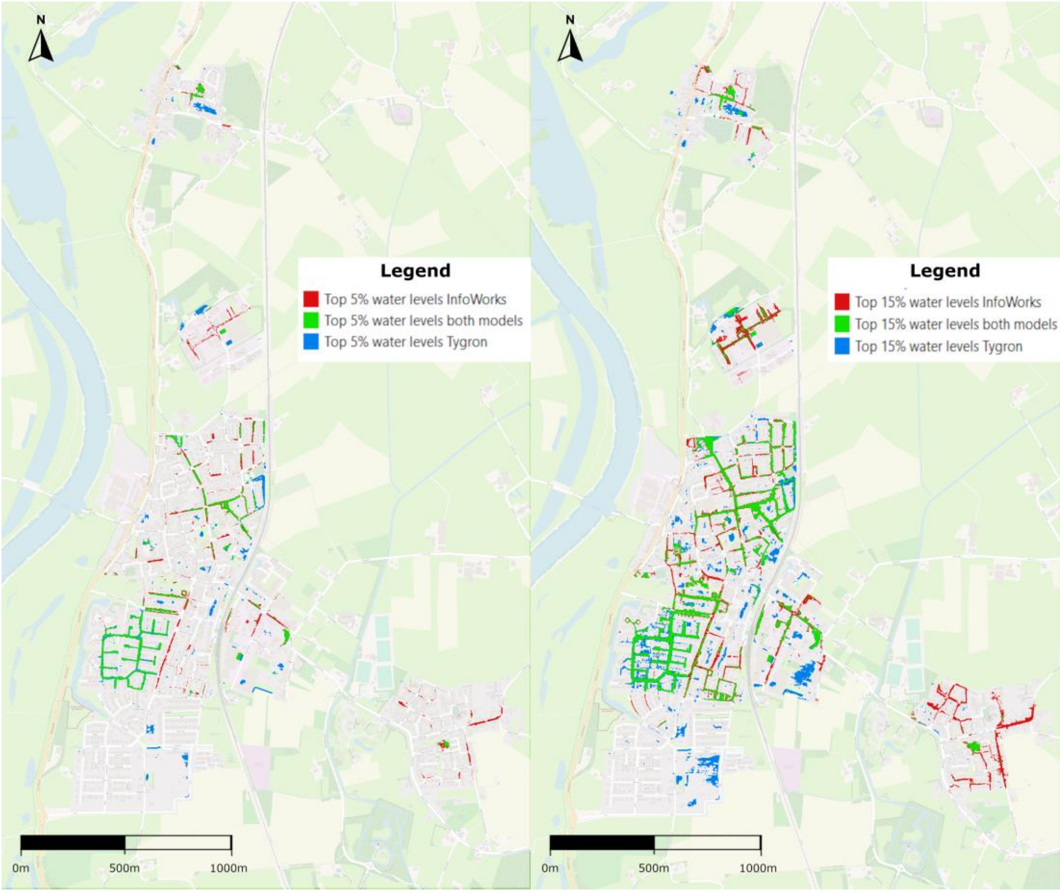


Figure 32a. 5% highest water levels *Figure 32b. 15% highest water levels*

Figure 32: Highest water levels in Tygron and InfoWorks for Herwijnen rain event

In the following table, the highest 5% per neighbourhood can be seen.

Table 29: Highest 5% water levels per neighbourhood

	Olst Zuid	Olst en Den Nul	Boskamp	Total
Highest 5% water levels InfoWorks	45.1%	43.6%	55.1%	41.3%
Highest 5% water levels both models	23.8%	70.5%	17.6%	58.7%
Highest 5% water levels Tygron	43.8%	51.8%	1.3%	41.3%

Table 30: Highest 15% water levels per neighbourhood

	Olst Zuid	Olst en Den Nul	Boskamp	Total
Highest 15% water levels InfoWorks	34.9%	37.5%	78.0%	39.4%
Highest 15% water levels both models	39.4%	71.1%	16.2%	60.6%
Highest 15% water levels Tygron	68.7%	44.9%	4.4%	39.4%

As can be seen is that the model is performing quite well for the Olst en den Nul neighbourhood. However, for Boskamp, the models have almost no similar high water level prediction