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An analysis to test the sensitivity of output values of flood modelling software D-HYDRO to characteristics of the river, dike and hinterland

Bachelor Thesis

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Preface

This research was written as a part of my bachelor study Civil Engineering at the University of Twente. Although this assignment was not executed the way it was initially planned, I have learned a lot while conducting my research. The bachelor's thesis in front of you closes my bachelor Civil Engineering at the University of Twente. My adventure in Twente will however continue since I have planned start my master Civil Engineer and Management in September 2020.

The reason my bachelor assignment did not go planned is because in March 2020 the Netherlands fell victim to the Corona virus. This meant that the Netherlands went into an 'intelligent lockdown' which had a great influence on almost every part of our daily life. For my bachelor assignment this meant that HydroLogic, a research and consultancy office which strives to come up with innovative water solutions with the help of ICT, withdraw the guidance of my research due to time issues.

At this time Martijn Booij was of great help. He helped to collaborate with HydroLogic to find a solution for this undesirable situation. In the end, we succeed to find a way that would work for both parties and I was able to conduct my research on the topic I had written my proposal for. The solution was that the University of Twente would be responsible for the (daily) guidance of my research while Annemarleen Kersbergen of HydroLogic would still be available to ask technical questions about the model I would work with.

During the execution of my research, I worked from home but still had a lot of contact with both Martijn Booij and Annemarleen Kersbergen. I would not have been able to finish my bachelor's thesis as successfully without the help of both of them. Therefore I first want to thank Annemarleen Kersbergen of HydroLogic for helping me solve the technical problems I ran into and for giving me advice on how to approach certain parts of my research. Furthermore, I want to thank Martijn Booij for the help collaborating with HydroLogic during the Corona crisis and guiding me during the execution of my research. He helped me through the hard times and gave me motivation to stay focused on the essence of my research.

Like I said before, I learned a lot while conducting the research and I hope you will while reading!

Marit Lambers

Enschede, 17 July 2020

Summary

Flood models are used to sketch an image of the possible effects of a flood from sea, rivers, lakes, regional and local water systems. Within flood models, 1D, 2D and 1D2D calculations are used to determine the course of a flood. Companies and institutes are working on developing new software packages which are able to simulate flood patterns even faster and more accurate than the already existing flood models can do.

HydroLogic is a research and consultancy office which strives to come up with innovative water solutions with the help of ICT. To live up to these standards, HydroLogic is collaborating with Deltares, which is an independent institute for applied research in the field of water and subsurface, to develop new software which can be used for the modelling of floods in coastal areas, estuaries, rivers and rural and urban areas. The new software, D-HYDRO, is in contrary to most other flood modelling software able to make a flexible grid of the study area with both squares and triangles with different sizes. This makes it possible to adapt the level of detail within a study area.

HydroLogic has already done two pilot studies to test the possibilities of the new software. Within this study, preliminary sensitivity analysis were performed to gather information about the way the output values of the flood model in D-HYDRO were influenced by different values of the input parameters. A more systematic and comprehensive sensitivity analysis is needed to evaluate the effects of changes in input parameters on output of D-HYDRO.

Therefore, the aim of the research is to "*determine the sensitivity of the output of D-HYDRO software to changes in input parameters which describe characteristics of the river, the dike and the hinterland*". The research will focus on designing a simplified flood model with only a few standard characteristics adapted the study area like a height map and an uniform friction. Furthermore, this study area will be a small area of 4 by 6 kilometer.

Within the study, 4 research questions were established. The first question was made to gather information about how to systematically conduct the sensitivity analysis of the research. The second research question was established to investigate which characteristics of the river, the dike and the hinterland should be tested within the sensitivity analysis of the research and find out how these characteristics are translated to input parameters and what the ranges of these tested parameters are. The third and fourth research question consisted of the sensitivity analysis of the characteristics of the river, the dike and the hinterland.

In the research, the determination of the method which should be used for the sensitivity analysis, is done by means of literature research. Hereby, literature regarding flood modelling with 1D, 2D and 1D2D calculations was searched for. It could be concluded that an independent and local sensitivity analysis needs to be done. This should be done by changing the input parameters One-At-a-Time (AOT). Furthermore, the chosen parameters should be varied over their whole parameter range. Before the sensitivity analysis can be conducted, a reference situation needs to be determined. When the different simulations runs of the sensitivity analysis has been completed, the output values of these runs should be compared with the output values of the reference situation. Hereby, a ranking can be made of the relative contribution to the output variability of the different input parameters which has been tested.

For the determination of the characteristics which are going to be tested within the sensitivity analysis, literature has been consulted again. Next to the guideline prepared by Deltares (2018), the reports of the pilot studies from HydroLogic were used to provide information about which input parameters, with

which ranges, should be used when building a flood model. In the end, for the tested characteristics of the river and dike, the location of the breach would be varied over two locations and the material of the dike would be varied over 5 values. For the characteristics of the hinterland, the roughness of the surface would be varied over 5 uniform friction values. Furthermore, also the roughness map of the pilot study of the Grebbedijk would be applied to test the influence if a non-uniform friction of the surface is used. Next to that, line element sand waterways will be added to different simulation runs on 8 different locations with different directions to test the sensitivity of the output values of the flood model to these characteristics.

Based on the guideline of D-HDYRO and with support from HydroLogic, the simplified flood model has been designed. Next to the height map of the pilot study of the Grebbedijk and an uniform friction equal to the friction of grassland, boundary conditions for the water level of the river and the discharge through the breach were added. These boundary conditions were derived from the pilot study of the Grebbedijk.

The results of the sensitivity analysis of the characteristics of the river and dike showed that the material of the dike has a far greater influence on the output values of the flood model in D-HDYRO than the location of the breach. A change in the material from the dike from clay to sand caused a doubling in the width of the breach which also resulted in a doubling of the maximum discharge through the breach.

For the sensitivity analysis of the roughness of the surface of the hinterland and the presence of line elements and waterways, less clear results were shown. Variation of the uniform friction always has an effect of the output values whereas the line elements and waterways only have an influence if they disturb the flow direction of the flood. Furthermore, the presence of waterways were often the reason for a smaller inundated area whilst the presence of line elements often lead to a bigger inundated area. This could be because a waterway makes it more easy for the flood to travel to the lower places in the area, whereas a line element makes it harder for the flood to travel to these places since they can block (some of) the easy routes of the flood. Whilst it was difficult to draw a clear conclusion, it could still be concluded that, based on the ranking that was done, the roughness of the surface caused the biggest ranges for most of the output values compared to the other characteristics of the hinterland that has been tested.

A big limitation of this study is the use of the small study area and the use of the simplified model. This meant that some interesting characterises of the river, the dike and the hinterland could not be tested with the sensitivity analysis. On top of that, simplistic representations have been used for, for example, the line elements and waterways. Therefore, the results of the sensitivity analysis should be taken with a grain of salt. Furthermore, the limited time that was set for the research leaded to a univariate sensitivity analysis where the mutual relationships of characteristics could not be tested. Moreover, this limited time ensured that a link between the sensitivity analysis of the characteristics of the river and dike with those of the characteristics of the hinterland could not have been made. For further research it is therefore advised to make use of a real existing study area and a fast super computer which will make it possible to carry out a lot of simulation runs where the sensitivity analysis can be based on.

For the final conclusion of the research, it can be said that the aim of the research is party fulfilled. The sensitivity of the output of D-HYDRO software is determined for the characteristics which were chosen to test. Still, due to the scope and other limitations of the research, not all of the important characteristics could have been tested and no link could be made between the sensitivity analysis of the characteristics of the river and dike and those of the characteristics of the hinterland.

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1 Introduction

In this chapter, first of all, some background information about flood modelling and the state of the art of flood modelling will be discussed (1.1 - 1.2). Thereafter, the research gap of the study will be introduced (1.3). Subsequently, the research aim and questions will come forward and the scope of the study is described (1.4 - 1.5). Lastly, the outline of thesis will be explained (1.6).

1.1 Background

A large part of the Netherlands lies below sea level and several major rivers are on their way to the sea while crossing the Netherlands (Rijkswaterstaat VNK Project Office, 2016). With the inevitable effects that climate change is bringing with it, the sea level is rising and, especially in the winter period, river flows are rising (Rijkswaterstaat, 2019). This causes the threat and the potential consequences of a flood event to increase.

The project 'Veiligheid Nederland in Kaart' (VNK2) started in 2006 and was completed in 2014. The goal of this project was to analyse the flood risks in the Netherlands. This was done by executing a fully probabilistic risk analysis for the low-lying parts of the Netherlands. An innovative method was used to link the probabilities of a flood to the consequences of a flood in terms of economic damage and casualties (Jongejan & Maaskant, 2013). With the outcomes of the VNK2 project, the Dutch government was able to take targeted, well-founded and cost efficient measures to protect for the possible floods (Rijksoverheid, 2020B). Furthermore, the VNK2 project has had a big effect on the development of accurate flood models (Deltares, 2018).

Flood models are used to sketch an image of the possible effects of a flood from sea, rivers, lakes, regional and local water systems. Furthermore, flood simulations are used to analyse the effect of possible measures that should lower the threat of a flood on the short term (Deltares, 2018). Moreover, flood models form the base to determine hazard maps for crisis management (Deltares, 2018).

In 2018, Deltares has developed a guideline called 'guideline for development of flood simulations' (Deltares, 2018) which will help to develop accurate flood models. The guideline aims to provide practical support for modellers. Furthermore, the guideline aims to contribute to consistency between calculations, reproducibility of calculations and better and more standard reporting of calculations and results (Deltares, 2018).

Within flood models, many input parameters and boundary conditions are used which have an influence on the final flood simulations. For instance the way a breach develops, the type of land use (roughness) and the presence of certain line elements such as elevated rail roads and waterways. All those elements have an effect on where and how fast the water will flow after a flood. These elements should be well implemented in a flood model to be able to give a reliable image of the economic damage and casualties that will be the consequence of a flood. In Figure 1, a small representation of the different elements which have an impact on the course of a flood is visualised.

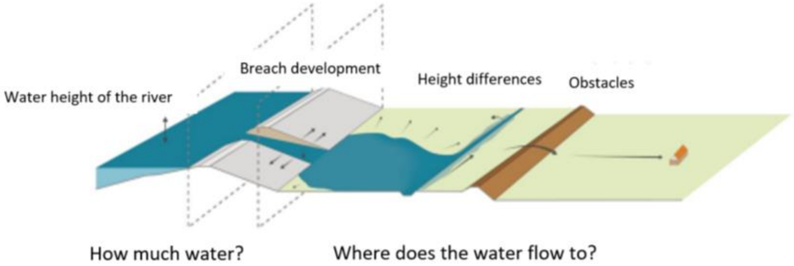

Figure 1: Elements which have an influence on the course of a flood ((Bruijn & Slager, 2018), based on (Klingen, 2016)).

1.2 State of the art flood modelling

There are many different hydraulic models which are used to make flood simulations, such as 1D, 2D and 1D2D models. In a flood model, 1D calculations are often used to include the impact of waterways on a flood (Deltares, 2018). 2D calculations are used in flood models to determine the overland flow pattern itself (Deltares, 2018). They take into account characteristics of the area like elevation and land use. 1D2D models are able to combine both 1D and 2D flood calculations.

In the Netherlands, most of the already existing flood simulations are made with the use of SOBEK-1D2D, Delft-FLS or 3Di (Deltares, 2018) (3Di Water Management, 2020). For the rest of the world, there are a lot of different software packages used for flood modelling. Still, they are all, so called 'hydrodynamic' models, based on 1D, 2D or 1D2D calculations (Teng, et al., 2017). Examples of these software packages, next to SOBEK and DELFT 3D which is also software used all over the world, are 'Flood Modeller', 'TUFLOW' and 'HEC-RAS' (Teng, et al., 2017). The flood models used these days are capable of showing real-time and seasonal river flow processes and execute probabilistic flood forecasting (UK Centre for Ecology & Hydrology, 2020).

Still, there are some drawbacks of the currently used flood modelling software. Software packages like SOBEK-1D2D make use of cartesian grid cells of mostly 100 by 100 meter. On top of that, the grid is designed with a fixed number of rows and columns (HydroLogic, 2019A). These two facts have the consequence that there are cells taken into account in the calculation of the hydraulic model which do not belong to the investigated area. This makes the calculation time of the model longer than necessary. To prevent this, sometimes the area taken into account in a flood model is smaller than the area is in reality. This results in a flood model with a shorter calculation time but also being less accurate and less complete. Furthermore, the code in which SOBEK is written is out of date since it is not designed for the current high resolution of certain data available like elevation maps (Hydrologic, 2017).

To go on with the time, companies and institutes are working on developing new software packages which are able to simulate flood patterns even faster and more accurate. Right now, Deltares is developing a new software package named D-HYDRO which is supposed to become the new standard for the development of flood simulations in the Netherlands (Deltares, 2020). Since it is seen as the intended successor of SOBEK and other flood simulation software programs which are currently used, the development of D-HYDRO is in full swing (HydroLogic, 2019C).

Within D-HYDRO it is possible to make use of, contrary to the current most used flood modelling software in the Netherlands, a flexible grid with both squares and triangles with different sizes. This makes it possible to adapt the level of detail of an area to the needed detail. This lowers the calculation time of the model and makes it possible to give the investigated area the shape it is supposed to have. This way, there will be no cells in the grid which do not belong to the study area. Still, often there is chosen to make use of a certain buffer area to lower the effects that boundary conditions have on the studied area. In D-HYDRO, this buffer area can be modeled with a larger grid size so it will hardly increase the calculation time of the model.

HydroLogic has already carried out two pilot studies to test the current possibilities of the new D-HYDRO software. Within those studies, some preliminary sensitivity analyses were done. In this analysis they made use of a reference situation for comparison of the outcomes of the sensitivity analysis. In the pilot study of the Grebbedijk, 4 characteristics have been changed to only one different variation of that characteristic. Hereby, different simulation runs were done to test if the outputs of the flood model changed due to a change in one of these characteristics.

The sensitivity analysis was done for a very large study area (around 80 km^2) which made it difficult to execute a systematic sensitivity analysis due to computational constraints. Furthermore, since such a large study area was used, the calculation time of the model was very long. This made it unrealistic to test the sensitivity of the output values for the whole range of the different input parameters.

1.3 Research gap

To be able to know the sensitivity of the output of D-HYDRO to variations in relevant parameters, a more systematic and detailed sensitivity analysis is needed. When this sensitivity is known, it will be possible to draw better substantiated conclusions on the needed level of precision of input parameters when modelling floods with D-HYDRO software.

1.4 Research aim

The aim of the research is to determine the sensitivity of the output of D-HYRO to changes in input parameters. For these input parameters, there will be looked at the parameters which describe the characteristics of the river and the dike and the parameters which describe the characteristics of the hinterland of the chosen study area. This division has been made since, for the sake of the systematic and detailed sensitivity analysis, the flood model can, and should be, divided in a river and dike part and in a hinterland part. This way, there has to be looked at only a part of the flood model and the calculation time of the flood model will be shortened.

Relevant outcomes of the flood model are the inundation depths, flow rates, ascent rates, the course of the flood and the arrival time of the flood. These outcomes form the basis for the calculation of the economic damage and the number of casualties of the flood which are used by the Dutch government to take targeted, well-founded and cost efficient measures to protect for the possible floods (Rijksoverheid, 2020B; HydroLogic, 2019B).

1.5 Research questions

To be able to achieve the aim the research, 4 research questions have been formulated. Those questions lead to enabling, and subsequently, performing a systematic sensitivity analysis of a flood model in D-HYDRO. The research questions which will be answered in this thesis report are formulated as follows:

1. Which characteristics should the sensitivity analysis appropriate for this research have?
2. Which parameters that describe the characteristics of the dike, river and the hinterland with which ranges should be varied in the sensitivity analysis?
3. What are the sensitivities of the outcomes of a flood model for variations of the parameters of the river and the dike?
4. What are the sensitivities of the outcomes of a flood model for variations of the parameters of the hinterland?

1.6 Scope

For the scope of the research, an idealized flood model in D-HYDRO will be used. This means that only a small area is considered as study area and only a few parameters are going to be varied in the flood model. This makes it possible to have short simulation runs where the complete ranges of the implemented parameters can be tested. Furthermore, since only a small area is being used, it ensures the possibility to keep track of smaller changes in the output values. Lastly, it will be easy to change certain input parameters that describe the characteristics of the river, the dike and the hinterland by hand when only a small area is used.

For the small study area, a similar test area will be considered as used in the thesis project of Klingen (2016). In her thesis, Klingen designed a flood model for the Netherlands. She used the test area to determine the influence of including or excluding different elements on the arrival time of the water. The idealized test area in this research will be a small grid of six kilometres long and four kilometres wide. This area will be 'cut out' of the model which was used for the pilot study Hydrologic did for the Grebbedijk (see Figure 2).

Figure 2: Study area pilot Grebbedijk (outer black line), study area of this research (black rectangle).

In Klingen (2016), a horizontal and flat ground level was used for the study area. In the research which will be conducted, the height map of the pilot study of the Grebbedijk will be copied. This will be done since a height map is proven to be essential for a flood model to run and to be realistic. "To create a flood map, water is placed over the surface of the elevation data which is used to dictate where the water will flow and accumulate, allowing users to identify areas that are more or less prone to flood risk" (Cruz, 2018). So the height map, or the sometimes called elevation map, forms the base of the flood model. After the height map is added, certain characteristics can be added to the flood model to influence the course of the flood. The height map of the study area can be seen in Figure 3.

