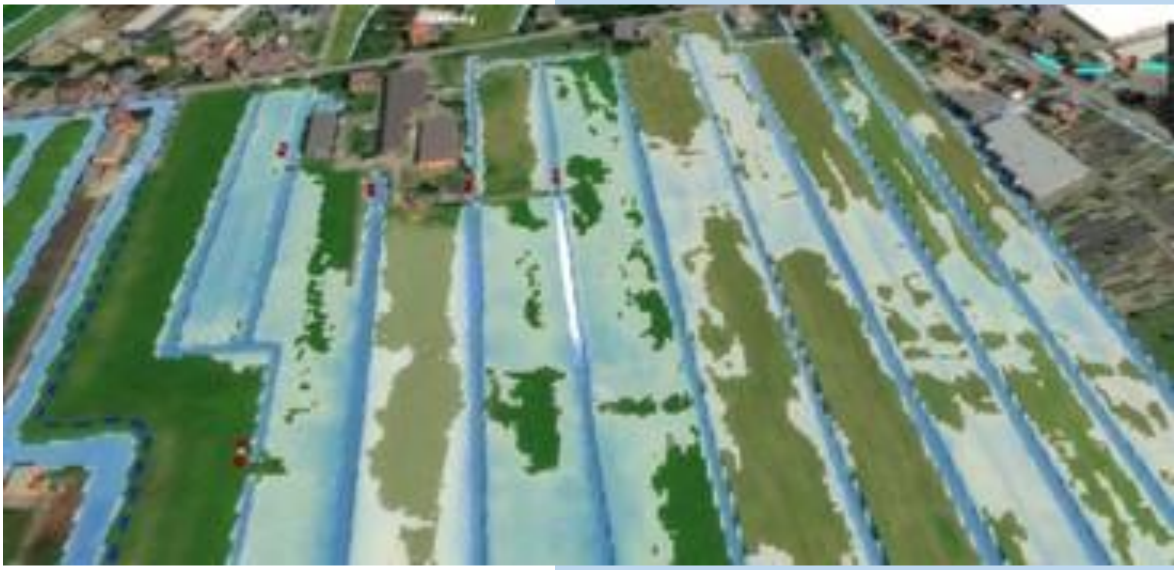
Karla Korporaal

5 July 2022

The influence of input parameters on flood calculation outcomes



(Tygron Support, 2021c)

UNIVERSITY OF TWENTE.

Aveco de Bondt
onderzoekt ontwerpt adviseert

Contact Details

STUDENT	
NAME	Karla Korporaal
STUDENT NUMBER	S2279304
EMAIL ADDRESS	k.korporaal@student.utwente.nl
PHONE NUMBER	+31653319751
INTERNAL SUPERVISOR	
NAME	Dr. Ir. Anouk Bomers
EMAIL ADDRESS	a.bomers@utwente.nl
PHONE NUMBER	+31534891062
EXTERNAL SUPERVISOR	
NAME	Ir. Willeke van de Wardt
EMAIL ADDRESS	wvdwardt@avecodebondt.nl
PHONE NUMBER	+31683087823
SECOND EXAMINATOR	
NAME	Dr. Ir. Léon Olde Scholtenhuis
EMAIL ADDRESS	l.l.oldescholtenhuis@utwente.nl
PHONE NUMBER	+31534896857

Preface

This report is the final product of a research of twelve weeks at Aveco de Bondt. I researched the influence of input parameters on flood model outcomes. This topic suits the bachelor of Civil engineering and management and my interests perfectly. During my study, it became clear that I am interested in models and floodings.

Last twelve weeks I enjoyed my time at Aveco de Bondt. For me, this was the first time to experience the working environment in a company. I have learned a lot about the modelling of floods, the reasoning behind flood calculations and the explanation of physical processes during floods. Next to that, I gained experience in working with QGIS and Tygron which I have used during this research.

I would like to thank Anouk Bomers from the University of Twente for the help and guidance of my thesis project. Especially, during the hard moments, her guidance was extra useful. Furthermore, I want to thank Willeke van der Wardt from Aveco de Bondt for her help, explanation and the talks we had. As last, I want to thank Reijn van Rooyen from Aveco de Bondt for his help with the MT-Polder. Moreover, I want to thank all the other colleagues from Aveco de Bondt for their help and for having a fun period at the company.

As of last, I hope that you enjoy reading my thesis and feel free to contact me if you have questions.

Karla Korporaal

Enschede, 5 July 2022

Summary

Since many people in the world are living in an area with flood risk it is important to know what will happen if a flood occurs. Therefore flood calculations are executed. This research aims to gain insight into the influence of input parameters on flood calculation outcomes. This can lead to more accurate flood model outcomes. During this research, there is looked at floods caused by dike overtopping. This means that the water level outside the dike will be higher than the dike, so the water will flow over the dike to the hinterland.

Only the inundation at surface level is taken into account, this means that the inundation at waterways is not considered during this research. The total water system must be taken into account during flood calculations, this gives a realistic view of what will happen in the hinterland during a flood. Therefore Tygron is chosen to work with. The input parameters precipitation and the roughness coefficient are changed during this research to invest their influence on the outcomes. The following outcomes are examined: maximum flow velocity, maximum water depth and maximum inundation extent.

Two test areas are used to study the effect of the input parameters on different areas. The first test area is the MT-Polder which is a rural and flat area. The second test area is Vortum Mullem, a rural and sloping area. A sensitivity analysis is performed to visualize the differences between two situations. The 'one-at-a-time' method is used during this research, which means that one single parameter will be changed to examine that influence.

For the precipitation, the results show that the intensity, duration and moment in time of the precipitation are influencing the maximum flow velocity, maximum water depth and maximum inundation extent in both areas. Increasing the intensity of rainfall has a higher influence on the polder area, than on the sloping area. This is since the amount of water from the precipitation is a higher percentage of the total amount of water in the area in the polder area than in the sloping area. This difference is caused by the fact that the amount of water coming over the dike during a flood in the sloping area is bigger than the volume of water which will come into the MT-Polder. The manning coefficient also has an important influence on the model outcomes. When increasing the manning coefficient the flow velocity is decreasing. The influence of the manning parameter on the water depth differs per area.

Based on this knowledge and information gathered during this research a recommendation for further research is on the development of the Tygron program and it is important to research the influence of other input parameters, such as trees. As of last, it is useful to change multiple parameters at the same time to see if this has a different influence on the flood model outcomes. Then possible interactions between input parameters are taken into account.

Table of Contents

Table of Figures

Table of Tables

1 Introduction

The introduction is divided into four parts. At first, the context will be outlined (1.1). Secondly, the problem description is given (1.2). After that, the research aim and question are given (1.3). As of last a reading guide is given (1.4).

1.1 Context

Many countries are experiencing trouble with water. This could be in any form. For example, sea level rising is nowadays very relevant for countries which are settled below sea level, or for delta areas in general. But also rivers can be a danger for humanity since increasing water levels may cause floods.

A big part of the inhabitants of the Netherlands is currently living in regions which are having a high flood risk. If there was no flood protection infrastructure almost half of the Netherlands would be flooded regularly. The Netherlands need to deal with the treatment of the sea, but next to that they have to deal with some big rivers, like the Rhine and the Meuse rivers (Oude Essink et al., 2010). Rivers are flooding due to the high amount of water that goes through the river. When the water levels are higher than the river can handle a flood will occur. When a flood would occur people need to be evacuated and it could lead to life-losses. For farmers, it would also mean economic loss, since their land will be completely flooded, which has as consequence lower profits. Also households, the industry and others can have material and economical damage (Pergens, 2017). Since rivers are useful for transportation people saw this as a benefit of living near a river. In the past, a lot of villages are settled down near the rivers. This is still the case nowadays. Therefore it is important to assure that people will live safely. For this research, the focus will lay on river floods.

The Netherlands have a big flood protection system, which has the main goal to protect the inhabitants. In higher economic areas the protection is higher than in areas with less economical value (Wesselink, 2007). In the future, more precipitation peaks will occur. Therefore it is important to know if the protection systems are still strong enough to be capable to resist the water in the rivers. But next to that it is also important to know what happens when a flood occurs in a river. With the use of hydraulic models, these situations can be simulated. In this research, the focus will be on flood modelling in the hinterland. This inundation must be modelled accurately, because decisions, like evacuation strategies and dike strengthening, are made based on the results of the inundation model (Lechowska, 2021).

Figure 1 - Example of a river flood (Crisis.nl, n.d.)

1.2 Problem Description

The problem description will give some more background information about the research subject. First, the problem statement is given (1.2.1). Secondly, the company that commissioned this research project is shown (1.2.2).

1.2.1 Problem Statement

A change in dike policy was made in the last decades in the Netherlands. In the old policy, the focus was on the chance that a flood would occur, but in the new approach, a more integrated approach is chosen to work with which means that also the consequences of a flood on the land behind the dike are taken into account (Nillesen & Kok, 2015).

Hydraulic models can be used to get insight into how the water distributes during flood events in a specific area. To perform the hydraulic simulations, the software Tygron will be used in this study, specific version 2022.7.0.1. Tygron is a suitable software since you can simulate the total water system and thus also can research the impact of an inundation in the area behind the dike. In this way, an integrated dike approach can be applied. This software uses a lot of different parameters to calculate and model floodings, such as topographical features and vegetation. In flood calculations, assumptions are made regarding parameter settings. The effect of these parameter values on the model results requires research. It is not possible for the people who work with the program to give all the parameters the exact value as they are in reality, this has different reasons. To search for all the specific values of parameters costs a lot of time since some parameters are uncertain and others are variable over time. Therefore, a lot of parameter choices are made based on expert-judgements. The effect of the input parameter choices is of interest so that during future calculations better-founded deliberations can be made between, for example, the use of default settings or adjusted parameters, depending on the overflow situation, which leads to more reliable flood models. Hence, it is necessary to look into different input parameters and to do research on the effect of changing these parameters on the model results.

1.2.2 Involved Parties

Aveco de Bondt is the company that commissioned this research project. This is a multidisciplinary engineering company located in the Netherlands. They carry out a lot of different projects in various disciplines. Their goal is to create a positive impact on everyone's living environment. They execute projects in the commission of other companies or governmental institutions (Aveco de Bondt, n.d.). Aveco de Bondt is doing projects for other companies and institutions. For their clients the outcomes of the model must be reliable, this will be achieved when the results are accurate. This research is of interest to everyone who needs to work with flood calculations in software programs or who has an interest in the results of the model.

The Tygron model is used in the past multiple times for stress testing and analyses to find bottlenecks of different precipitation situations, but the execution of flood calculations is relatively new for Aveco the Bondt. The execution of flood calculations is different from stress testing and analysis of bottlenecks. Within this project, the goal is to get insight into the influence of the input parameters on the flood model outcomes, which possibly leads to more accurate flood calculations. With these flood calculations, different things can be done, until now Aveco de Bondt has looked at two aspects: the maximum water depth on ground level and the Schade- en Slachtoffer module of Rijkswaterstaat. Since flood calculations are relatively new in Tygron, more insight into the input parameters is needed.

The Tygron model has different outcomes, two of them are the computed water depth and the flow velocity. With the different outcomes of the Tygron model, such as the water depth and the flow velocity it is possible to give a quantitative view of the flood. When the flood calculations are more accurate Aveco de Bondt and other companies can give a better recommendation for the area that is modelled.

1.3 Research Aim and Questions

This research aims to gain insight into the influence of input parameters on the flood model outcomes. With this insight, the goal is that the input parameters can be more accurately applied to the flood calculations which leads to more reliable model outcomes. This is of big importance since decisions will be made based on the flood calculations. The input parameters taken into account during this research are the roughness coefficient and precipitation. For the outcomes, the focus of this research will be on: maximum water level, maximum flow velocity and maximum inundation extent. An explanation of the choice of these input parameters and outcomes will be given in section 3.2.

A few failure mechanisms exist that can cause river floods. During this research, there will be looked at dike overtopping near rivers. This means that the dike will fail if the water levels are higher than the dike. The water will flow over the dike into the hinterland. Two test areas will be used to determine the differences. For this research, a sloping and a flat test area are of interest. During this research there will be only looked at the inundation at surface level, the water level increase in the waterways will not be taken into account. Next to that, the situation on the riverside will not be integrated, only the water levels of the river will be taken into account. The focus of this research lies on what happens in the hinterland. A schematic representation is given in Figure 2. The research on the input parameters will be done with the use of the Tygron model.

The main research question is formed by the research aim:

- **What is the difference in the influence of input parameters on flood calculation outcomes between a flat and a sloping area?**

To be able to answer the main research question some steps must be executed. First, the test areas must be determined and set up. After that, the values of the input parameters must be decided, to be able to change them. With these parameter values, the sensitivity analysis can be performed. The comparison between the influence of the input parameters on the different areas can be made after the execution of the sensitivity analysis.

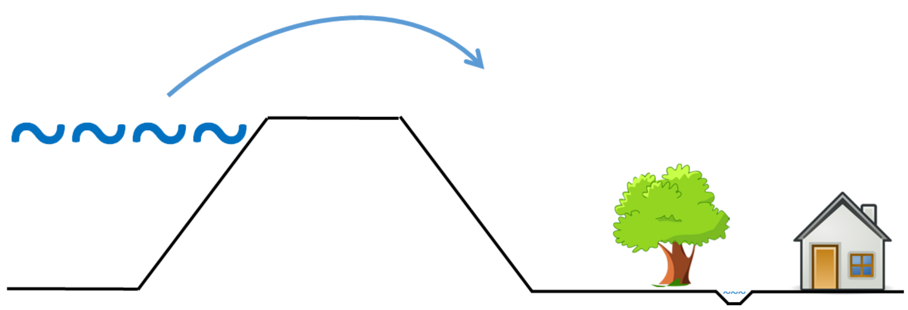


Figure 2 - Schematic representation of dike overtopping and hinterland. During this research, the left side of the dike will not be looked at, but only at what happens on the right side of the dike in the hinterland

1.4 Reading Guide

The remaining of this report exists out of different chapters. First, in chapter 2 the theoretical background will be given. Which exists out of a Tygron part and theory about flood modelling. In chapter 3 the methodology is explained. Here the test areas are defined and the methodology of the sensitivity analysis. The results of the sensitivity analysis are discussed in chapter 4. After that, a discussion is given in chapter 5, the conclusion of this research in chapter 6 and last a recommendation is given in chapter 7. After the recommendation, the references are shown and the appendices are given.

Before reading the rest of the report extra explanations are given upfront to help understand the research.

- Hydrograph
    - In Dutch afvoergolf

- Impoundment
    - In Dutch opstuwing

- Target water levels
    - These are the water levels which are defined by the waterboards. The goal is to always maintain these water levels (in Dutch: streefpeilen).

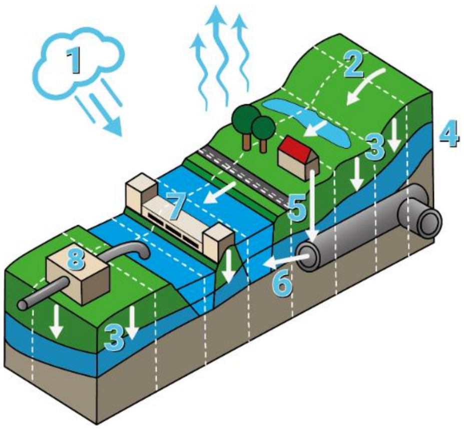
2 Theoretical Background

This chapter is divided into two subjects. First, the background of Tygron will be explained. Secondly, information about flood modelling is given.

2.1 Tygron

The program which will be used during this research is Tygron Geodesign Platform, hereafter referred to as Tygron. This program is a robust and open program developed to change and create a better set-up of work processes. The software can be used for complex projects with an enormous amount of data. With this program is it easier to analyse and visualize the data (Tygron, n.d.). Tygron can be used for different types of projects, in this research Tygron will be used for flood modelling.

Flood modelling is part of the Water Module of Tygron. The Water Module performs many hydrological calculations to make a simulation of how the water will flow. The water equations are based on the 2-D Saint-Venant equations. Tygron is a suitable program for flood modelling since the complete water system in the hinterland is taken into account (Tygron Support, 2021c). In Figure 3 a simplified picture is given of a general water system, which is used in the Water Module.



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

Figure 3 - Water Module Tygron (Tygron Support, 2021c)

Tygron works with rectangular model domains, but it is possible to work with a calculation area. This can be applied for example when a project area is not rectangular. When working with a calculation area, the calculations will be performed on a selection of the model. Also, it is not necessary to impose additional data for the area outside the calculation area, such as weirs and culverts. Next to that, since only calculations are executed within the calculation area it reduces the total calculation time. Every project area in Tygron is discretized by a two-dimensional (2D) grid. The smallest possible grid size in Tygron is 0.5m x 0.5m. A smaller grid size leads to more calculation time, than a bigger grid size. Therefore, it is important to look for each project which grid size is needed for accurate results (Tygron Support, 2021c). In Figure 4 a photo is given of a flood, in Figure 5 this same flood is modelled showing what flood modelling looks like in Tygron.

Figure 4 - Flood Reeuwijk (van Dijk, 2021)

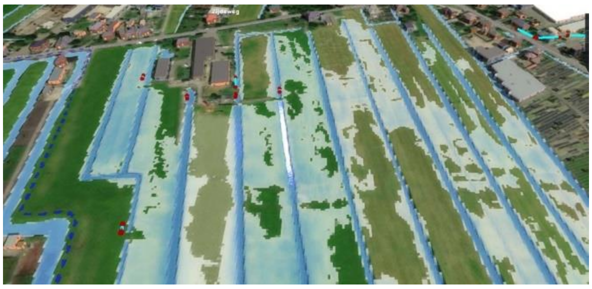


Figure 5 - Modelling flood Reeuwijk Tygron (van Dijk, 2021)

When setting up a flood model in Tygron a few steps must be taken to create accurate simulations. The first step is that Tygron makes a digital twin of the project location. This is done with the use of available open data. The AHN (Digital elevation model), BGT (Basic registration major topography) and BAG (Basic registration addresses and buildings) are three of the sources which are used to create a 3D map of the project area. More information about the open data in Tygron can be found at Open data Sources Tygron.

The model could be improved by adding location-specific data. This can be done by adding data to the model such as data about the weirs, culverts and water levels. Tygron works with a boundary system. This means that no water can leave and enter the model domain by default. When this is not wanted, inflow and outflow boundary conditions must be implemented at the upstream and downstream locations, respectively, to ensure the correct discharge within the river is modelled.

2.2 Flood Modelling

A lot of research on modelling river floods has been done in previous decennia. For this research, it is important to get more knowledge about which parameters are sensitive to flood model outcomes and how model outcomes can be compared.

Merwade et al. (2008) executed research about uncertainty in flood inundation mapping. They found that uncertainty in flood inundation mapping is created by the uncertainties in terrain elevations, which was confirmed by Hesselink et al. (2003) and Bajabaa et al. (2014). The discharge values are based on other models and not exactly the reality. Also, it affects the water surface elevation gained by the hydraulic models. And lastly, the terrain elevations affect the horizontal extent of flood inundation maps. The hydraulic models are very sensitive to geometric description, like the number of cross-sections, bottom slope, model parameters and the structures in the area (Merwade et al., 2008).

Bajabaa et al. (2014) found during research on flood hazard mapping that rainfall is one of the essential hydrological elements for the mapping of floods in basic systems. According to Merwade et al. (2008), there is many spatial and temporal variability of hydrologic processes, like precipitation, evapotranspiration and infiltration. When just one average value is given for this, this leads to uncertainty in the hydrologic process

Hesselink et al. (2003) found that the uncertainties in the friction factor had a significant influence on the simulation results, which was confirmed by Yu & Coulthard (2015) and Merwade et al. (2008). Next to that, they found that different land surface covers have a lot of variations in the hydraulic roughness coefficients. This uncertainty in de roughness coefficient is caused by seasonal and annual variation. When the roughness coefficient is increasing the velocity of the inundation front will decrease during the process.

Dutta & Nakayama (2009) researched the effects of spatial grid resolution on river flows and surface inundation simulation. They discovered that the simulation results are highly sensitive to the spatial grid size. The simulated river peak flow and surface inundation results change significantly when changing the grid size. This is because the topographic parameters change in the models when the grid size is different. Therefore, the grid size must be chosen in a way that the topographic features are as closest to reality as possible within other limitations for example running time of the model.

Concluding this sub chapter the following aspects are important for flood modelling: terrain elevations, grid size, precipitation and the roughness factor. The terrain elevations are taken into account since the test areas which will be compared are flat and sloping (3.1.1). The influence of the grid size is incorporated in section 3.1.2. The precipitation and the roughness factor are the input parameters which will be adapted during this research, to see if a difference in the influence of these parameters between the test areas exists (3.2).

3 Methodology

The methodology is divided into two subchapters. First, the area development is explained (3.1). After that, the methodology of the sensitivity analysis is provided (3.2). In Figure 6, a schematic representation of the methodology is given. The methodology is divided into steps which are needed to answer the main question.

The first part of the research will be the preparation, which exists out making the model in Tygron. Next, the values will be given to the input parameters and added to the Tygron model. After that, the sensitivity analysis (S.A) will be performed and the outcomes will be analysed. As of last a conclusion will be made which answers the main question.

