Improvement of rainfall runoff simulations on urban unpaved surfaces

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Kraaijvanger Architects (2021). https://www.kraaijvanger.nl/nl/projecten/contrast/

Summary

Preventing flooded streets and tunnels in urban environments during the past decades increasingly depends on the creation of simulation models. These models are used to simulate extreme rainfall events in order to test and to improve how current infrastructure or natural waterways handle excess of water. In urban environments these models can indicate vulnerable areas where during rainfall events sewage systems overflow or water floods the streets. For the rainfall-runoff process permeability of the surface plays an important role. If most of the surface is made from impervious materials, like pavements or streets, the rainfall runoff-process is fairly predictable as most of the overland flow will directly enter the sewage system. However, urban environments also consist of a lot of permeable surfaces. The flow of water across a surface following the rainfall-runoff processes can vary depending on soil characteristics due to changes in for example infiltration capacity.

Usually when a model is generated, it is calibrated by comparing model output to observational data. Highly influential or uncertain parameters that are used to create the model are then adapted to match the model output to observed values as close as possible. This generates a model that simulates actual processes better than with the use of standard parameter values. However, observational data is not always present. Calibrating the model is not possible in this case and parameter values need to be estimated. Although multiple methods exist to estimate these values, they are not always suited for urban environments.

This research focuses on finding the parameters that have the most influence on rainfall-runoff processes on unpaved urban areas and tries to find a method of applying parameter values based on soil types, so it will also be possible to apply parameter values to ungauged areas. With the use of a sensitivity analysis, the most important parameters are the initial infiltration and limiting infiltration parameters from the Horton infiltration model. The initial infiltration is the amount of infiltration that can infiltrate a soil at the start of a rainfall event, while the limiting infiltration is the lowest value of infiltration the soil can have when it is saturated. Two rainfall events were used in this sensitivity analysis: one with a return period of one year, and one with a return period of 100 years.

To calibrate the most important parameters, simulation results from sewage overflow were compared to observations at these locations. Based on Kling-Gupta Efficiency (KGE) scores the most optimal parameter combination was found. Using earlier research, the optimal infiltration values were transformed to values suitable for other soil types than the one the calibration was performed on. After that two validation methods were used. First a temporal validation was performed where two different rainfall events were used for the same study area. These results were also evaluated with the KGE scores, and the model with the Horton infiltration parameters performed similar to the original model, which does not uses Horton infiltration, but a more general constant infiltration value. The spatial evaluation was performed in a different study area that included different soil types and a larger permeable area. However, results from this validation were inconclusive, since it turned out that the original model and local observations did not match at all. Also the model with the newly found parameters does not match with observational data, but it generates similar results as the original model. It is uncertain if these results were caused by poor model performance or inaccurate observations.

Based on these validation results, it can be concluded that for large rainfall events the Horton infiltration parameters have the most influence on the rainfall-runoff process in urban unpaved areas. Small rainfall events however did not show good model results. This

might be caused by the influence of other parameters that were selected for the sensitivity analysis. Those parameters did not indicate model sensitivity due to the selection of very high Horton infiltration parameters, which resulted in a much stronger model sensitivity for the Horton parameters. Whether the application of Horton parameter values on different soil types to be used on ungauged areas is successful cannot be concluded, and therefore the goal of this research is not fully accomplished.

Recommendations for a follow-up research are calibrating more local soil types with the Horton infiltration method. In order to perform these calibrations, reliable observational data is required. This includes both high frequent rainfall observations during rainfall events, and also observations of water flow at critical locations. Since the Horton infiltration model is an empirical method, better results will be achieved with more data. With more real life and especially local samples, the estimations of Horton parameter values will become more accurate in case a calibration is not possible in ungauged areas.

Contents

1 Introduction

This introduction provides background information about urban rainfall-runoff processes in Section 1.1 after which is explained how these processes can be modeled in Section 1.2. The research gap in Section 1.3 provides the reason for this research and the research objective, which is stated in Section 1.4 together with the research questions. A short outline of the rest of this report is provided in Section 1.5.

1.1 Background

Rainfall-runoff relationships have been modeled in both urban and rural areas to better understand the flow of water in rivers, streams, canals, sewage systems and surface waters (Hrachowitz et al., 2013; Vojinovic & Tutulic, 2009). Modeling of (parts of) hydrological systems has become general practice. Not only are models used to simulate general water system behavior, but also in case of extreme events. Flood protection strategies are made based on hydraulic models to prevent flooding of downstream regions and vulnerable areas. Rural models can often simulate hydrological processes from entire river catchment areas, while models of urban areas generally focus on smaller scale hydrological systems. In this research, the focus lies on models in urban environments, and in particular the rainfall-runoff process. Figure 2 describes this process for urban environments.

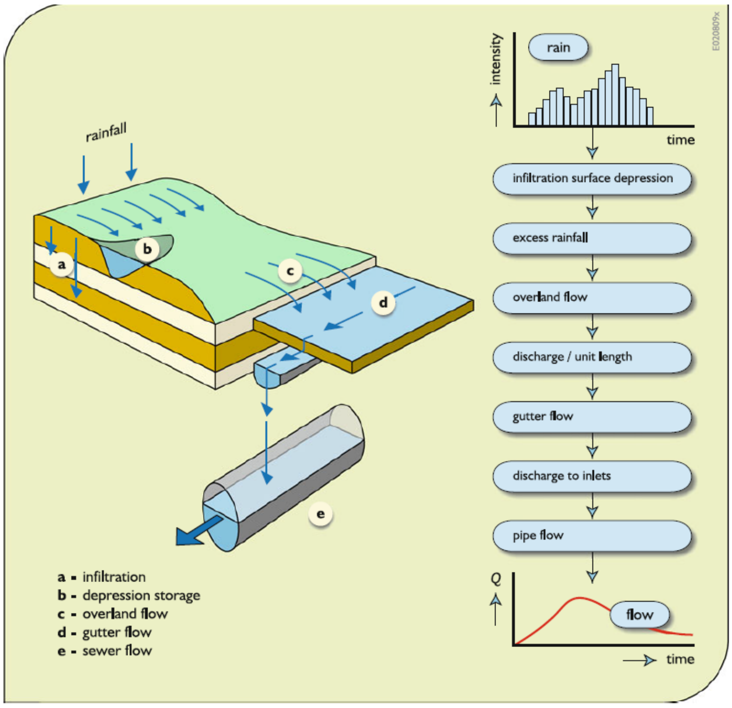


Figure 2: Rainfall-runoff process (Loucks & van Beek, 2017)

Properties of urban areas are large areas of impermeable surfaces like roads, pavements, parking areas, but also buildings that in case of a rainfall event generate runoff towards sewage systems. Modeling these flows is straightforward, since most of the rainfall water volume that falls on the impermeable surfaces flows directly to the sewage systems without much loss of water. If rainfall falls on permeable surfaces like gardens, parks or other public green spaces other factors influence the rainfall runoff-process. From Figure 2 can be seen that also infiltration and depression storage have an influence on the total amount of flow in the sewage systems. The influence of these variables can differ per location, so it is important to know these parameter values. Although when compared to rural areas, urban areas have a very high amount of impermeable surfaces, public green space in cities can take up to around 40% of the land use, with outliers close to 70% (World Cities Culture Forum, 2020). Simulating the rainfall-runoff processes from permeable surfaces is therefore essential in urban simulation models.

The rainfall events that are used for the evaluation of urban models are often short, high intensity rainfall events. These events can both be historical events, or hypothetical events used as a stress test. Urban water systems only have a limited water storage capacity and are more sensitive for these types of rainfall events then for the same amount of rainfall over a longer period. In case the storage capacity is exceeded, the sewage systems will overflow and water will flood the streets which causes disruptions or damages. By modelling the rainfall runoff processes, potential bottlenecks in urban design can be located in case of heavy rainfall events. With this information adaptations can be made by city planners to prevent flooded streets.

1.2 Modeling urban hydrology

Types of models Modelling of rainfall-runoff processes is performed with the use of hydraulic and hydrological computer models. Although models can be created in many levels of detail and different forms, two types of models are often used for urban simulations: semi-distributed 1D models and fully-distributed 2D models, or any combination of these two. The advantage of these models is the high amount of detail that can be included in the models. The main difference of these models is the way how hydrological processes are calculated. In a semi-distributed model, an area is divided in smaller subcatchments that have an inflow and outflow at discrete points. Calculations within these areas are based on uniformly assigned geographical and hydrological characteristics. The 2D models make use of a grid where in each grid cell the hydrological processes such as the amount of infiltration, water levels or flow speed and direction are calculated. The smaller grid sizes also directly simulate overland flow and can better account for rainfall-runoff routing based on height differences due to the smaller size of the grid (Pina et al., 2016). Even if height differences are not very large, the higher level of detail makes 2D models more useful than 1D models for urban rainfall-runoff simulations. The largest drawback of these types of models is that they require a lot more processing power. An example of how each type interprets an urban area is shown in Figure 3. For the 1D model, water flows to the manholes are calculated as a single point of inflow per subcatchment. For the 2D model, water will flow across multiple mesh elements towards the manholes, while at each cell hydrological fluxes and water balances are calculated.

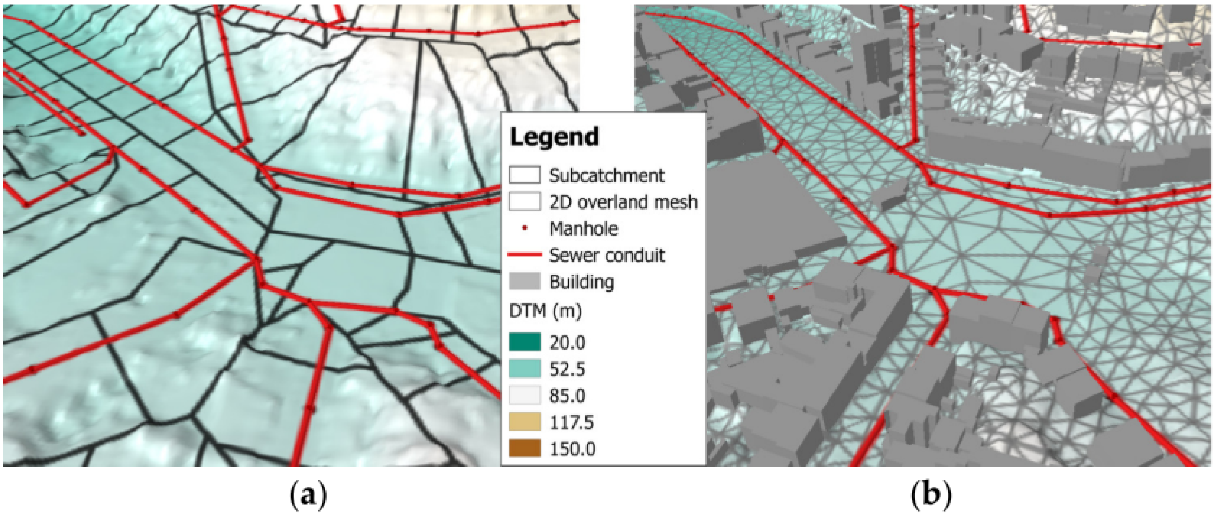


Figure 3: Semi-distributed 1D model with subcatchments (a) and fully-distributed 2D model with mesh elements (b) (Pina et al., 2016).

Infoworks ICM One of the modelling software packages that can handle both 1D and 2D models, and a combination of those, is the Infoworks ICM (Innovyze, 2021) model which is used in this thesis. Other software packages like D-Hydro (Deltares, 2021) or 3Di (Neelen & Schuurmans, 2021) can also be used for urban hydrodynamic simulations. The main reason for choosing the Infoworks ICM software is that existing model schematizations of the research ares are available. Compared to the other software packages however, Infoworks ICM provides accurate results on benchmark tests(Henckens & Engel, 2017). Like other software packages, surface water flows in the model are based on the Saint-Venant Shallow water equations (Néelz & Pender, 2013). Groundwater flows however are not simulated in this software package, while other software packages like the D-Hydro or 3Di provide at least partially groundwater support. Nevertheless, this small limitation does not generate poorer model performances in comparison to the other software packages (Henckens & Engel, 2017).

1.3 Research gap

Many theoretical calculations and empirical tests have been performed in order to simulate rainfall-runoff processes. These processes are mathematically described with equations where parameters are used to describe different variables. Selecting parameter values for these variables is difficult, especially for ungauged areas (Hrachowitz et al., 2013). Even with initiatives to improve parameter estimations in ungauged areas (Sivapalan, 2003), coupling area characteristics to parameter values proves to be difficult (Duan et al., 2006). Tests have revealed for example that the real life infiltration capacity can be much more than commonly used theoretical values for infiltration (Beven, 2012; Morbidelli et al., 2018; Pit et al., 1999) and initial losses from trees can range from a few millimeters to tens of millimeters in extreme cases in tropical rainforests per rainfall event (Inkiläinen et al., 2013). The issue that appears is that it is still difficult to estimate parameter values in ungauged areas, where simulation results cannot be compared directly with observed results in order to perform a calibration. Interpolated parameter values based on calibrated values from surrounding areas is one method of estimating parameters that prove to be more useful than estimation based on area characteristics (Merz & Blöschl, 2004), but without values of surrounding areas this is no option. Moreover, many studies regarding the predictions in ungauged areas and parameter estimations are focused on large scale rural catchments. Although for many relevant parameters estimations are used based on experience and comparable situations, they are far from perfect and result in inaccurate model predictions.

1.4 Research objective

The goal of this research thesis is:

To find appropriate model parameter values based on area properties for a rainfall-runoff simulation over unpaved surfaces in urban areas which are applicable in different areas and for different rainfall events

The parameter values have to result in a good fit when selected model output is compared to observed data of overflow locations and water levels. Since existing models will be used for this research, results will also be compared with the performance of the models in their current configuration. By using area characteristics as key factor for the parameter values, it should be possible to use these parameter values in areas with different soil types.

In order to achieve the research goal, three research questions are defined that each contribute to this. These questions are listed below with a short elaboration on the relevance of the question regarding the research goal.

1. *Which of the parameters influence the volume of overland flow over unpaved surfaces the most?*

Not all parameters within the model are relevant for the amount of overland flow during rainfall events, so after a selection based on literature only the most relevant parameters are used in a sensitivity analysis. The parameters that show the most influence on the modeled results based on this sensitivity analysis will be used to continue with the next research question.

2. *Which parameter values generate the best results when compared to observations?*

The most relevant parameters are calibrated to find their optimal values. Based on these values and the area properties of the calibrated model, parameter values for different soil types can be established.

3. *Do the optimal parameter values show accurate results when used for different rainfall events and different areas?*

For the parameter values to be useful, they also need to provide accurate results when used for other rainfall events and with other area properties. This means that the calibrated parameters are temporally and spatially validated.

1.5 Thesis outline

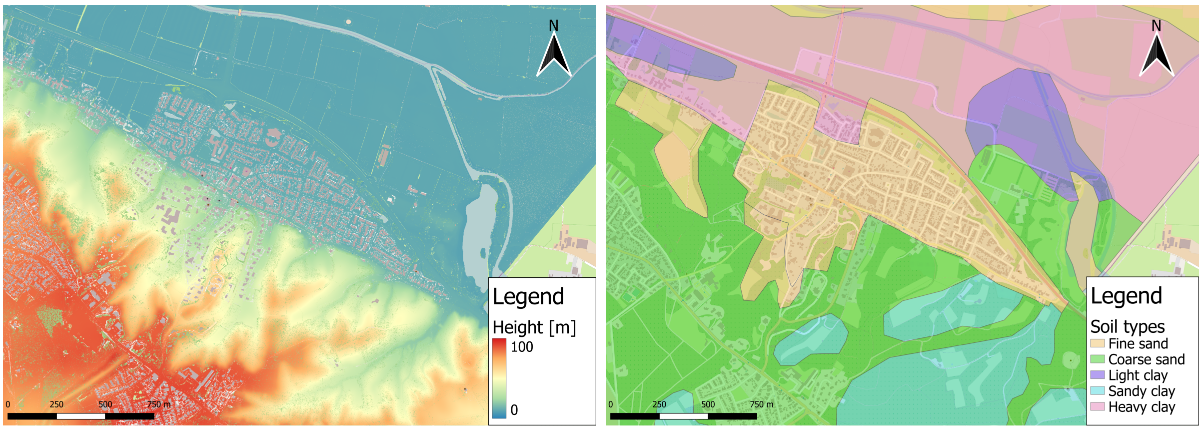
Chapter 2 provides an overview of the study areas and the models that are implemented in these areas. Available data and rainfall events that are used in this research are also covered in this chapter. Relevant processes and variables are explained in Chapter 3. After that, the methodology is explained in Chapter 4 where per research question an approach to answer the question is explained. The results of these methods are presented in Chapter 5, after which the results are discussed in Chapter 6. Finally, an answer to the research questions and recommendations is given in Chapter 7.

2 Study areas and models

For this research, two study areas that have been modeled in Infoworks ICM are selected. The first one is based around a small village with a lot of height differences, especially at some permeable areas. The second one is located on the outskirts of a residential area and has less height differences, but a more permeable surface. For both study areas, historical observations of water discharge at specific points are available to be able to compare with simulated discharges. Both study areas and their models are described in this chapter. For confidentiality reasons, the study areas have been anonymized.