Next to the height map, the idealized model will be an 'empty' model with uniform friction. Since 57% of the area used in the research consists of grassland, see Figure 4, a Nikuradse friction coefficient of 0,25 is used in the reference situation (HydroLogic, 2019B). Furthermore, there will only be one observation point which is in the middle of the area. This point will be used for the determination of the water height, flow rate and the arrival time of the water. The breach will occur in the middle of the land boundary 'upstream' which acts like the dike in the simplified flood model. The location of the observation point and the dike breach are also visualized in Figure 3 and Figure 4.

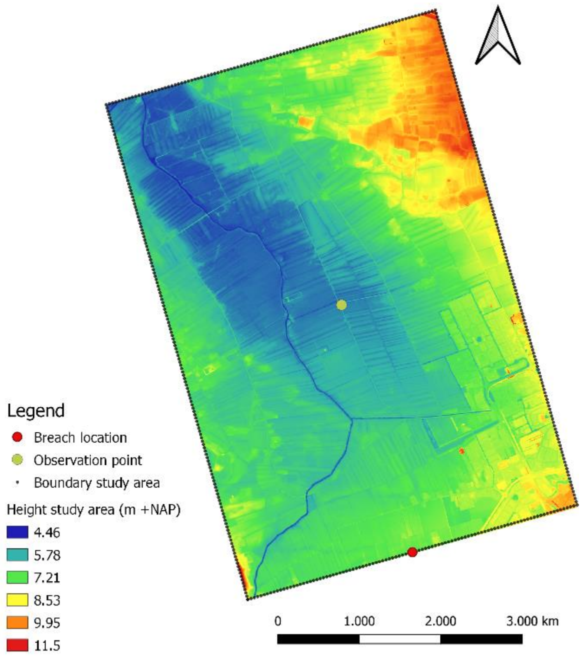

Figure 3: Map study area.

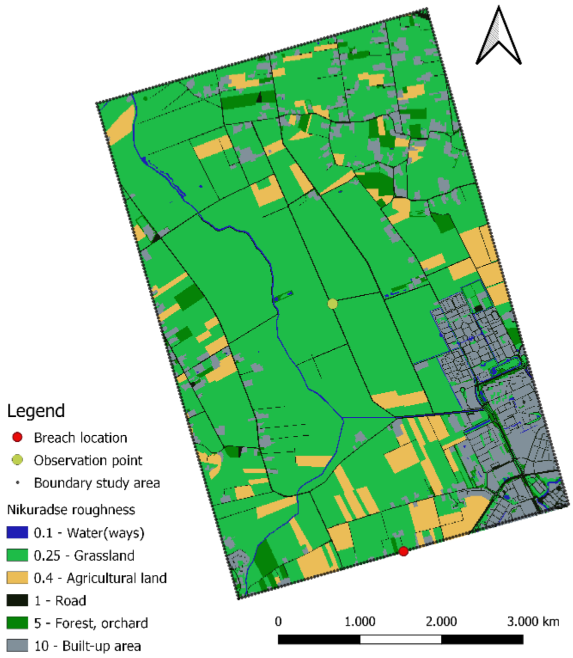

Figure 4: Land use map of pilot study Grebbedijk.

1.7 Thesis outline

This thesis has the following structure. In chapter 2 the methods which are used during the research will be described. Since the first two research questions form the foundation of the method used for the sensitivity analysis of the research, the answers of the first two research questions are stated in chapter 2 as well. Subsequently, the results of the sensitivity analysis of the flood model in D-HYDRO, the answers of research question 3 and 4, will be presented in chapter 3. Next, chapter 4 contains a discussion on the methods used and results found during the research. Lastly, in chapter 5, the conclusions of the research will be drawn and recommendations will be given for further research.

2 Methods

The study conducted in the research consist of two parts. The first part of the study contains a literature study to find an answer to the first two research questions. These research questions are needed to determine the method and boundaries of the sensitivity analysis of the research. Since the first two research questions are part of the method of the sensitivity analysis, the outcomes, and therefore answers of these research questions, are stated in this chapter directly (2.3 - 2.4).

The second part of the study consists of the sensitivity analysis of the designed flood model for an idealized area in D-HYDRO. Before the method and the boundaries of the sensitivity analysis are determined by answering the first two research questions, the method of building the flood model will be discussed in this chapter (2.2). This method will be used in both the third as the fourth research question but is also of great help to explain the way the parameters are going to be adapted in the flood model.

Before the methods used in the research will be described, an overview of the relation between the different methods used to answer the research questions will be given (2.1).

2.1 Schematic overview of research methods

In Figure 5, a shematic overview of the relation between the different methods used in the research can be seen. Also the data needed and the results from the different research questions are stated.

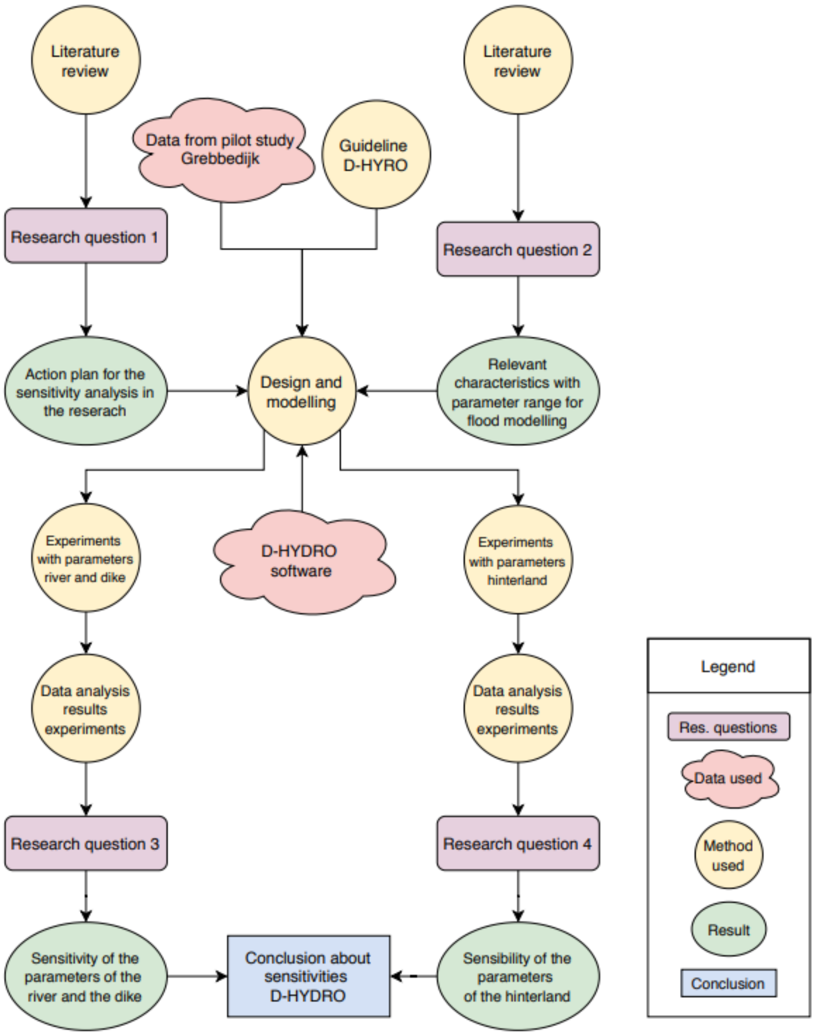

Figure 5: Schematic overview of research methods.

2.2 Method flood model

Before a sensitivity analysis can be conducted, the simplistic flood model with idealized area needs to be designed and modelled in D-HYDRO. In this section the available software, with its specifications and data will be discussed (2.2.1). Subsequently, some implementations and restrictions will be set for the sensitivity analysis of the research (2.2.2).

2.2.1 Available software with specifications

For the research, the flood modelling software D-HYDRO is used. D-HYDRO is part of Deltares' unique, fully integrated computer software suite for a multi-disciplinary approach and 1D, 2D and 3D computations for coastal, river and estuarine areas (Deltares, 2019).

In D-HYDRO the grid, also denoted as the network, consist of *net cells*. Those net cells are described by *net nodes*, which are the corners of the cells. The net nodes are connected by *net links* which are used to shape the net cells. In D-HYDRO those net links are simulated as 2D links. This makes it possible for the net cells to determine the course of the flood. Each net cell has a *flow node* which is the cell mid-point. This flow node contains the information about that certain net cell (like bed level, inundation depth, etc.). The flow nodes of the network are connected with each other by *flow links*. These flow links are 1D connections between the different net cells (Deltares, 2019). The grid topology is illustrated in Figure 6.

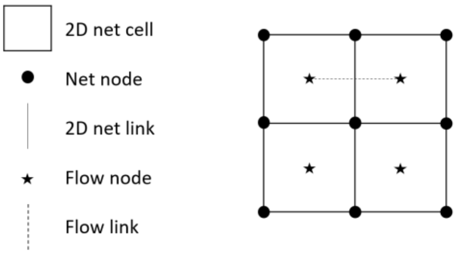

Figure 6: Topology and definitions for a grid as used in D-HYDRO (based on (Deltares, 2019; HydroLogic, 2019D)).

In D-HYDRO, certain elements like waterways and (higher) line elements can be added to the network. Those elements will be taken into account when the flood calculations are being executed. D-HDYRO is able to solve both 1D- and 2D- as well as 1D2D calculations.

Waterways

Waterways are simulated in D-HDYRO in 1D. This means that the net nodes are connected with 1D net links to simulate the location of the water ways. With 1D calculations, the inundation depths and flow rates of the waterways are calculated. Still, to be able to show the impact of the 1D waterway on the 2D net cells of the network, the 1D net link is connected to the flow node of the 2D net cell. D-HYDRO makes these 1D2D connections automatically enabling the integration of 1D calculations into the 2D network. In Figure 7 the way of simulating 1D water ways in D-HYDRO is illustrated.

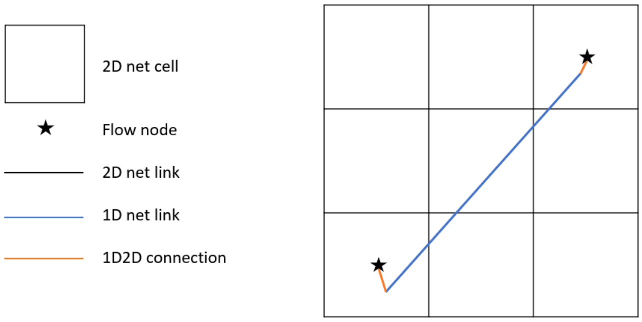

Figure 7: 1D waterway connected to 2D net cell in D-HDYRO (based on (HydroLogic, 2019D)).

Line elements

In contrast to the 1D waterways, (higher) line elements are added to D-HYDRO models with 2D connections to the net links of the net cells. Line elements are drawn through the network. Every time a line element crosses a flow link, a 2D connection will be made with the net link. This net link will now get the value of the line element that crossed the net link. In D-HYDRO these line elements are called 'fixed weirs'. In Figure 8 the way the fixed weirs are being simulated in D-HYDRO is illustrated.

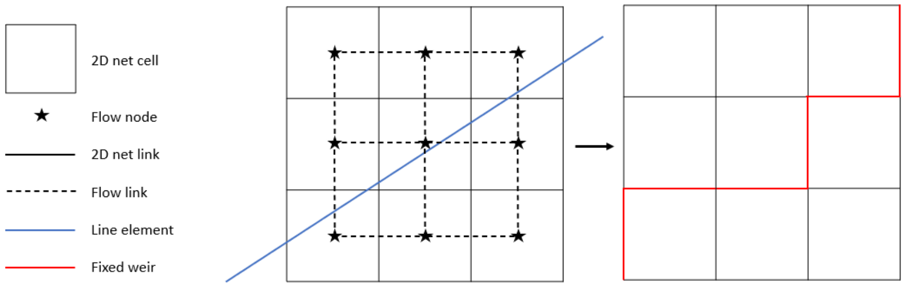

Figure 8: Line element connected to 2D net link in D-HYDRO (based on (HydroLogic, 2019D)).

2.2.2 Implementation in D-HYDRO

With the use of the D-HYDRO software , a flood simulation model will be made to simulate the reference situation and subsequently conduct the sensitivity analyses. In D-HYDRO, the flood calculations are already implemented as standard functions. For these calculations, D-HYDRO makes use of the input parameters which will be implemented for the different simulation runs of the sensitivity analysis.

Since the line element and waterways used in the research have specific locations and directions, they have to be made by hand. For the files that describe the characteristics of the river and dike as input parameters, the flood model developed for the pilot study of the Grebbedijk has been made available. The file that describes the dike breach can be, when modified to some characteristics of the study area of the research, be used in the flood model for the research. In this file, the different breach locations and upstream and downstream coordinates for the upstream and downstream water heights can be changed over the different simulation runs. Furthermore, the material of the dike can be changed in this file.

For the boundaries of the study area, a water level boundary will be applied. Those boundaries ensure that the water of the flood can leave the area and will not be 'locked up' in the study area. Furthermore, for the simulation of the river, boundary conditions will be used to set water levels and discharges at the location of the dike breach. This will be done since it is not feasible to design a part of the river in the flood model in the time set for the research. Furthermore, it would largely increase the calculation time of the model. The boundary conditions set at the breach location will not be taken into account in the sensitivity analysis of the research since this would largely increase the number of simulation runs that needs to be done.

For the sensitivity analysis of the research, only univariate sensitivity analyses will be executed. This means that the tested input parameters will be changed over their own parameter range while keeping the other parameters fixed. Furthermore, like already mentioned in the research questions, the sensitivity analysis is split into two parts. For the sensitivities of the characteristics of the river and dike the only output variables considered are the width of the breach and the discharge of the breach. For the sensitivities of the characteristics of the hinterland, the inundation depth, flow rate, arrival time and ascent rate of the water at the observation point will be measured. Furthermore, there will also kept track of the maximum water depth, the maximum flow rate and the total inundated area in the study area.

2.3 Requirements sensitivity analysis

The following paragraphs (2.3.1 - 2.3.3) describe different methods of sensitivity analysis. Furthermore, certain criteria for when which method should be used will be given. Also, a note will be made about post processing of the results of the sensitivity analysis. Finally, in section 2.3.4, a conclusion will be drawn about the way the sensitivity analysis in the research should be conducted.

2.3.1 Models vs sensitivity analysis

Models are used to simulate (non-)natural phenomena in the past or predict phenomena in the future. “The usefulness of any model depends in part on the accuracy and reliability of its output. Yet, because all models are imperfect abstractions of reality, and because precise input data are rarely if ever available, all output values are subject to imprecision” (Loucks & van Beek, 2017). This pictures the uncertainty of the output that a model produces. It is important to limit the uncertainty of the input parameters to decrease the uncertainty of the model output. The output of a model is not equally sensitive to every input parameter. “Before spending money and time to gather and analyze additional data, it is reasonable to ask what improvement in estimates of system performance or what reduction in the uncertainty associated with those estimates would result if all data and model uncertainties could be reduced if not eliminated” (Loucks & van Beek, 2017).

To investigate the way the output of a numerical model is influenced by variations of its input factors, a Sensitivity Analysis (SA) is used (Pianosi, et al., 2016). A SA can help to determine which input parameters should be well calibrated to upgrade the ‘usefulness’ and certainty of a model.

Within SA methods, a distinction can be made between ‘local’ or ‘global’ SA. ‘’Local SA applications typically consider model parameters as varying inputs, and aim at assessing how their uncertainty impacts model performance. Global SA applications may consider model parameters but also other input factors of the simulation procedure” (Pianosi, et al., 2016).

Furthermore, there is a difference between quantitative and qualitative SA. “The term quantitative SA refers to methods where each input factor is associated with a quantitative and reproducible evaluation of its relative influence, normally through a set of sensitivity indices (or ‘importance measures’). In qualitative SA, instead, sensitivity is assessed qualitatively by visual inspection of model predictions or by specific visualization tools” (Pianosi, et al., 2016).

Lastly, in SA methods different sampling strategies can be distinguished to estimate the sensitivity indices. This can be done by testing the inputs One-At-a-Time (OAT) or All-At-a-Time (AAT). With OAT the effect of varying the inputs is analysed one at a time while keeping all others fixed. With AAT, “output variations are induced by varying all the input factors simultaneously and therefore the sensitivity to each factor considers the direct influence of that factor as well as the joint influence due to interactions” (Pianosi, et al., 2016).

2.3.2 Purpose of the sensitivity analysis

Before an image can be sketched about the way the SA of a flood model in D-HYDRO should be conducted, the purpose of the SA of the research needs to be known. The purpose of SA can be classified into three groups (Pianosi, et al., 2016):

- *Ranking* of the input parameters according to their relative contribution to the output variability.
- *Screening* which input parameters have a negligible influence on the output variability.
- *Mapping* of the input parameters to determine the region of the input parameters variability space that produces significant output values.

2.3.3 Post processing results of the sensitivity analysis

When the results of the sensitivity analysis will be expressed in a quantitative way, the level of influence of the different parameters can be determined and a ranking of the level of influence of the input parameters on the output of the model can be made. “The difference in the model output due to the change in the input variable is referred to as the sensitivity or swing weight of the model to that particular input variable (Morgan & Henrion, 1990). The sensitivity also can be represented as a positive or negative percentage change compared to the nominal solution” (Frey & Patil, 2002).

Nevertheless, for some model outputs, it might be difficult to give a quantitative value. In these cases, a visual representation is considered to assess certain changes in output values if the input parameters are being changed.

2.3.4 Conclusion

Based on the statements made above and taking into account the aim of the research, the SA conducted in the research should be an independent and local sensitivity analysis. This to be able to consider model parameters as varying input. Furthermore, the input parameters should be tested on their influence One-At-a-Time (OAT) to be able to determine the change of outputs of the model due to a change in only one input parameter.

The main purpose of the model can be seen as making a ranking of the level of influence of the input parameters. Based on this ranking, an advice can be given on which parameters should be calibrated to full extent and for which parameters a default value can be accepted. Automatically, a screening will take place where the input parameters which have a negligible influence on the model output will come forward.