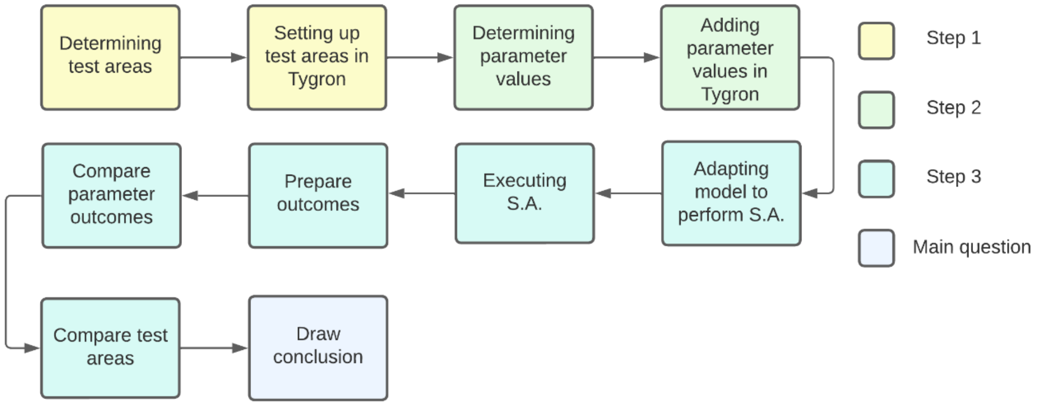


Figure 6 - Schematic representation methodology (sensitivity analysis = S.A)

3.1 Area Development

3.1.1 Area Description

This research uses two different test areas to determine the difference in the influence of the input parameters on the areas. The topographical features will be examined in these test areas. To be able to compare these test areas it is of importance that there is only one main differentiating factor between the test areas. The main difference between the two areas will be the slope of the area. The first test area will be a flat rural area, like a polder for example. The second test area will be rural and sloping. An area is rural when the address's density is below 1500 per square kilometre (CBS, n.d.). This relates to the terrain elevations as mentioned as an important parameter in section 2.2 by Merwade et al. (2008). One of the input parameters that will be changed is the roughness coefficient. Therefore, different land-use types must be available in the test area.

For the rural and flat area, the Polder Middelburg en Tempelpolder (MT-Polder) is selected as a case study. The second case study, rural and sloping, is located near Vortum-Mullem (Figure 7). The MT-Polder is the responsibility of waterboard Hoogheemraadschap van Rijnland. Waterboard Aa en Maas is responsible for the location near Vortum Mullem. According to KadastraleKaart.com (n.d.), both study areas are rural. Based on AHN (Actueel Hoogtebestand Nederland, ahn.nl) it is known that these areas are flat and sloping. The heightmaps of the test areas are shown in Figure 8 and Figure 9.

With the option 'Kaartviewer' on risicokaart.nl, the inundation maps of the Netherlands are found. This map is used to find out if the areas are vulnerable to floods, which is of importance for this study. For the test areas, it was imported that waterways are existing in the areas since it will inundate from a waterway and the total water system is taken into account in the hinterland. The waterway maps are shown in Figure 10 and Figure 11.

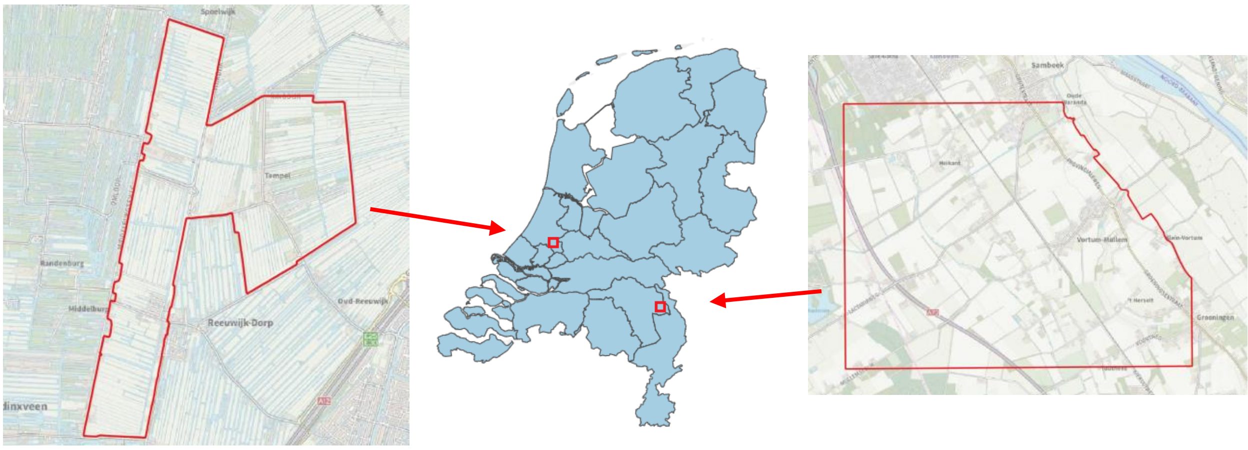


Figure 7 - Locations test areas in the Netherlands, left MT-Polder and right Vortum Mullem (Kamsma, 2019)

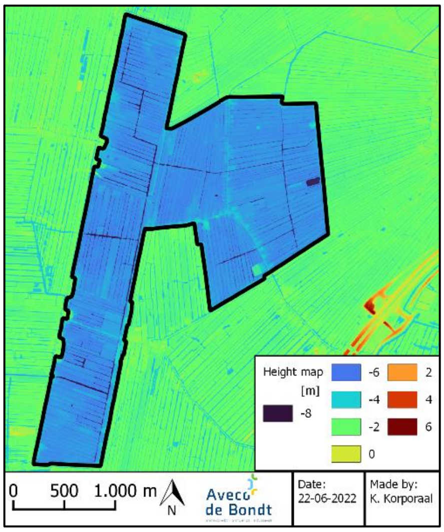


Figure 8 - Height map MT-Polder

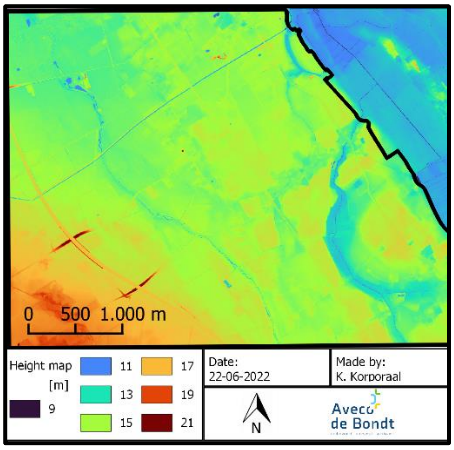


Figure 9 - Height map Vortum Mullem

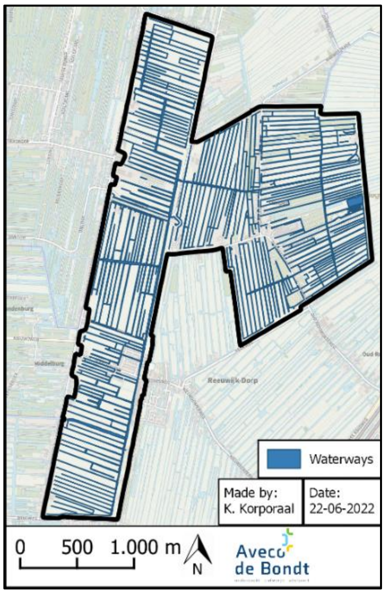


Figure 10 - Waterways MT-Polder

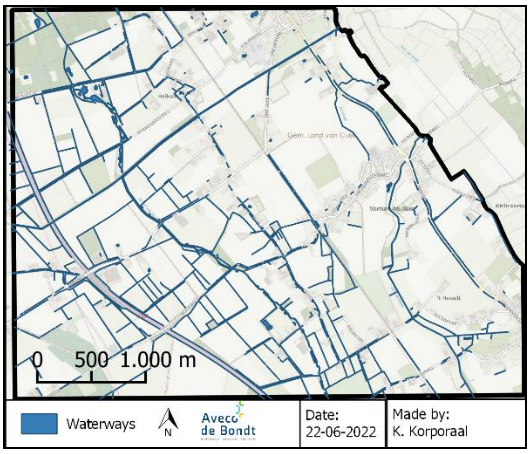


Figure 11 - Waterways MT-Polder

3.1.2 Model Description

Flat area: MT-Polder

Two models are created in Tygron for these test areas. For the MT-Polder data about weirs, culverts, target water levels and pumping stations was made available by the waterboard Hoogheemraadschap van Rijnland. On the location of the dike, the water levels were adjusted to a water level that dike overtopping will occur at some locations. So the water levels at the dike side will have a steady-state during the simulation and it will be a continuously overtopping situation. These water levels are set up in Tygron with the use of water areas. The simulation time will be three hours for the model of the MT-Polder.

Sloping area: Vortum Mullem

For the rural and sloping area, the data for the weirs and culverts were made available by waterboard Aa en Maas. The rural and sloping area will be inundated with water from the river Meuse. In this area, no target water levels are determined. Therefore, initial water levels one meter below surface level at the locations of the waterways were chosen to work with.

At the location of the boundary of the winter bed of the river Meuse the water levels were set up. For this area varying water levels have been chosen, this since the water levels in rivers are dependent on hydrographs. The water levels are set up with a hydrograph which will occur once in the 3000 years, according to the year 2075 based on the WAQUA model, to assure that dike overtopping will occur and that there is enough inundation in the hinterland to be able to see the influence of the change in parameter values. The data from the WAQUA model is interpolated over locations within 100 meters distance. Every 100 meters an inlet is created on the edge of the winter bed of the river Meuse. At these locations, the water levels are set up as inlets with interpolated data. Inlets are different from water areas which will be used in the MT-Polder. The use of water areas is the standard way of setting up the water levels in Tygron. In the model of Vortum Mullem varying water levels will be set up, this is not possible with the use of water areas in Tygron. Water areas can only be used when every area has one water depth for the whole simulation.

Inlets are points where water can flow in and out of the model if the right conditions are available (Tygron Support, 2021a). For the inlets a water height is given, the water will only flow into the model when a difference in water height occurs and when the potential difference which is needed to let the water flow is reached. The water will flow out of the model when the water depths of the inlets are lower than the water depth in the hinterland (Tygron Support, 2021b).

The hydrograph used for this model does not cause at timestep zero directly inundation. After some time the flood will start, this can differ per location near the dike. For example inlet 96 is visible in Figure 12.

Overlay and grid size

An option to add the data about weirs, culverts and pumps to the model is by adding an overlay. For this research project, this is the rainfall overlay. In this overlay, the location-specific data can be added. Firstly, the precipitation is added. The values of the precipitation will be discussed in section 3.2.3. After that, the initial water levels can be set up. Next are the weirs, culverts and pumps. For the grid size, it must be chosen in a way that the topographic features are sufficiently captured such that the flood patterns are modelled accurately (section 2.2). A grid size of 1mx1m is used for the models. In this way, the topographical features are still sufficiently captured while ensuring reasonable computation times.

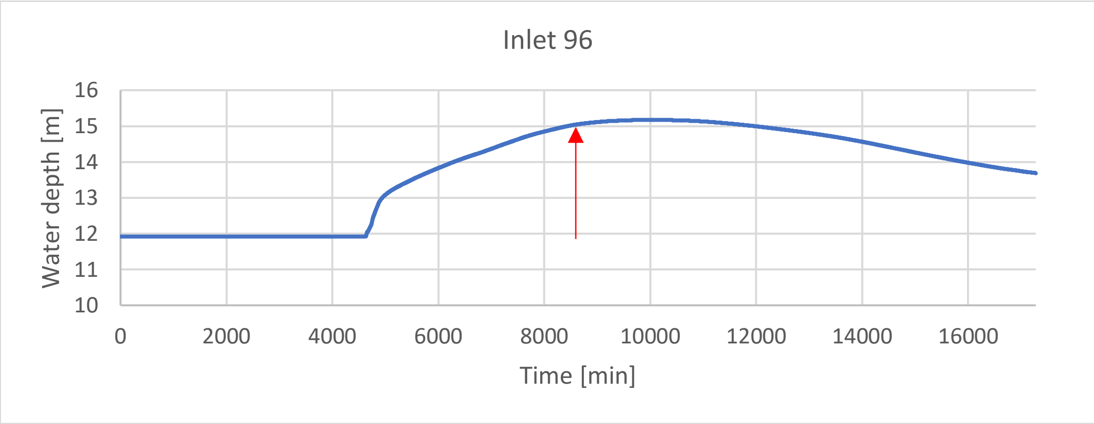


Figure 12 - Inlet 96 water depth wave Vortum Mullem (red arrow is at t=8640 min for precipitation)

3.2 Sensitivity Analysis

A sensitivity analysis is a study on how the uncertainty in the model outputs is related to the uncertainty in the model inputs. For this research, it is important to know how the input parameters act individually on the outcomes, but more than one parameter will be examined. Therefore, a method will be chosen based on global sensitivity analysis (Morio, 2011). For the sampling of parameters, the 'one-at-a-time' method will be used. This method will change one input parameter for each analysis. The main advantage of the 'one-at-a-time' method is that the influence of that specific parameter can be found (Saltelli et al., 2008).

Different parameters will be examined during this research. From the literature research in section 2.2, it became clear that it is important to look into the precipitation and the roughness factor.

3.2.1 Reference Situation

To examine the influence of the input parameters a reference situation must be defined. The situations with changed input parameters will be compared with the reference situation. Both test areas will have a reference situation. The reference situation is the model as how it is after setting up the test areas in Tygron, with the water levels needed for the flood to occur. So, all the location-specific data is added and the only difference with the other models is that the input parameters have their default values. In the reference model, no precipitation will be added and the default manning values will be applied. The default Manning values in Tygron are the same as the normal values of Chow (1959).

3.2.2 Roughness Coefficient

The roughness coefficient influences the flow velocity. When the roughness coefficient increases this results in a lower flow velocity (Lau & Afshar, 2013). Therefore, it is important to investigate how much this input parameter affects the model outcomes. In Tygron the Manning roughness coefficient is used. To determine the bandwidth of this parameter value the table of Chow (1959) will be used. In this table, the roughness coefficients are given for each land use type with a minimum and maximum value (Chow, 1959). Every object was assigned a Manning value. These objects can be summarized into six categories: buildings, cultivated areas, pasture high grass, pasture low grass, pavement areas and trees. In Table 1 the Manning values according to these categories can be found. The minimum, normal and maximum values are based on Chow (1959).

Table 1 – Manning's values categories (Chow, 1959)

Category	Minimum	Default Tygron	Maximum
Buildings	0.011	0.013	0.015
Cultivated areas	0.030	0.040	0.050
Pasture high grass	0.03	0.035	0.050
Pasture short grass	0.025	0.030	0.035
Pavement areas	0.012	0.015	0.017
Trees	0.070	0.100	0.160

The simulation will be executed two times. Each time, the Manning value will be adapted for all categories. This means that it is not possible to draw conclusions about individual categories. The two versions will be:

- The minimum values
- The maximum values

3.2.3 Precipitation

During a river flood, precipitation may occur. When it rains during a river flood the total water volume in the hinterland can increase. The amount of extra water is dependent on the type of rainfall. It is not clear yet if rainfall has a significant influence on the flood model outcomes. Therefore, the effect of precipitation on the model outcomes will be evaluated. This will be done by investigating multiple types of rainfall. The rainfall events will be different in duration, intensity and moment in time that they take place. The rain events that will be used are:

- Short and high-intensity rainfall
- Long time and low-intensity rainfall
- Extreme situation

The short and high-intensity rainfall will be a rain event which takes one hour and will have a total rainfall of 40 mm. This short rainfall event has a return period of 25 years (Beersma et al., 2019). The next event is the long-time rainfall with low intensity. A 48 hours during rainfall is chosen with the same return period as the short and high-intensity rainfall. According to Beersma et al. (2019), this means that the rainfall will be a total of 89 mm. The last rain event is extreme rainfall. The prediction is that extreme rainfall will occur more in the further than currently, when calculating the extreme conditions the predicted values of 2050 will be used. For this rainfall event, the climate rainfall of 70 mm during one hour will be chosen. This rainfall will have a return period of 100 years in 2050 (Kennisportaal Klimaatadaptatie, n.d.).

The rainfall events will take place at two different moments. Between the two test areas, there is a difference in moments when the rainfall will start. For Vortum Mullem they will start at t=0 min and t=8640 min. The t=0 min rainfall starts before the inundation starts and the t=8640 min rainfall will start before the peak of the flood. Figure 12 shows with a red arrow where t=8640 min is on the wave, also the location of the peak of the flood is visible.

For the MT-Polder the rainfall will start at t=0 min and t=60 min, where t=0 min starts when the flood and the simulation start and the t=60 mm rainfall will start an hour after the flood did start. It was not possible to let the rainfall start before the flood since the flood starts directly at t=0 min in the model. The 48 rainfall will not be simulated for the MT-Polder. For a polder like the MT-Polder, it is not likely that a flood takes 48 hours since pumping stations are available to pump the water out.

In Appendix 1 the figures for the different types of rainfalls are given. All the different types of rainfalls for both areas are uniformly distributed. In Table 2 an overview is given of the rain events and in Table 3 a scheme of which situations will be compared is given.

Table 2 - Rain events (Beersma et al., 2019; Kennisportaal Klimaatadaptatie, n.d.)

Rain event	Duration (d) (min)	Total amount of water (a) (mm)	Intensity (mm/hour)	Return period (1/n years)	Return period in 2050 (1/n years)	Vortum Mullem (t) (starting time in min)	MT-Polder (t) (starting time in min)
Short and high intensity	60	40	40	25	Unknown	T=& T=8640	T=0 & T=60
Extreme situation	60	70	70	200	100	T=0 & T=8640	T=0 & T=60
Long and low intensity	2880	89	1.85	25	Unknown	T=0 & T=8640	x

Table 3 - Scheme precipitation

Subject	Rain type 1	Rain type 2	Amount of times
Intensity	Reference situation	With all types of precipitation	Both moments
	40 mm	70 mm	Both moments
Short/high intensity vs long/low intensity	40 mm	89 mm	Both moments (Not for MT-Polder)
Moment in time	Type x on moment 1	Type x on moment 2	All types

3.2.4 Model Outcomes

The outcomes for this research are chosen since they are given a good view of a flood. And the outcomes between different situations can be easily compared since they are all maximum values. Therefore, for this research the following outcomes will be taken into account:

- Maximum water level
- Maximum flow velocity
- Maximum inundation extent

3.2.5 Data Analysis

The outcomes of the flood calculations are given according to the 2D grid. For all the outcomes except the maximum inundation extent, the values are given by Tygron. This research will only look at inundation at surface level and not at the effect on waterways. Therefore, all the results of the waterways are removed from the outcomes and also from the visualization. For each input parameter, different model outcomes are investigated related to the reference situation. When comparing two flood situations, the outcomes are subtracted from each other. This will be done for the water depth and the maximum flow velocity. In this way, the absolute difference per grid cell can be found. Also, the relative differences in terms of percentages will be examined.

Next to that, the difference in maximum water depth and maximum flow velocity are quantified for the different situations. This is done by dividing the model results in different categories. For instance, for the maximum water depth these categories are 0-0.10 m, 0.1-0.25 m, 0.25-0.75 m and >0.75 m. After determining the area per category, these areas are expressed in percentage of the total area. To compare the results of the different situations, the percentage change between the results and the reference situation is determined, such that a comparison with the reference situation can be made.

The maximum inundation extents will be determined based on the computed water levels. Every grid cell which has reached an increase of one-centimetre water is determined as inundation in this research, except for the cells in the waterways, these are not taken into account as inundation. In this way, it can be calculated which percentage of the modelled area is inundated. This percentage is called the maximum inundation extent. The maximum inundation extent of the different situations can be compared with the maximum inundation extent of the reference model.

4 Results

After setting up the model in Tygron, the models are modified to perform the sensitivity analysis. For the analysis, three outcomes will be used: maximum water depth, maximum flow velocity and maximum inundation extent. Hereafter referred to as: water depth, flow velocity and inundation extent. The water depth and flow velocity of the reference situation of the MT Polder and Vortum Mullem are given in Figure 13 and Figure 14. The outcomes of the other situations for Vortum Mullem in Appendix 2 and for the MT-polder are given in Appendix 3. With the simulation outcomes, the next step of the sensitivity analysis is executed, which is determining the absolute and relative differences between the different situations. The outcomes of these calculations are given in sections 4.1 and 4.2.