2.1 Study area 1

Physical properties Study area 1 is located in a small urban village surrounded by a large rural area. To the south of the residential area, the terrain is significantly higher than the north as can be seen in Figure 4a. This causes water to flow from this high area towards the residential area in case of a rainfall event. The height profile is based on Actueel hoogtebestand Nederland (2020) from which the AHN 3 database is used. The soil types of this area are presented in Figure 4b and are provided by Basisregistratie ondergrond (2020). The two most relevant soil types are fine sand in most of the residential area, and coarse sand to the south at the location of the higher located terrain. In the north most of the soil consists of clay, which is not relevant for this research since it is located downstream of the study area.



(a) Height profile (b) Soil types

Figure 4: Height profile and soil types of Study area 1

Original model In the model, also the smaller residential area to the northwest is included due to the larger scope of the project for which the model was initially created. That area is not included in this research. The focus area for this research is chosen because there are more locations available with observational data. The model consist of both 1D subcatchments and a 2D layer to calculate surface water flows. Since a 2D model requires a lot of computational performance, the 2D mesh outside the residential area has a lower resolution than the one inside the residential area. Figure 5 shows the boundaries of the low resolution and high resolution areas. To the south of the residential area, some extensions are created in the higher resolution, smaller mesh elements part of the model. The reason for this is that at those locations, natural channels due to local height differences exist. These channels are important to simulate accurately since overland flow generated from the higher terrain will flow through them towards the lower urban area. Elements in the small model mesh area have surface areas from 1 m^2 to 3 m^2, while the elements in the large model mesh have areas ranging from 25 m^2 to 100 m^2. These elements are generated by the model which all have a triangular shape. The method of infiltration that is applied in the model is a constant infiltration. The relevance of this will be explained in Chapter 4.

The original model has been calibrated by adapting parameters in the 1D model for which 10 rainfall events are used by comparing observational data from the overflow locations with simulated overflow. The parameters that have been optimized are percentage of surface connected to the sewage system and the height of weirs inside the sewage system. The 2D model was calibrated without the observations at the overflow locations, but instead pictures and video material were used. The observed amount of flooded water on specific locations were compared with water height at those locations simulated by the model. The rainfall events mentioned in Section 2.4.1 and 2.4.2 at the temporal validation are also used to calibrate the original model.

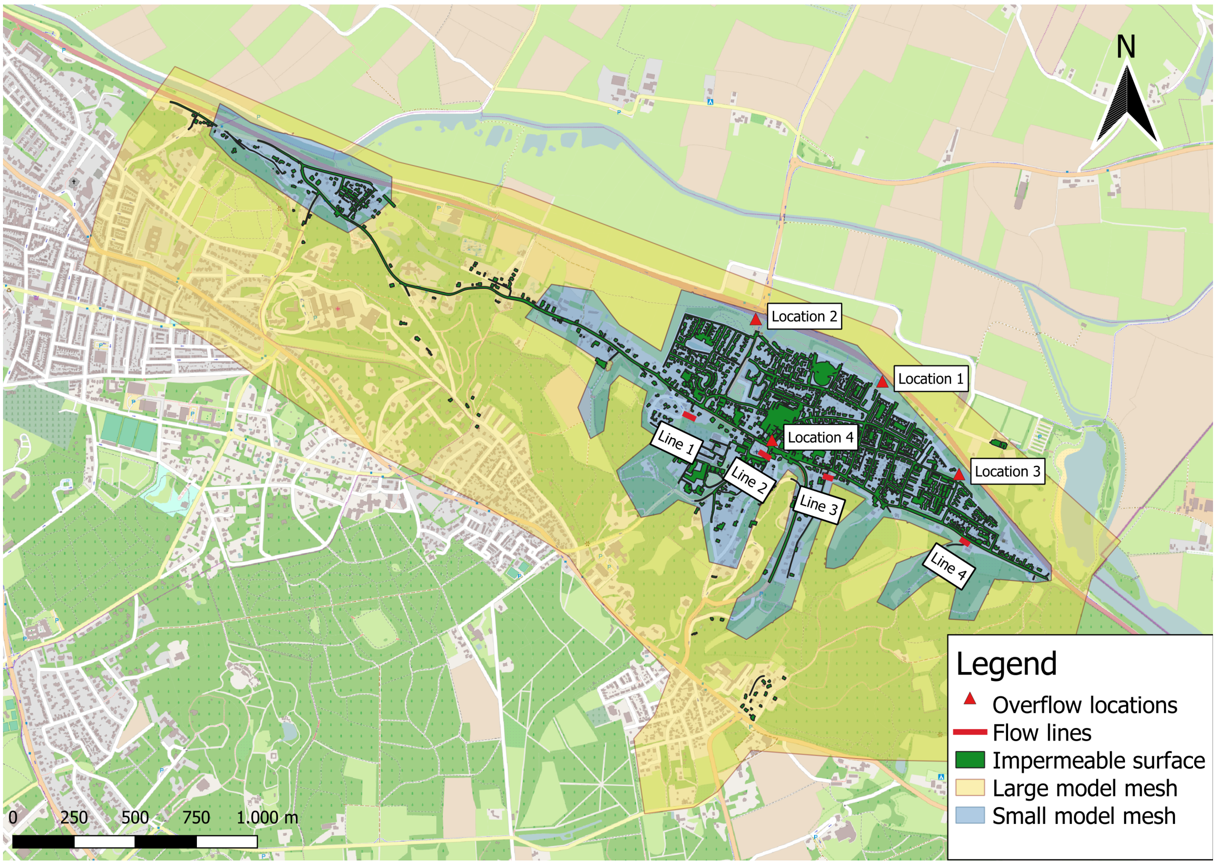


Figure 5: Overview of Study area 1

Model output locations In order to exclude impermeable surfaces from contributing to infiltration, they do not generate runoff in the 2D model, but only in the 1D part of the model. The impermeable surfaces consist of elements like buildings, pavements and roads. To evaluate model performance, multiple locations have been selected from where simulated results are exported. Four of these locations are overflow locations, that already exist in the model. In case of a large rainfall event, at these locations water will overflow the sewage system if the storage limits are reached. These are also the locations where observations are available from historical rainfall events, except for Location 4 which is an internal overflow location.

To evaluate model performance of overland flow from permeable areas, four lines are created in the model from which overland water flows can be observed in a simulation. These are the four flow lines in Figure 5. They have been placed at locations where water from the higher grounds will flow towards the residential areas. Since the lines only exist within the model, no observational data is available for these locations.

2.2 Study area 2

Physical properties Study area 2 is different from the first one, since it is located on the edge of a city with very little height differences as compared to the first study area, as can be seen in Figure 7a. The database used for the height profile is the AHN 3 database from Actueel hoogtebestand Nederland (2020). The soil types of this study area are different from Study area 1. The soils in this area contain much more loamy and clay soil types, as can be seen in Figure 7b. These soil types are taken from the national database of Basisregistratie ondergrond (2020). Within the brook, a weir is located from which discharges are measured.

Original model This model is less elaborated as the one from Study area 1. The main function for this model is to serve as input in a hydraulic model that includes discharges from the brook, and has therefore less details than the previous model. The size of 2D mesh elements in this study area are all in the range from 1 m^2 to 5 m^2 without an area with higher resolution like in Study area 1. Also in this model, the infiltration method that is used is a constant infiltration. The weir in the brook is not included in the model, but instead multiple lines are present within the model which each provide a flow of its own subcatchment towards the observation point. These locations are chosen based on their relatively low location compared to the surrounding area, so that overland flow will cross these lines. The combination of flows across these lines simulates the discharge at the weir location.

The model is calibrated to match the observed runoff during a single rainfall event by multiplying the surface roughness across the whole area with a factor 10, and also implement an unknown runoff factor that changes how much of the total surface runoff would actually be modeled as runoff. However, since increase of the roughness coefficient with a factor 10 was found to be unrealistic, this has been discarded in the end. The runoff factor was also changed back to normal. The event used for this is Event 1 from the spatial validation, which can be found in Section 2.4.2.

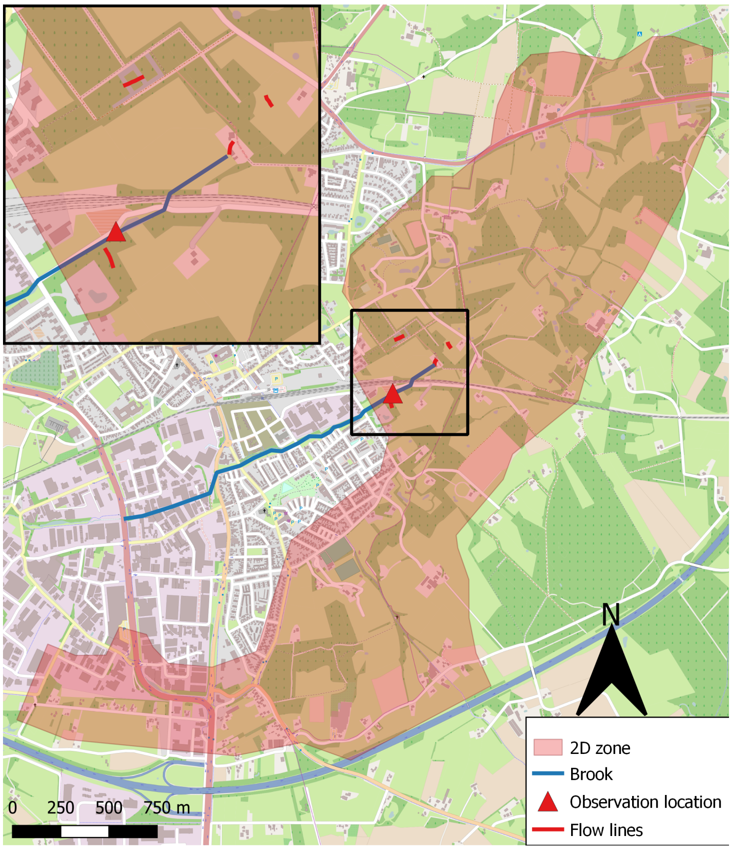
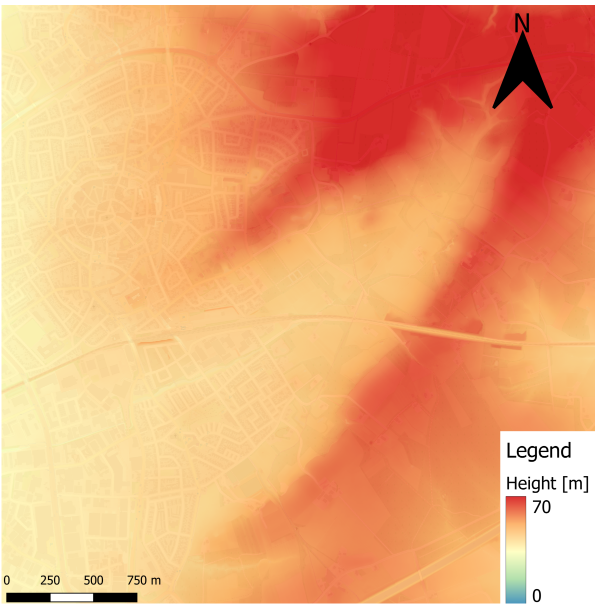
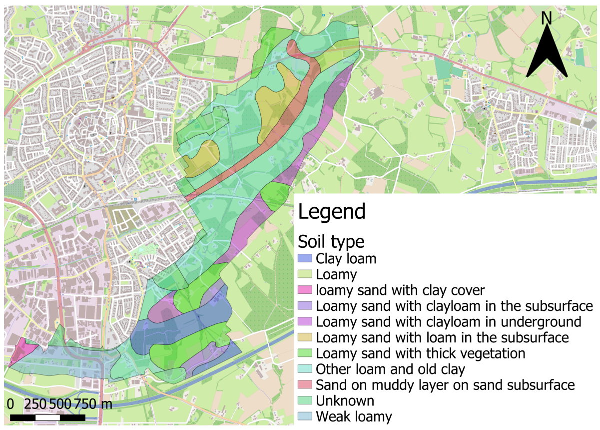


Figure 6: Overview of Study area 2



(a) Height profile



(b) Soil types

Figure 7: Height profile and soil types of Study area 2

2.3 Available data

Observations of water discharge The data that is available for both study areas is shown in Tables 1 and 2. For Study area 1, the three overflow locations provide observations during different time periods over the past years. Since overflow only takes place during large rainfall events, most of the time the data from these locations show no information. Even though, every 15 minutes the water height is measured. In case of overflow, this increases to every minute. Therefore, because of this system it is possible that the first 14 minutes of an overflow event are not registered.

Table 1: Data characteristics Study area 1

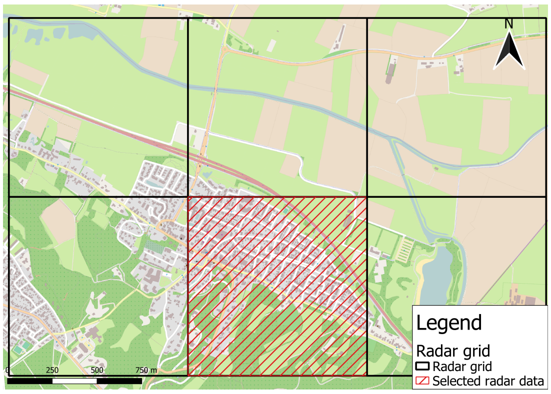
Overflow locations	**Available measurements**	**Time interval**	**Time step**
Location 1	water height [$mNAP$]	5/11/2013-5/11/2018	15 min/ 1 min
Location 2	water height [$mNAP$]	5/11/2016-5/11/2018	15 min/ 1 min
Location 3	water height [$mNAP$]	5/11/2013-5/11/2018	15 min/ 1 min

For Study area 2, only one location is available for observational data. These measurements are less frequent than for the other area with only one measurement per hour. Also, there is only one year of data available, so there is less choice in selecting large rainfall events for this location.

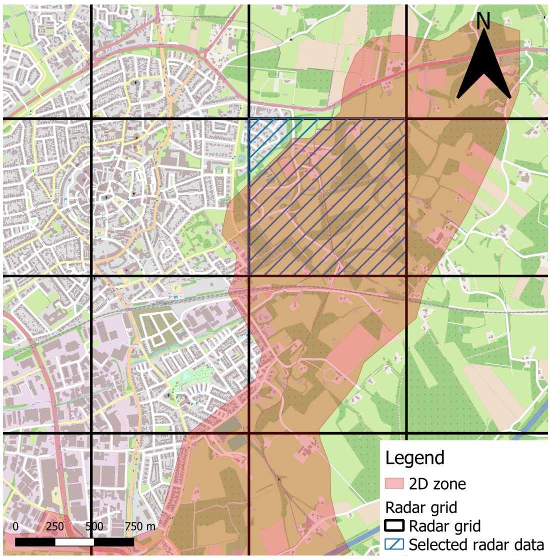
Table 2: Data Study area 2

	Available measurements	**Time interval**	**Time step**
Observation point	water height [$mNAP$]	1/8/2017-19/7/2018	1 hour

Rainfall observations Rainfall data is provided by the National rainfall radar (Nationale Regenradar, 2020) for both of the study areas due to lack of other local measurements. By selecting the location of the modeled area as a reference point, the rainfall has been downloaded from the database. In Figure 8 the locations of the selected radar observations are presented. The rainfall data provides a rainfall sum for every 5 minutes with a spatial resolution of one square kilometer (Royal HaskoningDHV; Nelen & Schuurmans, 2013).



(a) Study area 1



(b) Study area 2

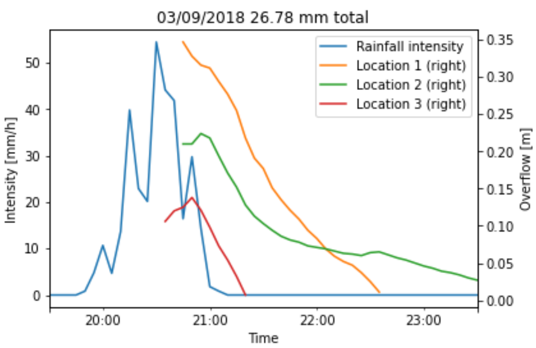
Figure 8: Selected rainfall radar observation locations for both study areas

2.4 Rainfall events for calibration and validation

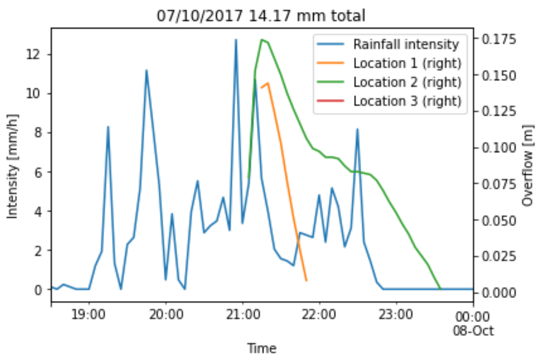
From the data described in the previous section, rainfall events are selected to be used for calibration and validation. The selection is based on a total amount of rainfall of 14 mm during a four hour timespan, and available observations on these dates.

2.4.1 Calibration

The events used for calibration took place on the 3^{rd} of September 2018 for Event 1 and the 7^{th} of October 2017 for Event 2. In Figure 9 both rainfall events and observations of the overflow locations are combined. Event 1 is a high intensity rainfall event where most of the total rainfall falls within one hour. Event 2 is an event with lower intensity and total rainfall, but it takes place over four hours. For both events, the overflow observations start at a value above 0 due to the delay in sensor registration. All observations of values below 0 are deleted from the data, since negative overflow is not possible.