To test the independent local sensitivity of input parameters, the input parameters need to be changed over their whole range while keeping the other input parameters fixed (Hambly, 1994). This way, the parameters will be changed OAT over their entire possible range (Frey & Patil, 2002). To determine if the output values change due to a input parameter change, first a reference situation needs to be determined wherein the reference output values are generated (Hambly, 1994).

For the research, all of the outputs which will be kept track of for the examination of the sensitivity analysis can be visualized in a quantitative way. Still, a visual representation should be used to look for spatial properties of the course of the flood. Those spatial properties can be used as additional information to make conclusions about the sensitivity analysis.

2.4 Characteristics and ranges of river, dike and hinterland for sensitivity analysis

In section 2.4.1, the different input parameters which are used in different flood models will be listed. Subsequently, in section 2.4.2 and 2.4.3, there will be elaborated on the different parameters listed in 2.4.1 and a decision will be made on which input parameters will be used for the sensitivity analysis in the research. Hereby, also the ranges of these parameters will be given. Finally, in section 2.4.4 a conclusion will be given that sums up the different parameters, with their parameter range, which will be tested within the sensitivity analysis in the research.

2.4.1 Overview characteristics in different studies

In Table 1, an overview of the different elements taken into account in flood models in different studies can be seen. The input factors are divided in characteristics of the river and the dike and characteristics of the hinterland.

Table 1: Overview of the characteristics of the river, dike and hinterland present in the flood models discussed in different studies.

	'Leidraad voor het maken van Overstromingssimulaties' (Deltares, 2018)	Pilot HydroLogic: Grebbedijk (HydroLogic, 2019B)	Pilot HydroLogic: Bommelerwaard (HydroLogic, 2019C)
Characteristics of the river and dike	*- Boundary conditions* *- Location of the breach* *- Moment of the breach*	*- Boundary conditions* *- Location of the breach* *- Material of the dike*	*- Boundary conditions* *- Location of the breach* *- Material of the dike*
Characteristics of the hinterland	*- Height map* *- Roughness/land-use* *- Line elements* *- Underpasses* *- Waterways*	*- Height map* *- Roughness/land-use* *- Line elements* *- Underpasses* *- Waterways*	*- Height map* *- Roughness/land-use* *- Line elements* *- Underpasses* *- Waterways*

	Multi-method global sensitivity analysis of flood inundation models (Pappenberger, et al., 2008)	Distributed Sensitivity Analysis of Flood Inundation Model Calibration (Hall, et al., 2005)
Characteristics of the river and dike	*- Upstream inflow → Boundary condition* *- Roughness channel* *- Initial slope at downstream boundary*	*- Upstream inflow → Boundary condition* *- Roughness channel* *- Channel width* *- Channel bed elevation*
Characteristics of the hinterland	*- Roughness of floodplain*	*- Roughness floodplain* *- Land surface elevation*

2.4.2 Characteristics of the river and dike

Boundary conditions

Boundary conditions are added to a flood model to determine the amount of water in the river. This amount of water (the water height or discharge over time) is an important factor for the dike breach development and for the amount of water which will flow into the study area.

There are two ways of setting those boundary conditions for a flood model. The first option is to upstream add a discharge wave, which can be seen as a discharge over time (Q(t)), and to downstream add a relation between the discharge and water height (Qh-relation) to the model (Deltares, 2018). This is often done when (a part of) the river is added to the flood model. When only the threatened area is considered in the flood model, often just a relation between the water height and time (H(t)-relation) is added to the flood model (Deltares, 2018). This relation describes the water height over time at a certain boundary.

In the pilot study of the Grebbedijk, a large part of the river is included in the flood model. Therefore, HydroLogic has selected the first option for boundary conditions. As upstream discharge wave, HydroLogic has made use of the upstream discharge wave of the river (the Nederrijn) at Driel located around 13 km upstream of the dike breach location. As downstream Qh-relation, HydroLogic has made use of the Qh-relation at Hagestein around 40 km downstream of the breach location.

In the idealized flood model designed for this research, only a small area, that acts as the threatened area, will be added. To limit the calculation time and thereby maximize the number of tests, the second option for boundary conditions will be applied. The H(t) relation that will be added to the designed flood model is derived from the H(t) relation upstream of the breach location as chosen in the pilot study of the Grebbedijk. This H(t) relation can be seen in Figure 9.

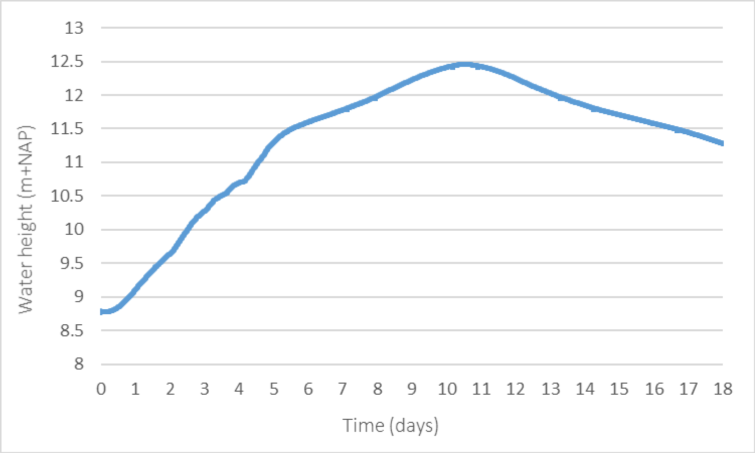

Figure 9: H(t) relation upstream location pilot study Grebbedijk.

In the pilot study of the Grebbedijk, the dike breach occurred when the water height in the river was at its highest point. This will also happen in the flood model designed for this research. To limit the calculation time, only the H(t) relation from that highest point onwards will be added to the flood model. Furthermore, the model of the research will only be run for 51,5 hours, hence the time scale of the H(t) relation of the pilot study of the Grebbedijk should be adjusted to this 51,5 hours. This 51,5 hours is chosen since this is the maximum time the water needs to travel from upstream inflow location to the downstream land boundary in the different simulation runs conducted in the research.

Lastly, the water height over time as seen in Figure 9, should be lowered. This has to be done since the bed level of the location where the H(t) relation of the pilot study of the Grebbedijk is located is higher than the location where the dike breach occurs in the flood model designed for the research. The final H(t) relation used in the research is shown in Figure 10. This H(t) relation will be added as boundary condition to the flood model when the characteristics of the river and dike are being tested.

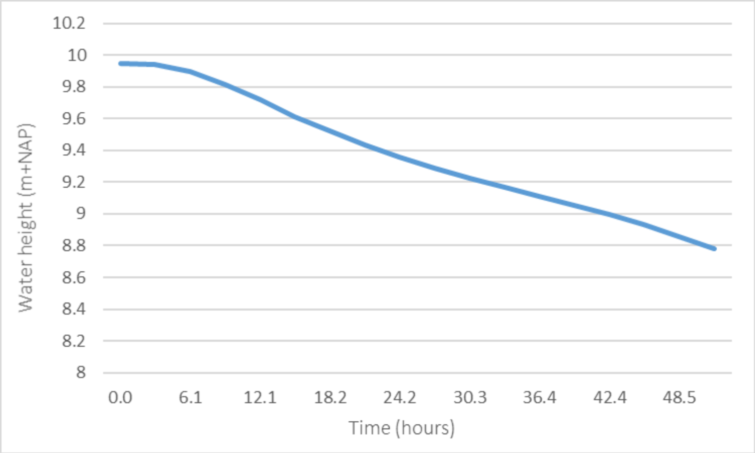

Figure 10: H(t) relation used as boundary condition in the flood model designed for the research.

For the sensitivity analyses of the characteristics of the hinterland, it is enough to implement a discharge over time through the breach as a boundary condition. In this way, D-HYDRO does not have to execute any dike breach development calculations which will lower the calculation time. For this discharge, a percentage of the discharge (10%) through the breach as seen in the reference situation of the pilot study of the Grebbedijk will be used, since a small study area will be used. If the total discharge will be used, the whole study area will be flooded within only five hours. Changes in the output of the model due to a change in one of the input parameters will therefore be hard to detect. The boundary condition as used in the sensitivity analyses for the characteristics of the hinterland is shown in Figure 11.

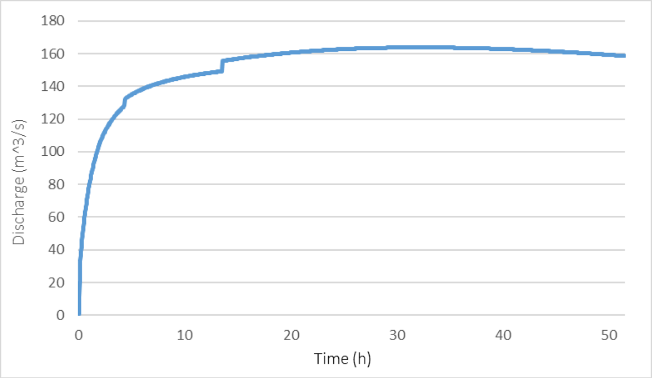

Figure 11: Boundary condition for sensitivity analysis of the characteristics of the hinterland.

Roughness, initial slope and width of river

The roughness of the river determines, together with the slope and the width of the river, the velocity of the river flow. These characteristics are taken into account in the sensitivity analysis of Pappenberger et al. (2008) and those of Beven et al. (2005). Nevertheless, it is not possible to test these characteristics within the scope of the research since no water flow will be simulated in the model, because a H(t) relation as boundary condition for the river is used.

Development of the breach

The way a breach develops over time has an influence on the results of the flood model. The width of the breach and the height difference between the water in the river and the water/bed level in the hinterland determine the amount of water which can flow through the breach.

To determine the width of a dike breach, the breach development formula of Verheij and Van der Knaap can be used. Next to the height difference between the water level in the river and the water/bed level in the hinterland, also a critical flow velocity for the material of the dike is taken into account. The calculation of Verheij and Van der Knaap is as follows (Verheij, 2003):

$$W = 1{,}3\frac{g^{0{,}5}H^{1{,}5}}{u_c}\log\left(1+\frac{0{,}04.g}{u_c}t\right) \qquad (1)$$

In which W is the width of the breach, H is the difference between upstream height (a point in the river or in this research, the boundary condition) and downstream height (the bed or water level at a point in the hinterland). $\mathrm{u_c}$ is the critical flow velocity in m/s and g is the gravitational constant. Lastly, t is the time in seconds.

In the breach development, there are three factors which can be changed to test the influence of these factors on the way the width of the breach develops. These factors are the upstream height (the height/water level of the river), which depends on the moment the dike breach occurs, the height downstream (the height/water level of a point in the hinterland), which depends on the location of the breach, and the critical flow velocity which depends on the material of the dike.

These factors will all be discussed in the next sections. Furthermore, an indication will be given on the way the effects of these factors on the breach development will be tested.

Moment of the breach

In a flood model, the breach can be simulated to occur on a certain point in time or when the river has a certain water level. Based on the guideline written by Deltares (2018), it is advised to simulate the breach development when the water level is at the highest point. This is also done in the VNK2 approach. It is advised to take this moment because of the ambiguity and the great uncertainty about the moment of the breach (Deltares, 2018).

As mentioned in section 2.4.2, the breach in the reference situation will start to develop right from the start since, as seen in Figure 10, this is the moment when the water height in the river is at its highest point. The influence of the moment of the breach (so that the height upstream will differ), will not be tested within the sensitivity analysis of the research since this does not fit within the time set for the research.

Location of the breach

If a breach occurs at a different location, the bed level of the downstream point will be different as well. If the downstream point will be higher at a different location, the width of the breach will develop slower and the final width of the breach will be smaller.

To test the influence of the location of the breach, next to the location of the breach in the reference situation, two different locations for the dike breach will be assigned. These locations will be at 250 m on either side of the location of the dike breach in the reference situation (see Figure 12). As seen in Figure 12, the 'location left' has a lower downstream height than the reference situation whereas the 'location right' has a higher downstream height than the reference situation. In this way, the influence of a lower downstream point as well as a higher downstream point can be tested.

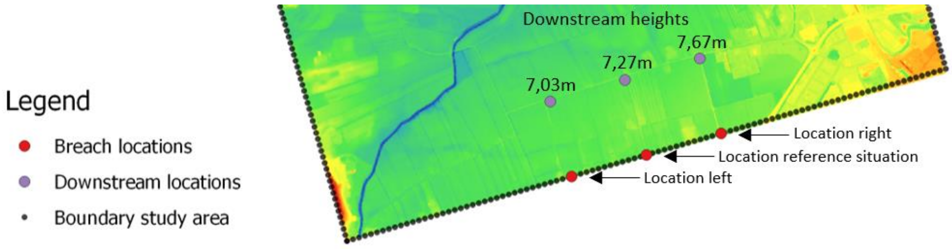

Figure 12: Different dike breach locations at 250 m on either side of the location of the dike breach in the reference situation.

Material of the dike

The material of the dike is incorporated in the calculation of the dike breach development as a critical flow velocity. In the guideline written by Deltares (2018), they advise to use a value of 0,5 m/s for a clay dike and a value of 0,2 m/s for a sand dike. In the sensitivity analysis conducted in the research, the whole range of critical flow velocities for sand and clay will be tested. These values can be found in Table 2. For the reference situation of the flood model in the research, a critical flow velocity of 0,2 m/s should be used since this should cause the most extreme values in breach width. According to Deltares (2018), the most extreme values should be used to determine the worst case scenario.

Table 2: Critical flow velocity used in sensitivity analysis (based on (Deltares, 2018; Verheij, 2003)).

Dike material	u_c (m/s)
Good clay	1.0
Regular clay	0.5
Bad clay	0.40
Sand with 17% silt	0.225
Sand with 10% silt	0.20
Sand with 0% silt	0.16

2.4.3 Characteristics of the hinterland

Height map

The height (differences) of an area play a big role in the course of a flood. In the Netherlands, the 'Actueel Hoogtebestand Nederland' (AHN) is being used as an input for the height map of an area. The AHN is a dataset which consists of the height of the ground level of every square meter up to a 5 cm vertical accuracy (Actueel Hoogtebestand Nederland, 2020).

Based on the VNK2 project, it is preferred to use AHN data at a spatial resolution of 5 by 5 m to get a realistic view of the height differences in the area (Asselman, 2006). In the height map used in the study, the height map is aggregated to grid cells of 5m (HydroLogic, 2019B). At locations where buildings and waterways are present, the average height of the surrounding grid cells is used (HydroLogic, 2019B).

Land use

The land use of an area determines the roughness of the surface. The smoother the surface, the faster a flood flows over that surface and the faster the flood is spreading over the area. In the pilot studies of HydroLogic (2019), as well as in the guideline of Deltares (2018), the 'Landelijke Grondgebruikskartering 4' (LGN4) is being used to determine the land use of the surface of the area. LGN is a raster file which shows the land use with a resolution of 25 by 25 meter (Hazeu, 2018).

When the land use is known, the roughness coefficient can be linked to the different types of land uses. For the roughness the Manning coefficient or Nikuradse values can be used. The Manning coefficient is based on the roughness of the surface of a channel and a floodplain where the Nikuradse values are linked to the different types of land uses. In the pilot studies of HydroLogic (2019B;2019C), as well as in the guideline of Deltares (2018), Nikuradse values linked to the LGN4 land uses were used and can be found in Table 3.

Table 3: Land use with Nikuradse values (based on (HydroLogic, 2019B)).

Land use (LGN4)	Nikuradse value
Built-up area	10
Forest, orchard	5
Road	1
Agricultural land	0.40
Grassland	0.25
Water(ways)	0.10

In the idealized flood model designed for the research, an uniform roughness will be used for the reference situation of the model. In the sensitivity analysis, this uniform friction will be changed to a smoother surface as well as rougher one. Next to changing the uniform friction, the land use map of the pilot study of the Grebbedijk will also be added as a variation to see the difference in output values when the friction in the flood model is spatially variable in the hinterland.

Line elements

The presence of line elements is of great influence in a flooded area since they can block the water and disturb the 'normal' flow pattern of the flood. Since smaller but higher line elements like elevated roads and railroads are faded away in the height map, they need to be added to the flood model separately (HydroLogic, 2019B). The location and the height of these line elements can be gathered from top10nl or AHN data (Top10NL, 2020; Actueel Hoogtebestand Nederland, 2020).

In the sensitivity analysis, the influence of line elements in the hinterland can be tested by adding fixed weirs (like already explained in section 2.2.1). The height of the line elements will be copied from the height map of the research and then be increased with a certain height. The height of the fixed weirs applied in the sensitivity analysis will have a height that is 0,8 meter higher than its original height in the pilot study of the Grebbedijk. This is based on some basic experiments. With the implementation of the 0,8 meter higher line elements, the water will be accumulated and be pushed in a different direction but it will, after some time, also flow over the line elements. This way, also the influence of the flood just behind the line elements can be seen.

To test the influence of line elements present in the hinterland area with different positions, 8 different fixed weirs will be added to the flood model (in different simulation runs). Fixed weirs will be added both upstream and downstream of the observation point and parallel, perpendicular and diagonal with respect to the flow direction of the flood. In Figure 13 the line elements with different locations and directions are visualized.