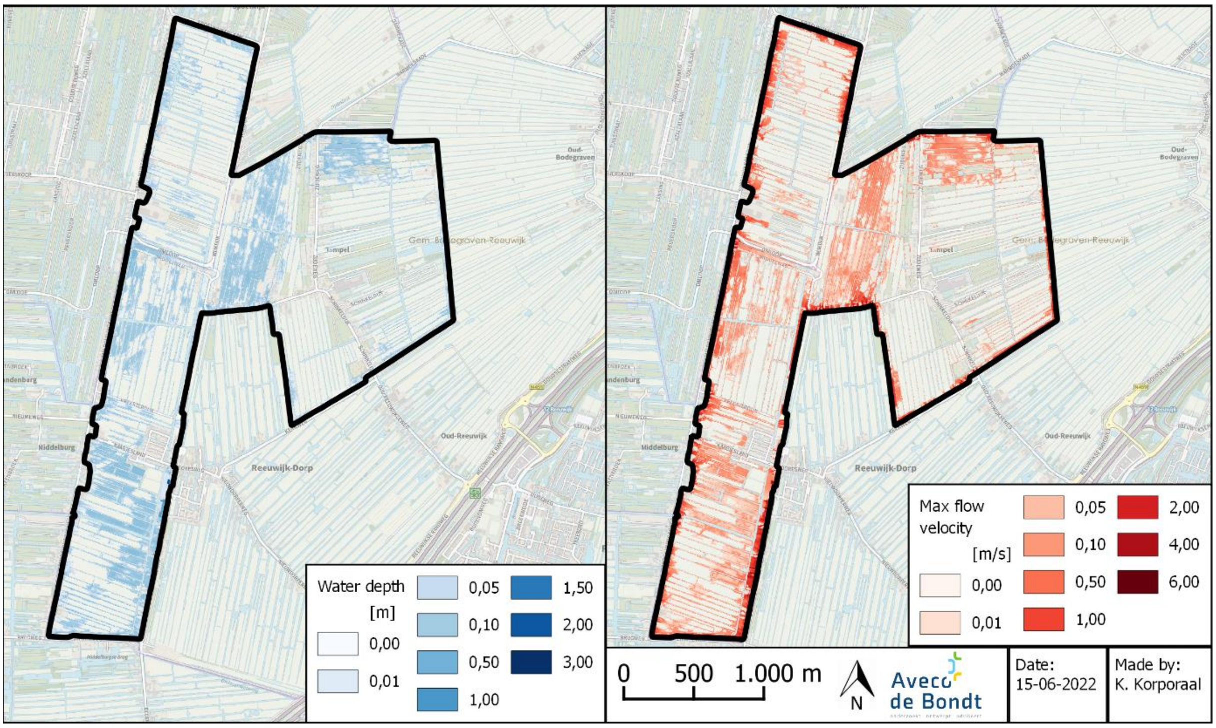


Figure 13 - Results reference situation MT-Polder with left the maximum water depths and right the maximum flow velocities.

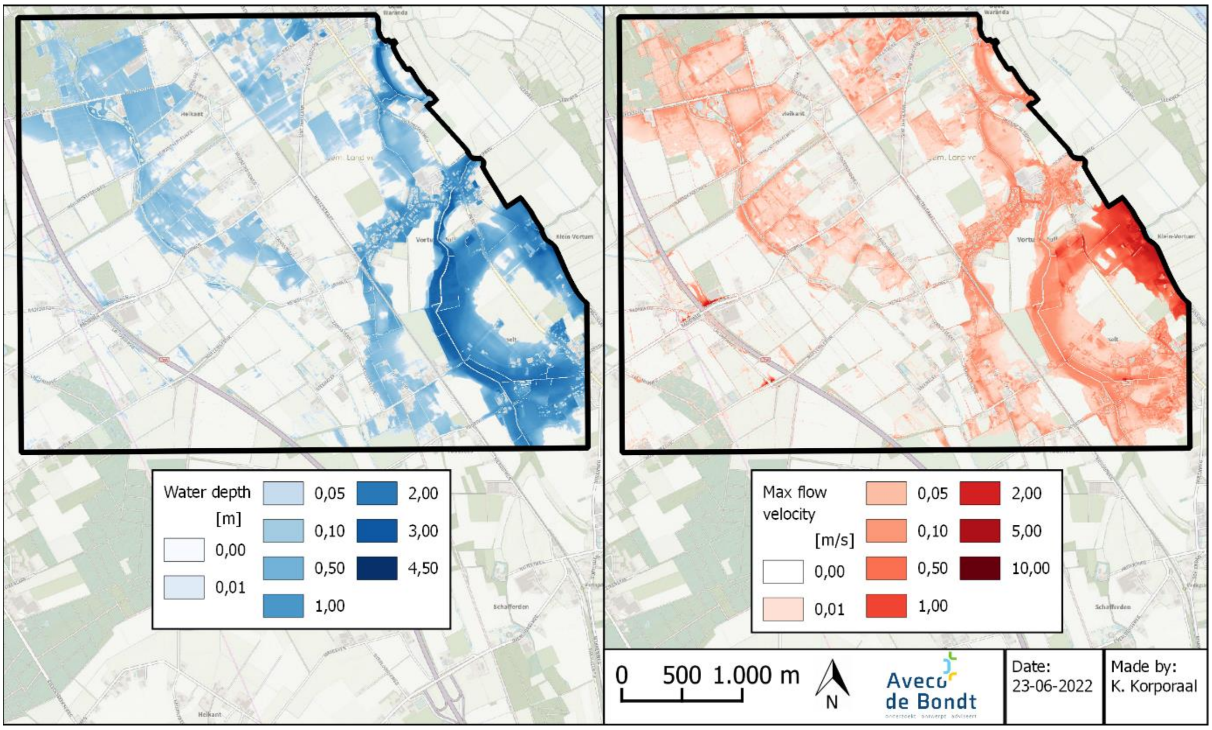


Figure 14 – Results reference situation Vortum Mullem with left the maximum water depths and right the maximum flow velocities.

4.1 Precipitation

The precipitation results can be divided into three subjects: intensity, short/high intensity vs long/low intensity and moment in time. In Table 4 the inundation extents of the situations compared in this chapter are shown. In Table 15 in Appendix 4 an overview is made which situations are compared with each other during this research for the precipitation input parameter.

Table 4 - Inundation extents precipitation situations

Vortum Mullem	Inundation extent	MT-polder	Inundation extent
Reference situation	34%	**Reference situation**	33%
a=40 mm, t=0 min, d=60 min	64%	**a=40mm, t=0 min, d=60 min**	63%
a=40 mm, t=8640 min, d=60 min	64%	**a=40 mm, t=60 mm, d=60 min**	59%
a=70 mm, t=0 min, d=60 min	72%	**a=70 mm, t=0 mm, d=60 min**	77%
a=70 mm, t=8640 min, d=60 min	74%	**a=70 mm, t=60 min, d=60 min**	74%
a=89 mm, t=0 min, d=2880 min	54%		
a=89 mm, t=8640 min, d=2880 min	56%		

4.1.1 Precipitation Intensity

Sloping area: Vortum Mullem

When adding rainfall to Vortum Mullem the water depth is increasing compared to the reference situation without precipitation. This is a consequence of the rainfall since rainfall increases the total amount of water occurring in the area. Since the area does not increase and the total amount of water increases the water depths must also increase.

In the reference situation, the inundation did not cover the complete area, but since the precipitation is covering the whole area more locations will be inundated. According to the data in Table 4, it is known that the inundation extent increases when precipitation is added to the model. Therefore, an increase in the water depths did arise at the locations where the reference version did not inundate.

The flow velocities in the situations with precipitation are increasing in comparison with the reference situation when taking into account the absolute differences. The relative differences give fewer locations where the flow velocity increases. This can be explained by the fact that the flow velocities at some locations are not increasing more than 1% and thus it is not shown as a relative increase since the difference is so small. The flow velocity increases a lot relatively seen at a few locations. This can be explained since those are the locations which were not inundated during the reference simulation and thus no flow velocity did occur. In the precipitation situation there is inundation and thus a flow velocity. When comparing these locations relatively seen there is a high increase in flow velocities, but seen at the absolute values the flow velocities are not very high. In general, the increase in flow velocities can be explained since the total volume of water is increased and more water will be transported which leads to higher flow velocities.

When the intensity of precipitation increases the water depths, flow velocities and inundation extents are increasing further during this research. Due to the higher intensity, there will be more water which leads to higher water depths. The inundation extents increases further since inundation is only taken into account when there is more than one centimetre of water on the surface, due to the higher intensity more locations will experience a water depth of more than one centimetre and thus the inundation extent increases.

The water depths increase relatively less at the higher located areas such as roads than at lower-laying areas. This can be explained by the fact that water will flow to lower parts of the model, which is caused by gravity. Therefore, the water depths will increase more at the lower parts of the model than at the higher locations. This occurs in all situations. The height map of this area is shown in Figure 9.

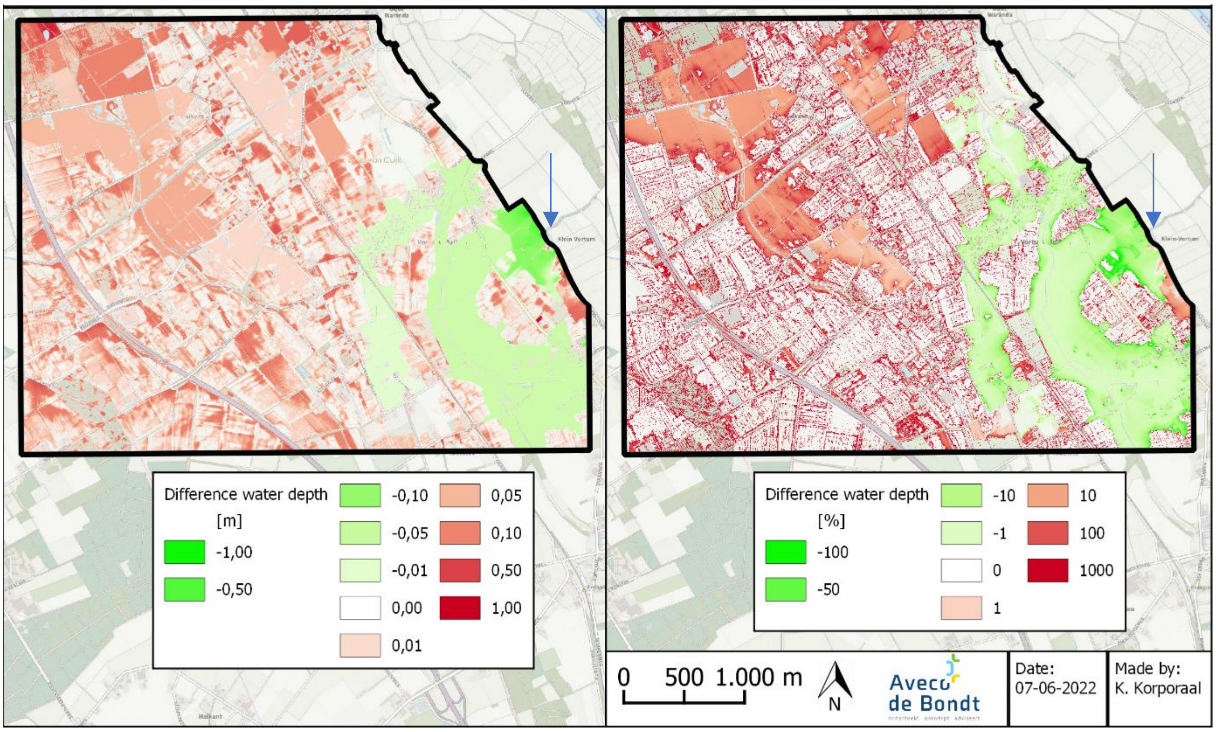


Figure 15 - Water depth differences for the precipitation situation a=40 mm, t=8640 min, d=60 min in comparison with the reference situation without precipitation at Vortum Mullem. With on the left the absolute differences and on the right the relative differences. Blue arrows are inlet 96.

When there is rainfall the water depths are decreasing at the green location in Figure 15. This is at a location which is low located, it is near a waterway and close to the location where dike overtopping occurs. This decrease cannot be explained from a physical point of view. The water depths near the dike overtopping are lower than the water height which is given to the inlets. The expectation would be that the water will flow into the area since the water level in the hinterland is lower than the water level of the river.

The different discharge values of the inputs in the water balance are investigated. A big difference did arise between the values of inlet 96 (Figure 15) for the reference situation and the precipitation situation a=40 mm, t=8640 min and d=60 min (Table 5). Unfortunately, these are net values over the whole simulation time. This means that the value is calculated by the inflow minus the outflow over the total input during the whole simulation. The expectation is that this difference is caused since less water will flow out of the river due to the precipitation volume. But since it is a net value it also could be that more water will flow back into the river due to the precipitation instead of less water out of the river. Therefore it cannot be said with certainty that less water will flow into the area. This location has multiple times different values compared to the rest of the area. Since there is no explanation for this behaviour, this location will be left aside for the rest of the results. Further research is needed for this outcome. This has as consequence that no quantification will be given for the water depths and flow velocities since the quantification is based on the whole area, as explained in section 3.2.5.

Table 5 - Inlet 96 water balance

	Inlet 96
Reference situation	141.545.056 m3
a=40 mm, t=8640 min, d=60 min	96.575.704 m3

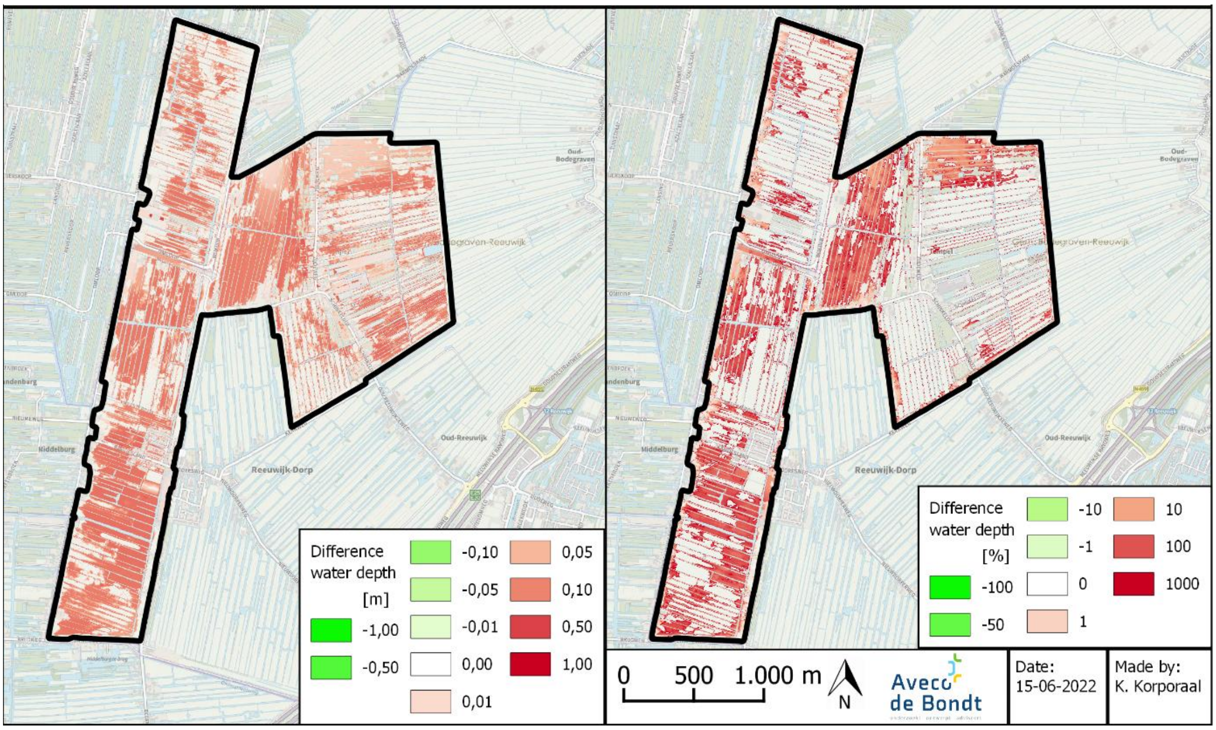


Figure 16 - Water depth differences for the precipitation situation a=40 mm, t=0 min, d=60 min in comparison with the reference situation without precipitation at MT-Polder. With on the left the absolute differences and on the right the relative differences.

Flat area: MT-Polder

In Figure 16 the precipitation situation a=40 mm, t=0 min and d=60 min is compared with the reference situation. The results of the other precipitation situations compared with the reference situation are in Appendix 4. In Table 7 the differences in flow velocity in comparison with the reference situation are given, it can be concluded that by adding precipitation to the model the flow velocities are increasing. For every comparison, it is seen that the water depths (Table 6), inundation extents and flow velocity are increasing. The high increases in flow velocities occur for the same reason as at Vortum Mullem. For the MT-Polder the same trend is visible as for Vortum Mullem. When adding or increasing precipitation the water depths, flow velocities and inundation extents are increasing.

Table 6 - Differences in water depth for the precipitation situations in comparison with the reference situation for MT-Polder

Water depth (m)	**<0.10**	**0.10-0.25**	**0.25-0.75**	**>0.75**
a=40mm, t=0 min, d=60 min	-26.05%	124.15%	310.59%	128.57%
a=40 mm, t=60 mm, d=60 min	-21.21%	108.95%	222.66%	91.43%
a=70 mm, t=0 mm, d=60 min	-49.04%	172.62%	812.37%	697.14%
a=70 mm, t=60 min, d=60 min	-41.07%	167.09%	596.28%	425.71%

Table 7 - Differences in flow velocity for the precipitation situations in comparison with the reference situation for MT-Polder

Flow velocity (m/s)	**<0.25**	**0.25-0.50**	**0.50-1**	**>1**
a=40mm, t=0 min, d=60 min	-1.4%	29.9%	3.5%	0.6%
a=40 mm, t=60 mm, d=60 min	-0.8%	17.6%	1.9%	0.1%
a=70 mm, t=0 mm, d=60 min	-3.1%	66.2%	7.4%	1.2%
a=70 mm, t=60 min, d=60 min	-2.0%	44.1%	3.3%	0.3%

Comparison
For both Vortum Mullem and the MT-Polder, there is an increase in water depths, inundation extents and flow velocities when precipitation is added to the model. The increase of intensity has more impact on the MT-Polder than on Vortum Mullem. This is since the total amount of water in the area of the MT-Polder is less, so the amount of precipitation is a higher percentage of the total amount of water in the MT-Polder than at Vortum Mullem.

4.1.2 Short and High Intensity vs Long and Low Intensity

For this comparison, there is a difference in duration and intensity of the precipitation at the sloping area Vortum Mullem. The rain events have the same return period as mentioned in section 3.2.3. At the higher parts of the area (Figure 9), the water depths of the precipitation situation a=40, t=8640 min, d=60 min are higher (Figure 17). This is the case since in the precipitation situation a=40, t=8640 min, d=60 min more water is falling at once and the moments where the water depths are occurring at the higher parts of the area are just after the rainfall.

The locations where there is an increase in water depth visible for the precipitation situation a=80, t=8640 min, d=2880 min are near the spillways of the bigger waterways in the area. The precipitation situation a=80, t=8640 min, d=2880 min has a higher volume of rainwater than the precipitation situation a=40, t=8640 min, d=60 min. The surroundings of the waterways cannot handle that extra water and thus the water depths will increase. Also, the inundation extent is higher for the precipitation situation a=40, t=8640 min, d=60 min (64% in comparison with 54%). It is called inundation when there is more than one centimetre of water on the surface. Since the 40 mm falls in one hour it is more likely that this threshold is reached.

The flow velocity is higher for the precipitation situation a=40, t=8640 min, d=60 min. Since the water falls in one hour there is a lot of water to transport in a short time. For the precipitation situation a=80, t=8640 min, d=2880 min the water needs more time to fall, so there will be less water at once to transport. Therefore, the flow velocity of the precipitation situation a=40, t=8640 min, d=60 min is higher.

So, the flow velocity and the inundation extents are higher for a short rainfall in comparison with a long time during rainfall. The influence on the water depths is location-dependent. At high locations, the short rainfall has higher water depths and near waterways, the long rainfall has higher water depths.

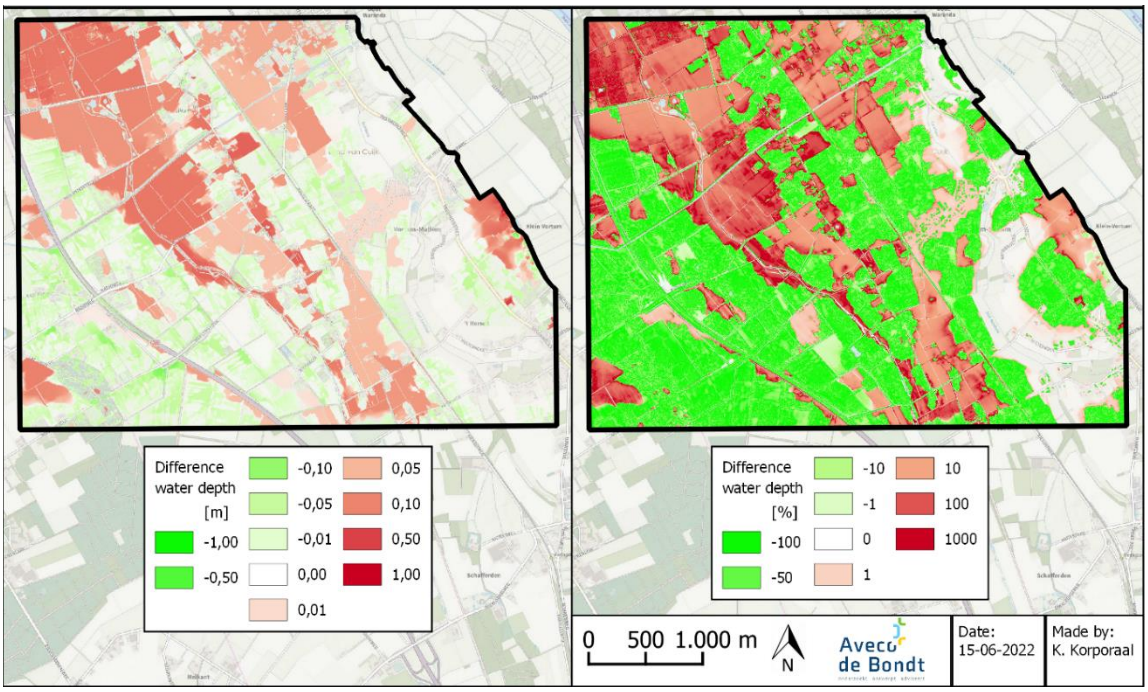


Figure 17 – Water depth differences for the precipitation situation a=89 mm, t=8640 min, d=2880 min in comparison with the precipitation situation a=40 mm, t=8640 min, d=60 min at Vortum Mullem. With on the left the absolute differences and on the right the relative differences.