(a) Event 1

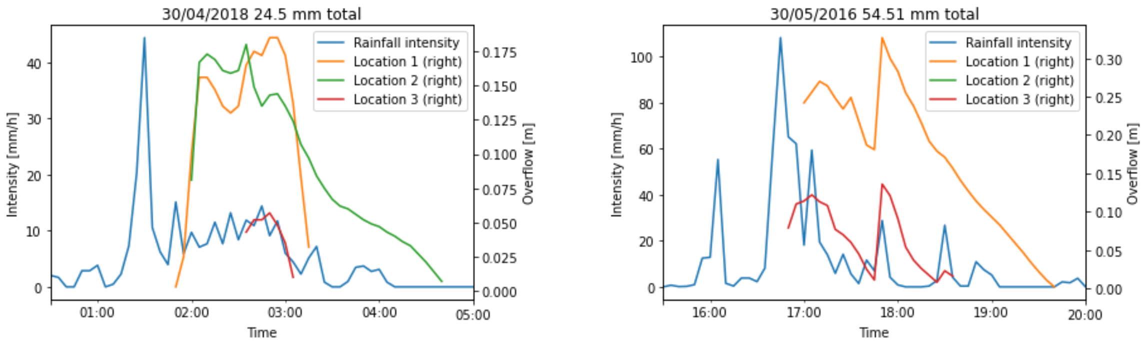


(b) Event 2

Figure 9: Rainfall events and overflow measurements at three locations that are used for calibration

2.4.2 Validation

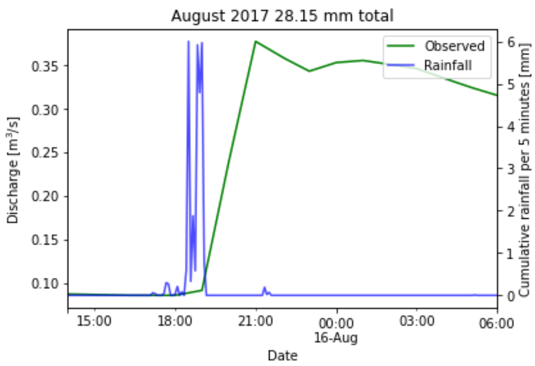
Temporal validation Two events are used for the temporal validation. Event 1 selected for validation took place on the 30^{th} of April in 2018, while Event 2 took place on the 30^{th} of May 2016. In Figure 10 the rainfall events, together with observed overflow from multiple locations are presented. Event 1 has a similar total amount of rainfall as Event 2 from the calibration, while validation Event 2 has more than twice the amount of cumulative rainfall of that same calibration event. The latter event will therefore be a validation outside the calibrated range.



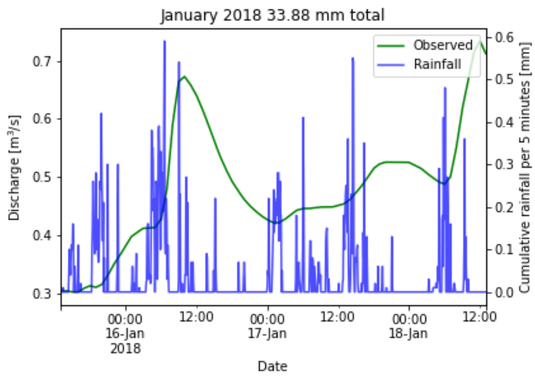
(a) Event 1 (b) Event 2

Figure 10: Rainfall events and overflow measurements at four locations that are used for temporal validation at Study Area 1

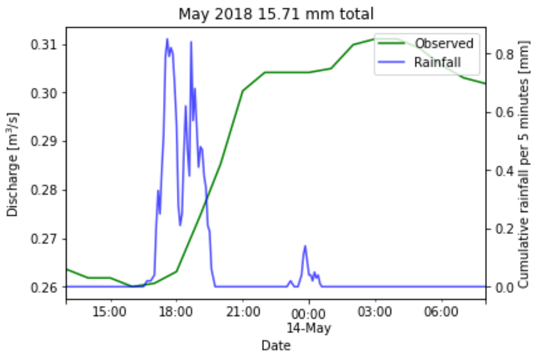
Spatial validation For the spatial validation, the rainfall events and observations that are used include a longer time than the events used in calibration and temporal validation. This is due to the observational intensity of only one measurement per hour at Study Area 2. Figure 11 shows these rainfall events and the observations. These events are the four largest rainfall events that occur within the available observational data.



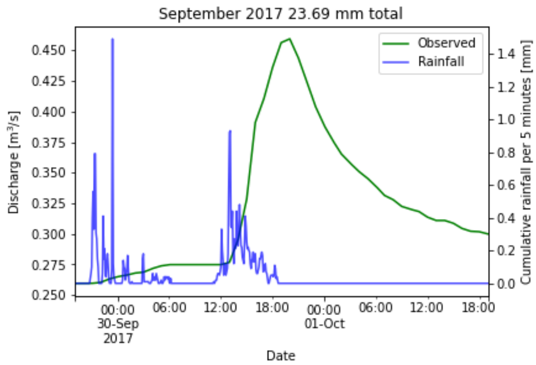
(a) Event 1



(b) Event 2



(c) Event 3



(d) Event 4

Figure 11: Rainfall events and discharge for spatial validation at Study area 2

3 Processes

Not every change in model parameters will lead to a direct effect on the amount of overland flow of water, and only the parameters with the largest direct effect on surface runoff will be the focus of this research. The selection of these parameters is based on variables in the rainfall-runoff process. The preselection of the most influential variables that will be used in this research are based on literature. The variables that will be described in this section are infiltration in section 3.1, initial losses in section 3.2, roughness in section 3.3 and soil moisture in section 3.4. Other variables that are not included in this research are described in section 3.5.

3.1 Infiltration

Infiltration is an important process that influences the rainfall-runoff transformation, and changing the infiltration rate in models has a clear impact on stormwater runoff processes in urban environments (Ren et al., 2020). Infiltration can be expressed as the amount of water that will infiltrate in the soil in a certain amount of time. Multiple methods are available to account for this in computer models, that each have their benefits and downsides. Popular methods are the Horton method (Horton, 1939), Green-Ampt method (Green & Ampt, 1911), Soil Conservation Service (SCS) Curve Number method (United States Department of Agriculture, 1985) or using a constant infiltration value. The first two methods have a similar performance in an urban environment (Fernández-Pato et al., 2016), while the Curve Number method performs better in rural catchments (Fernández-Pato et al., 2016; Wang et al., 2017). Using a constant infiltration rate is a simple and easy to use method for calibrated catchments, but determining the parameter values based on soil characteristics is not really possible due to the oversimplification of infiltration. While in itself this might not be a reason to dismiss this method in urban models, the scope of this research project demands a more detailed infiltration method. Based on this, the choice of methods is down to either Horton or Green-Ampt. Both methods show a similar performance, although the Horton method might perform slightly better due to the lack of need for assumptions that soils are homogenous and isotropic (Wang et al., 2017). Also, the empirical nature of the Horton method makes the Horton method easier to use. The more analytical Green-Ampt method requires more specific soil properties that can be more difficult to find for specific locations. The Horton method is also advised to be used by the Dutch umbrella organization of urban water management Rioned (Rioned, 2020a). Therefore, the Horton method will be used to simulate infiltration.

The Horton method is based on the infiltration capacity of the soil (Horton, 1939). This method makes use of empirically derived parameters which characterize the soil infiltration process. This is in contrast to the Green-Ampt method, where directly measured soil characteristics can be used. (Fernández-Pato et al., 2016). The advantage using Horton is that taking local soil samples is not necessary. In his equation Horton assumes that the infiltration rate declines as the soil becomes more saturated, with a minimum limiting infiltration value described as f_c. Each soil type has its own values for initial and limiting infiltration, as well as the decay rate k. With an increase in decay rate, the infiltration rate decreases stronger as a function of time than for a smaller value of the decay rate. The infiltration rate f at time t is given by the formula (Horton, 1939):

$$f(t) = f_c + (f_0 - f_c)e^{-kt} \tag{1}$$

Where:
f_0 is the initial infiltration rate (mm/hr)
f_c is the final (limiting) infiltration rate (mm/hr)
k is the decay rate of infiltration (1/hr)

The cumulative infiltration is given by:

$$F(t) = f_c t + \frac{f_0 - f_c}{k}(1 - e^{-kt}) \tag{2}$$

Both the change in infiltration rate and the cumulative infiltration according to Horton's method are presented in Figure 12.

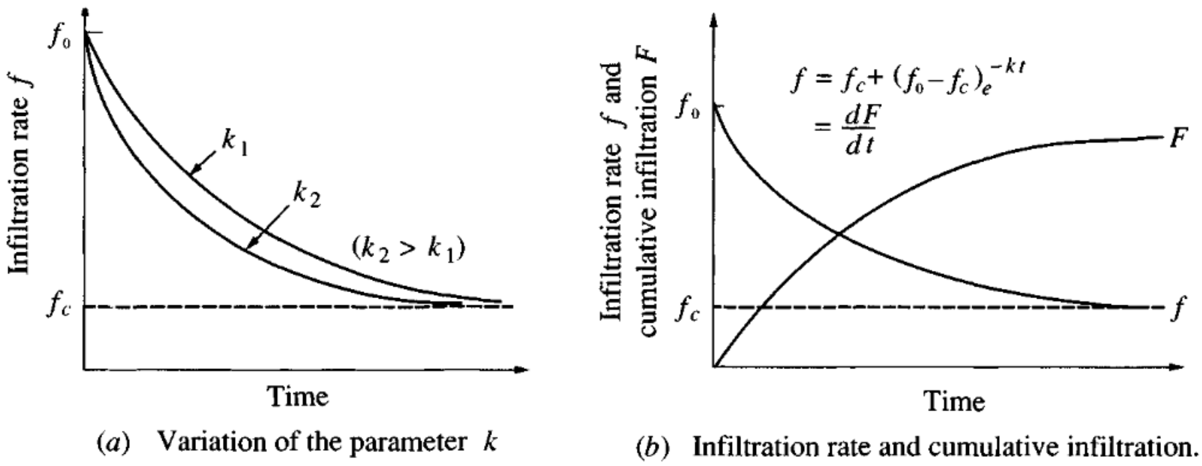


Figure 12: Infiltration for Horton's equation (Horton, 1939)

3.2 Initial loss

Initial loss is a combination of multiple factors that decrease the amount of rainfall that can create runoff. The most important factors are depression storage and interception of rainfall by vegetation. Infiltration can also be a form of initial loss, but is represented as a separate parameter in the Horton infiltration method since it is not only relevant at the start of a rainfall event, but also during the event. On a larger scale, detention storage also prevents runoff, but water stored in this way is generated by altitude differences that are incorporated in the model and therefore do not require a separate parameter. Depression storage is water that is stored in relatively low laying areas compared to the surrounding area, also called depressions, so that runoff does not take place before these depressions are filled. These depressions can both be found in impervious surfaces, and pervious surfaces and are too small to be picked up by surface height measurements. An example of such a depression storage can be puddle forming on a street with an uneven cobblestone surface. A value for depression storage can also be used to simulate interception of rainfall on vegetation or the other way around, since they both consist of a fixed value when used in modeling (Rossman & Huber, 2016).

While the quantity of initial losses in millimeters for impervious areas are available and based on the degree of surface slope and roughness, measurements of pervious areas are lacking and most reported values are derived from simulation models. Rossman and

Huber (2016) therefore propose that *"... pervious area depression storage might best be represented as an interception loss, based on the type of surface vegetation"*. Based on estimates of interception for natural and agricultural areas, values for different types of vegetation can be applied. Depression storage is most sensitive for small rainfall events, but it is difficult to calibrate on these events due to the strong integration with the initial loss from interception from vegetation.

In the model, this combined initial loss is implemented by subtracting it from the start of the rainfall event.

3.3 Roughness

The roughness of the soil surface does not directly affect the amount of runoff, but rather how fast water will flow over the surface. Using the open channel flow theory and Manning's equation, the flow velocity of water over a surface can be determined. Other methods of calculating surface roughness include the Darcy friction factor or Chézy coefficient. Manning is chosen since it is the most widely used method around the world to describe roughness, and is also implemented in the modeling software. Surface roughness can have a large impact on runoff calculations. With a high roughness over a large area, the peak of rainfall-runoff volumes can be delayed. Krebs et al. (2014) indicated the Manning roughness parameter as a key parameter for urban runoff modelling that especially has an effect on less dense areas where the percentage of direct runoff towards sewage systems is smaller. Manning's equation is as follows (Manning, 1891):

$$v = \frac{R^{\frac{2}{3}}\sqrt{i}}{n} \tag{3}$$

Where:
v is the cross section average velocity [m/s]
n is Manning's roughness coefficient [-]
R is the hydraulic radius [m]
i is the slope of the surface [m/m]

3.4 Soil moisture

For the Horton infiltration model, adding initial soil moisture conditions to the model can influence the results of infiltration (Fernández-Pato et al., 2016). A fully saturated soil will not allow maximum infiltration, but will create runoff sooner than a dry soil. Although this can be seen as another form of initial loss, this variable requires interaction with hydrological processes rather than simply reducing the effective rainfall amount. Changes in groundwater can affect this soil moisture content, and therefore also the infiltration rates. Groundwater itself is not part of the simulation, but because of the effect soil moisture has on infiltration and therefore runoff, soil moisture is implemented in the sensitivity analysis. Especially for short rainfall events models are sensitive for soil moisture, since relatively more rain of the total rainfall event will infiltrate during a short rainfall event (Beven, 2004).

3.5 Other relevant variables not included in this research

The before mentioned variables are the ones most relevant to surface runoff over unpaved areas, which is the main focus of this research. However, there are other factors that can contribute to runoff volume or runoff flow. One of those influences is the groundwater flow. Infiltration in a soil can cause groundwater levels to rise and can eventually result in groundwater flow from higher groundwater levels to lower groundwater levels. However, significant groundwater level changes do not occur within the time span of a couple of hours so it is not relevant for this research. The impact of initial groundwater is already indirectly included in the initial soil moisture content.

Another relevant factor for surface water flow is the slope of the terrain. Change in the slope can vary the amount of infiltration, depression storage and also the flow speed of surface runoff and modeling of slope effects is considered an open problem (Morbidelli et al., 2018). Terrain height in the model is generated by importing the AHN3 data from Actueel hoogtebestand Nederland (2020), which is a fixed condition for the model and is potentially only changed in case of known inaccuracies. Differences in spatial resolution when using other methods of including terrain height in the model can have an impact on the results but are not included in this research.

The last relevant variable for modeling surface runoff is the size of the 2D triangles that are generated in the model. This is connected to the spatial resolution of the terrain height data. Changing these influence for example the slopes and detail in transitions of land uses. Also, modeling time is greatly influenced and the results of changing resolution of the model in this way is worth a research paper on its own.

4 Methodology

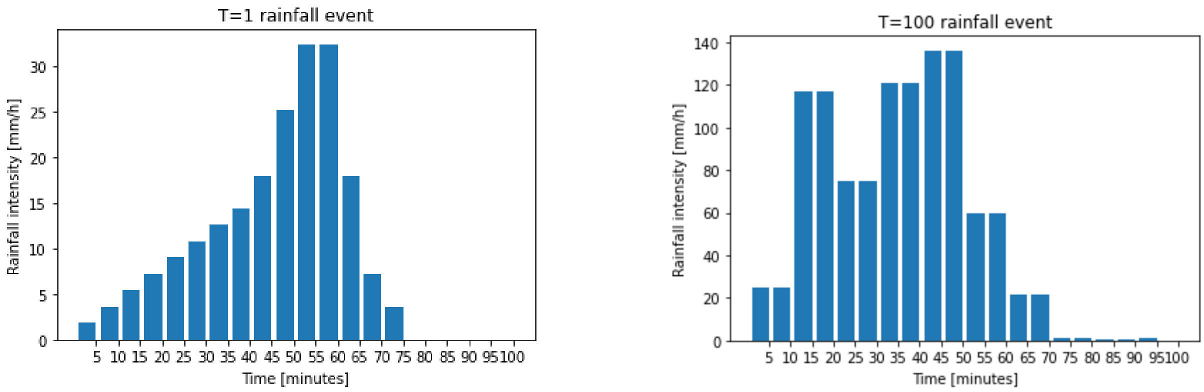
This chapter will provide the methods that are used in this research in order to answer the research questions and is divided into three sections: sensitivity analysis in section 4.1, calibration in section 4.2 and validation in section 4.3.

4.1 Sensitivity analysis

The goal of the sensitivity analysis is to find the parameters that have the most effect on the volume of surface runoff on unpaved surfaces in urban areas during high intensity rainfall events. This includes both the transformation from rainfall to discharge over land, and the flow over unpaved areas. The analysis will be performed with the use of the existing model of Study area 1.

4.1.1 Rainfall events

To be able to measure the influence of model sensitivity for parameter variations during different rainfall events, two rainfall events will be used in the sensitivity analysis: one that under normal circumstances will probably create runoff but is not very extreme, and one that is considered an extreme event with a very large amount of rainfall in a short time period. Both rainfall event durations will be only several hours. The reason for two events is that different rainfall events can generate different amounts of overland flow, on which the parameters have a different effect. In the case of smaller events, a relatively large amount of rainfall might not run off at all due to vegetation loss or infiltration. During a large event, the soil will be saturated before the event is finished, so more surface runoff will probably take place.