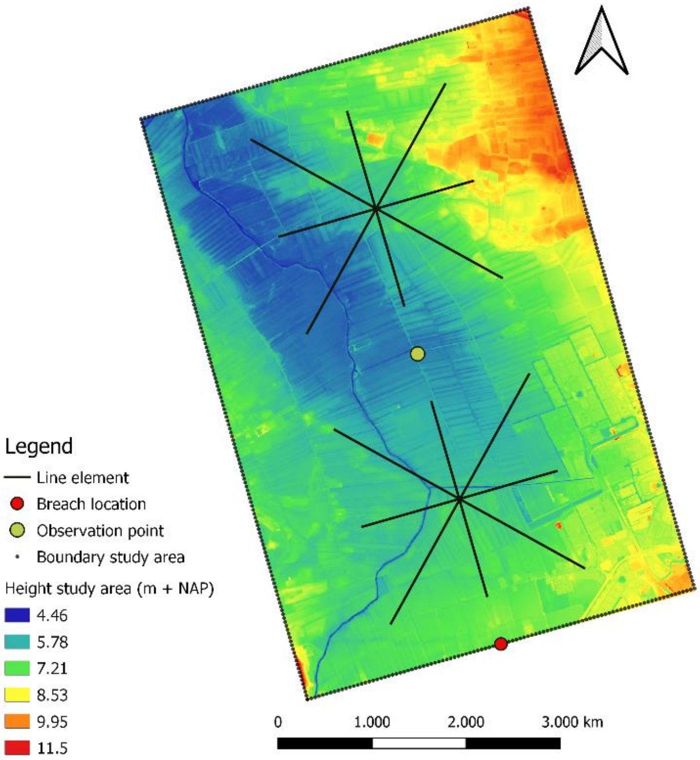

Figure 13: Line elements added as fixed weirs in different simulation runs in sensitivity analysis research.

Underpasses

Just like line elements, underpasses can have a big influence on the course of the flood. If there is an underpass in a higher line element, the water of the flood will flow through the underpass to the other side of the line element.

Unfortunately, not enough time was available for the research to implement underpasses in the sensitivity analysis of the research. In the pilot studies HydroLogic did with D-HYDRO, they advised to take underpasses into account as 1D line elements but with a 1D2D connection with the flow node of the grid cell (HydroLogic, 2019B; 2019C). This way, water can flow under the fixed weirs which have been added to a flood model.

Water ways

Waterways can be seen as line elements which have a different roughness then the surface around it. This causes an accelerated water flow into the hinterland (HydroLogic, 2019C). Furthermore, the flood can reach places in the area it would not have reached if waterways were not present. Waterways should be implemented as 1D elements just as underpasses to make sure they can have a different value for roughness (Deltares, 2018).

The influence of waterways in a threatened area will, just like the line elements, be tested with different locations and positions. The same locations and positions will be applied for the waterways as was done for the line elements already visualized in Figure 13. For the width of the waterways, a width of 20 m will be implemented. This width is also used for the waterways in the pilot study of the Grebbedijk.

2.4.4 Conclusion

In Table 4 an overview of the parameters found in the literature as listed in Table 1 can be found. When the parameter is being tested in the sensitivity analysis, the range of variation of the parameter is given.

Table 4: Overview (tested) parameters within flood models.

	Tested in the sensitivity analysis of the research	When tested, the parameter range
Characteristics of the river and dike:		
Boundary conditions	X	-
Roughness channel, Channel bed elevation, channel width	X	-
Moment of the breach	X	-
Location of the breach	V	Location 250m on either side of location of the breach in Reference situation (see Figure 12).
Material of the dike	V	Sand and clay dike over different values between an u_c ratio of 0,1 and 1 m/s (see Table 2).
Characteristics of the hinterland:		
Height map	X	-
Roughness/land-use	V	Uniform friction between 0,1 and 10 and the land use map of the pilot study of the Grebbedijk implemented in the study area (see Table 3 and Figure 4).
Line elements	V	Added to the network as fixed weirs with 8 different positions/locations (see Figure 13).
Underpasses	X	-
Waterways	V	Implemented in new networks as 1D line elements with 1D2D connections to the net node of the grid cell. Furthermore, the same positions/locations as the line elements.

3 Results

In this chapter the results for research question 3 and 4 will be discussed (3.1 - 3.2). At the end of each section, a short conclusion will be drawn that sums up the answer(s) of that research question. The overall conclusion of the research can be read in chapter 5.

3.1 Sensitivity of the model output to characteristics of the river and dike

In this chapter the influence of the parameters that describe the characteristics of the river and dike on the output of the designed flood model in D-HYDRO will be discussed. The different steps of the sensitivity analysis will be described in this chapter within different sub chapters (3.1.1 - 3.1.4). In section 3.1.5, a conclusion will be drawn about the different sensitivities of this part of the sensitivity analysis.

3.1.1 Step 1: Reference situation

The reference situation for this part of the sensitivity analysis will be as follows:

- Height map of the pilot study of the Grebbedijk
- Uniform Nikuradse friction in the hinterland of 0,25
- H(t) relation as boundary condition as shown in Figure 10
- Breach location in the middle of the upstream boundary (see for example Figure 3)
- Material of the dike is sand with an u_c of 0,2 m/s

When the reference situation of the flood model is ran, the width of the breach and the discharge through the breach as seen in Figure 14 and Figure 15 occur.

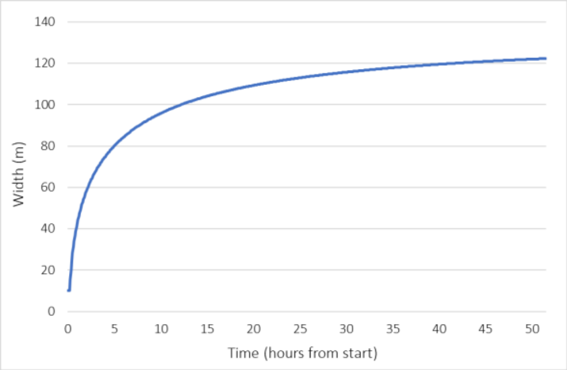

Figure 14: Width of the breach in reference situation.

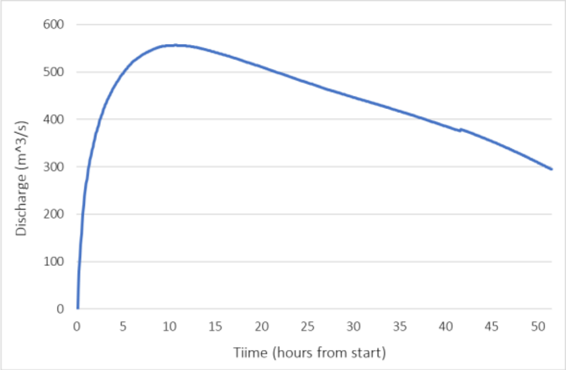

Figure 15: Discharge through the breach in reference situation.

After the total run time of the flood model of 51,5 hour, the breach is still developing. Because of the H(t) relation used for the reference situation (see Figure 10), the water height in the river is getting lower, the discharge through the breach is also getting lower over time. Since the upstream water height in the 51,5 hour run will not become lower than the downstream height, there will still be a discharge through the breach. The breach will only stop growing if the velocity of the water through the breach is lower than that of the critical flow velocity (u_c).

In the reference situation, the width of the breach is 122 meter after 51,5 hours. The maximum discharge through the breach is 556 m^3/s, this is after 10 hours of the simulation run.

3.1.2 Step 2: Input parameters and ranges

In the conclusion of research question 2 (section 2.4.4), the parameters which should be tested within the sensitivity analysis part of the river and dike, with their parameter ranges, came forward.

It is concluded that the location of the breach as well as the material of the dike should be tested within the sensitivity analysis. Testing the influence of the other characteristics of the river and the dike mentioned in Table 4 did not fit within the scope of the study or were not able to test due to time constrains of the research.

3.1.3 Step 3: Sensitivity analysis with dike parameters and comparison with reference situation

In the following sections, the outcomes of the sensitivity analysis of the location of the breach and the material of the dike will be shown and discussed.

Location of the dike breach

In Figure 16 and Figure 17 the width of the breach and the discharge through the breach are given for the different locations. The different locations (with downstream height) were already visualized in Figure 12.

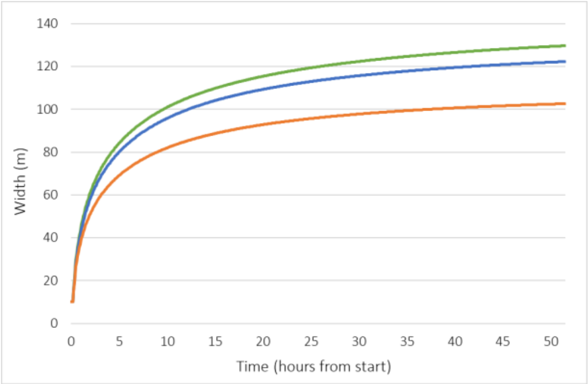

Figure 16: Width of the breach for different breach locations.

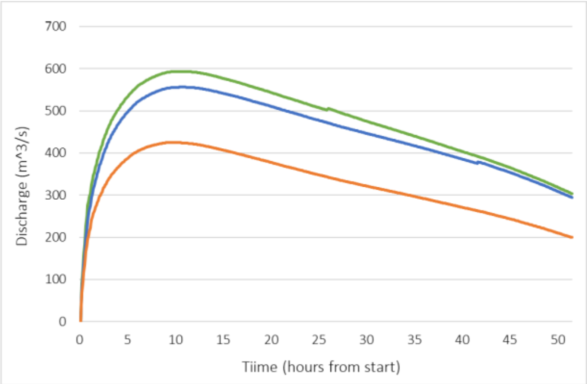

Figure 17: Discharge through the breach for different breach locations.

In Table 5, the different downstream heights and the different outcomes of the simulation runs are shown in numbers. Also the absolute differences with the values in the reference situation are given between brackets. As shown, the lower downstream height of the ‘location left’ results in a wider breach and therefore a larger maximum discharge through the breach. On the other hand, the higher downstream height of the ‘location right’ results in a breach that is less wide and a discharge which is less at its maximum point than the breach and the discharge through the breach of the ‘location reference situation’. When looking at the absolute differences with the reference situation, it can be seen that a relatively larger downstream height difference, ensures a relatively larger difference in the width of the breach and the maximum discharge through the breach.

Table 5: Downstream height, breach width and maximum discharge through the breach per breach location.

Location	Height downstream (m +NAP)	Breach width after 51,5 hours (m)	Maximum discharge through the breach (m^3/s)
Location left	7,03 (0,24)	130 (9)	593 (37)
Location reference situation	7,27	122	556
Location right	7,67 (0,40)	103 (19)	425 (131)

Material of the dike

When the simulation runs are done for the parameter range of the critical flow velocity for sand and clay, as already shown in Table 2, the widths and discharges as shown in Figure 18 and Figure 19 occur.

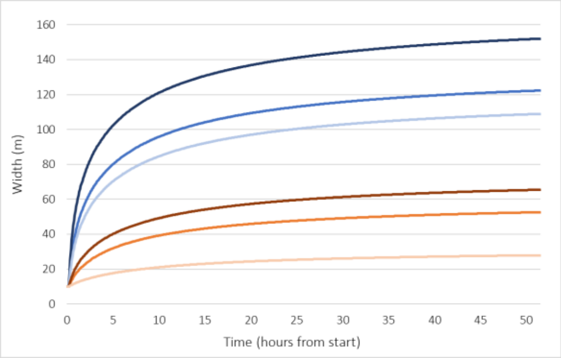

Figure 18: Width of the breach for different dike material.

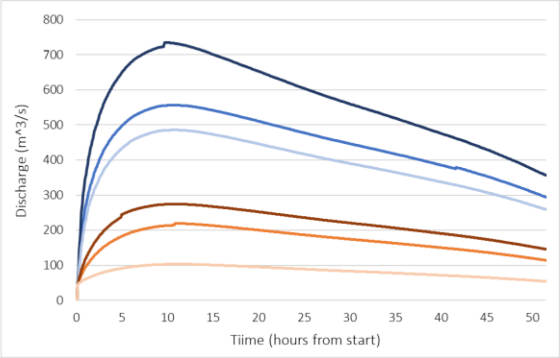

Figure 19: Discharge through the breach for different dike materials.

As shown in Figure 18 and Figure 19, a larger critical flow velocity results in a smaller width of the breach and a smaller maximum discharge through the breach. Both the sand and the clay dike have their own region where the width of the breach and the maximum discharge through the breach can be found.

In Table 6, the different breach widths and maximum discharges through the breach of the simulation runs are shown in numbers. Also the absolute differences in u_c, breach width and maximum discharge through the breach with the values in the reference situation are shown. As shown, the bigger the absolute difference in u_c the bigger the absolute difference in the width of the breach and the maximum discharge through the breach.

Table 6: Breach width an maximum discharge through the breach for different materials of the dike (different value for u_c).

U_c (m/s)	Breach width after 51,5 hours (m)	Maximum discharge through the breach (m^3/s)	Absolute difference in u_c with u_c used of reference situation	Absolute difference in breach width with breach width in reference situation	Absolute difference in maximum discharge through the breach with maximum discharge through the breach in reference situation
Reference situation (u_c = sand 0,2)	122	556	-	-	-
Sand u_c = 0,16	152	736	0,04	30	180
Sand u_c = 0,225	109	486	0,025	13	70
Clay u_c = 0,4	65	274	0,2	57	282
Clay u_c = 0,5	53	219	0,3	69	163
Clay u_c = 1,0	28	103	0,8	94	453

3.1.4 Step 4: Ranking of dike parameters based on relative contribution to output variability

For the ranking of the sensitivities tested within this part of the sensitivity analysis, the influence of the location of the breach and the influence of the material of the dike need to be compared. In Figure 20 and Figure 21 this comparison can be seen.

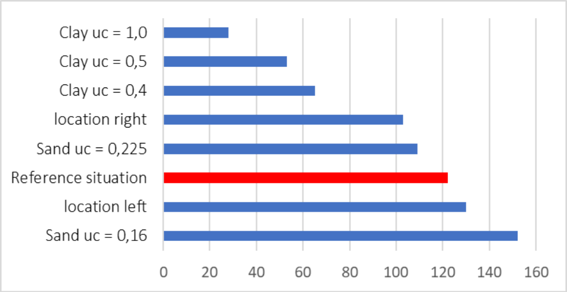

Figure 20: Width of the breach for the different characteristics.

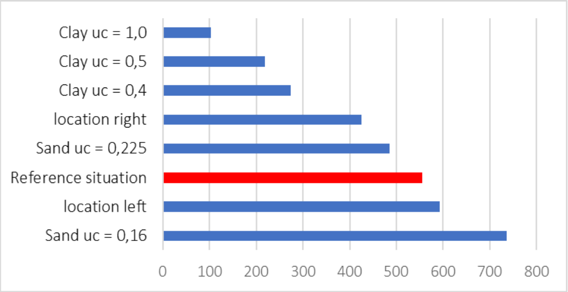

Figure 21: Maximum discharge through the breach for the different characteristics.

What can be seen is that the smallest change in output due to a change in one of the input parameters occurs when the location of the breach is being changed to a location left. The biggest change in output is caused by changing the material of the dike to clay with an critical flow velocity of 1,0 m/s.

In Table 7, the different ranges of the outcomes of the sensitivity analysis can be seen in numbers. the ranges of the output due to variations of the material of the dike are a lot bigger than those due to variations of the location of the breach. Based on this, it can be concluded that the material of the dike has a larger relative influence on the output of the flood model than the location of the breach.

Table 7: Ranges of the outputs due to variations of characteristics of the river and dike.

	Range width of the breach (m)	Range maximum discharge through the breach (m^3/s)
Change the location of the breach	103 - 130 → 27	425 - 595 → 170
Change the material of the dike	28 - 152 → 124	103 - 736 → 633

3.1.5 Conclusion

Based on the sensitivity analysis of the characteristics of the river and the dike, it can be concluded that the largest changes in the output can be seen when the material of the dike is being changed. This could be concluded because when the material of the dike is being changed over the whole parameter range of the critical dike flow velocity of clay and sand, a large range in the outcomes was seen. This range was a lot bigger compared to the range in outcomes when the location of the breach was changed.

3.2 Sensitivity of the model output to characteristics of the hinterland

In this chapter the influence of the parameters that describe the characteristics of the hinterland on the designed flood model in D-HYDRO will be discussed. The different steps of the sensitivity analysis will be described in this chapter within different sub chapters (3.2.1 – 3.2.4). In section 3.2.5, a conclusion will be drawn about the different sensitivities of this part of the sensitivity analysis.

3.2.1 Step 1: Reference situation

The reference situation for this part of the sensitivity analysis will be as follows:

- Height map of the pilot study of the Grebbedijk
- Uniform Nikuradse friction in the hinterland of 0,25
- Q(t) relation as boundary condition as shown in Figure 11 (discharge through the breach)
- Breach location in the middle of the upstream boundary (see for example Figure 3)
- Observation point in the middle of the area (see for example Figure 3)

When the reference situation of the flood model is ran, inundation depths and flow velocities occur as respectively shown in Figure 22 and Figure 23.

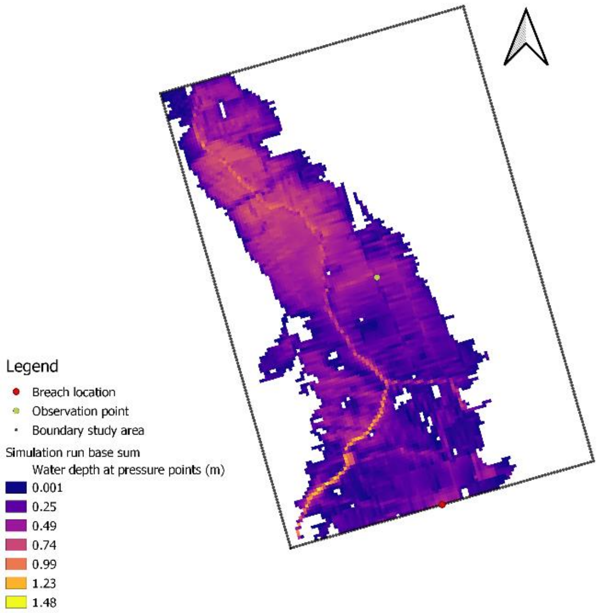

Figure 22: Inundation depths in simulation run reference situation.