4.1.3 Moment in Time

Sloping area: Vortum Mullem

For Vortum Mullem there are two moments in time for which the precipitation is added to the model, this is at t=0 min and t=8640 min. An increase in water depths is visible when the precipitation begins at t=8640 min instead of t=0 min, this increase is visible for all rain types simulate in this research. At that moment there is a flood going on and extra water is added, since it is near the peak the maximum heights are increased. At t=0 min the precipitation is not added to the flood and can be transported in the area before the flood reaches its maximum height. Therefore, the precipitation has more influence when it falls near the peak of the flood. In some places, the situations with starting time t=0 min have higher values, absolute seen these are very small but relatively they are more visible (Figure 18). This could be the case since the water is divided differently. At the locations where higher differences occur the ground level is lower compared to locations where small differences occur.

The maximum flow velocities are higher at the locations where the water depths are increasing. Since the water depths are increasing, more water needs to be transported which has as consequence higher flow velocities. For the inundation extents, small differences did arise, which can be explained since higher flow velocities occur which has as a consequence that the water will travel a bit further. The inundation extent of the rain events beginning at t=8640 is a bit higher. But these differences are small. So, in general, the water depths, the flow velocity and the inundation extent are increasing when adding precipitation during the flood.

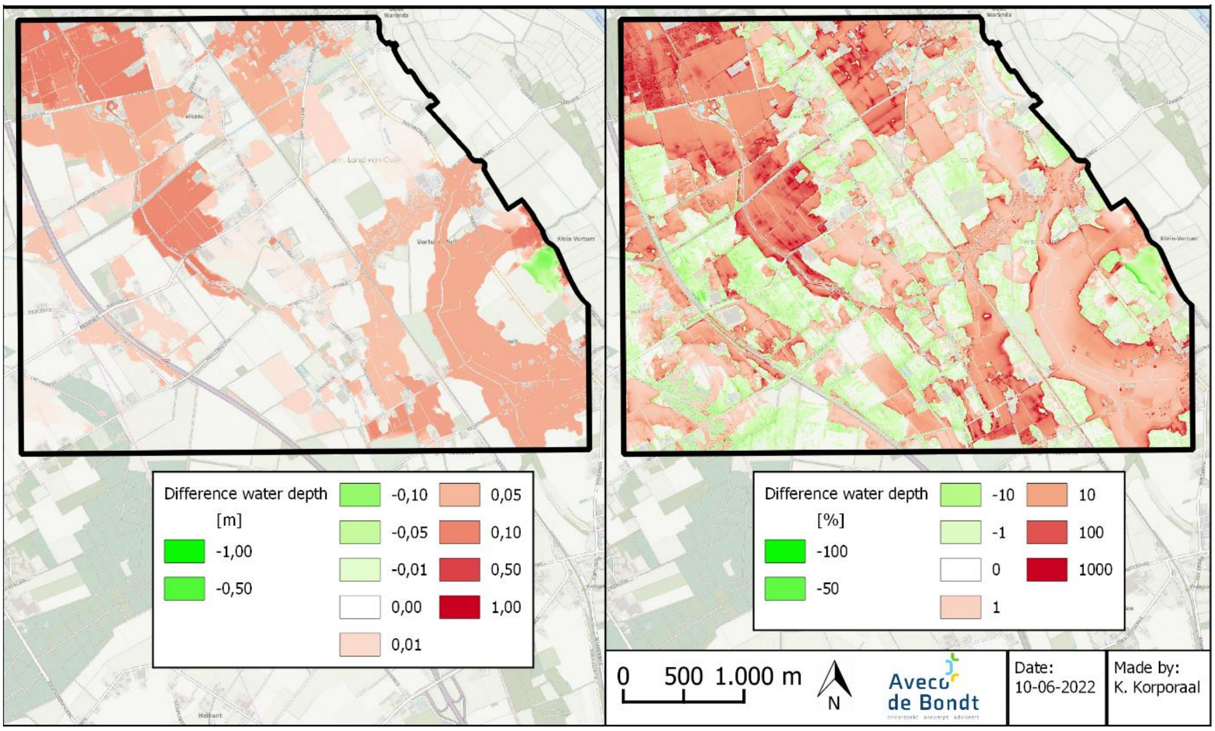


Figure 18 - Water depth differences for the precipitation situation a=70 mm, t=8640 min, d=60 min in comparison with the precipitation situation a=70 mm, t=0 min, d=60 min at Vortum Mullem. With on the left the absolute differences and on the right the relative differences.

Flat area: MT-Polder

The two moments that the precipitation can take place in the model of the MT-Polder are at t=0 min and t=60 min. In general, the flow velocities of the precipitation situations at t=0 min are higher (Table 8), an example of this is shown in Figure 19. The highest flow velocities will occur when the flooding starts, at that moment the height differences between the water at the dike side and the water in the MT-Polder are the biggest so the highest flow velocities can occur. When there is even more water due to the precipitation, which starts also at t=0 min, higher flow velocities will occur. When the precipitation at t=60 min starts there is already at most places some water and thus less high difference between locations with water. So the precipitation will have the most influence on the flow velocity when starting at t=0 min.

Table 8 - Differences in flow velocity for the precipitation situations at t=60 min in comparison with the precipitation situations at t=0 min for MT-Polder

Flow velocity (m/s)	<0.25	0.25-0.50	0.50-1	>1
a=40mm, t=60 min, d=60 min	0.60%	-9.44%	-1.57%	-0.50%
a=70mm, t=60 min, d=60 min	1.14%	-13.31%	-3.77%	-0.95%

Between the inundation extents, there is a small difference. The inundation extents of the situation at t=0 precipitation are a bit higher (Table 4). Since the flow velocity is higher, the flood will come further which leads to higher inundation extents.

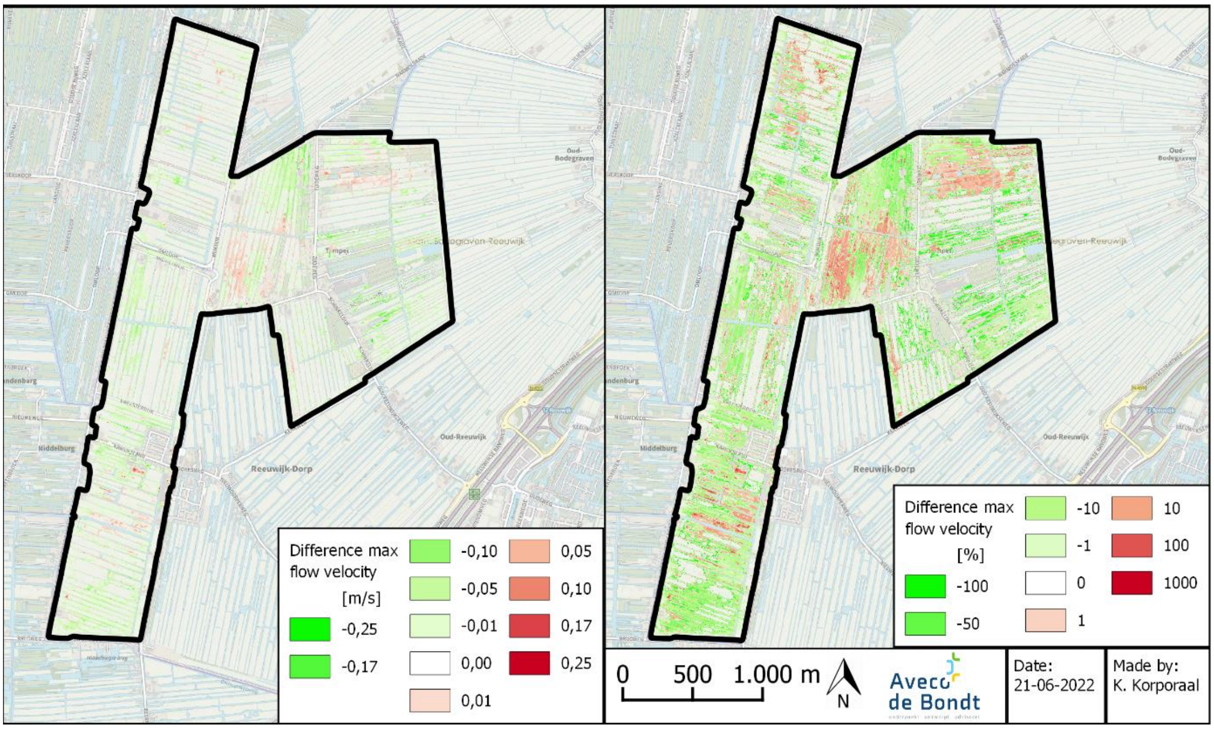


Figure 19 - Flow velocity differences for the precipitation situation a=40 mm, t=60 min, d=60 min in comparison with the precipitation situation a=40 mm, t=0 min, d=60 min at MT-Polder. With on the left the absolute differences and on the right the relative differences.

The water depths are higher when the precipitation falls at the start of the flood (Table 9). This is the case for all precipitation events. The maximum values are increasing for both situations, with the precipitation at different moments in time, until the simulation stops. This can be explained since the flood will last as long as the simulation time. When looking at how the water distributes over the area it can be seen that it needs some time to spread around the area. The precipitation beginning at t=60 min starts at a later moment than the precipitation beginning at t=0 min and thus the water which is falling on the surface also starts later by spreading around the area.

Table 9 - Differences in water depth for the precipitation situations at t=60 min in comparison with the precipitation situations at t=0 min for MT-Polder

Water depth (m)	**<0.10**	**0.10-0.25**	**0.25-0.75**	**>0.75**
a=40 mm, t=60 mm, d=60 min	6.55%	-6.78%	-21.42%	-16.25%
a=70 mm, t=60 min, d=60 min	15.64%	-2.03%	-23.68%	-34.05%

Since the total amount of water will stay the same, the expectation was that there would be no difference in water depths, but differences did occur this could be explained by that the water is still spreading around and not has reached a stable phase in the three hours of the simulation run. To check if this is correct an extra simulation is done for a simulation duration of 20 hours to check what the long-term effects are. What we see in Figure 20 is that the precipitation at t=0 min (yellow line) has a lead on the precipitation of t=60 min (red line) but they will reach each other after some time. So the difference is caused by the fact that the water has not come to a stable phase in three hours. So the water depths are higher in the t=0 situation until the simulation time is long enough to come to an equilibrium.

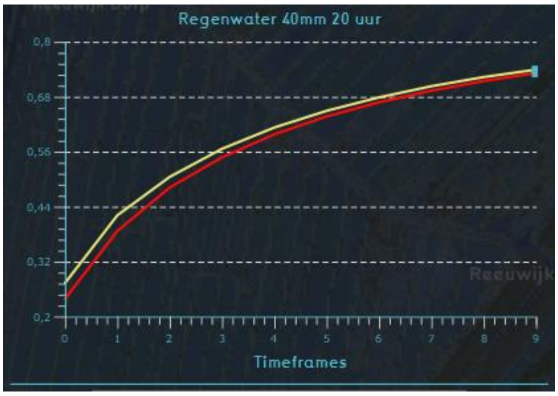


Figure 20 - MT-Polder 20 hour run water depth precipitation situation a=40 mm, t=0 min, d=60 min (yellow) and precipitation situation a=40 mm, t=60 min, d=60 min (red)

Comparison

The two simulations of Vortum Mullem are different from the two simulations of the MT-polder. Vortum Mullem has rainfall before and during the flood. The MT-polder has precipitation during the beginning of the flood and during the flood. One thing that can be said is that the moment of rainfall influences the model outcomes for both areas. When there is a steady-state water level which causes the flood a rainfall during the start gives higher values and when working with a wave which represents the water levels the rainfall which takes place around the peak will give the highest values. Therefore, it is important to look into the type of water levels which are set up to determine what the influence of the moment of the precipitation would be.

For Vortum Mullem precipitation during the flood has higher water depths and flow velocities. Between the inundation extents, there are no big differences. For the MT-Polder the highest flow velocities occur when precipitation begins at the start of the flood. Also, the inundation extent is slightly higher. The difference between the water depths is dependent on the simulation time.

4.2 Results Manning Coefficient

In Table 16 in Appendix 5Appendix 4 an overview is made which situations are compared with each other during this research for the manning input parameter.

Sloping area: Vortum Mullem

When adapting the manning values in the Vortum Mullem model, the water depths are decreasing when the manning values are increasing and vice versa (Table 10). Tygron works with equations based on the 2-D Saint-Venant equations to describe the surface flow (Tygron Support, 2021b). According to these equations, a higher potential difference is required to let the water flow when the roughness increases. When this higher potential difference does not occur the water will not flow from the river into the area. This means less water from the river flowing into the area, which leads to lower water depths. This is also what happens in the area. According to the water balance in Tygron, there is a difference of approximately 42.000.000 m^3. As explained in section 4.1.1 this is a net difference, but since there are no other inputs of water in the area such as precipitation the changes are high that less water flowed into the area, but this cannot be said with 100% certainty. When there is less water in the area, the water depths will decrease.

Table 10 - Differences in water depth for the manning situations in comparison with the reference situation of Vortum Mullem

Water depth (m)	**<0.10**	**0.10-0.25**	**0.25-0.75**	**>0.75**
Minimum manning	-1.30%	5.89%	6.59%	17.53%
Maximum manning	0.48%	-2.63%	-1.50%	-6.67%

At some locations, there is an increase in water depths for an increase in manning values, the red parts in Figure 21. The parts where the water depths are increasing are not characteristic locations, their height and function type are the same as their surroundings. If the function was different it could be clarified since the manning values are not adapted all with the same amount. That the roughness in that area is so different from other areas that the water will flow there, but that is not the case here. Therefore, no explanation is found for the red parts in the model.

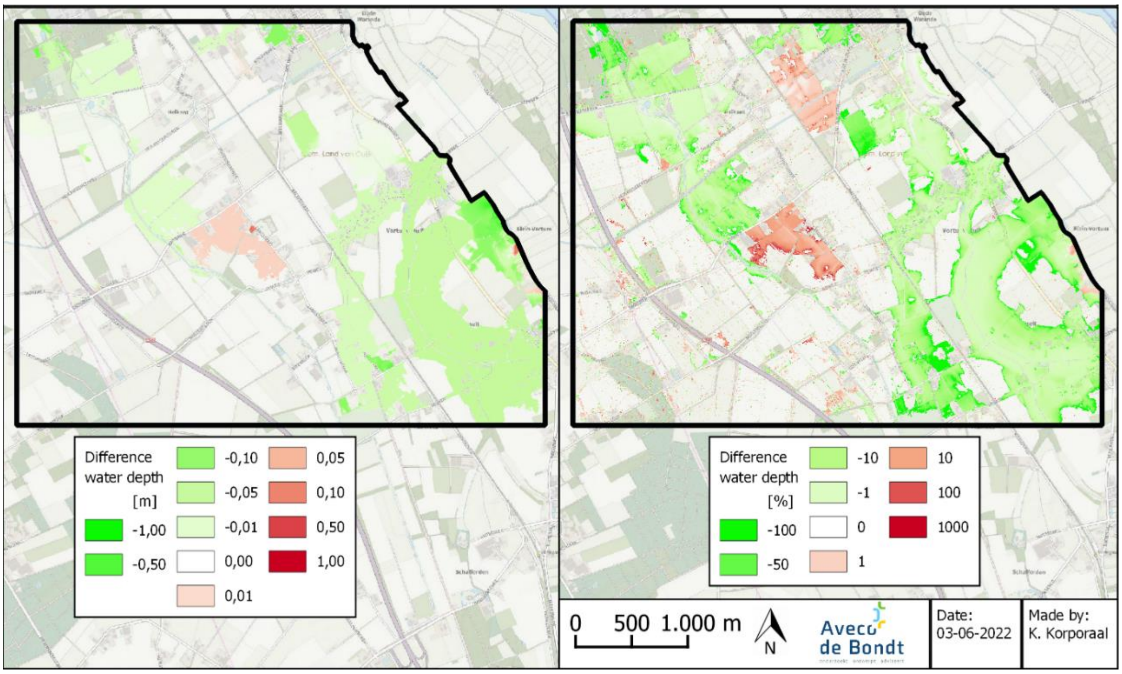


Figure 21 – Water depth differences for the maximum manning in comparison with the reference situation at Vortum Mullem. With on the left the absolute differences and on the right the relative differences.

An increase in manning values results in lower flow velocity (Figure 22) and a decrease leads to higher flow velocity. This is supported by the Gauckler-Manning formula (Equation 1), where the manning coefficient is given with the letter n and the flow velocity with a V (Gaitan, 2014):

$$V = \frac{k}{n} R_h^{2/3} S^{1/2}$$

Equation 1

When water is experiencing higher resistance it is more difficult to flow over the surface, which has as consequence lower flow velocities. In Table 11 the flow velocities are given, the flow velocities did decrease when increasing the manning values and the flow velocities did increase for the minimum manning values. To give a better view of the influence of resistance, an example of resistance during cycling will be given. When you are cycling on a sand path, you are experiencing more resistance than when you are cycling on a paved road. The resistance of the sand path has as a consequence that you will cycle slower when you are putting in the same amount of energy as when you are cycling on a paved road.

Table 11 - Differences in flow velocity for the manning situations in comparison with the reference situation of Vortum Mullem

Flow velocity (m/s)	0-0.5	0.5-1	1-2	>2
Minimum manning	-0.84%	26.55%	42.07%	54.76%
Maximum manning	0.69%	35.20%	-95.00%	-41.50%

The inundation extents are decreasing for the maximum values and increasing for the minimum values (Table 12). This can be explained since for the maximum manning values the flow velocity and the water depths are decreased, so the water will flow less far than in the reference situation.

Table 12 - Inundation extents Manning

Vortum Mullem	Inundation extent	MT-polder	Inundation extent
Minimum manning	37%	**Minimum manning**	34%
Maximum manning	32%	**Maximum manning**	62%

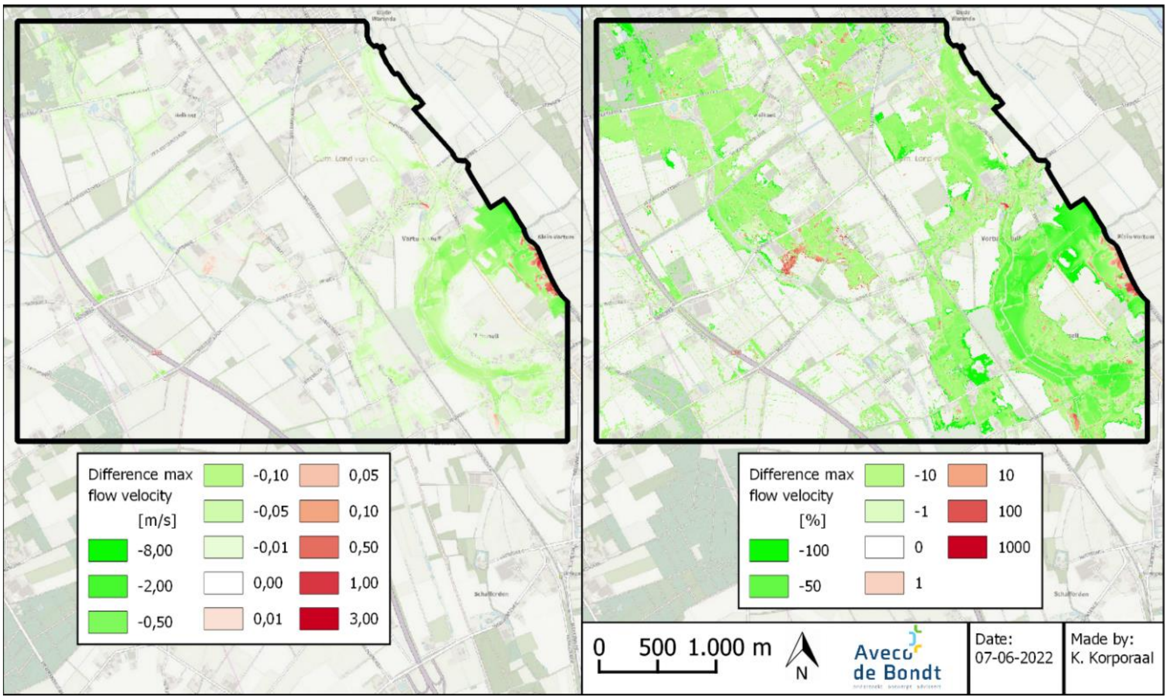


Figure 22 – Flow velocity differences for the maximum manning in comparison with the reference situation at Vortum Mullem. With on the left the absolute differences and on the right the relative differences.