(a) T=1 year rainfall event

(b) T=100 year rainfall event

Figure 13: Hyethographs of both rainfall events

The first rainfall event used in the sensitivity analysis is a relatively small synthetic event with a return period of 1 year, while the other one is an extreme rainfall event that was measured at the KNMI measurement station at Herwijnen in 2011. Both events are used in hydrological models to check the functioning of the models and as stress test (Rioned, 2020b, 2020c). The cumulative rainfall amount of the latter event was 93 mm that fell almost completely within one hour. For comparison, the accumulated rainfall of the smaller event is 16.8 mm for the whole event during 75 minutes. According to most recent rainfall statistics, the large rainfall event has a return period of 100 years (STOWA, 2018). In Figure 13 the rainfall intensities over time are presented.

4.1.2 Parameters

In this model, only the relevant parameters as described in section 3 will be included in the sensitivity analysis, while the rest of the model parameters are kept constant. While the research area consists of different types of soil that can each have different characteristics in terms of parameter values that will be discussed below, these differences are neglected in the sensitivity analysis. For each parameter, the whole range of physically possible values is evaluated, so it will include all types of soils. The reason for this is that this sensitivity analysis focuses on the parameters itself to represent different soil types. This ensures that results found from the sensitivity analysis also can be applied to other areas.

4.1.3 Sampling parameter values

Latin Hypercube Sampling Since the time needed to perform one model run varies from 5 to 50 minutes, sampling methods that require numerous model runs are not an option. An efficient way of selecting samples, while not requiring a large sample size, is to use Latin Hypercube Sampling (LHS). The LHS method divides parameters into different 'levels' inside the total range of possible parameter values. For example, if a parameter has a value range of 0 to 100, a level could consist of samples between the values of 0 and 20, or 20 and 40, etc. Each level contains the same number of points. However, they do not have to be spaced evenly within these levels and based on probability distributions the levels do not have to be the same size (Saltelli et al., 2008). An example of a Latin Hypercube is given in Table 3, where 9 parameters each consist of 6 levels with two samples per level. The total number of simulation runs required in this case is 12.

Table 3: LHS design with 12 simulations for 9 parameters on 6 levels (Saltelli et al., 2008)

X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9
0	4	5	0	5	4	0	2	0
4	4	1	0	4	3	5	1	4
2	2	4	5	1	0	2	0	0
5	0	5	3	0	5	3	3	5
3	2	3	2	2	5	3	2	3
2	5	2	4	2	1	4	1	1
1	3	3	3	3	4	1	5	5
5	1	0	2	1	3	2	0	4
1	5	4	1	4	2	5	4	2
0	1	1	1	5	1	1	3	1
3	0	2	5	3	0	0	4	2
4	3	0	4	0	2	4	5	3

To examine the influence of each parameter with a randomized Latin Hypercube design is a very effective way in case the number of simulations is much larger than the number of parameters (Saltelli et al., 2008).

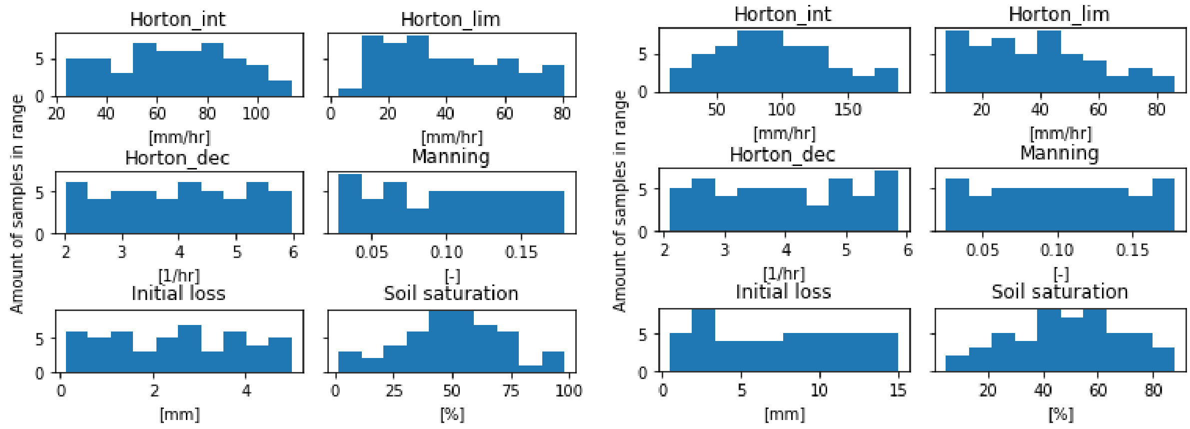
By using the Latin Hypercube Sampling, 50 unique sets of parameters are generated per rainfall event. Both of the rainfall events will be simulated with every set of these parameters, which makes a total of 100 simulations for this sensitivity analysis. For the generation of these sets of parameters, per parameter the range of possible values is divided in 10 levels, with 5 random samples from each level. In creating this LHS, a modification has to be made in order to apply it to the model. The limiting Horton parameter value has a restriction that it must always be lower than the initial Horton parameter value. To overcome this, random LHS designs are generated and used only if that condition is met, otherwise a new design is generated.

Boundaries of parameter values In Table 4, the minimum and maximum values of the parameters as used in the Latin Hypercube Sampling are presented. Literature suggests extremely high potential values for both initial Horton infiltration, and limiting Horton infiltration. For the first mentioned parameter, this can be as high as 914 mm/hr (Rossman & Huber, 2016), while the limiting infiltration can reach values of 300 mm/hr (Horton, 1939). Also field measured infiltration rates are in some cases that high (Pit et al., 1999; Sweco, 2019). Since these amounts of infiltration exceed the total amount of rainfall in the rainfall events used for the sensitivity analysis, the maxima of these parameters are decreased to a more realistic limit. Tests of the model revealed that from a Horton initial value of around 200 mm/hr and a limiting value of 100 mm/hr, no surface runoff took place for even the T=100 years rainfall event. Therefore, these values are set for those parameter limits. For the T=1 year rainfall event, more restrictions are applied. Above an initial Horton parameter value of 120 mm/hr, there was no surface runoff, so that value has been set as the maximum. Also, the minimum value of initial loss has been set to 5 mm instead of 15 mm, since the total amount of initial loss would be as much as the whole rainfall event if the 15 mm had been used. Like the decrease of the maximum initial Horton infiltration parameter this was necessary since without it, none of the calibration simulations generated surface runoff. The limits of other parameter values are based on the sources mentioned in the *Source* column in Table 4.

Table 4: Minimum and maximum values for the parameters

		T=1 year		T=100 years		
Parameters	units	min	max	min	max	Source
Horton_int	mm/h	0.000	120.00	0.000	200.00	
Horton_lim	mm/h	0.000	100.00	0.000	100.00	
Horton_dec	1/h	2.000	6.00	2.000	6.00	Rossman and Huber (2016)
Manning	-	0.025	0.18	0.025	0.18	Chow et al. (1988)
Initial loss	mm	0.000	5.00	0.000	15.00	Pazwash (2016)
Soil saturation	%	0.000	100.00	0.000	100.00	

Distributions in the LHS Samples in the Latin Hypercube design can be assigned a certain distribution. The standard distribution is a uniform one, so each level in the parameter range has the same size. However, parameters are not always distributed uniformly over the parameter ranges and some values are more likely to occur than others. To account for this, three parameters have a different distribution in this research. Both the initial Horton infiltration and limiting Horton infiltration are distributed with a triangular distribution based on an analysis of multiple field test results. Based on the analysis of (Pit et al., 1999), the median value of initial Horton infiltration rates is 76 mm/hr, while the median value of the limiting Horton infiltration is 10 mm/hr. This can then be translated to a triangular distribution with the given parameter value limits. Also, the soil saturation has been given a triangular distribution, since soil in the Netherlands is unlikely to be either completely dry or fully saturated with the same probability as everything in between. However, literature about the distribution of soil moisture is lacking, so the distribution is assumed to be symmetrically triangular. Figure 14 shows the histograms of the occurrence of each parameter value in the total sample. The reason that the histograms do not all have a perfectly uniform or triangular shape is because of the limited amount of samples and the randomness of both the distributions functions and the LHS sampling. The full sets of parameters for both rainfall events can be found in Appendix A.1.



(a) T=1 year

(b) T=100 year

Figure 14: Histograms of parameter values for the Latin Hypercube Samples

4.1.4 Quantification

The effect of parameters on model output will be examined with the use of scatterplots and a quantitative analysis. The scatterplots will provide visual information, while for quantification of these results Sobol' indices are used. The latter method is often used as a global sensitivity analysis method and is based on variances caused by the input parameters. The first order Sobol' indices are relevant for this analysis, and indicate the sensitivity without interactions of the input parameters. The method of calculating the first order Sobol' indices from Li and Mahadevan (2016) is used in this research, because this method outperforms the original Sobol' method and *"... is especially useful in ranking and identifying important variables, no matter whether the variables are correlated or not."* (Li & Mahadevan, 2016). The equation is as follows:

$$S_i = 1 - \frac{E_{xi}(V_{x-i}(y \mid x_i))}{V_y} \tag{4}$$

Where:
S_i is the Sobol' first order index
$V_{x-i}(y \mid x_i)$ is the conditional variance of y caused by all input parameters other than x_i
E_{xi} is the expected value if parameter x_i is fixed
V_y is the variance of y.

The sum of the individual Sobol' indices corresponding with the separate parameters should be 1. Parameters with the highest score are the ones that the model is most sensitive for.

4.2 Calibration

The parameters that are used for calibration are based on the results of the sensitivity analysis. In this case, the initial infiltration rate and limit infiltration rate of the Horton infiltration method are the two parameters the model is most sensitive to. Since most of the soil within Study area 1 consists of only coarse and fine sand, the model will be calibrated for only these two soil types. However, parameters used in the Horton infiltration model for different types of sand are difficult to find. Most tables for parameter references include only the differentiation of compacted or non-compacted sand or clay (Pit et al., 1999) or also including loam (Ren et al., 2020), while others are very specific for a single location (Rawls et al., 1976). This calibration is based on both studies, and results from the sensitivity analysis. The rainfall events and observations used for the calibration are described in Section 2.3.

4.2.1 Parameters

The ranges for especially initial infiltration can be very large, also when a differentiation is made in soil types. To include the variation between fine and coarse sand, more specific parameter estimations need to be used. Unfortunately, for the initial infiltration this is not possible due to lack of available literature, but for the limiting Horton infiltration Akan (1993) has presented a more specific range of possible parameter values depending on soil type. In Table 5 these values are presented.

Table 5: Horton limiting infiltration parameter values suggested by Akan (1993)

Soil Type	**(in/hr)**	**(mm/hr)**
Clay loam, silty clay loam, sandy clay, silty clay, clay	0.00 -0.05	0.00 - 1.3
Sandy clay loam	0.05 -0.15	1.3 - 3.8
Silt loam, loam	0.15 - 0.30	3.8 - 7.6
Sand, loamy sand, sandy loam	0.30 - 0.45	7.6 - 11.4

This source also has no specific parameter value range for different types of sand, but the extremes of the value range will be used to define the types of sand found in the study area. The soil type in the figure of 'sand, loamy sand, sandy loam' can be used for this. Assuming the category 'sand' can be distinguished as coarse sand, and 'sandy loam' as fine sand, the lower value in the parameter range corresponds to sandy loam and the higher one to sand. This assumption is based on the principle that saturated hydraulic conductivity increases with soil grain sizes, which also corresponds to the change in infiltration values in Table 5. When taking the infiltration values of 7.6 mm/hr for fine sand and 11.4 mm/hr for coarse sand, we find that coarse sand has a 1.5 times larger infiltration value than fine sand. This number will be used in calibration by creating a parameter value for the coarse sand limiting Horton value that is 1.5 times higher than that of the fine sand.

Since the modeling time per run can be more than half an hour, creating a more extensive set of calibration runs takes too much time. A total of 40 runs will therefore be created for each rainfall event. This number is based on increasing the initial Horton parameter value with 5 mm/hr and for each of these values, creating four limiting Horton values evenly spaced between 0 and the initial Horton value. Table 6 reads: four runs are created with an initial Horton value of 5 mm/hr, with the first one having a limiting Horton value of 1 mm/hr for fine sand and 1.5 mm/hr for coarse sand. The total range of parameter values from 0 mm/hr to 50 mm/hr is based on the sensitivity analysis, where for the T=1 year rainfall event no direct rainfall-runoff was simulated for Horton parameter values above 50 mm/hr.

Table 6: Parameters used for calibration, all in mm/hr. For each column, the initial Horton parameter value is fixed for four simulations, while the limiting Horton parameter values change

Initial Horton	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**
Fine sand limiting Horton	1	2	3	4	5	6	7	8	9	10
	2	4	6	8	10	12	14	16	18	20
	3	6	9	12	15	18	21	24	27	30
	4	8	12	16	20	24	28	32	36	40
Coarse sand limiting Horton	1.5	3	4.5	6	7.5	9	10.5	12	13.5	15
	3	6	9	12	15	18	21	24	27	30
	4.5	9	13.5	18	22.5	27	31.5	36	40.5	45
	4.9	9.9	14.9	19.9	24.9	29.9	34.9	39.9	44.9	49.9

4.2.2 Evaluation of model results

One of the most widely used criteria of comparing differences in simulation results with observations is the Nash-Sutcliffe Efficiency (NSE) (Nash & Sutcliffe, 1970). Based on the Mean Squared Error (MSE), of which the NSE is a related normalization, model performance is expressed at an interpretable scale. An alternative criterion for the NSE is the Kling-Gupta Efficiency (KGE). Gupta et al. (2009) point out the drawbacks of using the NSE to favor the use of KGE: *"The decomposition shows that in order to maximize NSE the variability has to be underestimated. Further, the bias is scaled by the standard deviation in the observed values, which complicates a comparison between basins."* and *"... if NSE is used in optimization, then runoff peaks will tend to be underestimated. The same applies for KGE, but the underestimation will not be as severe."* The KGE is based on a decomposition of the NSE, representing the correlation, bias and a measure of variability:

$$KGE = 1 - \sqrt{(r-1)^2 + (\alpha - 1)^2 + (\beta - 1)^2} \tag{5}$$

$$r = \frac{Cov(h_s, h_o)}{\sigma_s * \sigma_o} \tag{6}$$

$$\alpha = \frac{\sigma_s}{\sigma_o} \tag{7}$$

$$\beta = \frac{\mu_s}{\mu_o} \tag{8}$$

h Represents the water height and σ the standard deviation and μ is the mean. Subscripts s and o represent simulated and observed values respectively.

Where r is the correlation coefficient, α represents the variability ratio, and β the bias ratio between the simulated and observed values. The optimal value of KGE is 1. In general, a KGE value above 0 can be considered good, although it depends on what the benchmark criterion is (Knoben et al., 2019). This means that all values above that threshold can be considered acceptable. For the elements α, β and r the optimal value is also 1, but unlike the overall KGE the values of α and β can also exceed 1. Values above 1 for β for example indicate higher simulated mean results than the observed mean. In terms of model performance, deviations either above or below the value of 1 perform equally, but it can be used to indicate imperfections in the simulations.

Since multiple locations are available to compare the simulated results with the measurements, a method is needed to find the calibration run that suits the complete model the best. From the available locations, the local KGE will be calculated and for each simulation, the average of the KGE values from the locations will be the final score for each model run. The simulation with the best average KGE has the best fitting input parameter values. Input for the KGE calculations are the observed water overflow height at the three overflow locations and the simulated overflow height at those locations.

4.3 Validation

After the calibration is completed, the best fitting parameter values for the calibration rainfall events are found. These parameter values are then used to run two more simulations, with two different rainfall events as temporal validation. The model including the new parameters will also be compared to the performance of the original model. Besides the validation for this study area, a validation is also performed in Study Area 2. This will provide information on how well the variables found in the calibration perform in another area containing a different soil composition. Both of the validations will use the criterion to evaluate the results. To give more insight in the goodness of fit of the simulated results, the KGE scores will also include scores for the three elements that contribute to the total KGE score.

4.3.1 Temporal validation

For this model, the overflow locations as used in the calibration will also be the reference for model performance in the validation. Within the available time period of measurement data, two rainfall events will be selected that generate an overflow at these locations. Results will be compared both visually, and quantitatively with the Kling-Gupta Efficiency scores. The new parameter values will be successful if the KGE scores are at least as high as the KGE scores of the original model.

Rainfall events and observations The rainfall events and observation that will be used for the temporal validation in Study Area 1 are described in Section 2.4.2.

4.3.2 Applying parameter values for different soil types

With the parameter values from calibration and validation of Study Area 1 and the Horton parameters as suggested by Akan (1993), parameter values for other soil types can be derived.

With the earlier assumption that the soil types *Sand, loamy sand, sandy loam* of Table 7 represent fine and coarse sand for 7.6 and 11.4 mm/hr minimum infiltration

Table 7: Horton parameter values as suggested by Akan (1993)

	Minimum (Asymptotic) Infiltration Capacity	Initial
Soil Type	**(mm/hr)**	**(mm/hr)**
Clay loam, silty clay loam, sandy clay, silty clay, clay	0.00 - 1.3	7.6
Sandy clay loam	1.3 - 3.8	7.6
Silt loam, loam	3.8 - 7.6	25
Sand, loamy sand, sandy loam	7.6 - 11.4	43

capacity respectively, the ratio between these theoretical values and the calibrated values is calculated and used to adapt the rest of the soil categories. For example: the calibrated limiting Horton value for fine sand is 14 mm/hr and the value from Table 7 is 7.6. This 14/7.6 ratio is used to translate the other soil types into Horton values. All soil types have an upper and a lower limit for Horton infiltration parameter values. Since that is not useful for defining Horton parameters in the model, the average of the two limits is used as limiting Horton value, except for the two sand types where the values are the calibrated values.