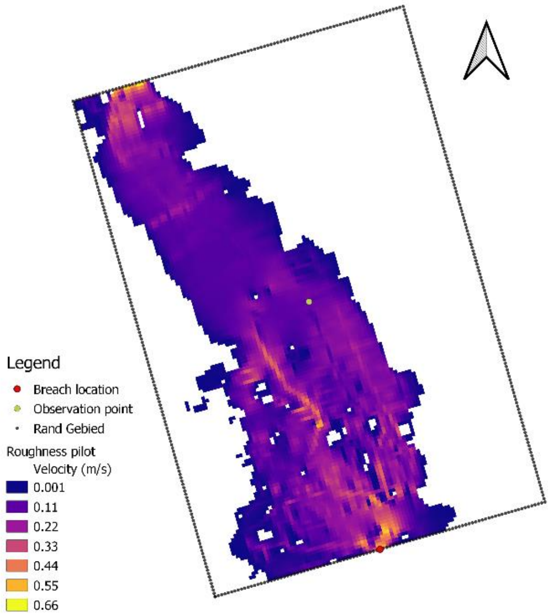

Figure 23: Flow velocities in simulation run reference situation.

The flow pattern which occurs in the simulation run of the reference situation can be explained with the height map of the study area as already seen in Figure 3. The water depts are the highest at places where the bed level is the lowest.

The velocity of the flood is, the highest in the hinterland just behind the breach, in the lower 'string' in the middle of the study area which is in the flow direction of the flood and in a couple of places at the downstream boundary. Where the hinterland behind the breach and the lower 'string' in the middle of the study area are predictable places for high velocities, the places and the downstream boundary are not. The reason for the higher velocity at this downstream point is the addition of the water level boundary around the study area. Since the level of the water level boundary is lower than the bed level of the downstream boundary, the water of the flood gets a higher speed. For the purpose of the research, this higher velocity at the downstream boundary should be ignored.

In the simulation run of the reference situation, the outputs as shown in Table 8 occur. These outputs will be compared in the sensitivity analysis, since these are the outputs which are important for the calculation of the economic damage and the number of casualties of the flood (HydroLogic, 2019B).

Table 8: Different output values from simulation run reference situation.

Output	Value
Inundation depth obs. Point (m)	0,27
Ascent rate obs. Point (m/s)	1,74E-06
Max. velocity obs. Point (m/s)	0,12
Arrival time obs. Point (hours after start)	08:30
Flooded area (km^2)	10,35
Max. water dept area (m)	1,48
Max. velocity area (m/s)	0.66

3.2.2 Step 2: Input parameters and ranges

In the conclusion of research question 2 (section 2.4.4), the parameters which should be tested within the sensitivity analysis part of the hinterland, with their ranges, came forward. It is concluded that the influence of the roughness of the ground of the hinterland, the presence of line elements as well as the presence of waterways should be tested within the sensitivity analysis.

3.2.3 Step 3: Sensitivity analysis with hinterland parameters and comparison with reference situation

Land use/Roughness

For the influence of the roughness, the (uniform) roughness of the network used in the research should be changed over the parameter range within different simulation runs. with the outputs due to the different friction coefficients are shown in Table 9.

Table 9: Output values for the different simulation runs of the sensitivity of the output of the model to roughness of the hinterland surface.

Output	Reference situation	Roughness pilot	0,1	0,4	1	5	10
Max. inundation depth obs. Point (m)	0,27	0,28	0,21	0,31	0,41	0,80	1,06
Ascent rate obs. Point (m/s)	1,74E-06	1,78E-06	1,34E-06	2,01E-06	2,85E-06	7,17E-06	1.02E-05
Max. velocity obs. Point (m/s)	0,12	0,13	0,14	0,11	0,085	0,04	0,032
Arrival time obs. Point (hours: min after start)	08:30	07:55	07:40	09:05	11:15	20:35	22:35
Max. flooded area (km^2)	10,35	10,35	9,94	10,58	11,29	13,57	13,90
Max. water dept area (m)	1,48	1,42	1,44	1,51	1,59	1.93	2.16
Max. velocity area (m/s)	0,66	0,61	0,74	0,61	0,53	0,34	0,25

When looking at the outputs individually, it can be observed that the maximum water depth in the observation point and the maximum inundation depth in the area become larger if the uniform friction coefficient is higher. Furthermore, the total flooded area, as well as the ascent rate increases when the uniform friction is higher. On the other hand, the maximum velocity in the observation point, as well as the maximum velocity in the area, gets lower is the uniform friction is higher. Furthermore, the arrival time of the flood at the observation point is later if the uniform friction is higher.

These results can all be explained by the effect that a rougher surface has on the flood. On a rougher surface, the water velocity is lower. Therefore, lower maximum velocities will arise and the flood will arrive later at the observation point. Still, the same amount of discharge is entering the study area every simulation run. This causes the flood to act like kind of a 'wave' which spreads out over the hinterland with higher water depths as a result. This 'wave' causes a higher ascent rate and a bigger inundated area. Since water depths are higher, the flood is able to reach the higher places in the hinterland. To show this effect, the water level over time in the observation point is visualised in Figure 24.

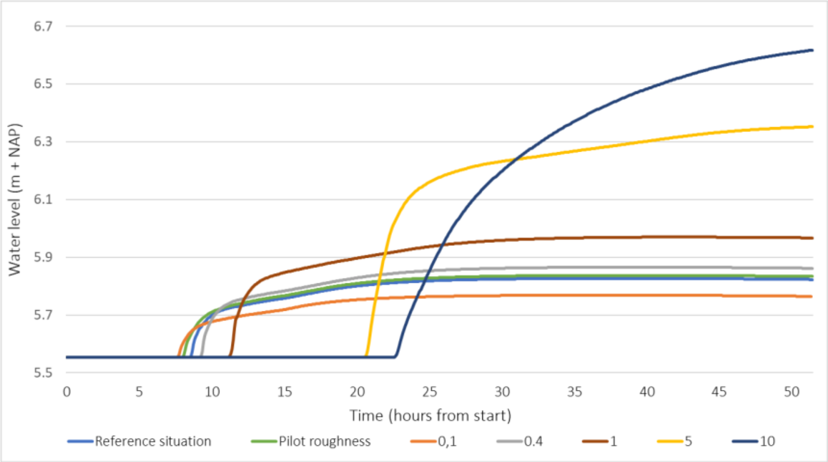

Figure 24: Water level at observation point as a function of time for different roughness values of the surface of the hinterland.

Looking at the output values of the simulation run where the roughness map of the pilot study is applied to the study area, only slight differences with the reference situation arise. This slight difference occurs in the arrival time at the observation point and the maximum velocity in the area can be seen. The fact that no major differences in output values arise have to do with the fact that, like already explained in section 2.4.3, the largest part of the land of the sturdy area has a Nikuradse friction of 0,25 which was also used in the reference situation. On top of that, when you compare the map of the flooded area of the reference situation (Figure 22) with the roughness map of the area (Figure 4), it can be observed that the water of the flood will mainly reach places where grass or sometimes agriculture land is present. For these land types, the Nikuradse roughness is respectively 0,25 and 0,4. The water will not reach places where a higher friction coefficient is present. Taking this into account, it is decided that the output values obtained in the simulation runs of the uniform friction coefficient higher than 0,4 will not be included in the final step of the sensitivity analysis of the research since these higher friction coefficients are not realistic for the study area with the chosen height map.

Still, when comparing the figures of the reference situation (which has a somewhat realistic friciton coefficient) with the figures of the roughness of the pilot study, some interesting differences can be seen. Where in the simulation run an uniform friction was applied, the maximum velocity of the water was always found directly after the breach (when the high velocities at the downstream boundary are ignored). In the simulation run where the roughness of the pilot study is applied, the maximum velocity is reached a bit to the right and a bit more downstream (see Figure 25 and Figure 26). When you compare the places these differences occur with the land use map used in the simulation run where the roughness of the pilot study is applied (see Figure 27), some remarkable things can be seen.

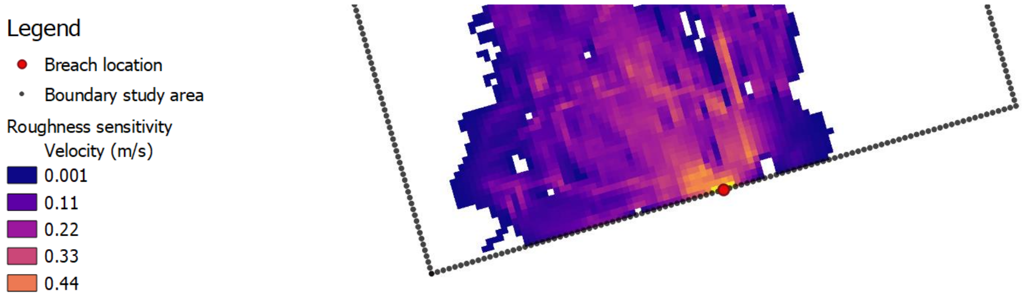

Figure 25: Velocity of the flood after the breach in the reference situation (uniform friction = 0,25).

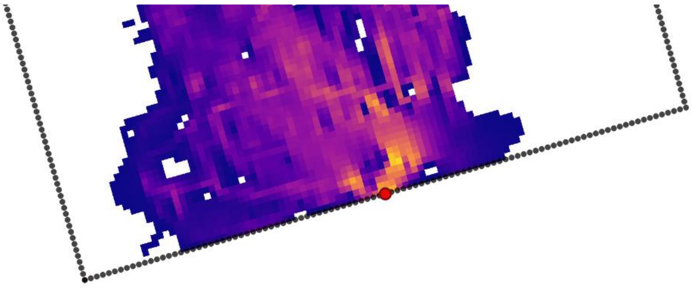

Figure 26: Velocity of the flood after the breach when the roughness pilot study Grebbedijk is applied.

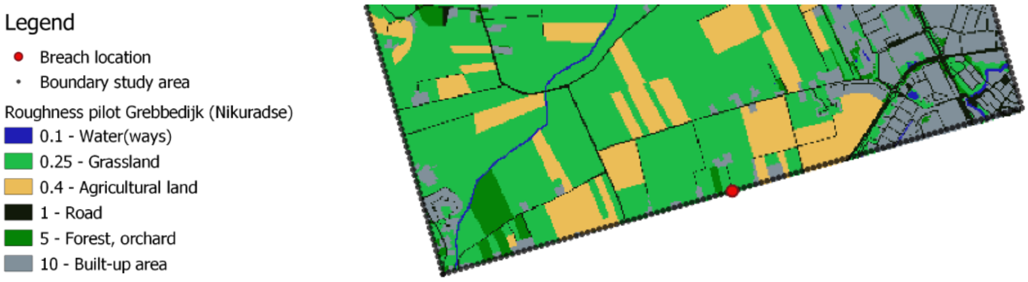

Figure 27: Land use map pilot study Grebbedijk.

You would expect that the place with the highest velocities in the simulation run where the friction of the pilot study of the Grebbedijk is used, is the place where the land use has the lowest friction. However, the place where the velocities are the highest is agricultural land, which has a Nikuradse value of 0,4 which is higher than the Nikuradse value of 0,25 used in the reference situation. The reason for the different locations of maximum velocity is that the location where the highest values are observed in the reference situation has land use forest and built-up (respectively Nikuradse values of 5 and 10). When the flood reaches these places in the simulation run where the friction of the pilot study is used, the water will be forced towards a different location where it experiences less friction. In this case this is to the right where the land use is agricultural land with a Nikuradse value of 0,4.

In Figure 37 until Figure 41 in Appendix A, the water velocity figures of the sensitivity analysis with the different implementations of roughness can be seen. Furthermore, the inundation depth figures of this part of the sensitivity analysis can be seen in Figure 42 until Figure 46 in Appendix B.

Line elements

Like already elaborated on in section 0, 8 different line elements will be added in different simulation runs of the sensitivity analysis. For the directions and locations already shown in Figure 13, the following names are used in the analysis:

- Upstream/Downstream Perpendicular (Up/DoPer)
- Upstream/Downstream Parallel (Up/DoPar)
- Upstream/Downstream Diagonal Left Right (from bottom left to top right) (Up/DoDiaLR)
- Upstream/Downstream Diagonal Right Left (from bottom right to top left) (Up/DoDiaRL)

The results of the tests with different locations and directions of line elements are shown in Table 10.

Table 10: Output values for the different simulation runs of the sensitivity of the output of the model to line elements in the hinterland.

Output	Reference situation	UpPer	UpPar	UpDia LR	UpDia RL	DoPer	DoPar	DoDia LR	DoDia RL
Max. inundation depth obs. Point (m)	0,27	0,27	0,27	0,29	0,27	0,28	0,27	0,36	0,27
Ascent rate obs. Point (m/s)	1,74E-06	1.77E-06	1,69E-06	1,85E-06	1,75E-06	1,83E-06	1,75E-06	2,28E-06	1,74E-06
Max. velocity obs. Point (m/s)	0,12	0,115	0,12	0,23	0,123	0,12	0,12	0,105	0,12
Arrival time obs. Point (hours: min after start)	08:30	09:10	07:05	08:25	09:20	08:30	08:30	08:30	08:30
Max. flooded area (km^2)	10,35	10,61	10,38	10,58	10,48	10,36	10,34	10,58	10,48
Max. water dept area (m)	1,48	1,52	1,47	1,46	1,50	1,48	1,48	1,48	1,48
Max. velocity area (m/s)	0,66	0,88	0,66	0,72	1,21	0,66	0,66	0,66	0,66

When looking at the outputs individually, only a few output changes stand out. First of all, an interesting change can be seen in the maximum inundation depth in the observation point when a diagonal line element is present downstream from bottom left to top right. Where this maximum value is around 0,27 meter in the other runs, this value is 0,36 meter in the simulation run where a downstream line element from bottom left to top right is present. In Figure 61 in Appendix D the water depth for the presence of this line element is visualised. Because of the presence of this line element, the water that flows against this line element 'bounces' back and flows towards the observation point. Just until the water level is high enough to flow over the line element, the water will be 'bounced' back and the inundation depth in the observation point will rise. This same phenomenon can be observed in Figure 55, Figure 57, Figure 58 and Figure 59 in Appendix D. Where a line element is perpendicular or diagonal to the flow direction of the flood, the water will be accumulated and the water levels will rise.

The effect of higher water levels at line elements perpendicular or diagonal to the flow direction of the flood also has another effect. Since higher water levels occur at these line element, higher velocities arise as well. The water gets propelled into a different direction then in the reference situation since it is looking for the easiest way to travel to the lowest places in the area. When it has found the 'weak spot' in the line element (the lowest spot), the water will flow over it and will then be looking for the lowest places in the area behind the line element. This phenomenon can be seen the clearest in Figure 49 in Appendix C. In this figure the velocity in the observation point is visualised where a line element upstream and diagonal from left to right is present. This line elements ensures the highest velocity in the observation point. After the water has flood over the line element, the water gets a higher velocity in the direction of the observation point. These higher velocities can also be seen when looking at Table 10. The maximum velocity in the area of 0,66 m/s in the reference situation occurs just behind the breach. This maximum value and corresponding location is also found in five simulation runs where a line elements is present. In the three other simulation runs, the maximum velocity was higher than this 0,66 m/s and was detected at the 'weakest points' of the different line elements.

Next to the changes in local and global velocities and the local water depts, a significant change can be seen in the arrival time of the flood in the observation point. This arrival time is different compared to the arrival time in all the simulation runs where a line element upstream is present. When a line element perpendicular or diagonal to the flow direction upstream of the observation point is present, the arrival time is delayed compared to the arrival time in the reference situation. In the simulation run where a line element is parallel to the flow direction upstream of the observation point, the arrival time of the water is smaller compared to the arrival time in the reference situation.

In Figure 28 the water level at the observation point is visualised. In this figure, the difference in arrival time and maximum inundation depth at the observation point can easily be seen.

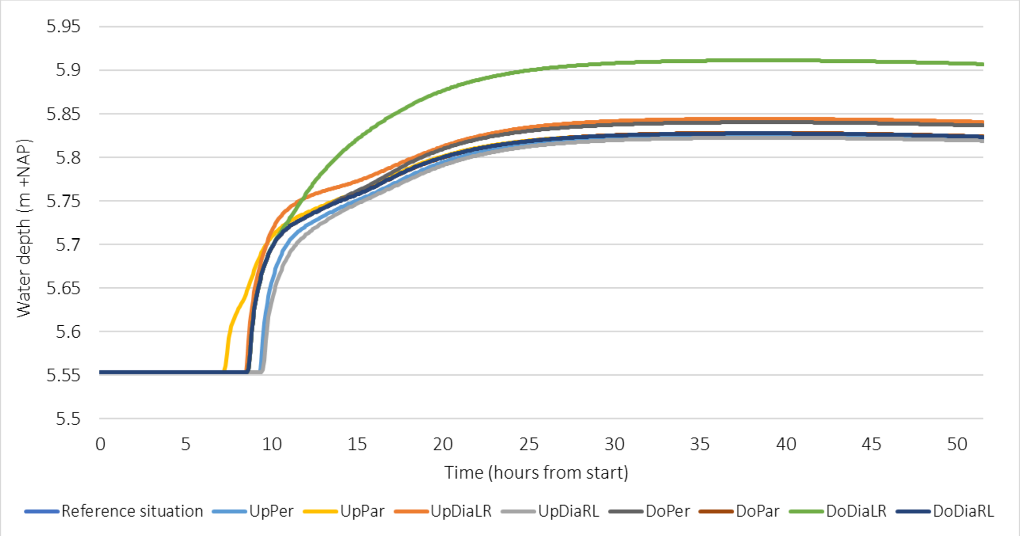

Figure 28: Water level at observation point as a function of time for different positions and directions of line elements in the hinterland.