Flat area: MT-Polder

When increasing the manning values of the MT-Poder to the maximum values the water depth increases (Table 13). Which is the opposite of what happens in the model of Vortum Mullem. A higher roughness coefficient leads to more impoundment, which causes an increase in water depths. Also, the inundation extent is increasing, since more locations are reaching the water depth threshold. Since in both the reference situation and the maximum manning situation the water reaches almost all locations, it is not about until where the water will reach, but since the water depths have increased the threshold is reached more for the inundation extent and thus a higher inundation extent.

Table 13 - Difference in water depth for the manning situations in comparison with the reference situation of the MT-Polder

Water depth (m)	<0.10	0.10-0.25	0.25-0.75	>0.75
Minimum manning	-0.20%	0.28%	4.99%	-2.86%
Maximum manning	-24.83%	123.32%	276.93%	120.00%

For the minimum manning values there is a limited difference in water depth. The water depths near the dike are a bit decreasing, with a lower roughness coefficient, higher flow velocities and less impoundment, this leads to lower water depths. But in the middle part of the MT-Polder, there is a small increase in water depths or no difference at all. Therefore, no big differences in inundation extent did occur between the minimum manning values and the reference situation. Since the MT-Polder is the lowest laying area of the surrounding, all the water will gather in the MT-Polder due to gravity. The total amount of water does not change in the area according to the water balance and the water will distribute a bit different around the area, so the small decreases near the dike are having as consequence a bit increase in the water depths in the middle of the MT-Polder.

For the maximum manning values the flow velocity decreases near the dike (Figure 23). According to the Gauckler-Manning formula as mentioned on the previous page, a decrease in manning values leads to a decrease in flow velocity and vice versa. The data given in Table 14 support this, for the maximum manning situation compared with the reference situation it is known that there are fewer high flow velocities (>1) and more lower flow velocities especially at the part 0.25-0.50 m/s. This means that indeed the flow velocities are decreased when increasing the manning values. For the minimum values, the flow velocities did increase.

In the middle of the MT-Polder, there are some small increases and decreases for the maximum manning situation. The small difference can be explained since the water will distribute a bit different around the area than in the reference situation, which has as a consequence that the flow velocities are also a bit different distributed.

Table 14 – Differences in flow velocity for the manning situations in comparison with the reference situation of the MT-Polder

Flow velocity (m/s)	<0.25	0.25-0.50	0.50-1	>1
Minimum manning	-0.71%	3.71%	-4.13%	14.47%
Maximum manning	0.57%	11.72%	7.03%	-26.81%

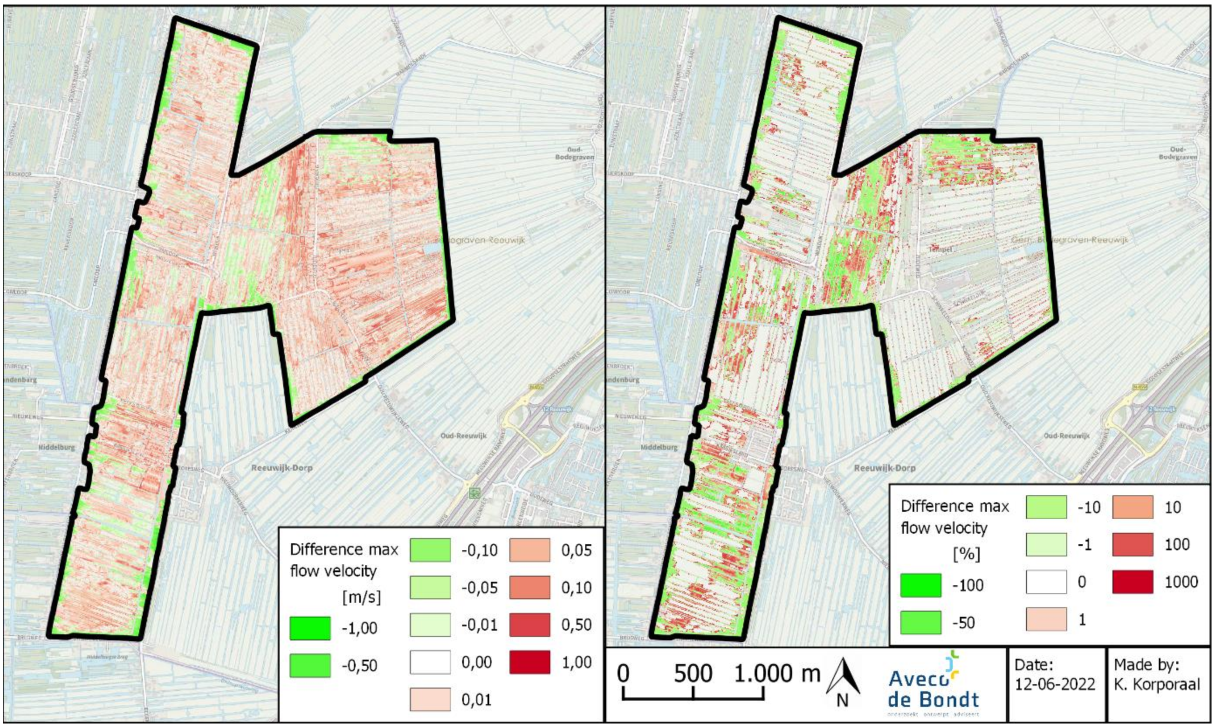


Figure 23 – Flow velocity differences for the maximum manning in comparison with the reference situation at MT-polder. With on the left the absolute differences and on the right the relative differences.

Comparison

The biggest difference between the MT-Polder and Vortum Mullem for the manning values is the difference in reaction on the water depth. The opposite happens between the two areas. Where the water depths are increasing for the MT-Polder when increase the manning values, are the water depths for Vortum Mullem decreasing. This difference could occur since the height differences between the outside of the dike and the hinterland is bigger in the MT-Polder than in the sloping area Vortum Mullem. At Vortum Mullem the potential difference between the two water levels is not high enough anymore to let the water flow, due to the change of the manning values and since there are no high differences in water depth. For Vortum Mullem the potential difference is still high enough to let the water flow after changing the manning values since there is a high difference between the water depths. So, the main reason why there is a difference in influence on the water depths is since the water depths differences are high enough in the MT-Polder and at Vortum Mullem it is not.

5 Discussion

This research aimed was to gain insight into the influence of input parameters on the flood model outcomes. This is done by the use of a sensitivity analysis, the 'one-at-a-time' sampling method is used to perform the sensitivity analysis. The main advantage of this method is that the influence of a specific parameter can be found, but this means that no relations between different input parameters will be found.

The values of the input parameters are chosen in a way that a general view of their influences became clear during this research. For the manning parameter, there is worked with the minimum, default and maximum manning values. Therefore, it is known now what an increase or decrease of manning values has for influence. This is also the case for precipitation, there have been looked into the effect of different types of precipitation, which is a good point of this research. But it is not possible to say what a parameter change would have as an outcome when it is changed for a specific amount. This is because during the research only the trends are investigated and no correlations.

For this research, the software Tygron is used, specific version 2022.7.0.1. This software is constantly under development and is improving parts. Therefore, a later version will possibly give not the exact same results as this research. Tygron works with a closed boundary system, as mentioned in section 2.1. This means that no water can go inside or outside the system, except at the inlets and outlets which are placed in the model. In the models used in this research, no outlets are created, except the inlets at Vortum Mullem. In reality, water is not limited to the borders of an area, especially not in a sloping area. For this research, it was assumed that there was no decline in water depth in the river Meuse due to inundation at other locations in the Meuse, but in reality, this could be the case. Therefore, the model which is used in this research can overestimate the total volume in the area and underestimate the water which will flow out of the area in reality. This can have an impact on the results since the water will flow a bit different when there are no borders or when less water flows into the area. It is not possible to make the model without assumptions, therefore these assumptions are made upfront.

In the results of the MT-Polder, it became clear that when precipitation takes place at the beginning of the flood that higher water depths are occurring than during a situation with precipitation at a later moment during the flood. When increasing the running time to twenty hours it became clear that the differences between the two situations with precipitation at different times became smaller. Therefore, it is important to look at how long it takes until the equilibrium position is reached. Since the water levels outside the MT-Polder are continuously over time in this model, it is easier to add the precipitation at t=0 min. Since then the maximum water heights are found, without increasing the simulation time. But when it would be the case like in Vortum Mullem that the water levels outside the dike are changing, then it could differ at which moment the precipitation gives the highest water depths. So, when having the same water levels over time the precipitation must be added at the start of the flood while having varying water levels the precipitation must be added near the peak.

The water depths of Vortum Mullem while changing the manning values are different than expected before executing the simulation. It was expected that the water depths would increase when the manning values are increased since more roughness leads to more impoundment and thus higher water levels. In section 4.2 it is explained how it could be that the water levels become lower. But in reality, the water system would react differently than what happens in the model. Also in reality it would be that a higher potential difference is needed to let the water flow. So at first, less water will flow into the area and the water will stay in the river. In the river, the water depths will increase, which leads to a higher potential difference and thus the water can go into the area. Since more water will flow into the hinterland the water level will increase. The situation that the water depths in the river are increasing is not taken into account in the model, since the inlets have a fixed value. Therefore, it could be that the outcomes would be different if the change in the water depths of the river is taken into account.

For this research, it is set that something is inundated when there is a minimum water depth occurred of one centimetre. Everything below that one centimetre is not taken into account when calculating the inundation extent. Therefore, the inundation extent can give a distorted picture of where the water has reached. For example, the rain has fallen over the complete area, but the area is not 100% inundated. Or locations, where the water depth was a bit under one centimetre, are not taken into account. When another threshold would be chosen for the inundation extent, the values of the inundation extent would be different. The inundation extent can still be used to see the difference between different situations.

Sometimes deviating values occur near the boundaries of a system. This is visible at Vortum Mullem since there is worked with a calculation system. These occur due to limitations of the model and are not explainable. Therefore, deviating values near the boundaries are not taken into account in the analysis. Since the expectation is that in reality, those areas would react the same as the others.

6 Conclusion

This research aimed to gain insight into the influence of input parameters on the flood model outcomes. This has been done with the following main question:

- **What is the difference in the influence of input parameters on flood calculation outcomes between a sloping and a flat area?**

During this research, the input conditions of precipitation and the roughness coefficient are examined on maximum flow velocity, maximum water depth and maximum inundation extent for the sloping and flat area. The first input parameter which has been changed is precipitation. Precipitation influences the total amount of water which will be in the water system. When increasing the intensity of the precipitation the flow velocity, water depth and inundation extent were also increased during this research for both test areas. Increasing the intensity of the precipitation has a higher influence on the flat polder area than on the sloping area, one of the reasons is that the rainwater amount is a higher percentage of the total amount of water in the polder area than in the sloping area.

For the duration of rainfall, it became clear during this research for the sloping area that the maximum flow velocity is higher at a short rainfall of 40 mm than at a long rainfall of 89 mm. The inundation extent is also higher for the short rainfall. The maximum water depths are location-dependent, they are increasing and decreasing in both situations.

The moment of precipitation differs between the two test areas. For the sloping area, the maximum flow velocities and water depths are increasing when the precipitation starts during the flood. The moment of precipitation has less influence on the inundation extent. For the polder area, the maximum flow velocity and inundation extent are the highest when the precipitation takes place during the start of the inundation. The water depths are also the highest when the precipitation starts at t=0 min, but the simulation time has a big influence on this. When the simulation is long enough almost no differences can be found in the water depths from the rainfall at the two different times.

The second parameter which is examined during this research is the manning coefficient. Based on the tables of Chow (1959) minimum and maximum values are assigned to the manning coefficient. During this research, it became clear that the manning coefficient acts differently in the two test areas. The opposite happens for the water depths and inundation extents between the two test areas. For the sloping area, an increase in manning values means a decrease in water depths, which is caused by the potential differences between two water levels. For the polder, an increase occurred when increasing the manning values. For both areas, the flow velocities are decreasing when increasing the manning values.

To answer the main question the manning parameter and the precipitation have a partly different influence on the flood model outcomes for a sloping area and a polder area. The manning parameter has a different influence on the area when looking at the maximum water depth and inundation extent, but has the same influence on the maximum flow velocity in both areas. For the precipitation, it is important to know that precipitation leads to higher flow velocities, water depths and inundation extents. The intensity, duration and moment in time all three can influence the model outcomes. The intensity of rainfall has a higher influence in the flat area than in the sloping area. The moment in time which must be chosen to set up the rainfall is dependent on the way the water levels outside the dike are set up.

7 Recommendations

This research has given insight into the influence of the input parameters: precipitation and the manning coefficient on the flood model outcomes. During this research, a few questions did arise that could not be answered during this research.

During this research, the parameters precipitation and manning coefficient are examined. But there are some more interesting parameters to research. One of them is trees, Tygron does not work with individual trees in forests but with an area which has one roughness factor. Next to that, water can flow through a tree, in the model it is not seen as a solid object. These two factors don't suit reality, since in reality water will not flow through the tree and a forest exists out of trees and space between trees. When changing this input parameter it is important to know how trees are exactly working in the program. Other parameters which could be changed are hedges and initial water levels for example. Initial water levels in the hinterland have influence the storage capacity in the waterways. When the initial water levels are increasing, less water can be stored from the flood in the waterways, which possibly leads to more inundation.

For this research, the 'one-at-the-time' method to sample the parameters was chosen. Only one parameter was allowed to change at the same time. Therefore, the interactions between parameters are not taken into account. When changing multiple parameters at the same time, the outcomes could be different. A suggestion is to look into the influence of changing multiple parameters at the same time on the flood model outcomes. For example, the initial water levels in the hinterland and the precipitation. Those two influence the amount of water in the water system.

During the analysis of the results of this research, there is no reason found why the water depths in a reference situation are higher than in a precipitation situation for the low laying parts (section 0). This may be since there is an error in the calculation near the border, but it also could be that something else is happening. During this research, no time was available to deep further into this. Therefore, it is useful for further research to look at what happens at that location which is causing that difference.

The water balance in Tygron works with net values for the inlets. Currently, it is not possible to see what the inflow and outflow of a specific inlet are. So, also the change in inflow and outflow cannot be determined. An improvement of Tygron would be to show for each inlet in the water balance the inflow and the outflow values instead of the net values. Then it would be possible to check if less water has flowed into the area, which helps by analysing the situations.

Right now it is possible to set up water levels for the surface level with the use of a height map according to NAP. This is useful when working in a flat area since the water levels for every ditch can be adapted to a certain level or to the target water level. On the contrary, this is not useful when working with a sloping area. In sloping areas, the water levels of ditches are often not known. But you want to work with a water level which is a specific value below surface level, instead of water levels based on NAP levels. Right now this is not possible to simulate in Tygron. So the water levels for the sloping area are set up with a detour in QGIS which is a lot of work. An improvement for Tygron would be if it is possible to set up water levels at a specific value below surface level.

8 References

Aveco de Bondt. (n.d.). *Aveco de Bondt - Over Ons*. Retrieved March 30, 2022, from https://www.avecodebondt.nl/nl/over-ons

Bajabaa, S., Masoud, M., & Al-Amri, N. (2014). Flash flood hazard mapping based on quantitative hydrology, geomorphology and GIS techniques (case study of Wadi Al Lith, Saudi Arabia). *Arabian Journal of Geosciences*, *7*(6), 2469–2481. https://doi.org/10.1007/s12517-013-0941-2

Beersma, J., Hakvoort, H., JIlderda, R., Overeem, A., & Versteeg, R. (2019). *Neerslagstatistiek en -reeksen voor het waterbeheer 2019*. https://www.stowa.nl/sites/default/files/assets/PUBLICATIES/Publicaties%202019/STOWA%20 2019-19%20neerslagstatistieken.pdf

CBS. (n.d.). *Landelijk gebied*. Retrieved April 26, 2022, from https://www.cbs.nl/nl-nl/onze-diensten/methoden/begrippen/landelijk-gebied

Chow, V. (1959). *Open-channel hydraulics*. McGRAW-HILL BOOK COMPANY.

Crisis.nl. (n.d.). *Wees voorbereid Overstroming*. Retrieved May 5, 2022, from https://crisis.nl/wees-voorbereid/overstroming/

Dutta, D., & Nakayama, K. (2009). Effects of spatial grid resolution on river flow and surface inundation simulation by physically based distributed modelling approach. *Hydrological Processes*, *23*(4), 534–545. https://doi.org/10.1002/hyp.7183

Gaitan, C. F. (2014). *Rediscovering Manning'S Equation Using genetic Programming*.

Hesselink, A. W., Stelling, G. S., Kwadijk, J. C. J., & Middelkoop, H. (2003). Inundation of a Dutch river polder, sensitivity analysis of a physically based inundation model using historic data. *Water Resources Research*, *39*(9). https://doi.org/10.1029/2002WR001334

KadastraleKaart.com. (n.d.). *Gemeenten in Nederland*. Retrieved April 26, 2022, from https://kadastralekaart.com/gemeenten

Kennisportaal Klimaatadaptatie. (n.d.). *Water overlast basisgegevens*. Retrieved April 20, 2022, from https://klimaatadaptatienederland.nl/stresstest/bijsluiter/wateroverlast/informatie-maat/basisgegevens/

Lau, T. W., & Afshar, N. R. (2013). Effect of Roughness on Discharge. *Journal of Civil Engineering, Science and Technology*, *4*(3), 29–33. https://doi.org/10.33736/jcest.124.2013

Lechowska, E. (2021). Approaches in research on flood risk perception and their importance in flood risk management: a review. *Natural Hazards*. https://doi.org/10.1007/s11069-021-05140-7

Merwade, V., Olivera, F., Arabi, M., & Edleman, S. (2008). Uncertainty in Flood Inundation Mapping: Current Issues and Future Directions. *Journal of Hydrologic Engineering*, *13*(7), 608–620. https://doi.org/10.1061/(ASCE)1084-0699(2008)13:7(608)

Morio, J. (2011). Global and local sensitivity analysis methods for a physical system. *European Journal of Physics*, *32*, 1577–1583. https://www.helpdeskwater.nl/publish/pages/132789/1220043-003-hye-0012-r-updated_and_improved_method_for_flood_damage_assessment_ssm2015_version_2.pdf

Nillesen, A. L., & Kok, M. (2015). An integrated approach to flood risk management and spatial quality for a Netherlands' river polder area. *Mitigation and Adaptation Strategies for Global Change*, *20*(6), 949–966. https://doi.org/10.1007/s11027-015-9675-7

Oude Essink, G. H. P., van Baaren, E. S., & de Louw, P. G. B. (2010). Effects of climate change on coastal groundwater systems: A modeling study in the Netherlands. *Water Resources Research*, *46*(10). https://doi.org/10.1029/2009WR008719

Pergens, T. (2017). *Is de randstad voorbereid op een overstroming*. https://theses.ubn.ru.nl/handle/123456789/4455

Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., Saisana, M., & Tarantola, S. (2008). *Global Sensitivity Analysis*. John Wiley & Sons.