4.3.3 Spatial validation

The spatial validation takes place in Study area 2. From the most optimal infiltration parameters that are found with the calibration, new infiltration parameters as described in Section 4.3.2 are used in this study area.

5 Results

In this chapter, the results are presented that were obtained by using the methods as described in chapter 4. First, the results of the sensitivity analysis are discussed in section 5.1 to determine the most relevant parameters. The results of calibration of these parameters are described in section 5.2. Finally, the new parameters are validated both temporally and spatially in section 5.3.

5.1 Sensitivity analysis

The results of the sensitivity analysis are divided in results for the small rainfall event and the results for the large rainfall event due to the differences in impact both events have on the model results.

5.1.1 Rainfall event T=1 year

Runoff from unpaved areas Almost all the simulations do not produce any runoff. Only two or three out of the 50 model runs result in a runoff volume above 1 m^3 for lines 1, 3 and 4. For line 2 however, all the runs do generate runoff, although most of them a small amount. Like the other lines, two out of the 50 model runs generate significantly more runoff, but the other ones all show a total flow volume of about 2 m^3. Figure 15 shows these model runs. Although the volume generated by the outliers is different for each line, the runs generating these runoffs are the same, namely number 11 and 50. The parameter values for these runs are presented in Table 8. Even with the reduced values of the Horton parameters compared to maximum theoretical values as described in Section 4.1 as well as the initial loss, most of the precipitation will not result in overland flow for this type of rainfall event. The initial loss with a maximum of almost one third of the total rainfall in the event does not show any influence on the runoff volume, which is strange. Combined with the very small runoff per simulation for only one of the four lines, this leads to a low confidence that these results are reliable. The figures with the results for all the lines can be found in Appendix A.2, where the outliers can be clearly seen.

Table 8: Runs in sensitivity analysis that generate outliers at the flow lines

	Run 11	Run 50
Horton int [mm/hr]	36.36	27.93
Horton lim [mm/hr]	2.96	12.83
Horton dec [1/hr]	3.34	5.40
Manning [-]	0.031	0.033
Initial loss [mm]	1.55	0.46
Soil saturation [%]	36.14	71.94

Overflow locations For the overflow locations, a similar result as with the flow over the lines in the unpaved areas can be seen. Only a few occurrences exist where the total water volume is greater than zero. Like the total water flow over the flow lines, only the runs 11 and 50 like in Table 8 generate the overflow. The figures of results at these locations can be found in Appendix A.3.

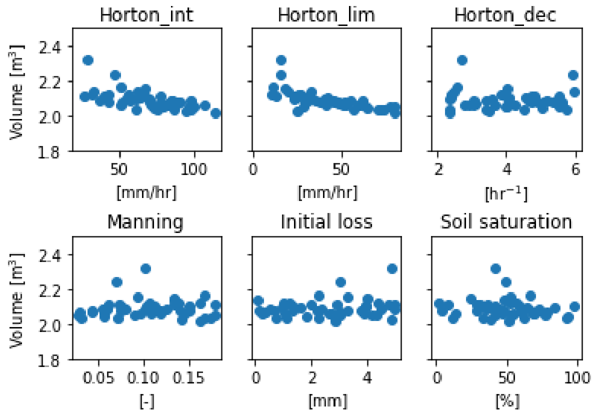
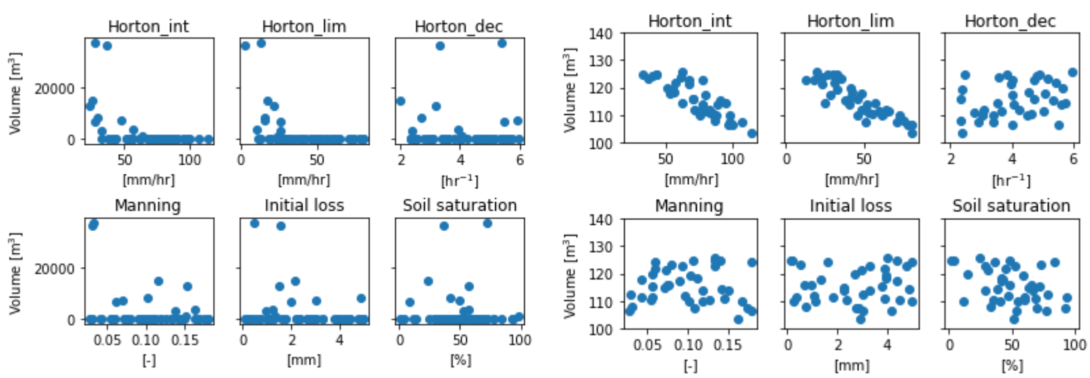


Figure 15: Flow over Line 2 for T=1 year rainfall event, excluding the two outliers

Total flood volume Since the discharge of water over the flow lines as well as the overflow locations for this rainfall event is too small or non-existent for most of the model runs, a third method of finding parameter influences is applied. Instead of comparing the water flow at specific locations, the total volume of water on the surface in the entire area during each run is compared. This total volume is found by multiplying the water depth and area size of each mesh triangle at every time step in the model, and sum these for the whole model run.

Due to the larger area these results are based on, all the model runs show surface water as can be seen in Figure 16. For eleven model runs, the total volume is several magnitudes higher than the other model runs. While Figure 16a shows that for the initial and limiting Horton values these excess values are all positioned within the first half of the parameter range, a clear trend is not visible in the scatter plot. On a smaller detail level however, a trend can be seen and also the other parameters show more spread across the graphs. In Figure 16b the y-axis is limited from to 140 m^3 of total volume which excludes the large outliers. Within this figure, a clear negative correlation between both the initial, and the limiting Horton values and the volume is apparent.



(a) All runs included

(b) With y-axis limit

Figure 16: Total peak flood volume for T=1 year event, full and detail

A reason for these outliers is that the infiltration for most of the simulations is too high to generate any runoff from unpaved areas. The ones where the infiltration is low enough to generate runoff are the outliers. All the other simulations from Figure 16b are a result of indirect runoff, generated from flow from paved areas. This means that the outliers are the results that are the most relevant for this sensitivity analysis. The correlation between increasing Horton parameter values and decreasing total volume is caused by the increase in volume of infiltrated water from these unpaved areas.

Other parameters do not show any correlation, with or without the outliers. It is possible that the outliers are the simulations where the parameters have a direct effect on overland flow over unpaved surfaces, instead of indicating only indirect effects from the other simulations. There are too few outliers to indicate any correlation between these results and parameter values.

Sobol' indices Since both the volumes for the lines and the overflow locations do not provide a sample with enough discharge results to be analyzed, also the Sobol' indices cannot be estimated. However, based on the total volume of flooded water within the model this is possible. Excluding the model runs that produce the outliers, the Sobol' indices are presented in Table 9. These Sobol' indices show that both the initial value, and the limiting value of Horton are key parameters regarding model sensitivity. These high indices confirm the visual representation that the model has a high sensitivity for these two parameters, while the other parameters do not show any significant sensitivity. An important sidenote is that this sensitivity for these parameters is most likely not caused by the direct effect on overland flow over unpaved surfaces. The sum of the Sobol' indices is far greater than 1, which is an indication that the sample size that is used to calculate the Sobol' indices is not large enough (Bomers et al., 2019). Taking into consideration that for these indices only 39 runs were used, this is not strange. There are ways to overcome this problem using resampling methods, but they are not included in this research. The large difference in Sobol' indices unmistakably indicate the two most important parameters: initial Horton infiltration and limiting Horton infiltration.

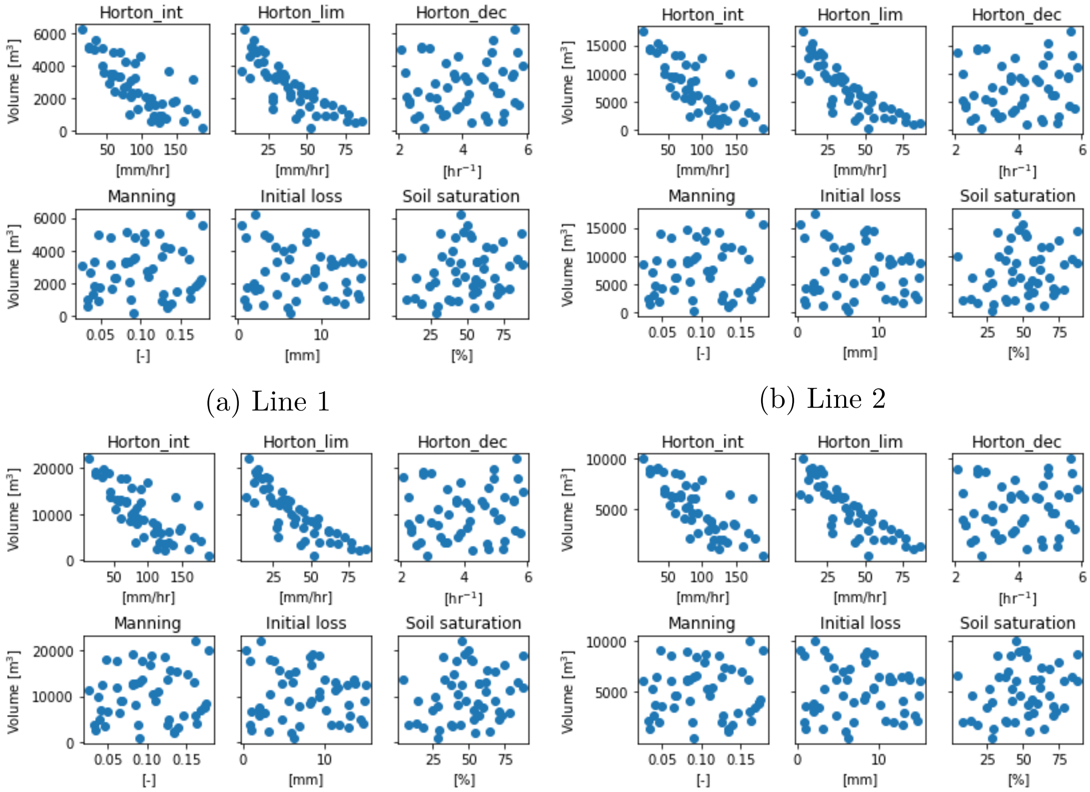
Table 9: Sobol' indices quantifying the sensitivity of the total flooded area to model parameters disregarding outliers of total flooded area

	Horton int	Horton lim	Horton dec	Manning	Initial loss	Soil saturation
Si	0.78	0.78	0.09	0.00	0.02	0.02
Stotal	1.70					

5.1.2 Rainfall event T=100 years

For the T=100 year rainfall event, all the model runs created surface runoff volumes, unlike the small rainfall event. Without the need to remove model runs due to no runoff, conclusions from this rainfall event will be a good substantiation of the former rainfall event results.

Runoff from unpaved areas In all the scatter plots, the negative correlation between the initial and limiting Horton parameters and the total volume of water crossing the lines is evident. The results of parameters for each flow line are very similar, as can be seen in the scatter plots in Figure 17. The scales of total volume differ for each line, but the influence of parameter changes is similar for each flow line. Besides the two Horton parameters, no other parameter shows visible correlation in the scatter plots, although for the initial loss, it seems that with increasing initial loss, the volume decreases slightly.



(a) Line 1 (b) Line 2

(c) Line 3 (d) Line 4

Figure 17: Total flow over all four lines for T=100 years rainfall event

Overflow locations Like the flow over the lines, also the overflow locations show that the total water volume decreases with the increase of both the initial and limiting Horton parameters. The shapes of the scatter plots are similar to the ones from Figure 17. This is as expected, since the same parameter values are used for the same rainfall event without any adaptations to the model.

Total flood volume The total flood volume confirms the other conclusions from the T=100 years rainfall event scatter plots. The distribution of dots in Figure 19 is very similar to those of Figures 17 and 18. The scale of total volume however, is significantly larger due to the large amount of precipitation across the whole modeled area.

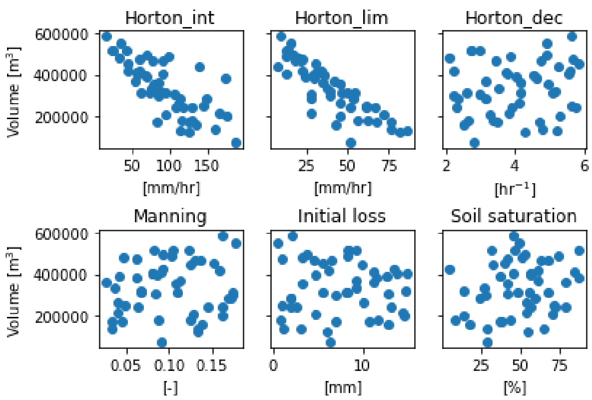
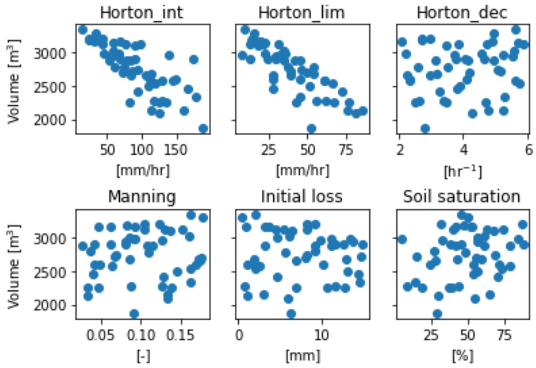
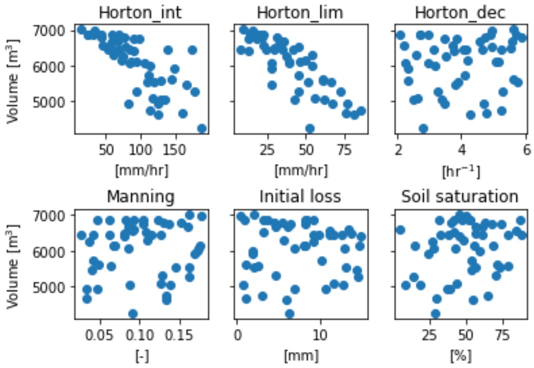


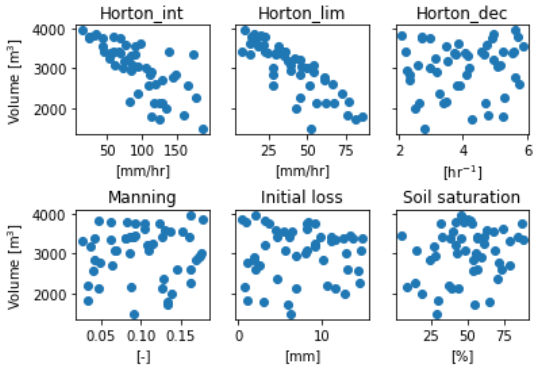
Figure 19: Total flood volume for T=100 year rainfall event



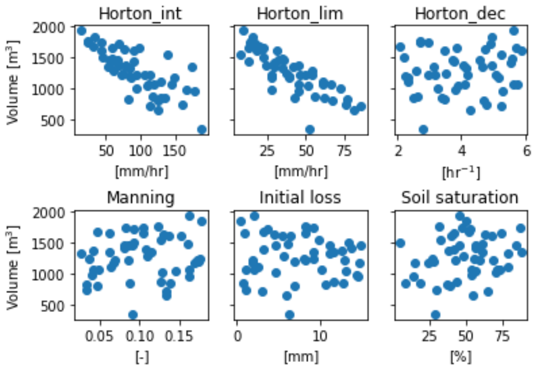
(a) Location 1



(b) Location 2



(c) Location 3



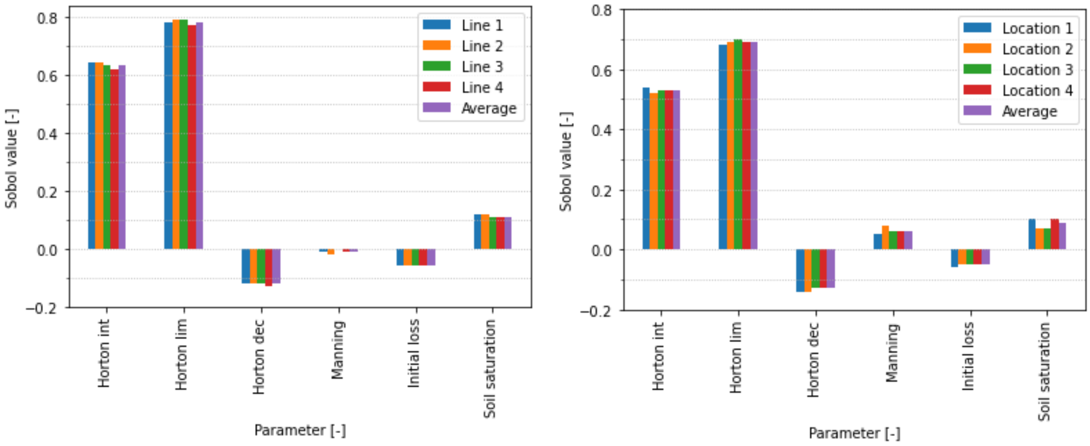
(d) Location 4

Figure 18: Total flow over overflow locations for T=100 year rainfall event

Sobol' indices The Sobol' indices indicate a strong model sensitivity for both the initial Horton parameter, as well as the limiting Horton parameter. In Figure 20 this is visible by the high Sobol' values compared to the other parameters. For this rainfall event, some values are negative, which should not be possible for Sobol' indices in theory (Li & Mahadevan, 2016). However, these negative values are present due to the same reason as discussed before: the small number of samples. Negative values can simply be seen as having no effect on model sensitivity. Again the sum of the Sobol' indices is larger than 1 for the same reason of the limited number of model runs. For the flow lines the average of total Sobol' values is 1.33 and for the overflow locations this is 1.18. One thing that stands out when comparing these figures, is that in Figure 20a the values for the initial and limiting Horton parameters are higher than in 20b and Table 10. This indicates that the model is more sensitive for Horton infiltration for runoff at those locations. This is in line with what can be expected, since the upstream area of the lines is almost all unpaved area from where the water flows, while the overflow locations and total model area both also include runoff from paved areas.