In Figure 47 until Figure 54 in Appendix C, the water velocity figures of the sensitivity analysis for the line elements can be found. Furthermore, the inundation depth figures of this part of the sensitivity analysis can be seen in Figure 55 until Figure 62 in Appendix D.

Waterways

The waterways have been implemented for the same locations and directions as the line elements. Furthermore, the same names will be used for the locations and directions as for the line elements explained in the previous section. Like already explained in section 0, the waterways will be added to different networks that will be ran in the different simulation runs of the sensitivity analysis. The results of these different simulation runs are shown in Table 11.

Table 11: Output values for the different simulation runs of the sensitivity of the model output to waterways in the hinterland.

Output	Reference situation	UpPer	UpPar	UpDia LR	UpDia RL	DoPer	DoPar	DoDia LR	DoDia RL
Max. inundation depth obs. Point (m)	0,27	0,28	0,28	0,29	0,26	0,27	0,27	0,27	0,27
Ascent rate obs. Point (m/s)	1,74E-06	1,78E-06	1,70E-06	1,79E-05	1,70E-06	1,74E-06	1,74E-06	1,74E-06	1,74E-06
Max. velocity obs. Point (m/s)	0,12	0,15	0,125	0,18	0,18	0,12	0,12	0,12	0,12
Arrival time obs. Point (hours: min after start)	08:30	08:00	06:35	05:55	09:00	08:30	08:30	08:30	08:30
Max. flooded area (km^2)	10,35	10,28	10,18	10,04	10,19	10,34	10,35	10,35	10,36
Max. water dept area (m)	1,48	1,47	1,47	1,42	1,48	1,48	1,48	1,48	1,48
Max. velocity area (m/s)	0,66	0,66	0,66	0.66	0,66	0,66	0,66	0,66	0,66

When looking at the results of the different simulation runs of the sensitivity analysis shown in Table 11, only a few changes in outputs can be seen due to the addition of the different waterways. Those changes can be seen in the maximum velocity at the observation point of the upstream waterways. Another difference in output can be seen in the arrival time of the flood at the observation point for all the upstream waterways. In the output of the flood model where downstream waterways are present, no significant changes in the output values can be detected. This can mostly be argued with the fact that the water of the flood hardly gets in those downstream waterways.

If the water of the flood reaches a waterway, the water of the flood will have a higher velocity since the friction in the waterway in less than the friction on the land. Furthermore, the water of the flood that gets into the waterway will get a different direction since the water will, like always, chooses the easiest way to travel, the way with the least friction and the largest height differences. In this case, the easiest way will be to travel in the waterway itself until the height difference are going to play a bigger role than the friction, or, until the waterway has a water level that it is higher than the bed level of the land besides it.

The waterways upstream of the observation point with a perpendicular, parallel and diagonal direction from bottom left to top right, ensure the water of the flood to flow with a higher velocity towards the observation point. Therefore, higher velocities at the observation point arise and the arrival time of the flood in the observation point will be earlier than in the reference situation. As seen in Figure 66, where a waterway upstream from bottom right to top left is present in the simulation run, higher velocities are present around the waterway. Still, when the water leaves the waterway, it chooses a different direction than the direction of the observation point. This way, the water will arrive a bit later in the observation point. In Figure 29 the differences in inundation depths and the arrival times in the observation point for the different directions and locations of waterways are visualized.

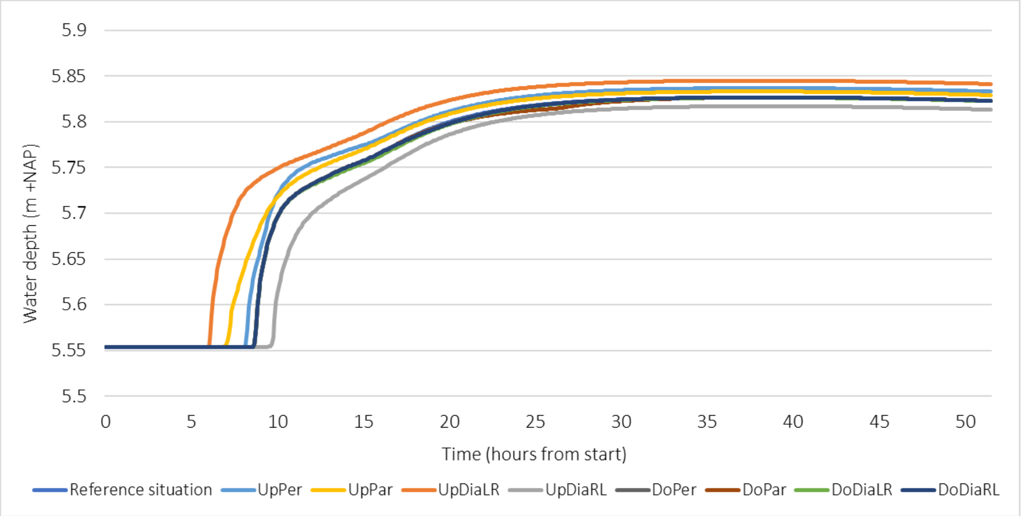

Figure 29: Water level at observation point as a function of time for different positions and directions of waterways in the hinterland.

In Figure 63 until Figure 70 in Appendix E, the water velocity figures of the sensitivity analysis of the different implementations of waterways can be seen. Furthermore, the inundation depth figures of this part of the sensitivity analysis can be seen in Figure 71 until Figure 78 in Appendix F.

3.2.4 Step 4: Ranking of dike parameters based on relative contribution to output variability

For the ranking of the sensitivities tested within this part of the sensitivity analysis, the influence of the roughness of the surface and the presence of line elements and waterways in the hinterland on different outputs of the flood model will be compared.

In Figure 30 till Figure 36, the different outputs gathered in the simulation runs of the sensitivity analysis are ranked. The outputs from the reference situation are shown in red, the roughness changes are visualised in green, the different line elements in black and the different waterways in blue. As mentioned before, the results of the simulation runs with a Nikuradse friction coefficient of 1, 5 and 10 are not included since these frictions are not realistic for this study area.

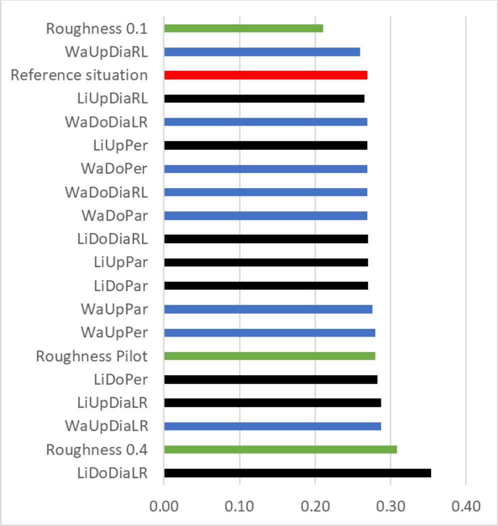

Figure 30: Maximum inundation depth in observation point (m)

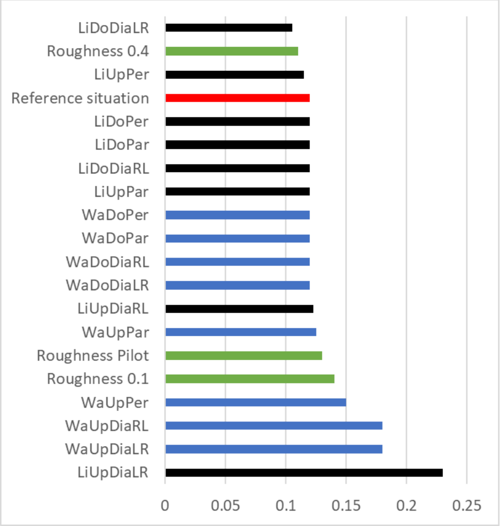

Figure 31: Maximum velocity in observation point (m/s)

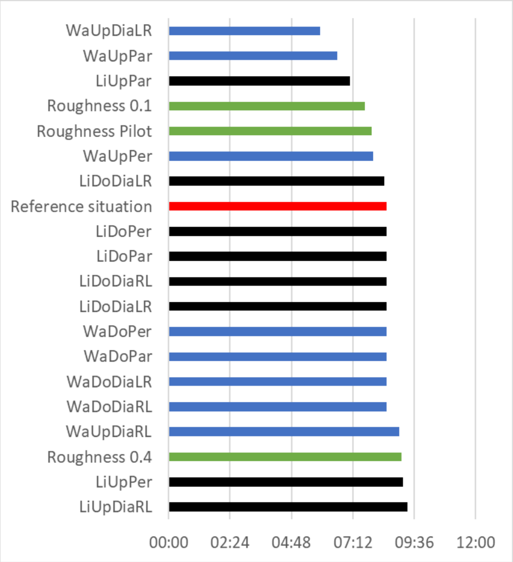

Figure 32: Arrival time in observation point (hours:minutes from start)

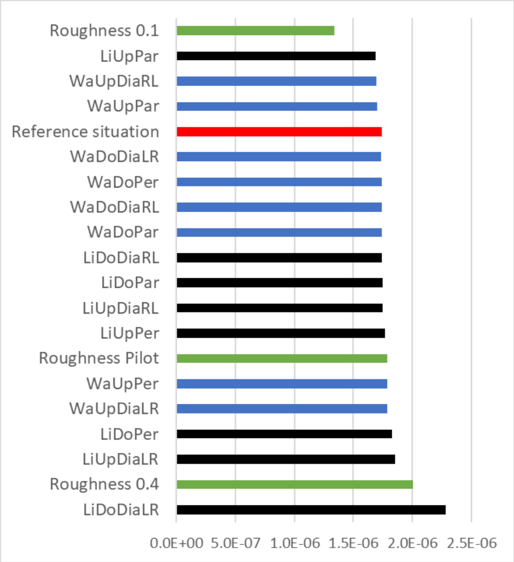

Figure 33: Ascent rate in observation point (m/s)

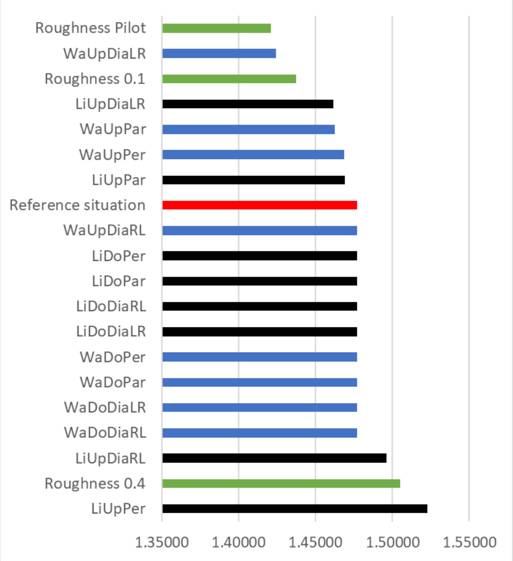

Figure 34: Maximum inundation depth area (m)

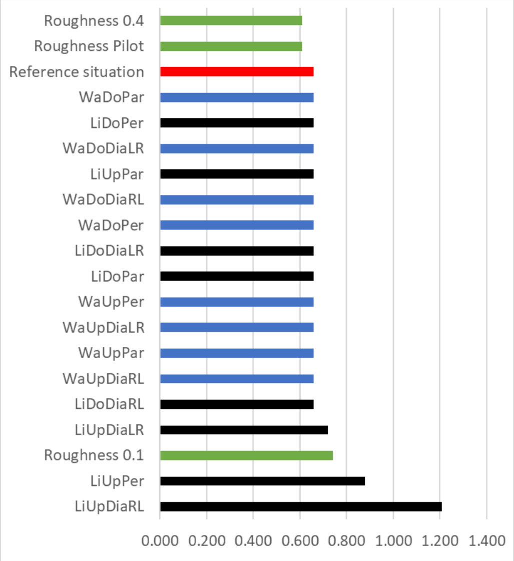

Figure 35: Maximum velocity area (m/s)

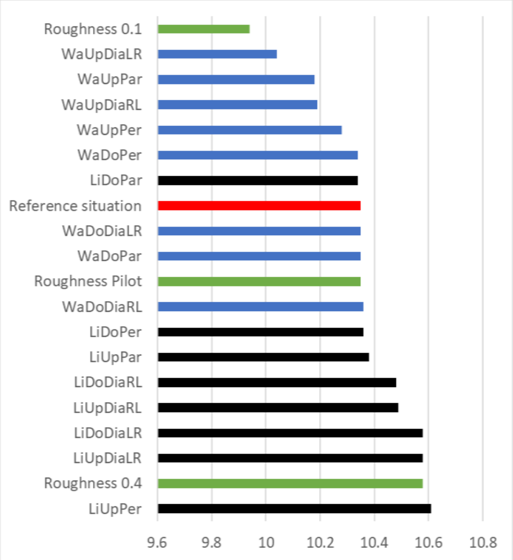

Figure 36: Maximum flooded area (km^2)

When looking at the different rankings shown in Figure 30 till Figure 36, no clear patterns can be seen. The only remarkable thing is that in all rankings, a line element is the cause of the highest value for all of the different outputs. The lowest values are mainly caused by a change in roughness of the surface.

Furthermore, it can be observed that the presence of waterways are often the reason for a smaller inundated area while the presence of line elements often lead to a bigger inundated area. This could be because a waterway makes it more easy for the flood to travel to the lower places in the area whereas the line elements are making it harder for the flood to travel to the lower places since they can block (some of) the easy routes for the flood.

Since it is hard to see any patterns or to determine which characteristic is often the cause of a higher or lower output values, the output ranges are also shown in numbers. With the help of these ranges shown in Table 12, it can be concluded that changing the roughness of the surface causes in 4 of the 7 outputs the biggest ranges. For 2 outputs the line elements causes the biggest range and only for the output value of the arrival time, the waterways cause the biggest range.

Table 12: Ranges of the outputs during the sensitivity analysis due to different characteristics of the hinterland.

	Max. inundation depth obs. Point (m)	Max. velocity obs. Point (m/s)	Arrival time obs. Point (hours: minutes)	Ascent rate obs. Point (m/s)	Max. inundation depth area (m)	Max. velocity area (m/s)	Total flooded area (km^2)
Roughness	**0.097**	0,03	01:25	**6.68E-07**	**0,068**	0,13	**0,64**
Line elements	0.088	**0,13**	02:15	5.93E-07	0,061	**0,55**	0,27
Waterways	0,028	0,06	**03:05**	8.97E-08	0,053	0,00	0,32

3.2.5 Conclusion

Based on the sensitivity analysis of the characteristics of the hinterland, it can be concluded that the largest changes in output values arise when the roughness of the surface is being changed. This could be concluded since the change of the uniform friction resulted in the largest range for most of the output values.

However, this does not directly mean that an uniform friction could not be applied in flood models. If the threatened area has one dominant land use type, the flood model does not show significant changes when a uniform friction coefficient is applied or when a spatially varying land use is used. In the study, this was shown when the outputs of the reference situation (with an uniform friction of 0,25) were compared with the outputs where the land use map of the pilot study of the Grebbedijk was used (where the majority of the flooded land has a friction coefficient of 0,25). Still, if a uniform friction will be applied in a flood model in D-HDYRO, it would be advised to use the real friction values just behind the breach. This because the biggest values in velocities are mostly seen just behind the breach, when the friction just behind the breach therefore does not have the real friction value, unrealistic flood patterns will occur.

The outputs where the largest ranges arise when the roughness is being varied, occur because of the influence on the velocity of the water. With a rougher surface the water, lower velocities will arise. Still, the same amount of discharge is entering the study area every simulation run. This causes the flood to act like kind of a ‘wave’ which spreads out over the hinterland with higher water depths as a result. This ‘wave’ causes a higher ascent rate and a bigger inundated area since, when the water depths are higher, the flood is able to reach the higher places in the hinterland. The influence on the above named outputs has proven to be bigger for the range of roughness values then for the addition of line elements and or waterways.

For the presence of line elements and waterways, it can be concluded that line elements provide a wider range in output values for every output except the arrival time. Waterways only have a significant influence on the outputs of the maximum velocity and arrival time at a certain location and on the total flooded area if they are located upstream of that specific location. Line elements only have a significant influence if they block the easiest way for the water to travel. In the study area, these were, except for one diagonal line element downstream, only the upstream line elements. When upstream line elements were present, the maximum velocity in the area was reached at the line element instead of at a point just behind the breach.

4 Discussion

In this chapter, several points will be discussed that have to be kept in mind before a relevant conclusion of the research can be drawn. First of all, some limitations of the research will be discussed (4.1). Subsequently, a link will be made with the results of the sensitivity analysis of the research and the results of the sensitivity analysis conducted within the pilot study for the Grebbedijk (4.2).

4.1 Limitations

Due to the scope of the study, some interesting characteristics of the river could not have been implemented in the sensitivity analysis of the research. One of these characteristics is the boundary conditions of the amount of water in the river. Since there was chosen to not attach a (part of) the river to the study area, it was not possible to simulate a flow in the river. This way, is was not possible to add a discharge wave upstream of the river and a relation between the discharge and water height downstream.

The scope of the study ensured that only a small study area was going to be used and a simplified flood model was going to be designed. Said so, also the line elements and waterways were going to have a simplified representation. This resulted in handmade straight line elements and waterways as well upstream as downstream with different directions. This is done to determine which locations and directions do have and which directions and locations do not have an influence on the outputs of the flood model compared with the outputs of the reference situation. Still, the given straight shapes and the height for the line elements and the given straight shapes and the width of the waterways used for the sensitivity analysis are not dimensions which are representative for a real study area. Therefore, the use of the simplified flood model in the research ensures that also the results will give a simplified representation and should therfore be taken with a grain of salt.