Tygron. (n.d.). *OVER TYGRON*. Retrieved April 3, 2022, from https://www.tygron.com/nl/over-tygron/

Tygron Support. (2021a). *Inlet (Water Overlay)*. https://support.tygron.com/wiki/Inlet_(Water_Overlay)

Tygron Support. (2021b). *Surface flow formula (Water Overlay)*. https://support.tygron.com/wiki/Surface_flow_formula_(Water_Overlay)

Tygron Support. (2021c). *Water Module Theory*. https://support.tygron.com/wiki/Water_Module_theory

van Dijk, H. (2021, November 11). *Validatie Watermodule Tygron op basis van dijkdoorbraak Reeuwijk*. https://www.tygron.com/nl/2021/11/11/validatie-watermodule-tygron-op-basis-van-dijkdoorbraak-reeuwijk/

Wesselink, A. J. (2007). Flood safety in the Netherlands: The Dutch response to Hurricane Katrina. *Technology in Society*, *29*(2), 239–247. https://doi.org/10.1016/j.techsoc.2007.01.010

Yu, D., & Coulthard, T. J. (2015). Evaluating the importance of catchment hydrological parameters for urban surface water flood modelling using a simple hydro-inundation model. *Journal of Hydrology*, *524*, 385–400. https://doi.org/10.1016/j.jhydrol.2015.02.040