Table 10: Sobol' indices of the total maximum flooded area for T=100 year rainfall event

	Horton int	Horton lim	Horton dec	Manning	Initial loss	Soil saturation
Si	0.58	0.77	-0.14	0.03	-0.06	0.10
S total	1.28					



(a) Flow lines

(b) Overflow locations

Figure 20: Sobol' indices for flow lines and overflow locations for T=100 rainfall event

5.1.3 Summary

Based on this sensitivity analysis that is performed for multiple locations in Study Area 1 with two different rainfall events, two parameters are found to be relevant in terms of model sensitivity: the initial and limiting Horton parameters. Especially for the larger rainfall event with an occurrence of once in 100 years, both scatter plots and the Sobol' indices confirm the model sensitivity to these parameters. For the T=1 year rainfall event, the runoff was too small to evaluate flow over the lines and the overflow locations, The results from the total flooded area for this event might be from indirect influences from the parameters on surface runoff instead of direct influences. Due to the large amount of infiltration in most of the simulations, these do not generate rainfall runoff from unpaved areas at all. Since it is not clear if the results for the T=1 year rainfall event are reliable, only the results of the T=100 year rainfall event are used to indicate the parameters for which the model is most sensitive to.

5.2 Calibration

The results of the calibration section are described for each of the two rainfall events that have been used.

5.2.1 Rainfall event 1

The simulations of the first rainfall event with a total rainfall amount of 26.8 mm all show overflow at the three measured locations, as can be seen in Figure 21. Location 2 is out of the three locations the only one where the observed overflow lies fully within the upper and lower limits of the simulated results for the whole period of observed overflow. The observed values at Location 3 however, do not match any of the simulation runs. Also, the observed peak at Location 1 does not comply with the simulations, although after the first hour the observations fall within the upper and lower limits of the simulations.

The simulations show that for each location, the overflow changes differently for the changes in parameter values. The simulations at locations 1 and 3 all start with very similar water heights in the first half hour and spread out more over time. Location 2 on the other hand, starts with a larger variation in simulation results and with a smaller range at the end of the simulations. The larger range in the first half at Location 2 indicate that the change in parameter values have a larger effect at that location than the other ones. The most likely explanation for that is that the runoff area towards this overflow location includes more unpaved surface area where infiltration can take place.

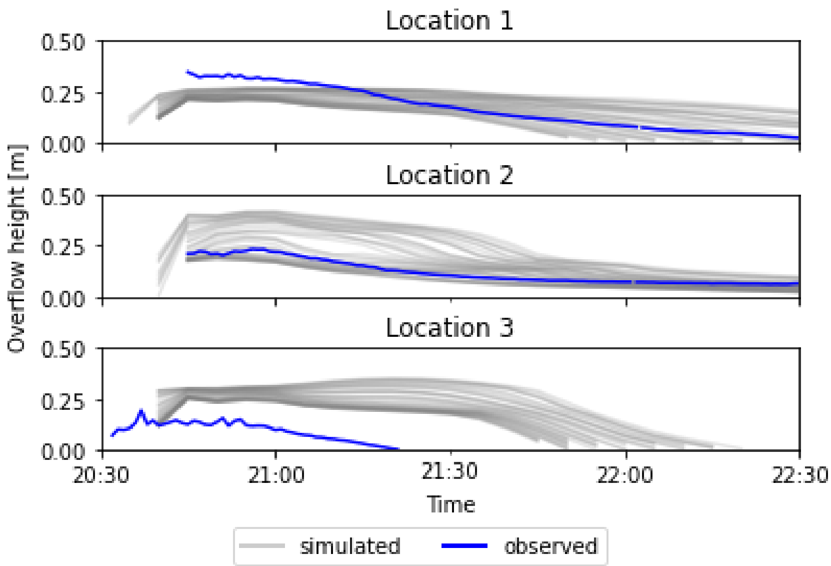


Figure 21: Simulated and observed overflow for rainfall event 1

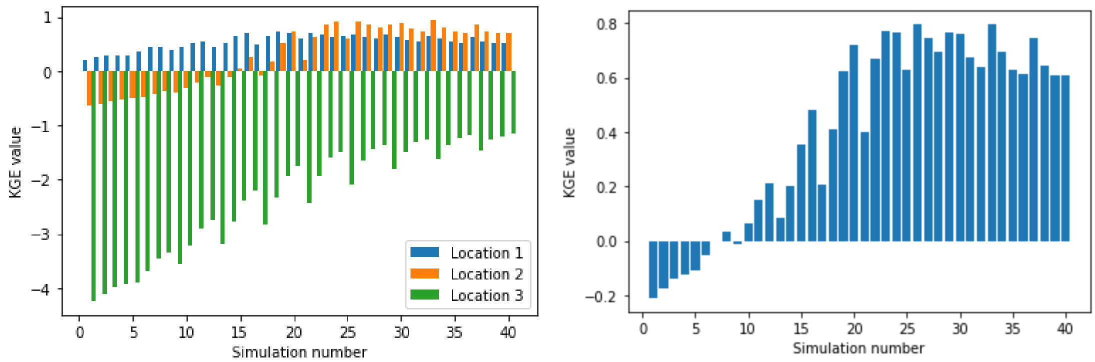
The opposite of that might be the reason for the smaller range of simulated overflow at Location 1. A relatively low amount of surface runoff over unpaved areas is the reason that changes in the infiltration parameters have little effect on the runoff towards this overflow location. The observed overflow height which exceeds the simulations can be caused by a larger actual historic rainfall event than used in the model. Since for the simulations rainfall radar observations are used, which are less accurate than locally observed values, it is possible that this is the reason for the discrepancy. This effect of the possible difference in rainfall radar data and actual rainfall has less of an influence at Location 2 if this theory is also applied for this location. This might be caused by very local changes in rainfall intensity during the rainfall event.

The reason for the misfit at Location 3 could be because of a different problem. It is likely that the original model has an incorrect implementation at this location and that the height of the modeled overflow threshold is too high. Later in this report, when a temporal validation is performed, it will become clear that this location structurally generates too much simulated overflow.

For each location and every simulation the KGE is calculated. As expected from Figure 21, Location 3 results in low KGE values. In Figure 22a where the KGE scores of the three locations are compared, the difference in score is clearly visible. A trend is visible in the KGE scores due to the manual selection of calibration values for parameters, which are not randomly generated. The negative KGE scores of Location 3 will heavily influence the average scores across the three locations. Other tests performed at that location proved a systematic error, and therefore this location is excluded from calculating the average KGE scores. Figure 22b includes therefore the average KGE values of simulations at Locations 1 and 2. Two maxima are reached with the same value: both run 26 and run 33 have an average Kling-Gupta Efficiency of 0.80. Since KGE has a maximum score of 1, this value indicates that the simulations represent the observed overflows fairly accurate with these two parameter configurations. The Horton parameter values used in these two simulations are presented in Table 11.

Table 11: Parameter values corresponding to the optimal runs, all in mm/h

	Simulation #	
	26	**33**
Fine and coarse sand initial Horton	35	45
Fine sand limiting Horton	14	9
Coarse sand limiting Horton	21	13.5



(a) All three locations (b) Averaged between Location 1 and 2

Figure 22: Kling-Gupta Efficiency scores

5.2.2 Rainfall event 2

The simulations from event 2 show different results when compared to event 1. Location 3 has no observed, but also no simulated overflow during the whole event, so that location is not included in these results. In figure 23 the overflow results of the two remaining locations are given. For this rainfall event, only a couple of simulations show any results in overflow. For Location 1 just two out of the 40 simulations create overflow, and at Location 2 there are 5 simulations that show any overflow. These all include the simulations with the lowest Horton parameter values and thus lowest infiltration. In Table 12 the parameter input corresponding to these runs is given, where for Location 1 only run 1 and 2 are visible in Figure 23 and for Location 2 all five of them are present.

Table 12: Parameter values in calibration runs, all in mm/h

	Simulation #				
	1	**2**	**3**	**4**	**5**
Fine and coarse sand initial Horton	5.0	5.0	5.0	5.0	10.0
Fine sand limiting Horton	1.0	2.0	3.0	4.0	2.0
Coarse sand limiting Horton	1.5	3.0	4.5	4.9	3.0

The KGE scores for this rainfall event are significantly lower than for the first event. Especially for Location 1 the KGE scores are low, but also location 2 only has negative KGE values. This means that for this rainfall event, none of the calibration runs are

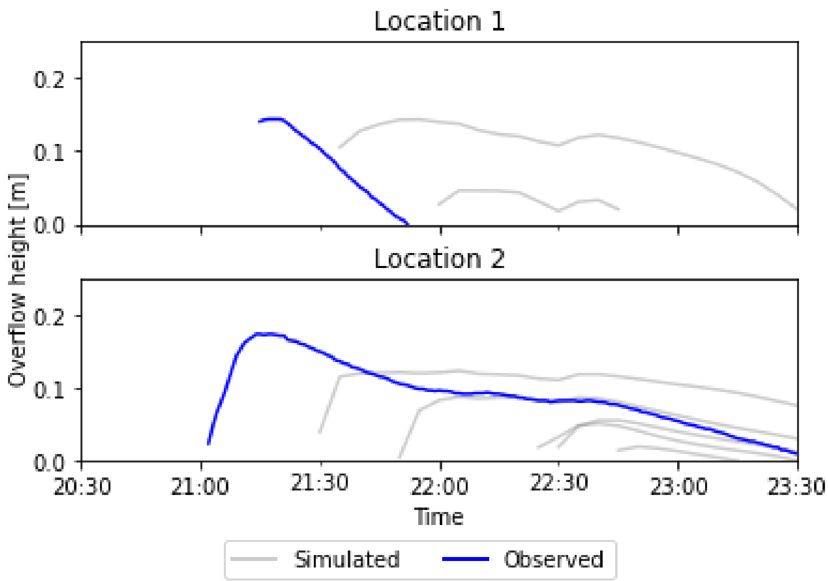


Figure 23: Simulated and measured overflow for rainfall event 2

accurate when compared to the measured overflow at these overflow locations. In Figure 24 the values for the simulations that generate overflow are presented for the two locations. The highest KGE value is achieved for simulation 1 at location 2 with a score of -0,47, which is not a good fit.

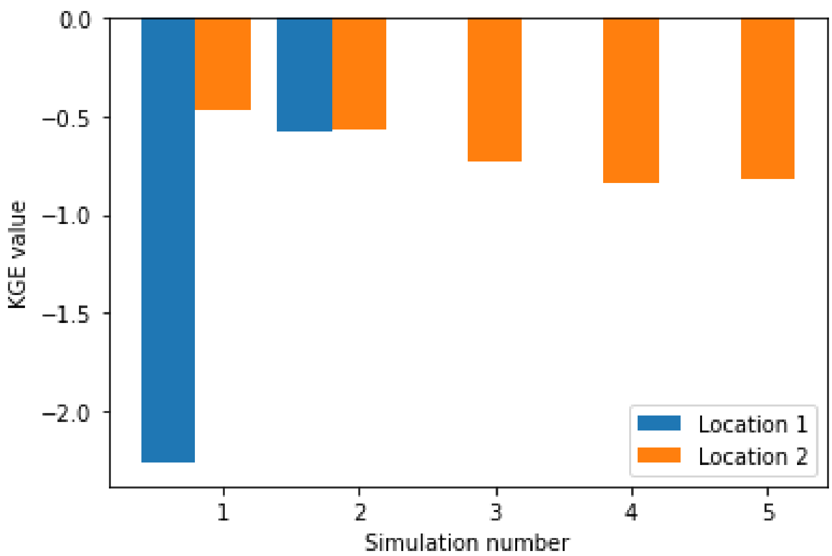


Figure 24: Kling-Gupta Efficiency scores for rainfall event 2

5.2.3 Summary

The two different rainfall events show that the current model with the adaptation of only the Horton parameters does not provide an accurate representation of overflow at the specified locations under all circumstances. Based on the results of only the first rainfall event, it is likely that Location 3 is not implemented in the model correctly. Where the other locations provide reasonable model output compared to the observations, it looks like the simulated values permanently overestimate the overflow at Location 3. For the high intensity amount short rainfall event 1, two parameter combinations were found that, according to the Kling-Gupta Efficiency score, result in a good fit for overflow. For rainfall event 2 that has a smaller total precipitation amount over a longer period of time, the modeled overflow only approaches the actual runoff in case the Horton infiltration parameters are very small. Even then, the KGE values are much smaller than the values found for the first rainfall event.

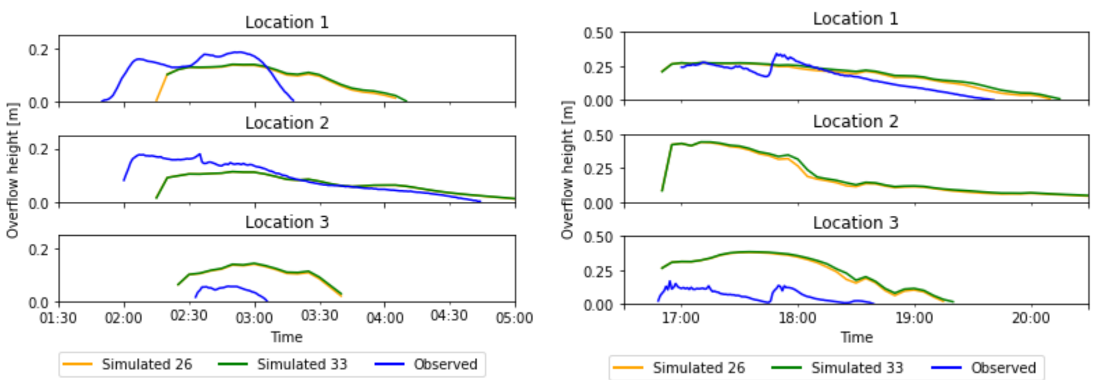
Due to the poor KGE scores of event 2, only calibration results for event 1 will be used to provide parameter values for the validation of the model. However, two model runs have exactly the same averaged KGE value and since no other criteria for optimal calibration results were defined, choosing either of them as the best fit is not possible. Therefore, both parameter combinations will be used to perform the temporal validation for this research area, after which the best performing parameter values will be chosen. These will then be used for spatial validation in Study Area 2.

5.3 Validation

The validation of the parameter values from the calibration is done in two different models for multiple rainfall events. First the temporal validation results of study area 1 are discussed to make the final selection which parameter set will be used to determine the parameter values of other soil types. After that, the spatial validation results from study area 2 will follow.

5.3.1 Study area 1

Since two parameter combinations resulted in the same Kling-Gupta Efficiency score from the calibration, both combinations also have been used for the validation at this location. For reference they are named with the number of the calibration run from the previous section, which are number 26 and 33. Figure 25 shows the performance of these parameter sets for rainfall event 1 25a and rainfall event 2 25b. Just like the calibration pointed out, the two parameter sets show almost the same overflow results. At first glance, the simulated results are similar to the observed values for Location 1 for both rainfall events, but also Location 2 shows a good fit for the first event. As expected from the calibration, the simulation results for Location 3 do not match with the observed overflow values and are overestimated. For event 2, Location 2 did not have observational data.



(a) Rainfall event 1 (b) Rainfall event 2

Figure 25: Validation results for study area 1

In order to compare the KGE scored on a more detailed level, not only the total KGE score is reviewed, but also the three components that are the base of the total score are analyzed. Tables 13 and 14 show all these values together with the scores from the original model when running these rainfall events. For the first rainfall event, both Location 1 and 2 show similar results: the bias terms β, but also the variability ratio α contribute to a good KGE score, while the linear correlation is slightly lower. Still, KGE scores between 0.3 and 0.4 indicate good simulations, especially considering the relatively short simulation period. The KGE scores for Location 3 in both the original and validation simulations confirm the permanent overestimation of the simulations with a very high β value, while the scores for r and α are similar to those of locations 1 and 2.