Next to the limitations due to the scope of the study, also some limitations of the research arose with the time restriction set for the research. Due to this, the influence of the presence of underpasses is not investigated in the sensitivity analysis of the research.

Furthermore, the time restriction set for the research has led to a missing link between the results of the sensitivity analysis of the characteristics of the river and dike and the sensitivity analysis of the characteristics of the hinterland. This link could have been made if the influence of the boundary conditions (in this case the discharge trough the breach) was tested. In the sensitivity analysis of the river and dike it could be observed that the discharge through the breach could be half of the maximum discharge if the dike was made out of clay instead of sand like in the reference situation. Although a smaller discharge as boundary condition would only show lower output values, it would strengthen and complete the conclusion and the aim of the research.

Besides the missing link explained above, the time restrictions ensured that only an univariate sensitivity analysis could be done. Therefore, the influence of the different characteristics could only be tested individually. Still, in a real flood model with a real study area, all of the different characteristics will be implemented in one simulation run. In that case, it would be interesting to see the sensitivity of the output values if all those different characteristics have been implemented and being changed over their parameter range All-At-the-Time (AAT). This way, certain mutual relationships of the characteristics could have been seen.

4.2 Pilot studies Hydrologic

As mentioned before, HydroLogic has done two pilot studies with a flood model in D-DHYDRO software. Hereby, also a sensitivity analysis was conducted. When looking at the results of the sensitivity analysis of the pilot study of the Grebbedijk and comparing these with the results of this research, some differences and similarities can be seen.

First of all, the width of the breach and the maximum discharge through the breach show similar differences when the location of the breach is changed. This is largely caused by the fact that the same H(t) relation was used (only a bit lower in this research) and that the same parameters needed for the breach development in D-HYDRO were used. The conclusions for this part of the analysis are therefore similar as well.

For the sensitivities of the characteristics of the area, different results are found and different conclusions are drawn. This mostly has to do with the use of smaller area and lower discharge through the breach in the research. Those lead to lower velocities than in the pilot study of the Grebbedijk. In a bigger area, the present water ways have more influence on the way the water is being transported to downstream places in the area. On the other hand, the essence of the influence line elements and waterways present in an threatened area show the same results. The (upstream) line elements cause higher water depths upstream which cause a delay in the inundation of downstream places. The (upstream) waterways are responsible for a faster transportation of the water to downstream places which cause lower water depths upstream but also higher velocities.

5 Conclusion and Recommendations

This chapter will describe the conclusions reached at the end of this study. Furthermore, some recommendations for further research will be given. The conclusions of the separate research questions were already given in the chapters where the research questions were examined. In this chapter these conclusions are leading to the answer on the aim of the research.

5.1 Conclusion

The research aim was to "*determine the sensitivity of the output of D-HYRO software to changes in input parameters which describe characteristics of the river, the dike and the hinterland*".

To determine these sensitivities, a sensitivity analysis was conducted in D-HDYRO. For the characteristics of this analysis, it could be concluded that an independent and local sensitivity analysis was needed to be done. This should be done by changing the input parameters One At a Time (AOT). Furthermore, the chosen parameters should be varied over their whole parameter range. Before the sensitivity analysis could be conducted, a reference situation is needed to be determined. When the different simulations runs of the sensitivity analysis have been completed, the output values of these runs should be compared with the output values of the reference situation. Hereby, a ranking can be made of the relative contribution to the output variability of the different input parameters which has been tested.

Before the sensitivity analysis could be executed, the parameters, with their ranges needed to be determined. In the end, for the tested characteristics of the river and dike, the location of the breach would be varied over two locations and the material of the dike would be varied over 5 values. For the characteristics of the hinterland, the roughness of the surface would be varied over 5 uniform friction values. Furthermore, also the roughness map of the pilot study of the Grebbedijk would be applied to test the influence if a non-uniform friction of the surface is used. Next to that, line element sand waterways will be added to different simulation runs on 8 different locations with different directions to test the sensitivity of the output values of the flood model to these characteristics.

When the sensitivity analysis for the characteristics of the river and the dike was done, it was found that the biggest ranges in the output variability can be seen when the material of the dike is being changed. The breach width and maximum discharge through the breach for a sand dike was almost doubled compared to a clay dike. A difference in location of the dike breach also caused a difference in output values, however these differences were far smaller than when the material of the dike was changed.

For the sensitivity analysis of the characteristics of the hinterland, it was harder to pinpoint the characteristic which causes the highest differences in output values. First of all, the roughness of the surface seems to have the biggest influence on the output variability. Still, after some consideration, the biggest parameter values of the roughness were kicked out of the final ranking because these higher values were unrealistic for the chosen study area. When this was done, it was hard to draw a conclusion based on the ranking made of the different outputs. It could be observed that a line element was always responsible for the highest output values for all the different outputs. The lowest output values were mainly caused by a change in roughness of the surface. Furthermore, it could be observed that the presence of waterways is often the reason for a smaller inundated area while the presence of line elements often lead to a bigger inundated area. This could be because a waterway makes it more easy for the flood to travel to the lower places in the area, whereas a line element makes it harder for the flood to travel to these places since they can block (some of) the easy routes of the flood.

In the end, it could be concluded that changing the roughness of the surface causes in 4 of the 7 outputs the biggest ranges. For 2 outputs the line elements causes the biggest range and only for the output value of the arrival time, the waterways cause the biggest range. Based on this, it could be concluded that, the roughness of the surface caused the biggest ranges for most of the output values compared.

Overall, no sustained conclusion can be drawn about which of the tested characteristics has the biggest influence on the output variability since no link has been made between the sensitivity analysis of the characteristics of the river and the dike and the sensitivity analysis of the hinterland. Still, the aim of the research is being answered for the separate sensitivity analysis.

5.2 Recommendations for further research

The biggest limitations of this research, like already stated in chapter 4, is the use of the small study area and use of a simplified flood model. Therefore, certain characteristics could not be tested (over their complete parameter range) in the sensitivity analysis. Furthermore, it was not possible to test the mutual relation of the input parameters in an ‘All At the Time (AAT)’ sensitivity analysis.

Therefore, the recommendation for further research will mostly consist of making use of a real existing study area where line elements and waterways are gathered from top10nl or AHN data (Top10NL, 2020; Actueel Hoogtebestand Nederland, 2020). This way, the influence of the line elements and waterways can be seen when they have real existing dimensions instead of the organised dimensions made by hand used for the line elements and waterways in the research.

When making use of this real existing study area, also a part of the river can be included to be able to test more characteristics of the river and be able to change the boundary conditions. This way, a link could be made between the characteristics of the river and dike and the characteristics of the hinterland.

To do these kind of flood calculations, there should be made use of strong super computers which are able to make fast calculations so it is feasible to conduct the sensitivity analysis with the real area and make both a OAT as a AAT sensitivity analysis.

5.3 Recommendations for flood modelling with D-HYDRO

With everything said above, as well in chapter 4 as in chapter 5, the results of this research should still be used as background information when flood modelling with D-HYDRO. If D-HYDRO is going to be used in real existing (and bigger) study areas, it is first of all advised to, if the material of the dike could not be determined correctly, made use of a sand dike in the flood model. This should be done since this way the ‘worst case scenario’ will be determined for the width of the breach.

Furthermore, there should be looked at the land use type of the study area. If the threatened area consists (for the largest part) of one land use type, an uniform friction could be used for the roughness of the surface. Still, since the velocity of the flood just behind the breach mainly depends on the roughness of the surface just behind the breach, it is advised to, if an uniform friction is applied in a flood model in D-HDYRO, still apply the real friction of the land just behind the breach. If the friction just behind the breach does not have the real friction value, unrealistic flood patterns will occur.

Lastly, if the goal of the flood model includes a correct visualization of the maximum velocity, the line elements of the study area should be adapted in the flood model. If the goal of the flood model includes a correct visualization of the arrival time of the flood, the waterways play a big role and should therefore be correctly adapted in the flood model. The line elements and waterways should be adapted with data gathered from top10nl or AHN data (Top10NL, 2020; Actueel Hoogtebestand Nederland, 2020).

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Appendices

A. Results sensitivity analysis hinterland – Roughness (velocity)

Legend

● Breach location
● Observation point
• Boundary study area

Roughness sensitivity
Velocity (m/s)
🟦 0.001
🟪 0.12
🟪 0.25
🟥 0.37
🟧 0.49
🟧 0.62
🟨 0.74

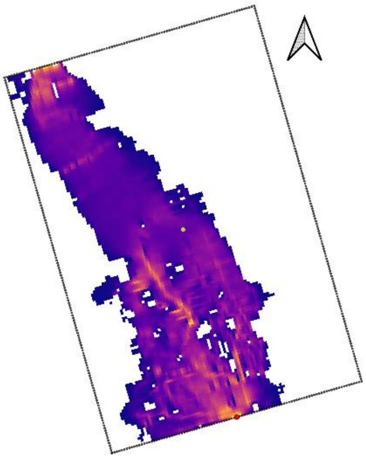


Figure 37: 0,1 Nikuradse

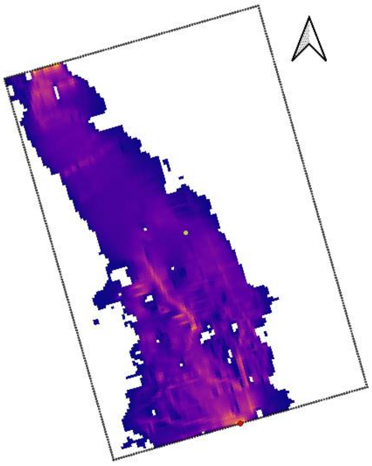


Figure 38: 0,4 Nikuradse

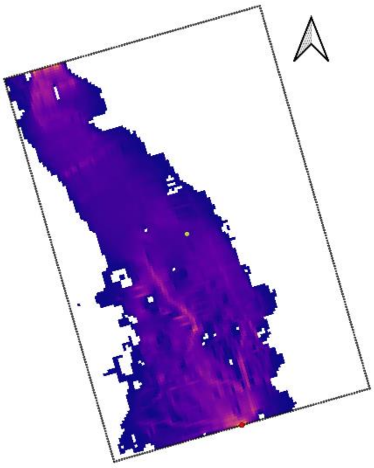


Figure 39: 1 Nikuradse

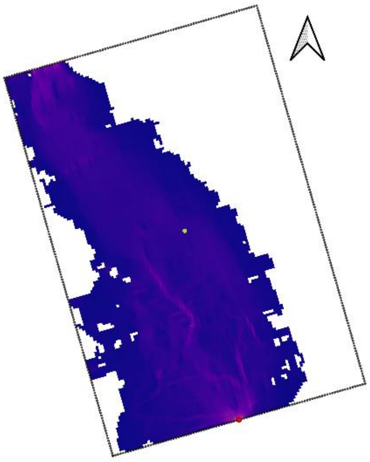


Figure 40: 5 Nikuradse

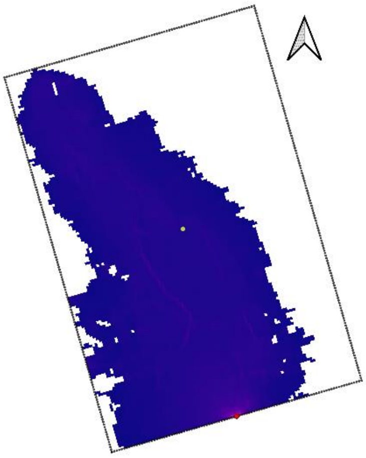


Figure 41: 10 Nikuradse

B. Results sensitivity analysis hinterland – Roughness (inundation depth)

Legend

● Breach location
● Observation point
• Boundary study area

Roughness sensitivity
Water depth (m)

🟦 0.001
🟪 0.36
🟪 0.72
🟥 1.08
🟧 1.44
🟧 1.80
🟨 2.16

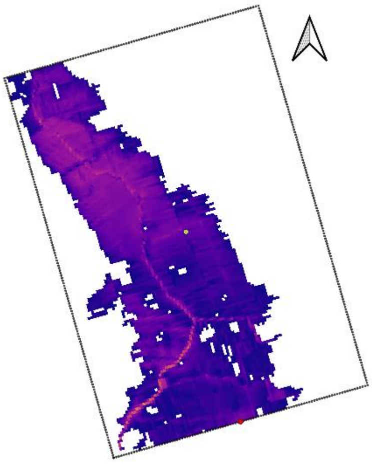


Figure 42: 0,1 Nikuradse

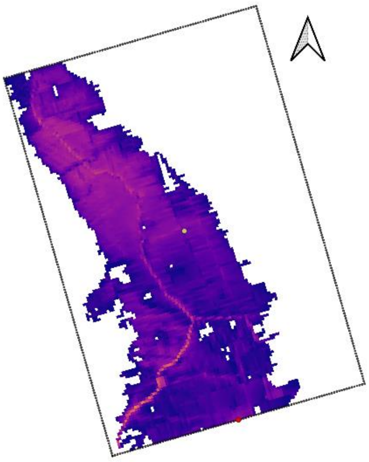


Figure 43: 0,4 Nikuradse

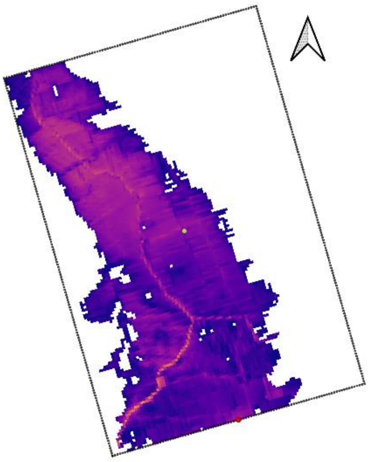


Figure 44: 1 Nikuradse

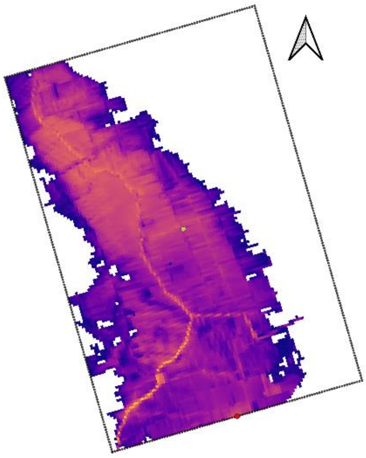


Figure 45: 5 Nikuradse

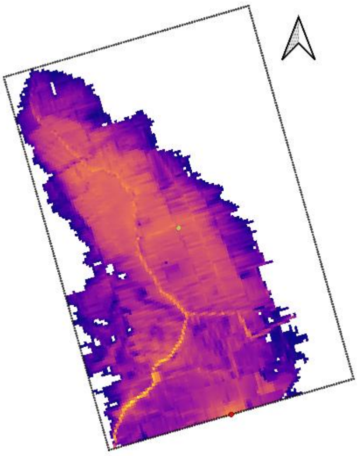
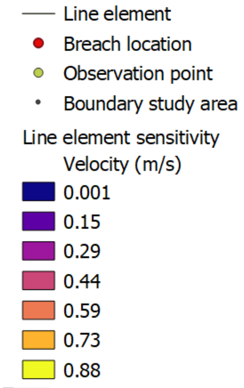