Appendices

Appendix 1 Rainfall

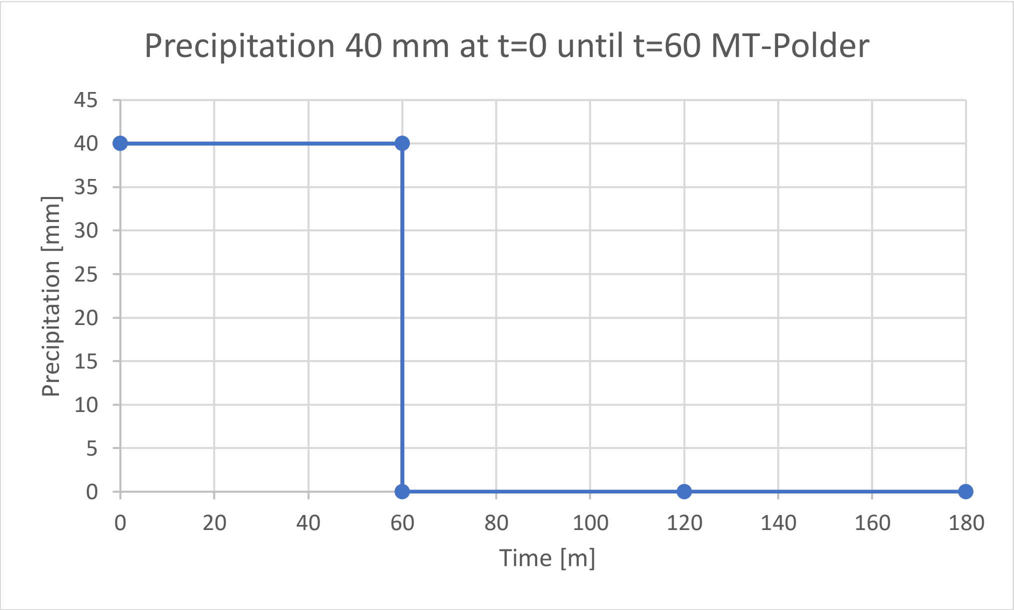


Figure 24 - Precipitation 40 mm at t=0 until t =60 MT-Polder

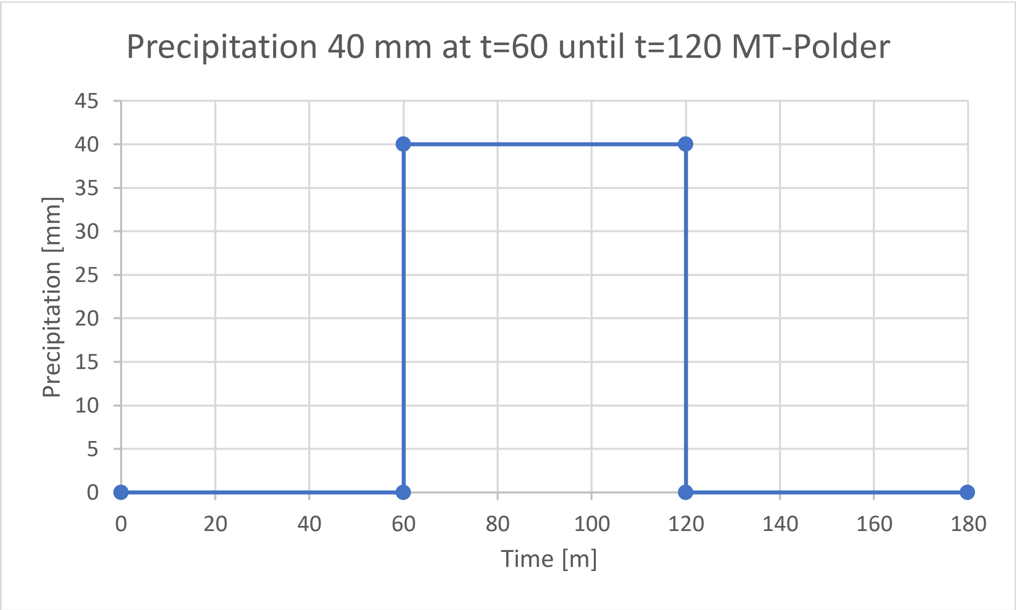


Figure 25 - Precipitation 40 mm at t=60 until t=120 MT-Polder

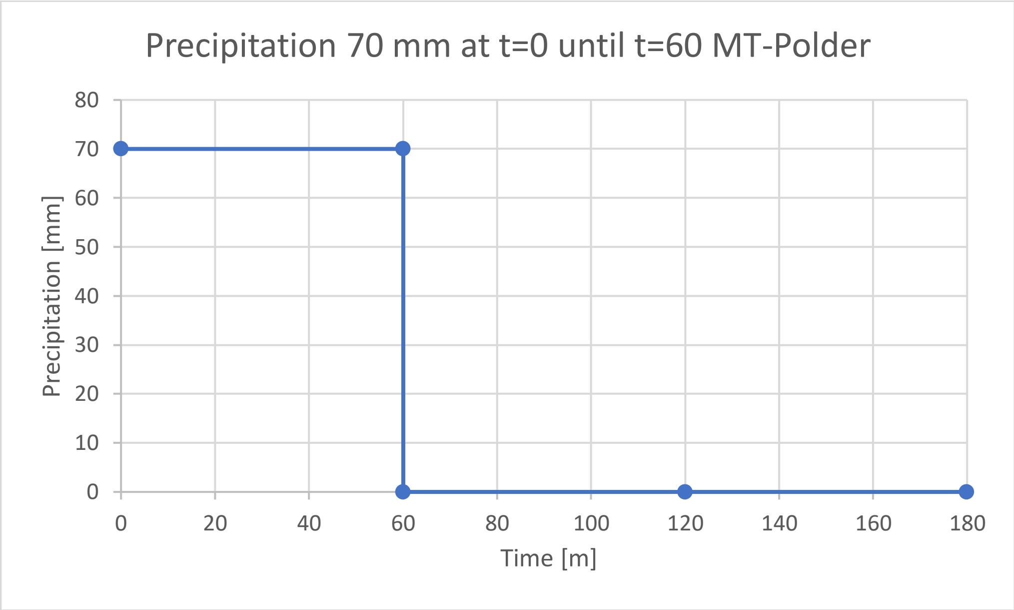


Figure 26 - Precipitation 70 mm at t=0 until t=60 MT-Polder

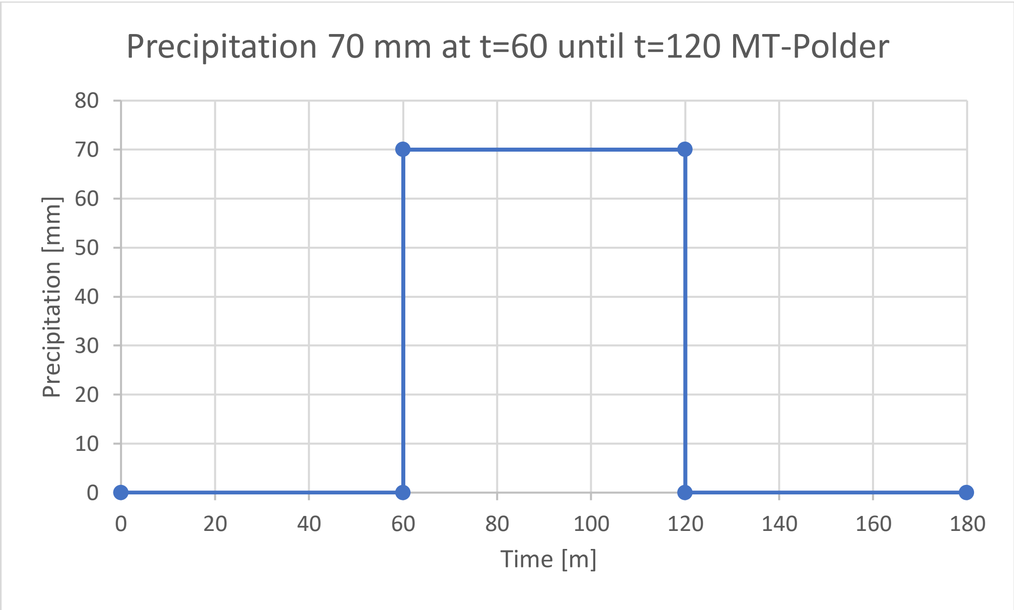


Figure 27 - Precipitation 70 mm at t=60 until t=120 MT-Polder

Appendix 2 Vortum Mullem

Vortum Mullem Reference situation

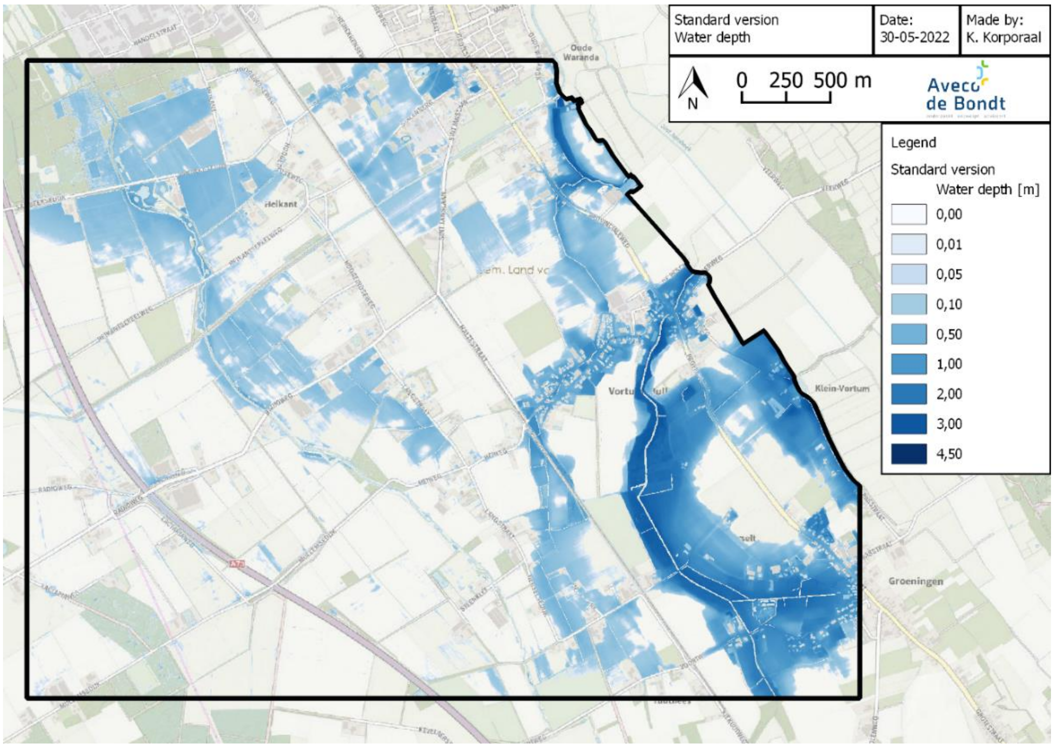


Figure 28 - Vortum Mullem - Reference situation - water depth

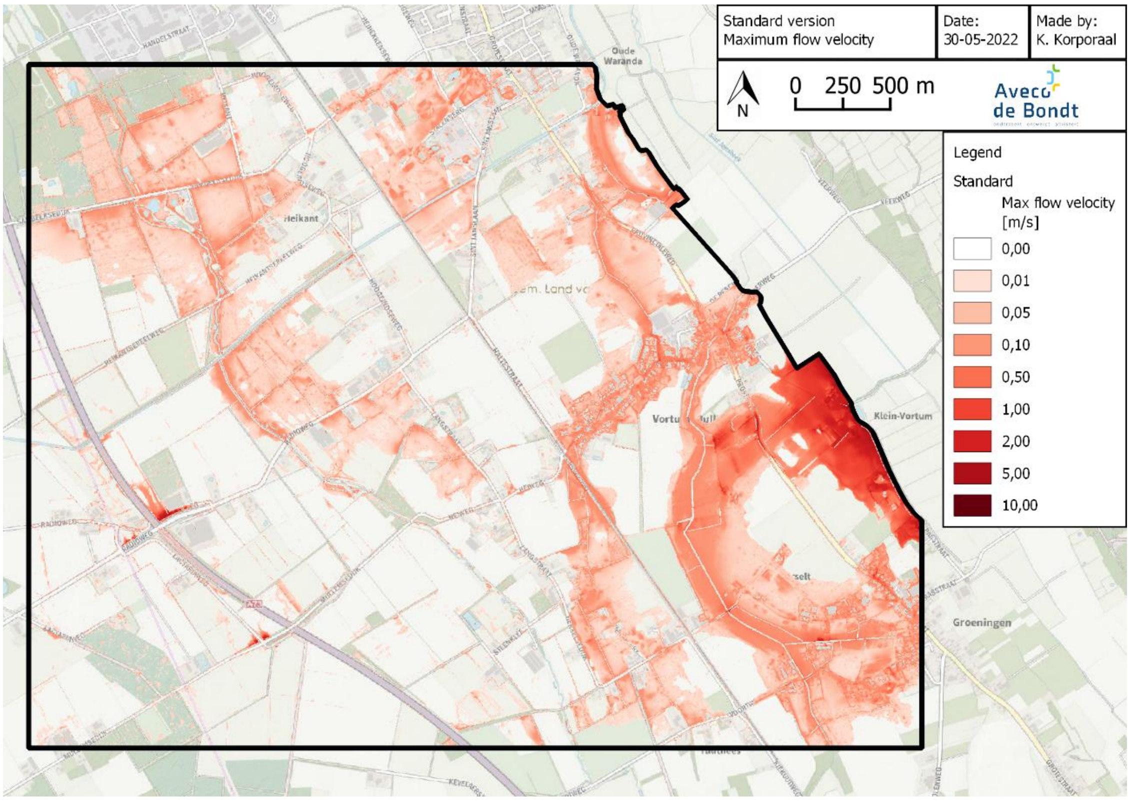


Figure 29 - Vortum Mullem - Reference situation - maximum flow velocity

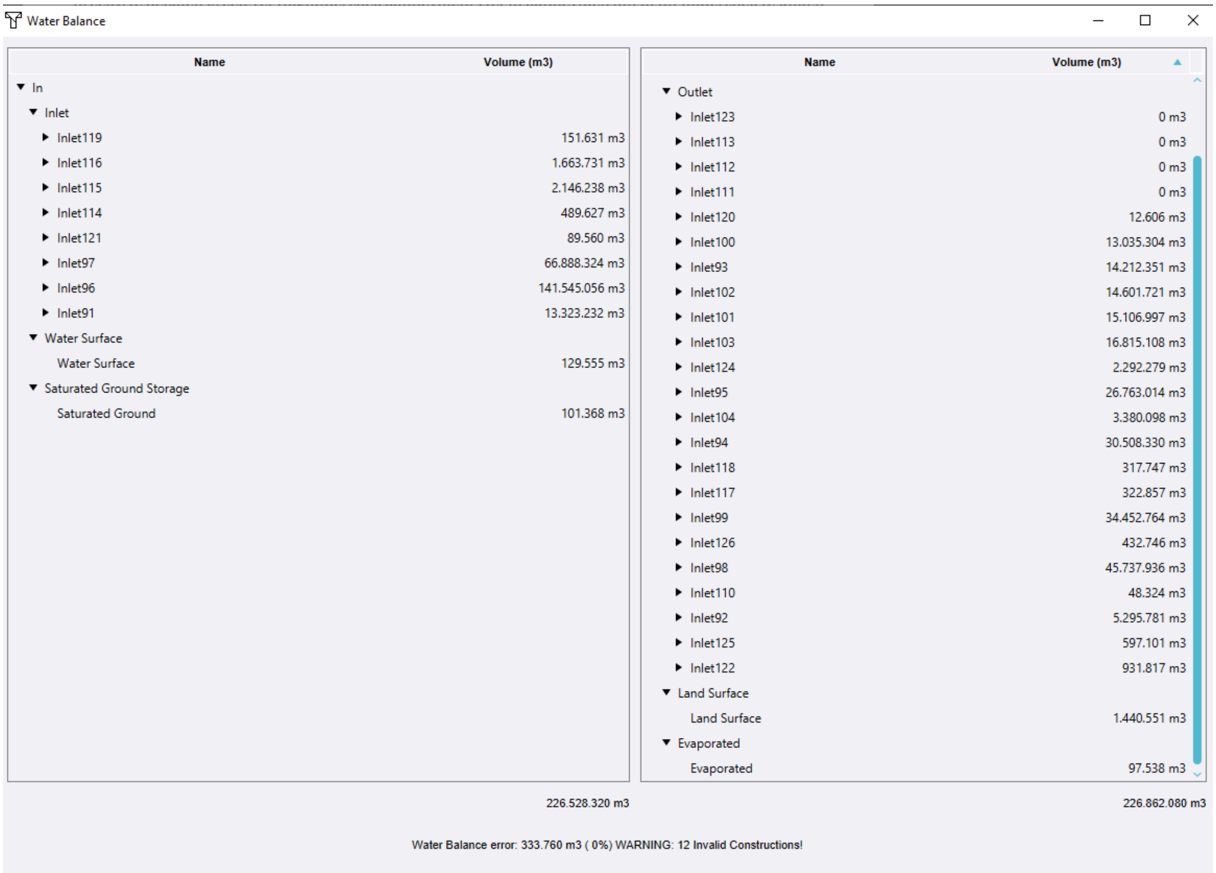


Figure 30 - Water balance reference situation Vortum Mullem

Vortum Mullem a=40 mm, t=0 min, d=60 min

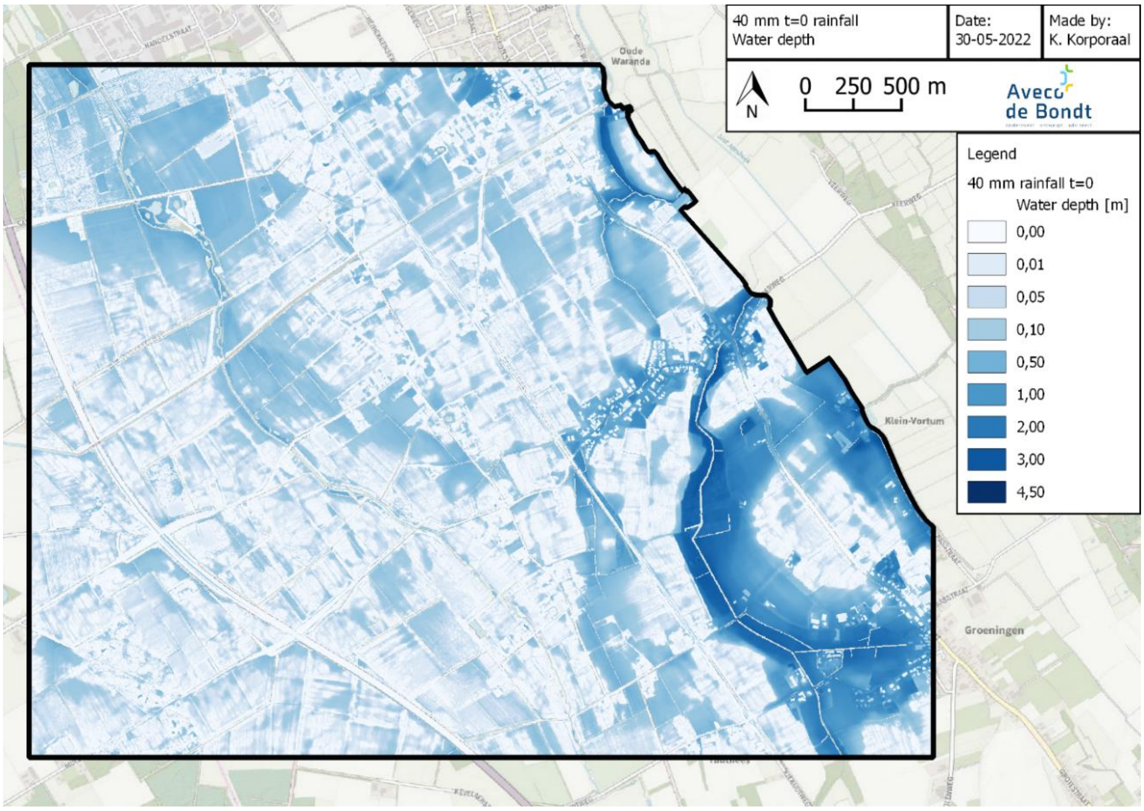


Figure 31 - Vortum Mullem – a=40 mm, t=0 min, d=60 min - water depth

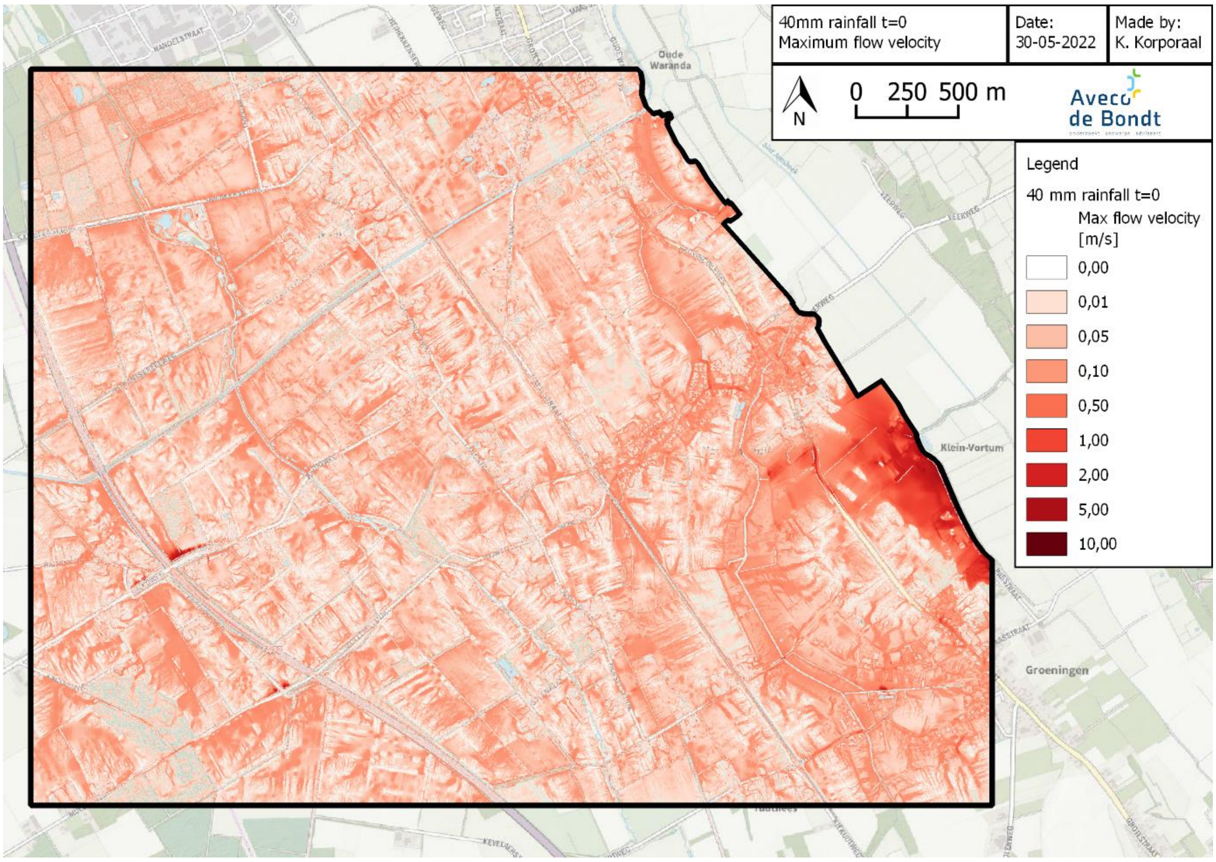


Figure 32 - Vortum Mullem – a=40 mm, t=0 min, d=60 min - maximum flow velocity

Vortum Mullem a=40 mm, t=8640 min, d=60 min

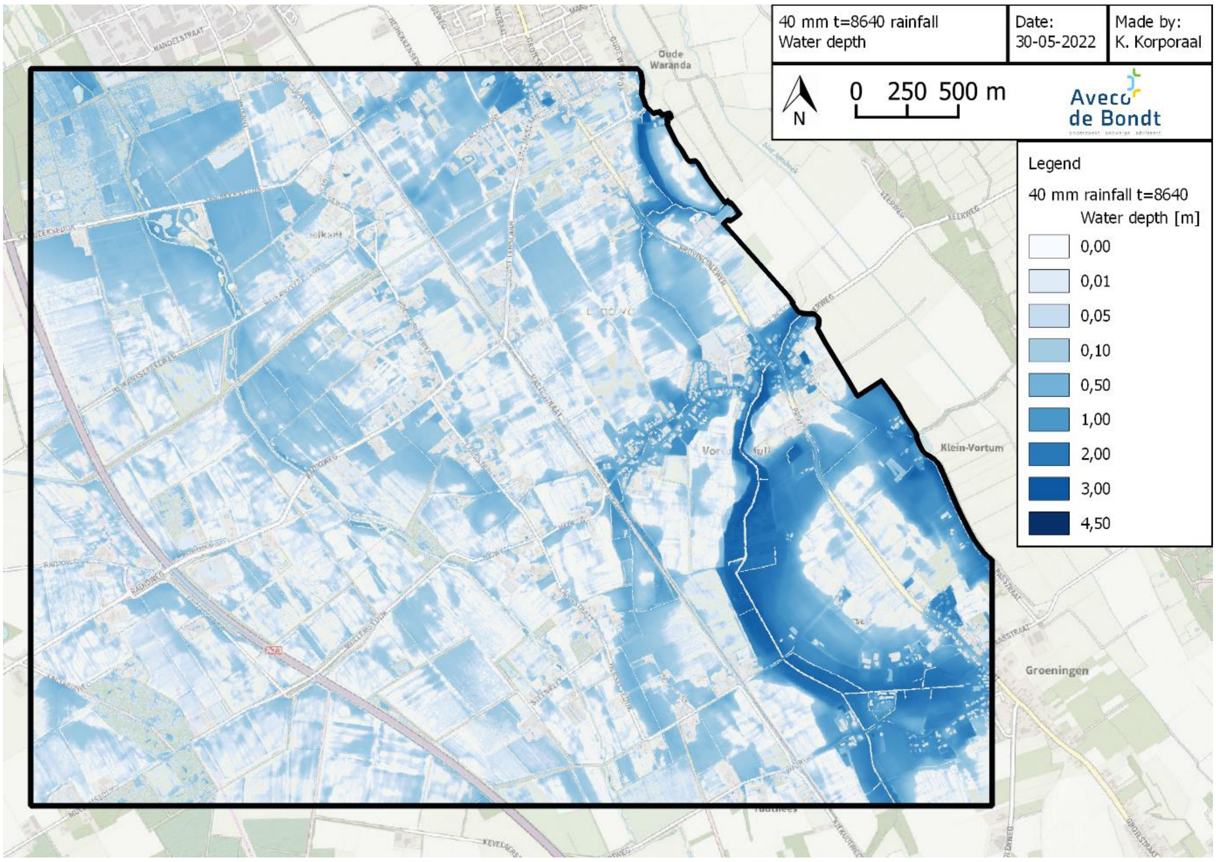


Figure 33 - Vortum Mullem - a=40 mm, t=8640 min, d=60 min - water depth

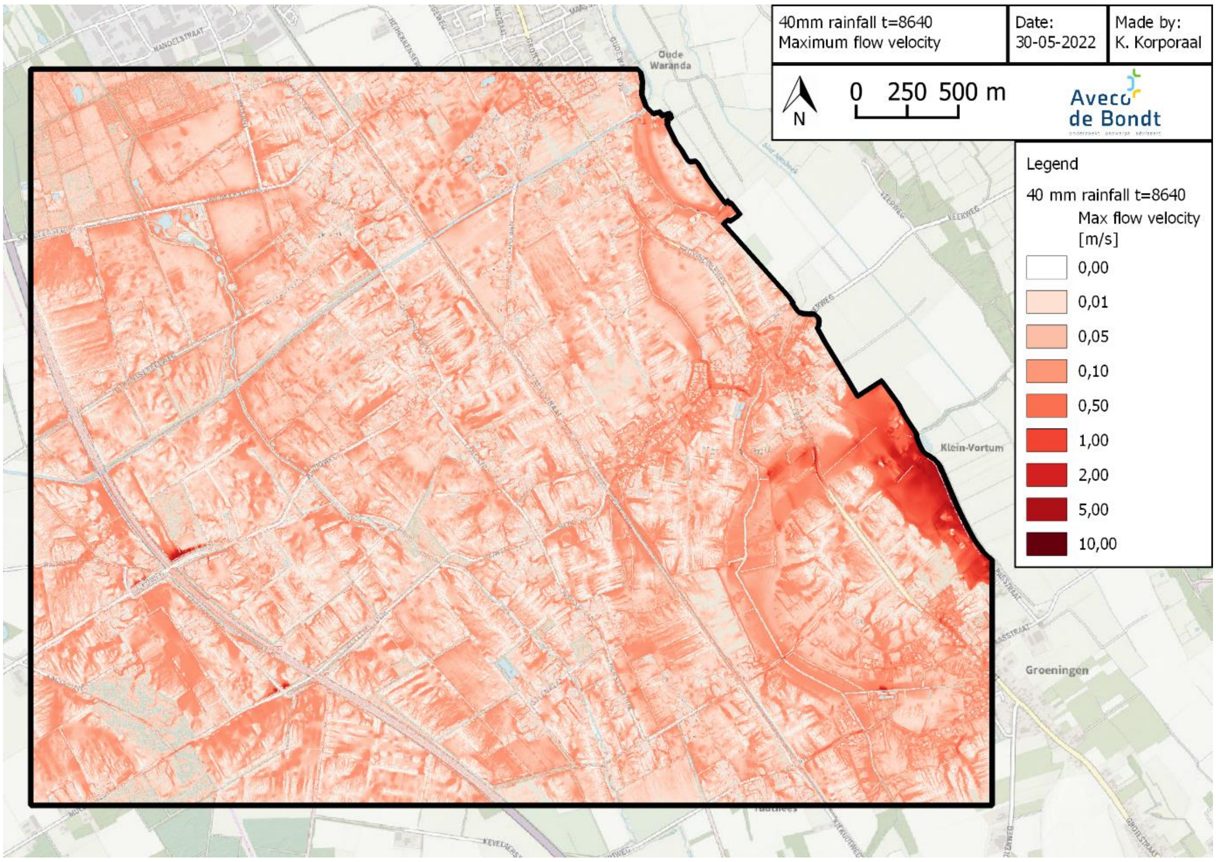


Figure 34 - Vortum Mullem – a=40 mm, t=8640 min, d=60 min - maximum flow velocity