Table 13: Kling-Gupta Efficiency scores for rainfall event 1

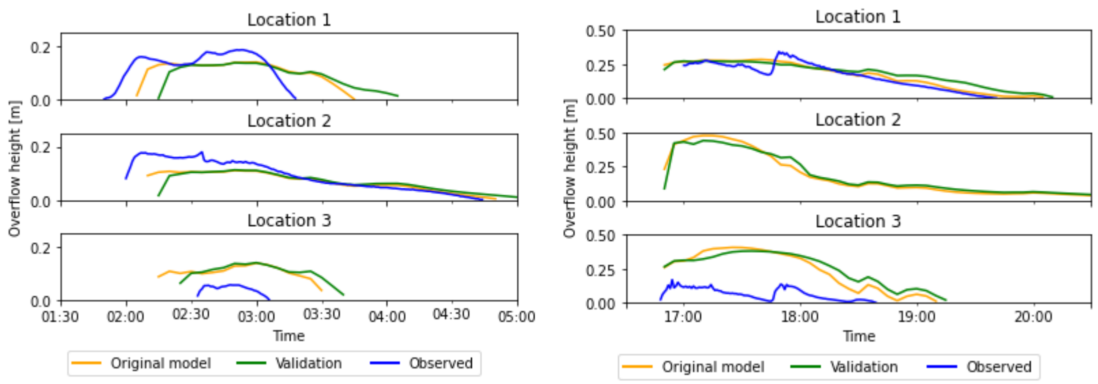
	Location 1			Location 2			Location 3		
	Original	26	33	Original	26	33	Original	26	33
KGE	0.51	0.38	0.35	0.49	0.32	0.31	-3.71	-3.61	-3.82
r	0.61	0.46	0.42	0.75	0.5	0.49	0.45	0.57	0.56
α	0.71	0.71	0.71	0.63	0.61	0.61	1.02	1.37	1.33
β	0.97	0.92	0.96	0.75	0.74	0.75	5.67	5.58	5.79

The simulations for rainfall event 2 result in an even better total KGE score for Location 1. The total scores of 0.59 and 0.51 for parameter sets 26 and 33 respectively, indicate simulations that are a good representation of the observed values. Like for the first rainfall event, the total score for the latter parameter set is slightly lower than the other one, although minimal. For both events, the scores of the original parameter settings are higher, although the differences are not very large. This means that the model with original parameter values performs slightly better than model used for validation. Out of the simulations from calibration, number 26 performs better than 33.

Table 14: Kling-Gupta Efficiency scores for rainfall event 2

	Location 1			Location 2			Location 3		
	Original	26	33	Original	26	33	Original	26	33
KGE	0.73	0.59	0.51	-	-	-	-3.26	-3.45	-3.63
r	0.83	0.84	0.85	-	-	-	0.74	0.72	0.70
α	0.94	0.81	0.76	-	-	-	3.06	2.66	2.57
β	1.2	1.32	1.41	-	-	-	4.73	5.13	5.34

In Figure 26 the simulated overflow from the original model is compared with the simulated overflow from the best calibration result. Just like Tables 13 and 14 also indicated, these simulation results are very close.



(a) Rainfall event 1

(b) Rainfall event 2

Figure 26: Validation for study area 1 compared to original model

Summary Based on the evaluation of the KGE scores, the validation of the two parameter sets indicate a good model fit for location 1 during both rainfall events, and also for location 2 for the first rainfall event. Location 3 is overestimated in the simulations, which is most likely caused by an incorrect implementation of the overflow location in the model or incorrect observational data. When the KGE scores of the original model are compared with the KGE scores of the calibrated model, the original performs better than the validated parameter values, although the differences are not very large. From the two validation parameter sets, the one from simulation 26 performs slightly better.

5.3.2 Parameter values based on soil type

Based on the results of the calibration and the temporal validation, the infiltration parameters from the calibration simulation number 26 are used to define the Horton infiltration parameter values for other soil types. Table 15 includes these values, which are based on the Horton parameter values from Akan (1993).

Table 15: Horton parameter values from calibration

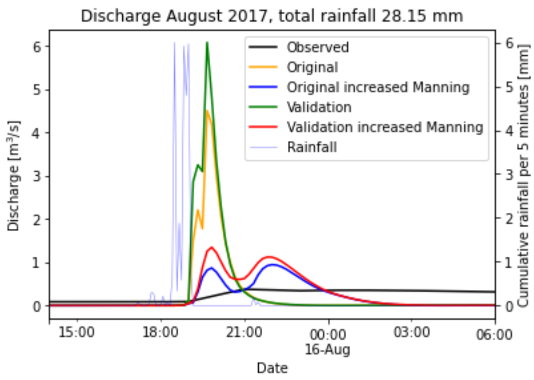
Soil Type	Minimum infiltration capacity [mm/hr]	Initial infiltration capacity [mm/hr]
Clay loam, silty clay loam, sandy clay, silty clay, clay	1.2	6.2
Sandy clay loam	4.7	6.2
Silt loam, loam	10.5	20.3
Fine sand	14.0	35.0
Coarse sand	21.0	35.0

5.3.3 Study area 2

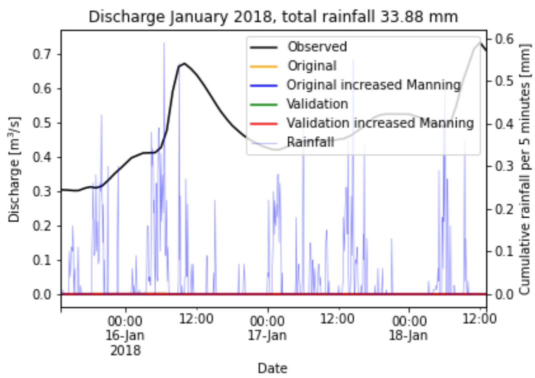
Soil types For validation in Study Area 2, the values from Table 15 are used as infiltration parameters. The original soil type categories are not similar to those of this table, so the original soil types are divided into the soil types from Table 15. The full table that includes these original soil types can be found in Appendix B.1.

Discharge The first rainfall event that is used for validation is the one that has been used to calibrate the original model and can be seen in Figure 27a. When viewing the results, it becomes clear that the simulated discharge is much larger than the observed discharge during the rainfall event.

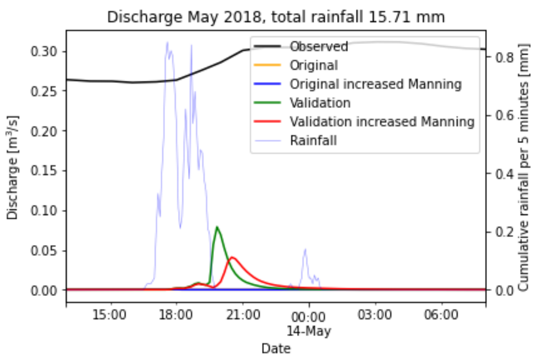
Since the calibrated original model had different values for surface roughness and an unknown runoff factor, validation results are also presented with the increased roughness coefficient, which is also applied to the original model. These results are presented in Figure 27. The 'Original' line is the original model without these adaptations, and 'Original increased Manning' is the result after the adaptation of surface roughness coefficient. The effect of increasing surface roughness is a large decrease in runoff peak. As can be seen from the graph, this was not enough to create a modeled discharge similar to observations, which is the reason for adding the unknown runoff factor.



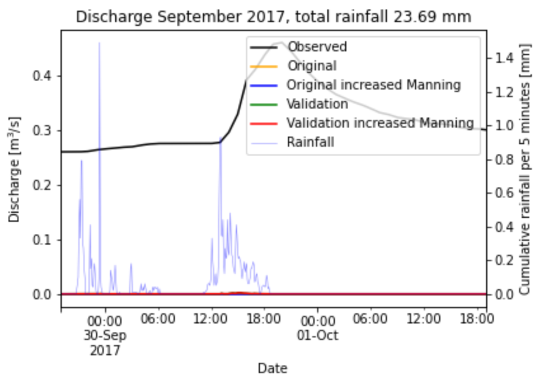
(a) Calibration event



(b) Event 2



(c) Event 3



(d) Event 4

Figure 27: Rainfall events and discharge from validation at Study area 2

From the graphs, it can be seen that the other three rainfall events generate more observed runoff than is simulated in any of the simulations. Furthermore, Event 2 and 4 show no simulated runoff at all, even for the original model. The model response to a rainfall event does not appear to be very slow so that a peak in discharge is generated hours after the event. The quick response can be seen in Figures 27a and 27c for both observed and simulated discharge. However, the simulations return to zero discharge quickly after the rainfall peaks while the observed values never return to zero. This indicates a base flow that is not simulated in the model. However, even if some form of constant base flow would be added to the model, the simulations would still not match the observations.

5.3.4 Summary

Based on the results of the validation in this study area, it is not possible to evaluate the effect of the new parameters on the discharge at the observation location. Also a comparison with the original model is not useful to further quantify, since no discharge is produced by the original model other than at the first rainfall event.

6 Discussion

In this discussion chapter different elements of this research are covered. Decisions and assumptions that are made during the process are evaluated and their impact on the results are discussed. First, the methods and results are evaluated in section 6.1 and after that the value of the results of this thesis are covered in section 6.2.

6.1 Limitations of methods and results

6.1.1 Observational data

The observational data that is used in this research has had a large impact on the overall results, since both for calibration and validation different forms of observations were used in the process to quantify model performance. The main input data in the models are the rainfall events from radar observations of the national rainfall radar. The rainfall radar observations provide decent results since they are calibrated using KNMI measurements from weather stations (Royal HaskoningDHV; Nelen & Schuurmans, 2013). However, the reference data from the weather stations often has a temporal resolution of one measurement per hour, or even one per day. The result of this is that peak intensities from radar data that are used for this research are not as reliable as daily total precipitation. Any differences in radar measurements compared to actual rainfall will have a direct influence on model performance, and therefore also on calibration and validation results. Furthermore, in this research a single location within the study areas has been set as location for radar observations to be applied all over the model equally. This location represents a 1x1 km area from the rainfall radar, since that is the radar resolution. If a measurement station was available within the research area, this would also be a single point of observation. In reality, rainfall is not evenly distributed all around the study area as there will most likely be locations with more and less rainfall when compared to a single location. It is possible to apply different amounts of rainfall within the model based on the radar observations across a large area. However, for simplicity this has not been used in this research. Rainfall input is more accurate to actual rainfall if this is applied, which also results in more realistic model output.

From the available observations at the overflow locations, two rainfall events were selected to be used for calibration, and two for the temporal validation. Unfortunately not all locations provided useful results in order to select the most optimal parameters based on KGE scores. More events should have been selected where observational data was available in order to create more reliable calibration and validation results.

6.1.2 Sensitivity analysis

In order to account for large rainfall events, the sensitivity analysis included an extreme rainfall event that generated 93 mm of rainfall. Also parameter values have upper limits that are very high, due to findings in literature. Due to this selection however, the influence of the parameters in the sensitivity analysis on smaller rainfall events is possibly overshadowed. The T=1 year rainfall event showed very little water flow from unpaved areas within the model, while in real life an event with over 16 mm of rainfall within 75 minutes should provide a lot more surface runoff, based on historical events and observations. The reason that this did not happen is most likely due to the very high amounts of infiltration from two of the Horton parameters. Any value of the limiting Horton parameter that exceeds the total amount of rainfall will most likely result in total infiltration of the rain on the unpaved areas. This is less of an issue for the larger rainfall event, since the larger amount of rainfall exceeds more limiting infiltration values, which causes runoff for a lot more simulations.

The Horton infiltration influences on the total flooded water volume for the T=1 year rainfall event are very likely indirect influences for most of the simulations. Only for the lower Horton parameter values, rainfall does not directly infiltrate and causes therefore a certain amount of volume of water on the surface. If a lower upper limit for the range of initial and limiting Horton parameter values would have been used, the results could have been different. Especially for the T=1 year rainfall event, more runoff would be generated and it would have been possible to see more correlation between parameter values and runoff volume. The sensitivity analysis results could show model sensitivity for different parameters than the ones that were found in this research.

The first order Sobol' indices used for evaluating the sensitivity analysis indicated clearly the two parameters with the most influence on the model output for the two rainfall events. However, the sum of Sobol' values also indicated the very limited number of simulations. Most likely the two parameters with most influence would have been the same if more simulations were performed due to the extreme differences in first order Sobol' values from the other parameters. These values would nevertheless change compared to the current situation, but that has no influence on the parameter selection.

6.1.3 Calibration

The parameter range used for calibration is on the lower side of the ranges used for the sensitivity analysis. The large infiltration values turned out to be not realistic since for the T=1 year rainfall event no surface runoff was simulated for infiltration values above 50 mm/hr. In reality, a rainfall event like that in this study area would definitely generate runoff, based on historical observations of overflow at overflow locations. As for the sensitivity analysis, due to the long computational times it was not possible to generate a large sample size for calibration. Due to this limited number of parameter combinations, it is possible that a more optimal configuration of parameter values can be found than presented in the results.

Since only two soil types are dominant in Study area 1, which are both sandy soils, the optimal parameter values for other soil types had to be estimated. This was done using the results from the calibration for the two sandy soil types and the literature values. This method assumes that the calibrated soil types can be translated directly to the uncalibrated soil types, which might not be true. Previous research did not generate consistent infiltration value differences between soil types (Davidsen et al., 2018; Wang et al., 2017). The only way to exclude this uncertainty is to do a calibration with a model that includes these other soil types as well. Unfortunately, this was not possible for this research.

The reason for the difference in modeled runoff compared to observed runoff might be due to differences in initial conditions that are not within the scope of this calibration. Rainfall prior to the events that are used for this calibration can have an impact on the potential infiltration at the start of the rainfall events. In order to find an explanation for the poor modeled results for especially rainfall event 2, in Figure 28 rainfall during the week prior to both events is presented. Day 0 includes of rainfall from 24 hours before the start of the event, until the start of the event which can be seen in Figures 21 and 23 on the x-axis. In the 72 hours prior to event 2 a total of 16 mm of rainfall occurred which, compared to the 1 mm prior to event 1, might have had an impact on the infiltration capacity at the start of the event. It explains at least some mismatch where the observed overflow is larger than simulated overflows. Whether this is the only reason for this discrepancy is not certain however, since the calibration would have to be extended to include initial soil moisture content.

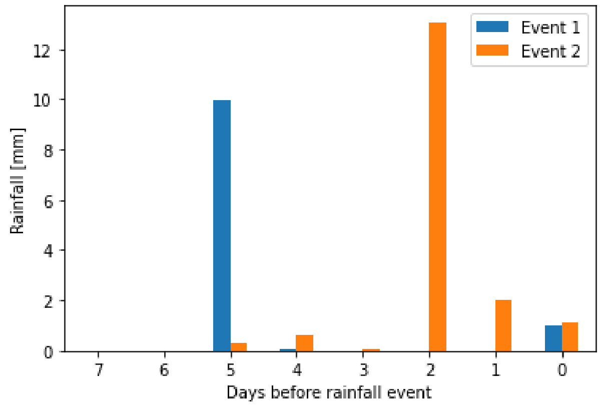


Figure 28: Rainfall during the week prior to calibration rainfall events 1 and 2

When comparing the results for the two rainfall events, it becomes evident that for larger rainfall events, the model reacts differently than for smaller events. For the latter one, infiltration values above 10 mm/hr do not generate any overflow in the model while the optimal parameter values for the larger event are above 10 mm/hr of infiltration. A limitation of the calibration method is that only two rainfall events are used. For a better calibration, it would be preferred to use more different rainfall events, but that was not possible because of limited observations. Also, since no local rainfall measurement station was available, rainfall radar observations are used. This generates an extra uncertainty in the calibration, since it is not known how accurate these observations are exactly. With an offset of rainfall data compared to actual rainfall, this can highly influence calibration and validation results.

6.1.4 Validation

For the temporal validation, only two rainfall events were used to calculate the Kling-Gupta Efficiency scores. Based on these results, the KGE scores for Study area 1 turned out to be close to the KGE scores of the original model. The rainfall events however are relatively short in order to make a solid conclusion about the KGE scores. Ideally, the validation considers more rainfall events over longer periods of time. For Study area 2 no conclusions about the parameter values could be made due to the inconclusive model results compared to observations and the original model. Even if the model would perform better, the uncertainty for this study area would still be larger than for the other study area due to the available observations that have a frequency of only one measurement per hour, compared to one measurement per minute, for study area 1. When using this data to evaluate short, high intensity rainfall events that last for only hours, an interval of one observation per hour is low. Combined with the uncertainty of the observations, this has a large influence on results.

6.2 Added value of results

This research has identified the most important parameters for rainfall-runoff modeling during large rainfall events and showed that when using the Horton infiltration method, model performance after calibration is similar to that of the calibrated original model using a constant infiltration rate. Theoretically the Horton infiltration method has more potential to simulate accurate infiltration rates than the current implementation of a constant rate. Although the selection of optimal parameter values for other locations could not be validated in this research, applying the Horton infiltration model proved to be working well for the temporal validation of large rainfall events. The model might not perform as well with smaller rainfall events, as the two Horton infiltration parameters could be less dominant for those cases.

7 Conclusions and recommendations

In this chapter the final conclusions of this research are presented by answering the three research questions and the research goal in Section 7.1. After that, Section 7.2 provides recommendations based on the results of this thesis.

7.1 Conclusions

1. *Which of the parameters influence the volume of overland flow over unpaved surfaces the most?*

From the sensitivity analysis, two parameters show the most influence on the volume of overland flow over unpaved surfaces: initial Horton infiltration and limiting Horton infiltration parameters. Two rainfall events are used for this sensitivity analysis, which are one with a return period of one year and the other event with a return period of hundred years. No overland flow or overflow at overflow locations could be determined for the T=1 year rainfall event, but total flooded water over the entire study area indicated an indirect sensitivity for initial Horton infiltration and limiting Horton infiltration parameters.

For overland runoff as well as overflow locations and total water volume on the surface, the first order Sobol' indices indicated a strong model sensitivity for the T=100 years rainfall event. The average Sobol' values from multiple locations for the volume of runoff from unpaved areas indicate high influence of the initial Horton and the limiting Horton parameters. The simulation results from overflow locations and total volume of flooded water showed the same sensitivity for these parameters.