Figure 46: 10 Nikuradse

C. Results sensitivity analysis hinterland – Line elements (velocity)



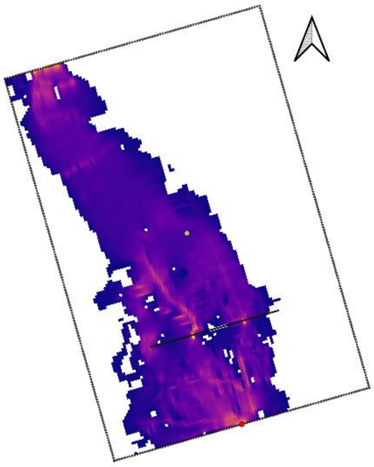


Figure 47: Upstream Perpendicular

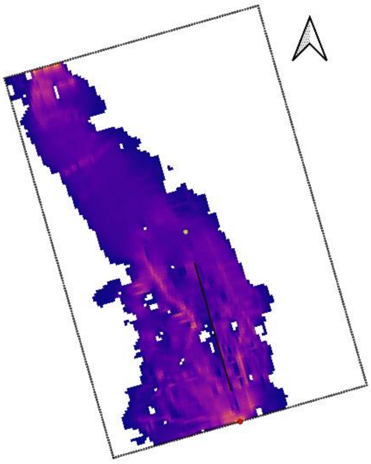


Figure 48: Upstream Parallel

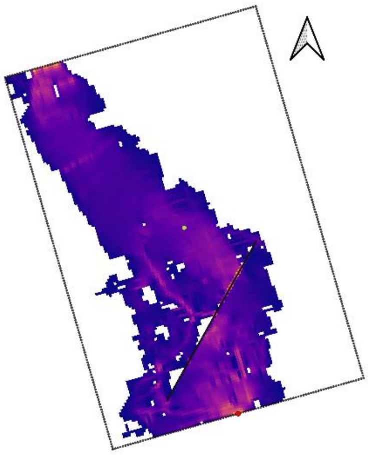


Figure 49: Upstream Diagonal Left Right

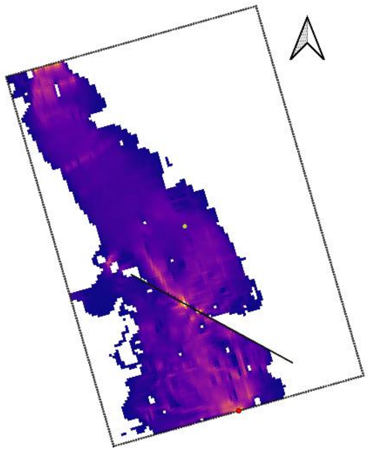


Figure 50: Upstream Diagonal Right Left

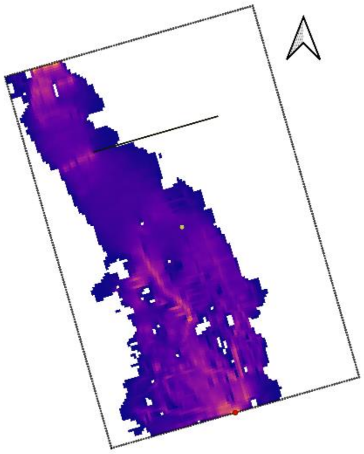


Figure 51: Downstream Perpendiculair

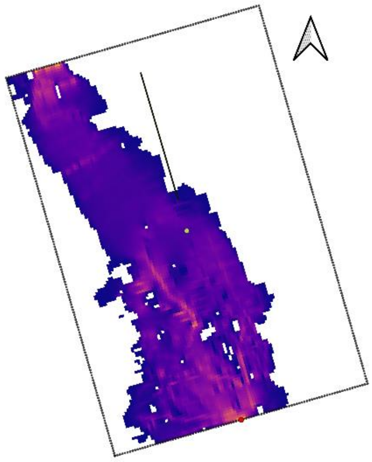


Figure 52: Downstream Parallel

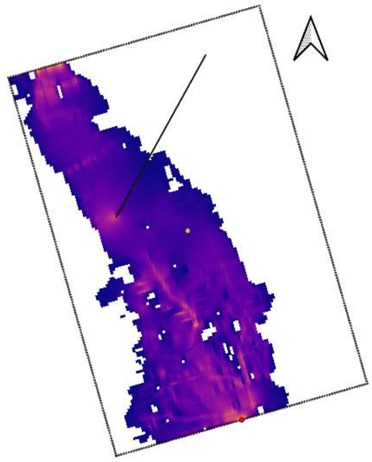


Figure 53: Downstream Diagonal Left Right

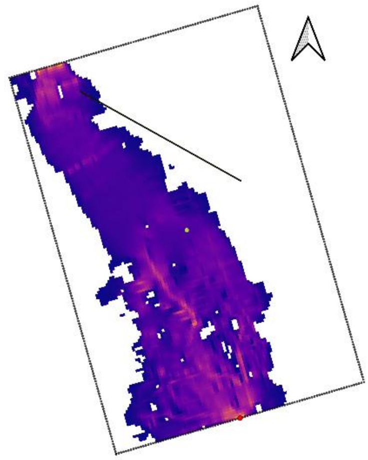


Figure 54: Downstream Diagonal Right Left

D. Results sensitivity analysis hinterland – Line elements (inundation depth)

— Line element
● Breach location
● Observation point
• Boundary study area

Line element sensitivity
Water depth (m)
■ 0.001
■ 0.25
■ 0.50
■ 0.75
■ 1.00
■ 1.25
■ 1.50

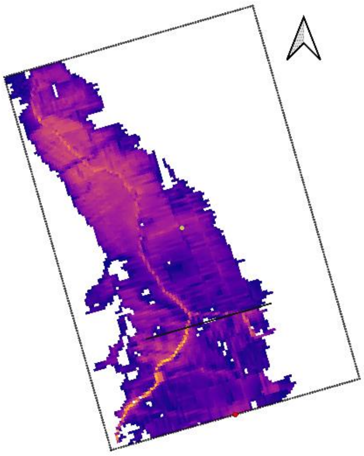


Figure 55: Upstream Perpendiculair

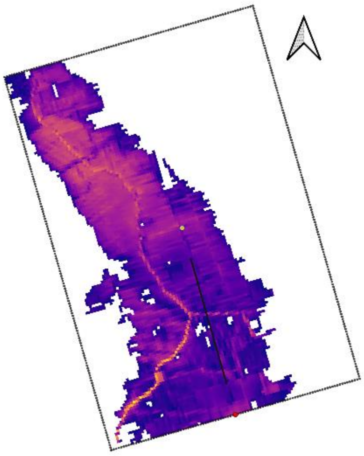


Figure 56: Upstream Parallel

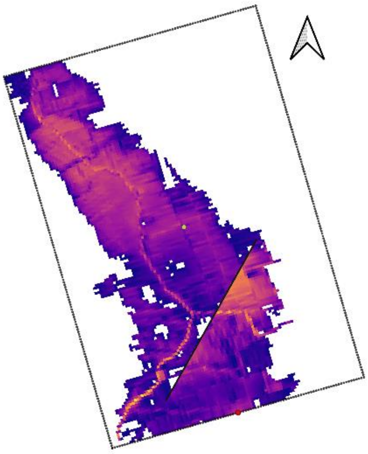


Figure 57: Upstream Diagonal Left Right

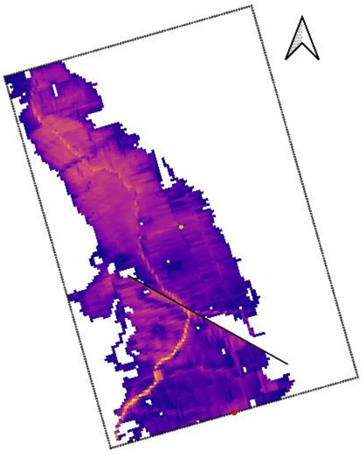


Figure 58: Upstream Diagonal Right Left

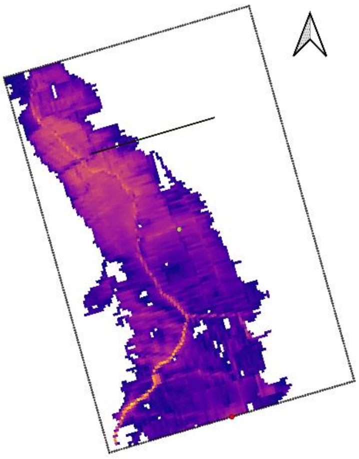


Figure 59: Downstram Perpendiculair

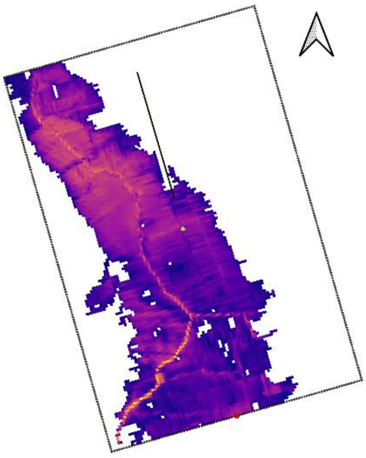


Figure 60: Downstream Parallel

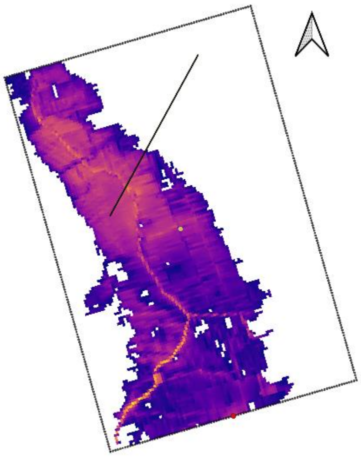


Figure 61: Downstream Diagonal Left Right

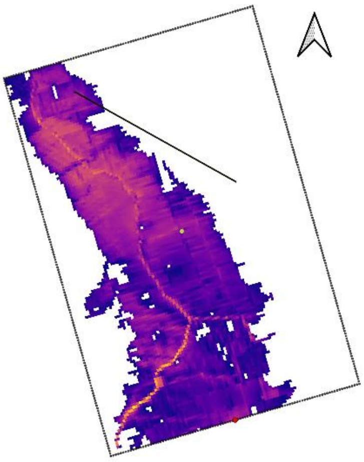


Figure 62: Downstream Diagonal Right Left

E. Results sensitivity analysis hinterland – Waterways (velocity)

— Waterway
● Breach location
● Observation point
• Boundary study area

Waterway sensitivity
Velocity (m/s)
■ 0.001
■ 0.11
■ 0.22
■ 0.3305
■ 0.44
■ 0.55
■ 0.66

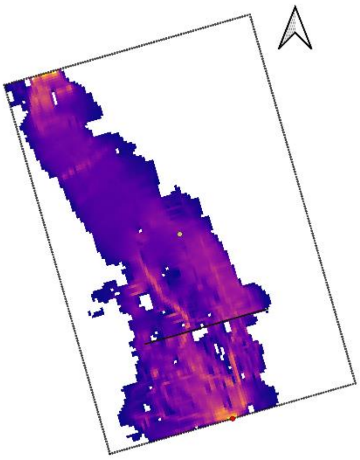


Figure 63: Upstream Perpendiculair

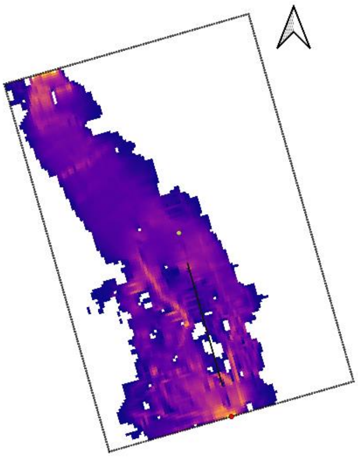


Figure 64: Upstream Parallel

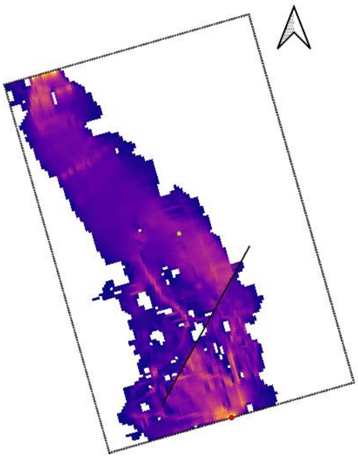


Figure 65: Upstream Diagonal Left Right

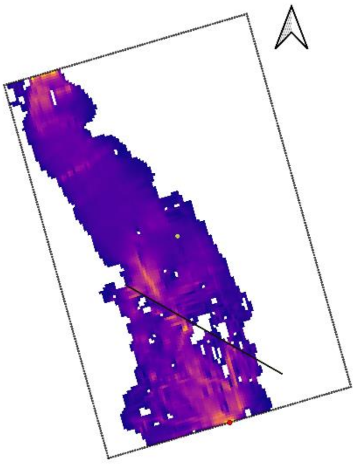


Figure 66: Upstream Diagonal Right Left

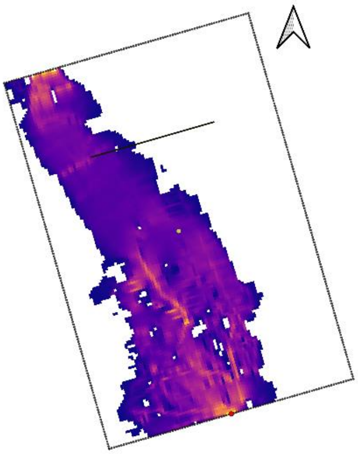


Figure 67: Downstream Perpendiculair

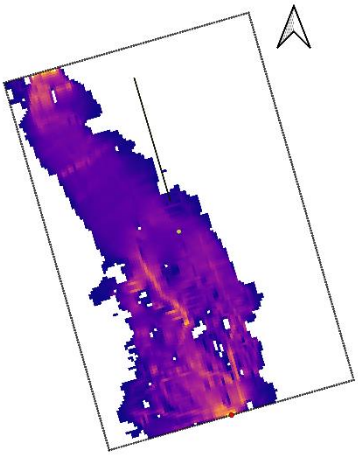


Figure 68: Downstream Parallel

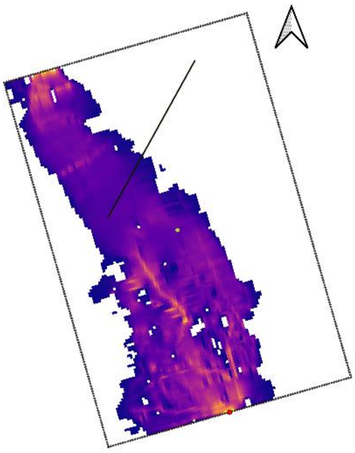


Figure 69: Downstream Diagonal Left Right

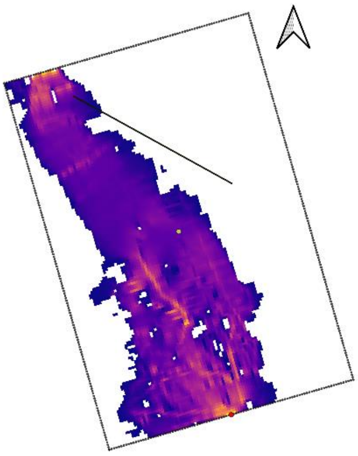


Figure 70: Downstream Diagonal Right Left

F. Results sensitivity analysis hinterland – Waterways (inundation depth)

— Waterway
● Breach location
● Observation point
• Boundary study area
Waterway sensitivity
Water depth (m)
🟦 0.001
🟪 0.25
🟪 0.49
🟥 0.74
🟧 0.99
🟧 1.23
🟨 1.48

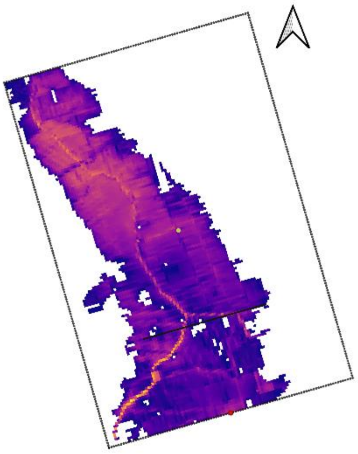


Figure 71: Upstream Perpendiculair

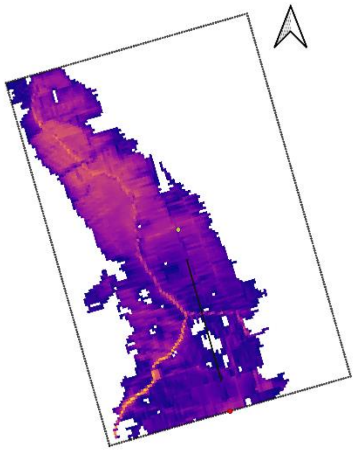


Figure 72: Upstream Parallel

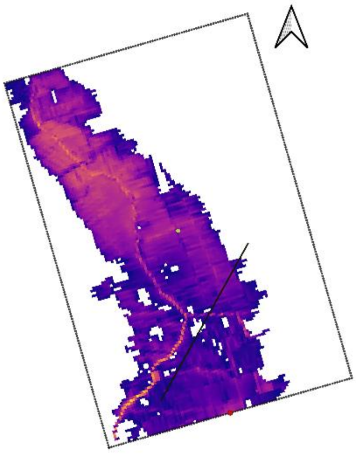


Figure 73: Upstream Diagonal Left Right

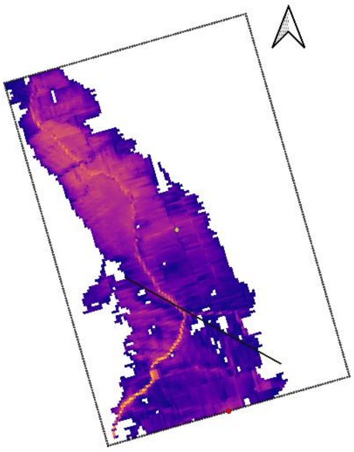


Figure 74: Upstream Diagonal Right Left

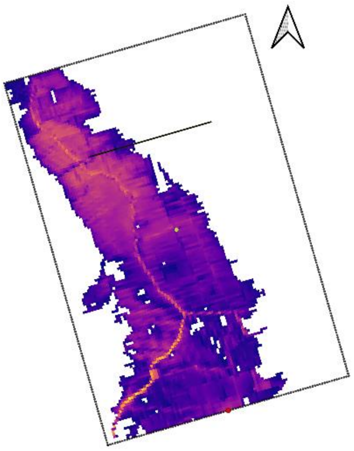


Figure 75: Downstream Perpendiculair

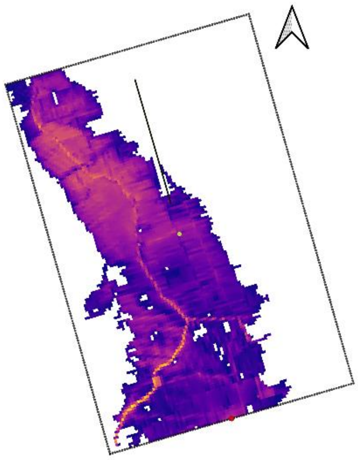


Figure 76: Downstream Parallel

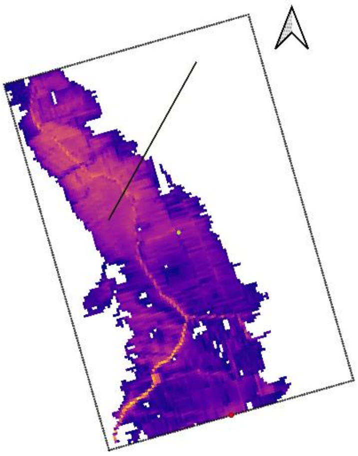


Figure 77: Downstream Diagonal Left Right

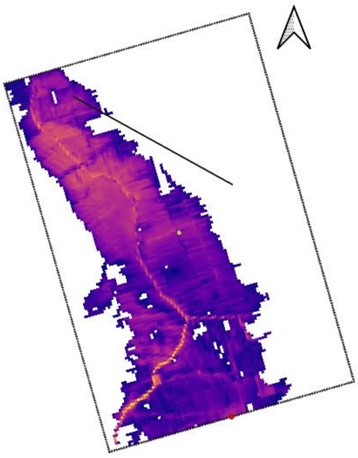


Figure 78: Downstream Diagonal Right Left