2. *Which parameter values generate the best results when compared to observations?*

The optimal parameters are based on a rainfall event that generates a total amount of 26.8 mm within one hour. These parameter values are 35 mm/hr for initial Horton infiltration for both coarse and fine sand, 14 mm/hr for the limiting Horton infiltration for fine sand and 21 mm/hr limiting Horton infiltration for coarse sand. These results are based on a combination of Kling-Gupta Efficiency scores from two overflow locations where observational water overflow height was compared to modeled water overflow height.

3. *Do the optimal parameter values show accurate results when used for different rainfall events and different areas?*

A validation of the optimal parameter values for different rainfall events results in accurate modeled results of overflow at the overflow locations. The Kling-Gupta Efficiency scores range from 0.32 to 0.59, which although not as good as the calibration results, are similar to the results of the original model. Overflow locations that showed a total misfit for results from both the calibrated model and the original model are excluded from these KGE scores.

The validation for a different area with other characteristics was not successful, due to either inaccurate observations, an inaccurate base model or both.

The research objective was:

To find appropriate model parameter values based on area properties for a rainfall-runoff simulation over unpaved surfaces in urban areas which are applicable in different areas and for different rainfall events

It can be concluded that for relatively large rainfall events, the initial Horton infiltration and limiting Horton infiltration parameters have the most influence on rainfall-runoff over unpaved surfaces in urban areas. For multiple rainfall events the calibrated parameter values show good results when compared to observed overflows. With these parameter values, the performance is similar to the original calibrated model. However, for smaller rainfall events these parameter values do not result in good model performance. Also the results could not be validated for a different area with other characteristics, so the performance of the parameter values for different soil types is uncertain.

7.2 Recommendations

Since the performance of the calibrated parameter values could not be spatially validated for areas with different soil types, it is recommended that this will be done for future research. Also, when using the Horton infiltration method calibrating these parameters is necessary for non-extreme rainfall events with a total rainfall amount of less than 24 mm within three hours. A future spatial validation with an extreme rainfall event will indicate if this will also be necessary for use with different soil types. Based on literature however, calibrating the Horton infiltration parameters is always recommended for optimal results. From the conclusions of this research and literature, constant infiltration parameters perform well in case an elaborate calibration is not possible, but applying the Horton infiltration performs better when a calibration is possible.

For this case, the overflow locations provided the observational data, but they had some limitations. Not all locations could be used due to missing or inaccurate data. The overflow locations are usually not the places where excess water causes the most inconvenience during extreme rainfall events. Placing measuring equipment of water levels on critical spots like low-lying streets, tunnels or other places where water can accumulate can improve calibration and validation efforts. For these measurements frequency is important. High intensity rainfall events can have a duration of less than two hours and there have to be enough observations within that period. For a better calibration, especially for rainfall events that have a smaller return period of up to 5 years, multiple rainfall events need to be observed. For these smaller rainfall events, it is recommended to perform a new sensitivity analysis using the same parameters as in this research, but with much smaller maximum Horton infiltration rates.

More accurate observational data also includes locally observed rainfall data. The KNMI has a lot of measurement stations that accurately measure rainfall every 10 minutes, but like in this case they are not always near the study area. Like the water level observations, high frequency observations of rainfall are more useful than for example accumulated rainfall per hour. To calibrate urban models for high intensity rainfall events, accurate high frequent historical rainfall data is necessary. Without this data, models cannot be calibrated properly.

Recommendations for a follow-up research are calibrating more local soil types with the Horton infiltration method. Since the Horton infiltration model is an empirical method, better results will be achieved with more data. With more real life and especially local samples, the estimations of Horton parameter values will become more accurate in case a full calibration is not possible in ungauged areas. That being said, the original model for study area 1 performed slightly better than the one with calibrated Horton parameters for high intensity rainfall events. This means that the use of a constant infiltration parameter is sufficient.

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Appendix

A Sensitivity analysis

A.1 Latin Hypercube Sampling

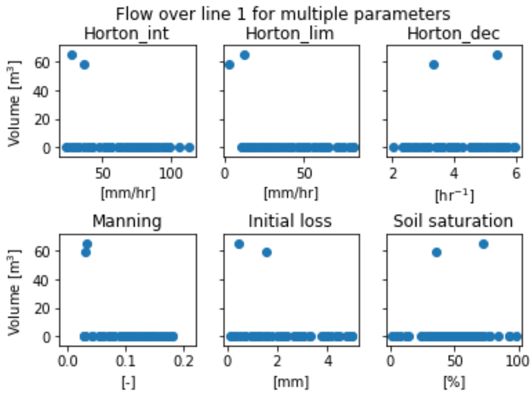
Table 16: Parameter values for T=1 year rainfall event

Simulation #	Initial Horton	Limiting Horton	Horton decay	Manning	Initial loss	Soil saturation
1	82.3	52.7	2.8	0.146	3.9	68.4
2	51.4	41.7	5.6	0.056	2.7	14.3
3	61.9	23.1	3.6	0.060	1.6	84.2
4	40.1	31.1	4.8	0.179	5.0	36.0
5	99.5	80.6	5.5	0.028	3.0	77.3
6	79.8	28.6	4.0	0.090	4.4	41.9
7	56.2	10.8	3.9	0.162	1.2	57.0
8	70.4	46.0	4.7	0.074	0.7	48.2
9	25.2	17.4	2.0	0.116	2.2	23.4
10	87.9	61.0	3.1	0.119	0.3	54.9
11	36.4	3.0	3.3	0.031	1.5	36.1
12	84.1	62.2	4.7	0.055	2.4	60.0
13	70.6	40.9	2.3	0.077	1.0	65.0
14	29.8	15.4	2.7	0.102	4.9	41.8
15	64.1	24.6	4.1	0.151	1.4	98.1
16	43.2	29.8	4.9	0.141	0.2	4.2
17	77.4	52.1	5.6	0.119	3.3	28.8
18	96.5	78.2	4.0	0.179	4.2	53.6
19	57.1	31.0	5.4	0.059	3.9	45.4
20	106.4	50.8	2.9	0.108	2.7	70.1
21	51.9	11.1	2.6	0.168	2.2	66.8
22	62.3	19.6	6.0	0.133	4.0	24.4
23	82.2	48.7	3.1	0.029	3.0	78.1
24	94.4	25.0	3.5	0.142	4.9	38.3
25	71.1	63.6	4.2	0.097	1.1	47.1
26	56.1	42.5	4.5	0.112	4.0	42.2
27	78.0	59.9	3.7	0.043	0.4	60.1
28	37.1	35.8	5.2	0.080	0.5	72.6
29	113.5	80.6	2.4	0.163	2.9	51.9
30	27.7	25.7	5.5	0.062	2.0	8.2
31	90.6	38.0	5.4	0.056	3.8	72.3
32	62.0	57.3	5.7	0.072	2.2	62.8
33	86.7	74.9	2.4	0.031	0.7	33.2
34	53.0	48.4	5.1	0.042	1.3	43.3
35	77.7	13.3	4.7	0.133	4.7	28.6
36	67.9	18.1	4.0	0.093	3.3	52.2
37	23.7	22.1	3.2	0.153	1.5	57.4
38	33.0	32.8	2.5	0.134	0.1	48.5
39	97.9	70.9	3.4	0.174	2.9	92.9
40	43.0	26.9	3.8	0.107	4.4	1.5
41	55.5	32.6	2.4	0.104	3.9	58.6
42	97.8	46.2	3.4	0.101	5.0	40.4
43	88.4	40.9	4.1	0.150	2.2	66.3
44	75.1	72.6	4.5	0.168	1.1	11.8
45	73.8	65.3	5.0	0.056	1.8	93.3
46	67.3	23.4	4.0	0.073	2.9	31.1
47	47.7	15.3	5.9	0.070	3.0	49.9
48	32.9	26.3	2.4	0.138	1.0	52.5
49	85.5	55.6	3.1	0.126	4.5	35.0
50	27.9	12.8	5.4	0.033	0.5	71.9

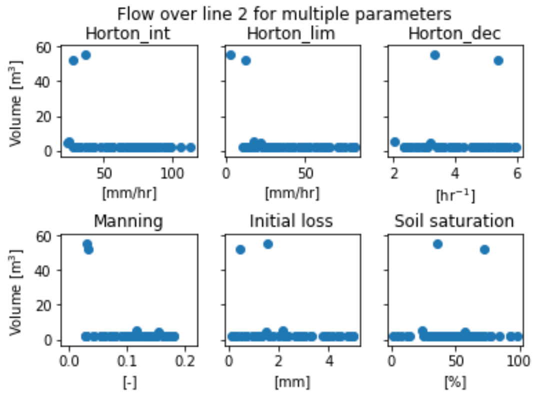
Table 17: Parameter values for T=100 years rainfall event

Simulation #	Initial Horton	Limiting Horton	Horton decay	Manning	Initial loss	Soil saturation
1	55.1	32.6	3.7	0.091	11.2	84.4
2	85.8	39.6	5.1	0.067	14.8	14.5
3	139.5	7.6	5.2	0.126	9.9	33.0
4	32.6	20.3	2.1	0.047	3.3	51.6
5	89.9	18.4	3.5	0.137	6.4	68.3
6	106.0	28.1	3.0	0.085	12.9	42.5
7	118.6	66.7	5.8	0.162	2.0	73.0
8	73.5	50.1	4.2	0.175	8.1	55.9
9	61.1	54.5	2.6	0.110	5.6	48.1
10	159.7	76.4	4.8	0.034	1.1	29.4
11	94.1	72.3	3.3	0.128	4.7	70.8
12	176.5	45.8	5.3	0.163	14.6	13.8
13	148.4	27.7	2.3	0.169	2.0	24.5
14	124.9	67.8	4.7	0.046	7.0	38.7
15	84.4	34.9	4.2	0.026	11.2	78.9
16	59.9	22.3	5.7	0.062	0.9	41.8
17	53.3	42.1	3.2	0.114	9.3	61.5
18	68.5	17.6	4.9	0.093	3.8	52.7
19	109.1	51.9	3.9	0.146	13.1	56.9
20	23.7	13.5	2.7	0.082	8.5	47.1
21	82.0	76.7	3.5	0.033	10.8	37.6
22	129.5	61.5	2.3	0.064	2.6	79.0
23	34.7	15.4	4.9	0.178	0.5	49.9
24	135.2	43.0	2.5	0.139	12.8	18.2
25	98.7	12.7	3.9	0.104	8.3	74.7
26	58.0	29.8	5.5	0.081	13.7	56.8
27	44.1	30.9	5.9	0.152	5.5	39.8
28	76.7	22.0	4.7	0.130	4.5	63.2
29	187.8	52.1	2.8	0.091	6.3	29.0
30	112.3	45.3	4.1	0.041	10.2	53.8
31	93.7	46.5	5.1	0.068	8.3	68.4
32	67.3	36.0	4.6	0.086	4.7	56.9
33	84.5	39.1	2.2	0.174	7.0	28.1
34	42.7	14.4	3.0	0.105	9.3	87.7
35	166.4	28.0	3.8	0.040	14.4	53.9
36	14.1	9.5	5.6	0.162	2.1	45.5
37	129.8	62.5	3.4	0.088	0.9	8.3
38	116.7	56.1	2.6	0.126	11.7	43.9
39	68.5	24.4	4.1	0.042	12.7	37.7
40	113.4	86.3	5.2	0.134	3.1	65.0
41	124.6	81.7	4.3	0.134	6.0	54.8
42	79.5	45.5	4.9	0.108	3.3	42.0
43	90.2	12.8	3.8	0.081	15.0	45.4
44	113.4	54.0	3.2	0.173	2.0	59.8
45	23.9	14.3	2.7	0.123	8.2	31.9
46	75.1	37.4	3.5	0.037	9.3	26.9
47	173.3	29.4	4.6	0.062	11.6	87.9
48	44.9	22.8	2.2	0.093	13.5	4.9
49	59.9	34.6	5.6	0.160	6.1	61.6
50	145.4	61.6	5.6	0.049	1.1	71.5

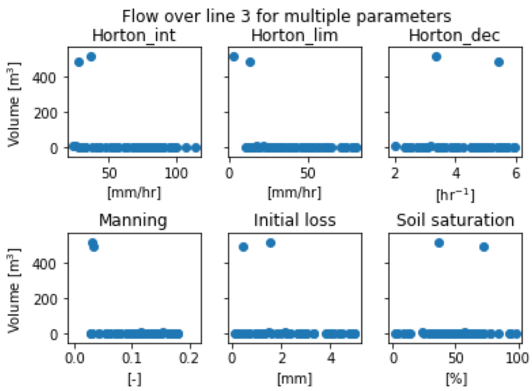
A.2 T=1 year runoff over lines



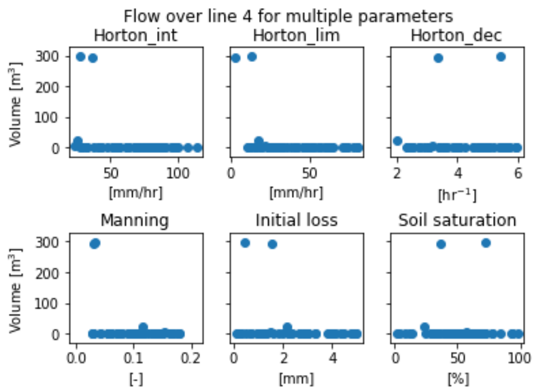
(a) Line 1



(b) Line 2



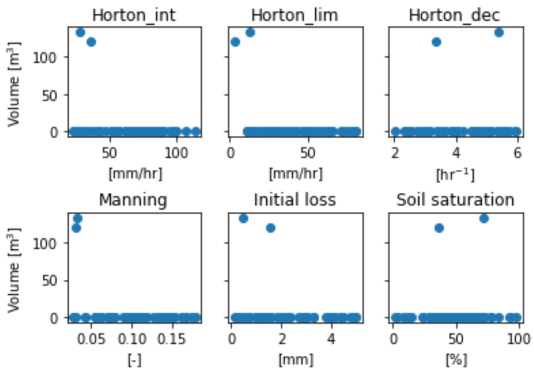
(c) Line 3



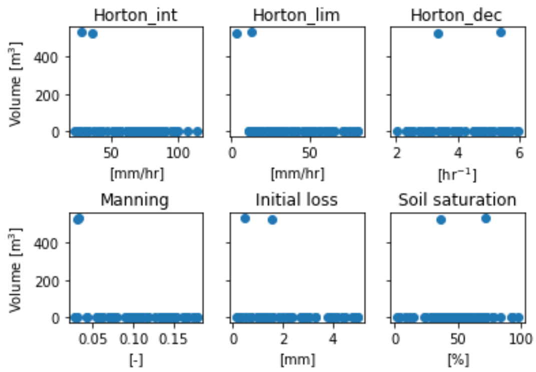
(d) Line 4

Figure 29: Total runoff across the lines for the T=1 year event for 50 model runs

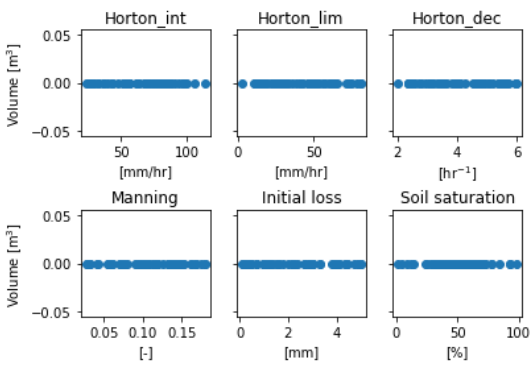
A.3 T=1 year overflow locations



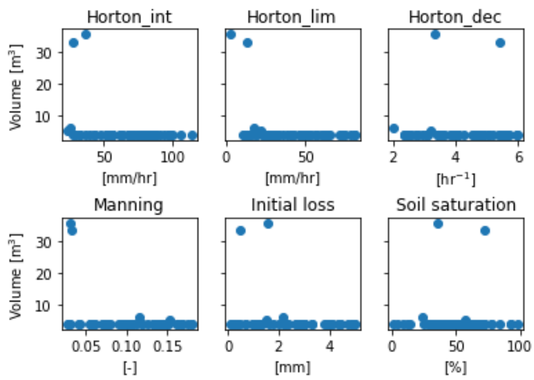
(a) Location 1



(b) Location 2



(c) Location 3



(d) Location 4

Figure 30: Total discharge out of overflow locations for the T=1 year event for 50 model runs

B Validation

B.1 New soil categories for Study area 2

Table 18: Horton infiltration parameter values for soil categories in Study area 2

Original soil category (in Dutch)	**New category**	**Horton limit [mm/hr]**	**Horton initial [mm/hr]**
Zanddek op moerige tussenlaag op zandondergrond	coarse sand	21	35
Zwak lemige (podzol-) gronden	fine sand/sandy loam	14	35
Lemige (podzol-) gronden	silt loam, loam	10.5	20.3
Lemige zandgronden met leem in de ondergrond	silt loam, loam	10.5	20.3
Lemige zandgronden met keileem in de ondergrond	sandy clay loam	4.7	6.2
Lemige zandgronden met een kleidek	clay loam	1.2	6.2
Lemige zandgronden met een dik cultuurdek (enkeergronden)	sandy clay loam	4.7	6.2
Lemige zandgronden met een dik cultuurdek en keileem in de onder	sandy clay loam	4.7	6.2
Overig leem en oude klei	clay loam	1.2	6.2
Keileemgronden	clay loam	1.2	6.2