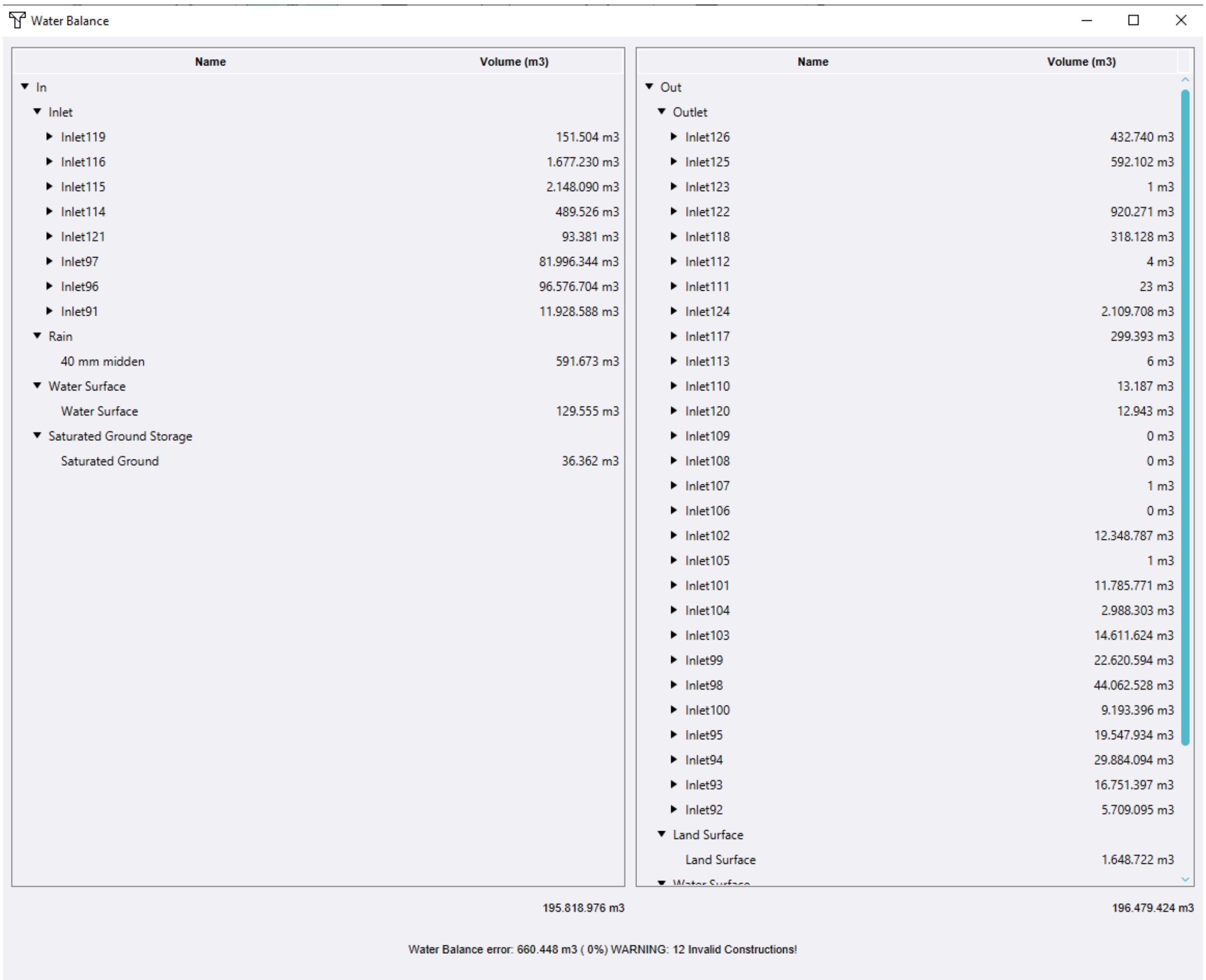


Figure 35 - Water balance a=40 mm, t=8640 min, d=60 min Vortum Mullem

Vortum Mullem a=70 mm, t=0 min, d=60 min

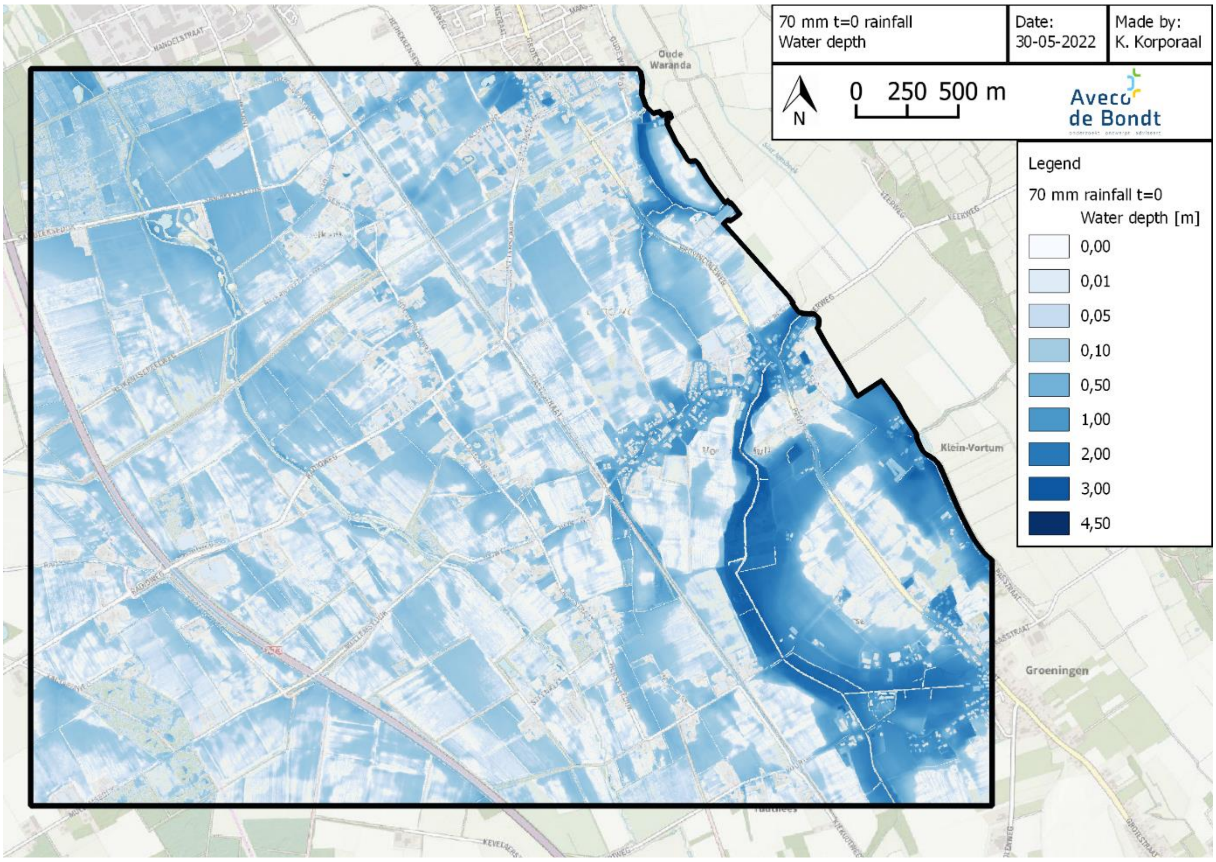


Figure 36 - Vortum Mullem – a=70 mm, t=0 min, d=60 min - water depth

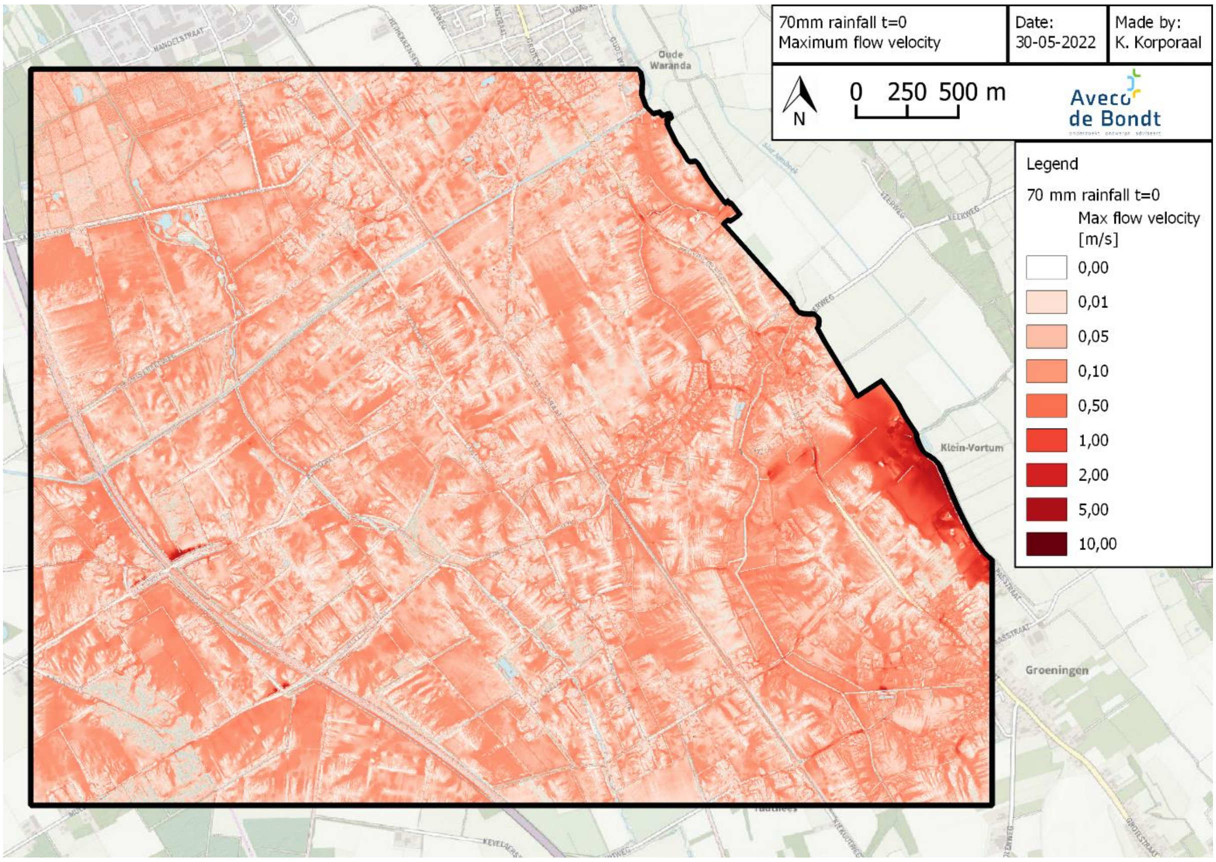


Figure 37 - Vortum Mullem – a=70 mm, t=0 min, d=60 min - maximum flow velocity

Vortum Mullem 70 mm t=8640

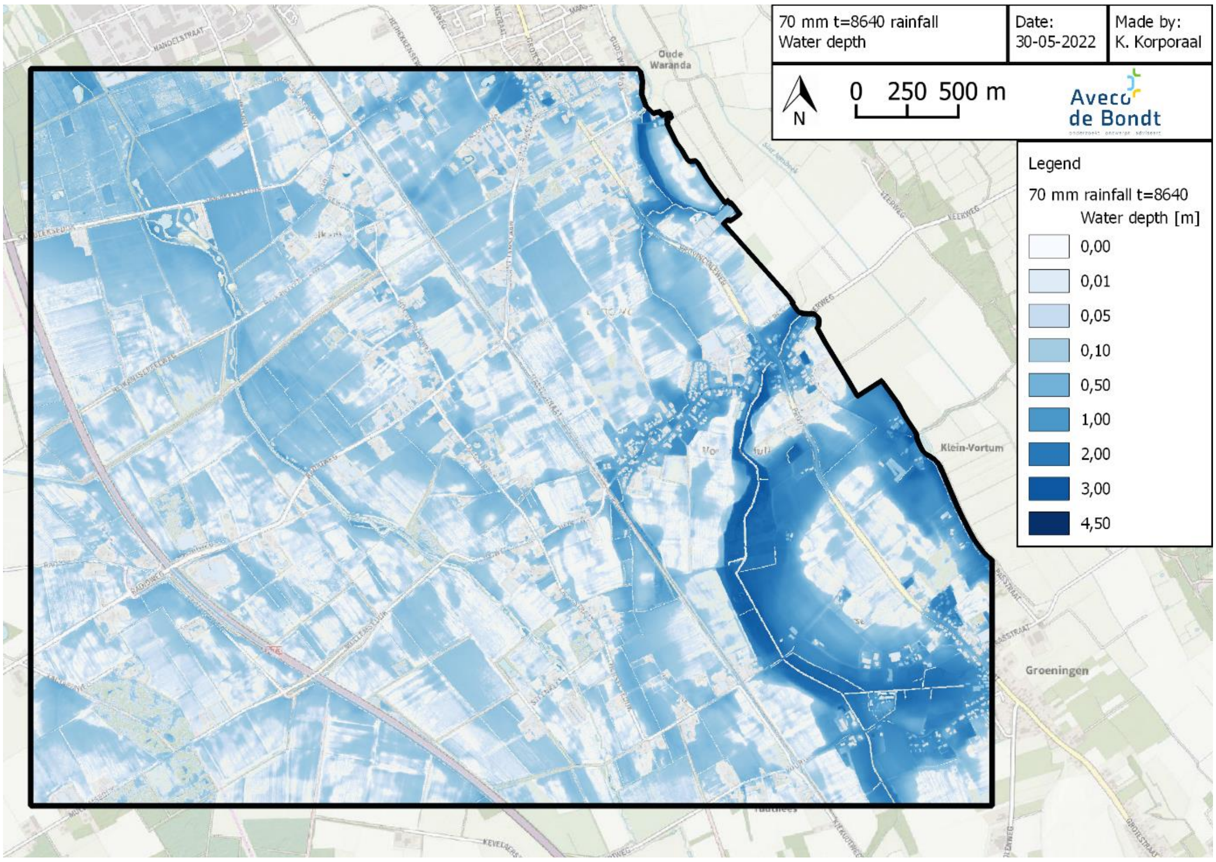


Figure 38 - Vortum Mullem – a=70 mm, t=8640 min, d=60 min - water depth

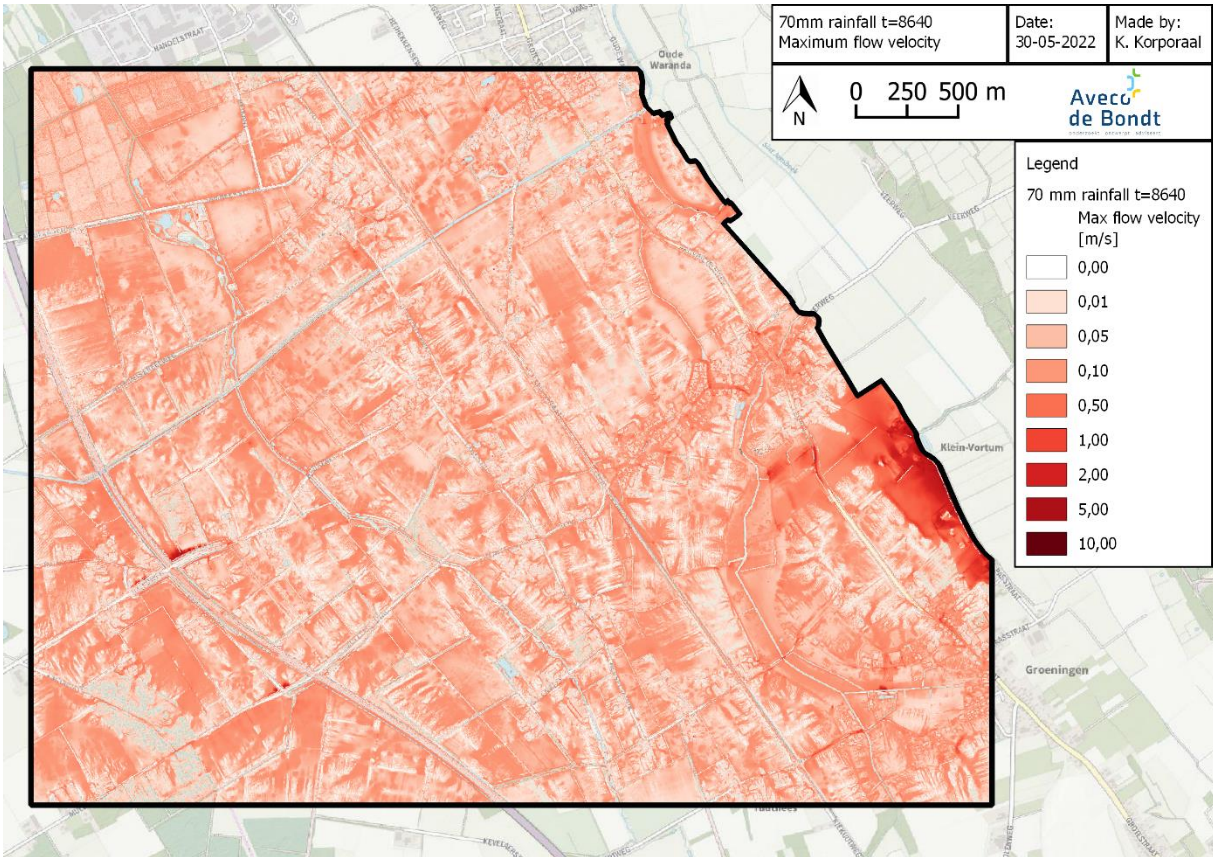


Figure 39 - Vortum Mullem - a=70 mm, t=8640 min, d=60 min - maximum flow velocity

Vortum Mullem a=89 mm, t=0 min, d=2880 min

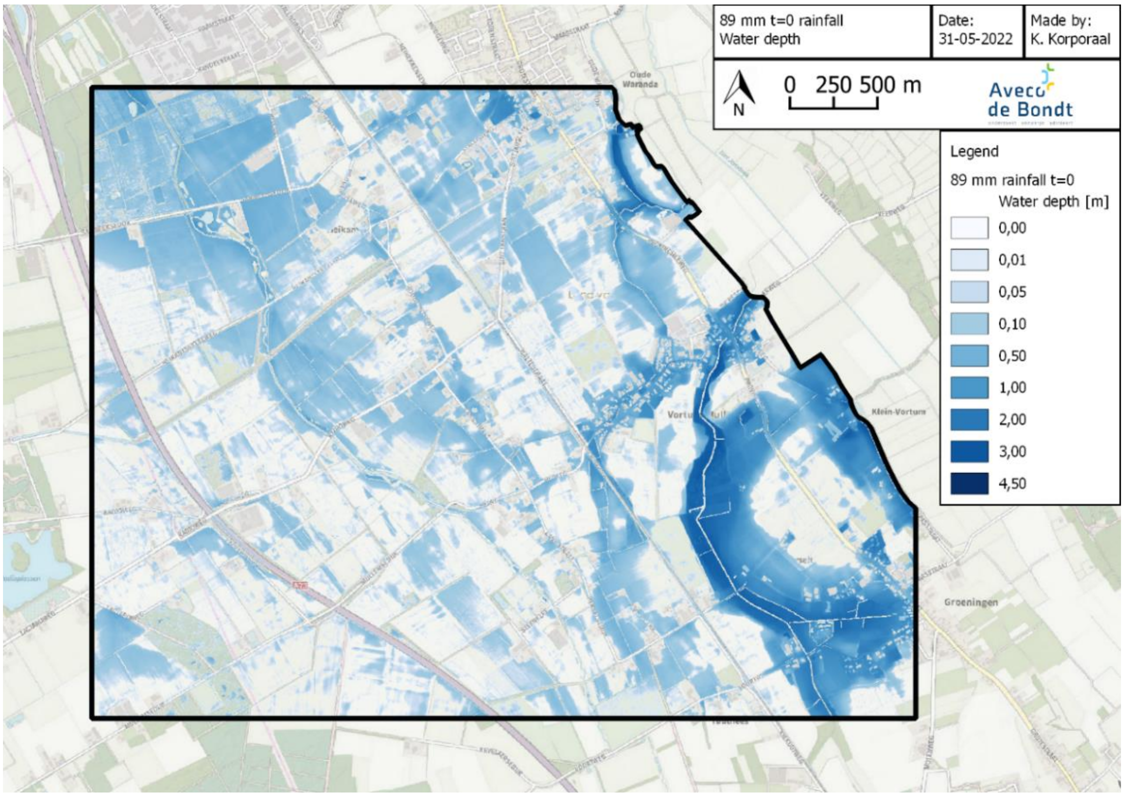


Figure 40 - Vortum Mullem – a=89 mm, t=0 min, d=2880 min - water depth

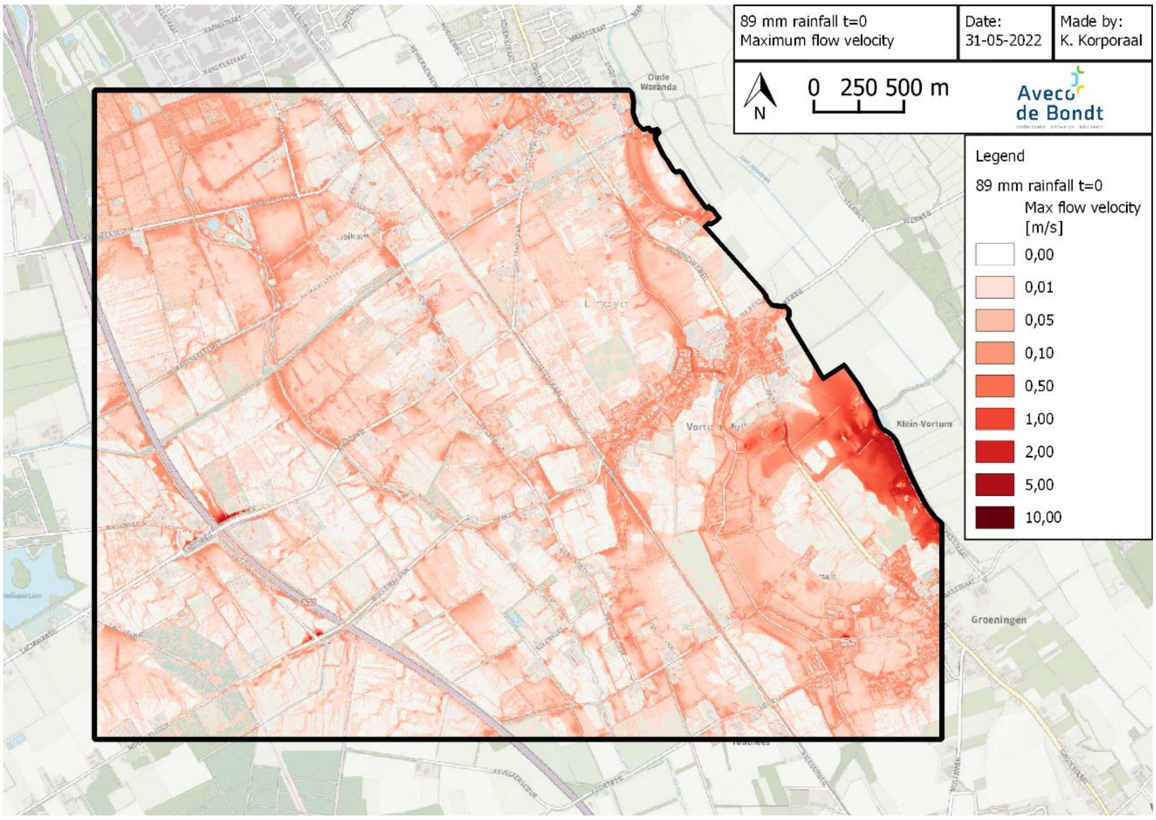


Figure 41 - Vortum Mullem - a=89 mm, t=0 min, d=2880 min - maximum flow velocity

Vortum Mullem a=89 mm, t=8640 min, d=2880 min

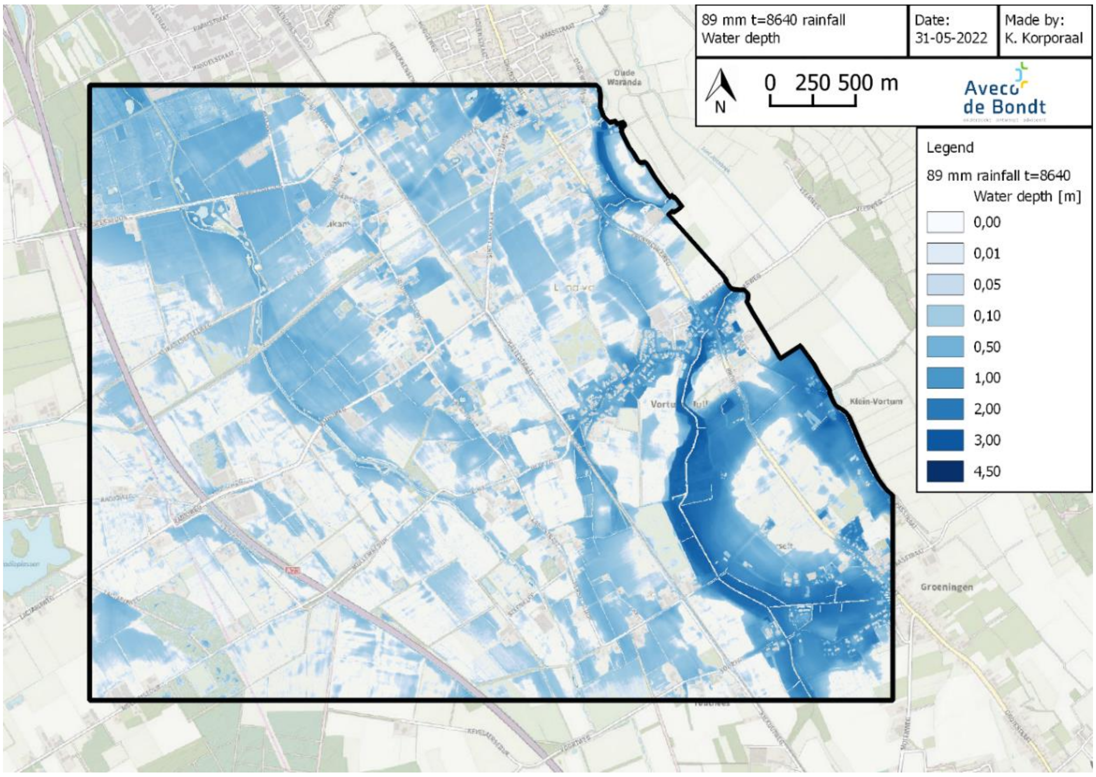


Figure 42 - Vortum Mullem - a=89 mm, t= 8640 min, d=2880 min - water depth

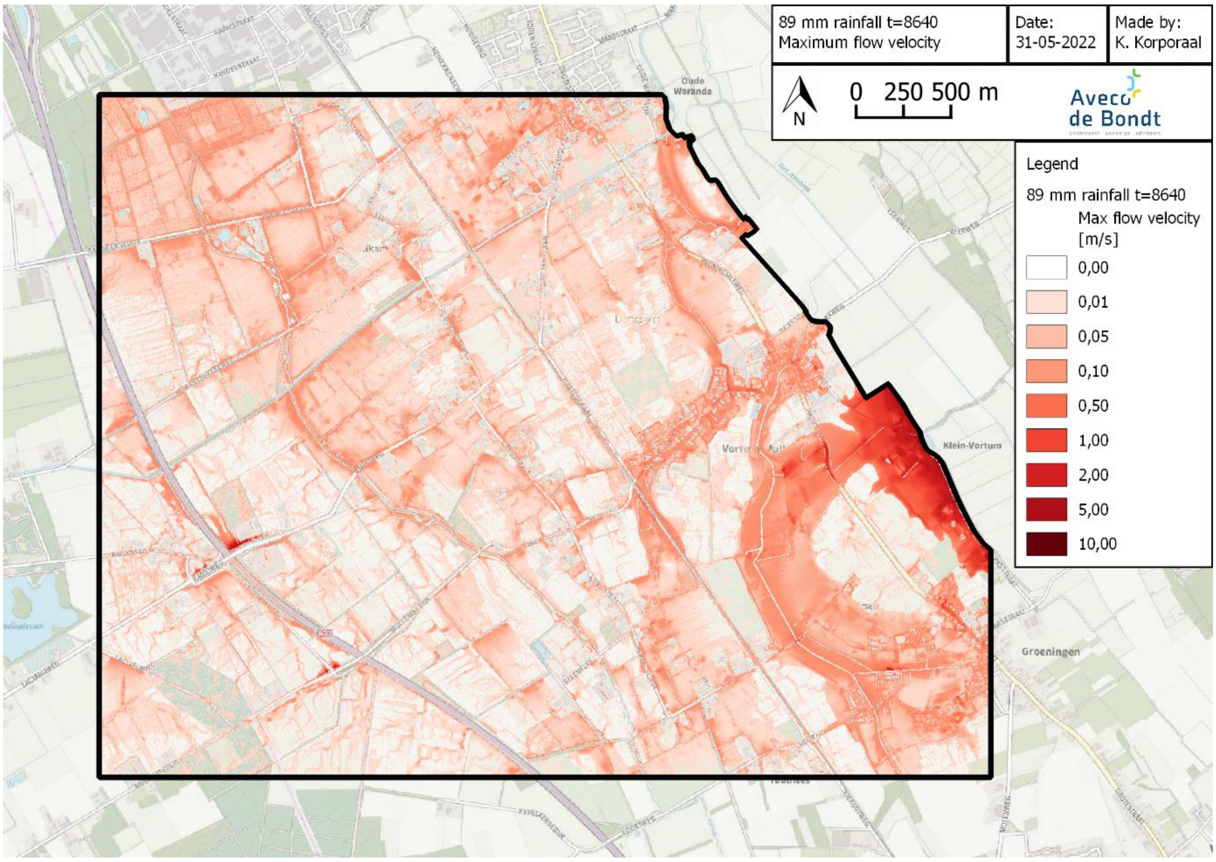


Figure 43 - Vortum Mullem - a=89 mm, t=8640 min, d=2880 min - maximum flow velocity

Vortum Mullem Minimum Manning

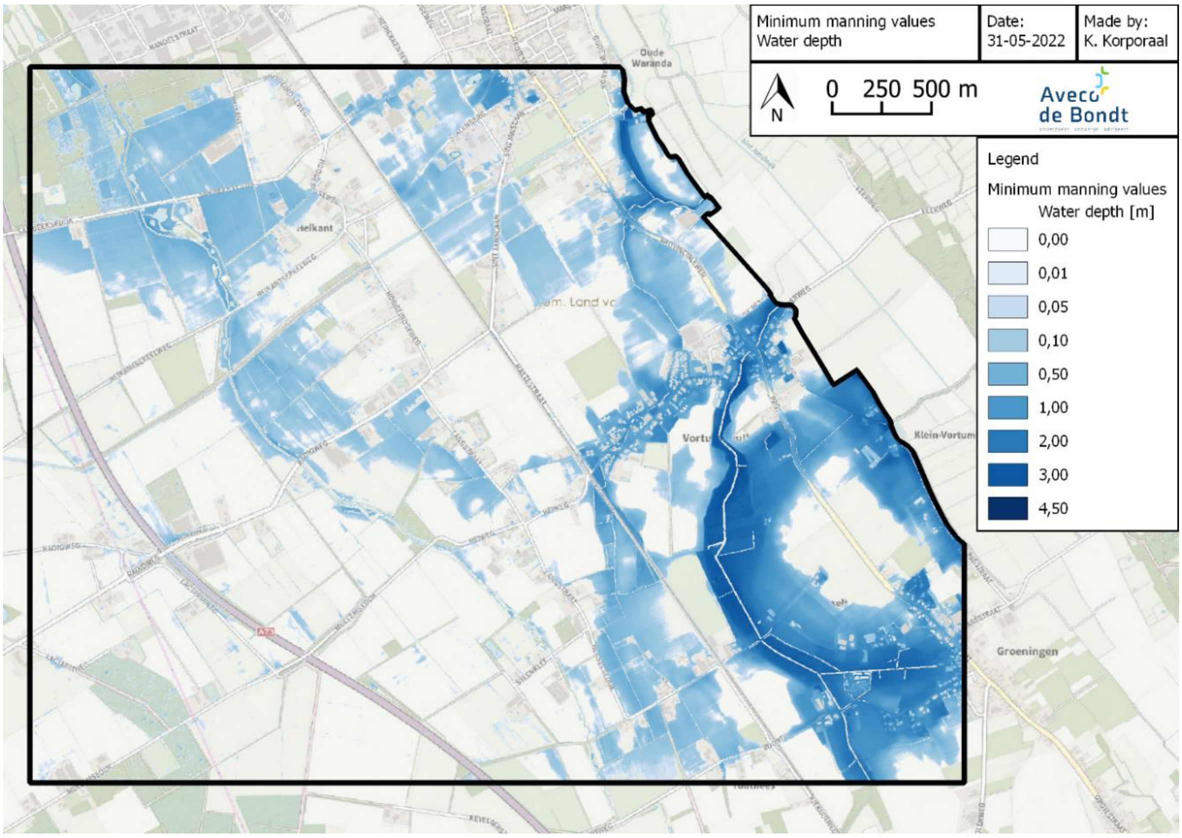


Figure 44 - Vortum Mullem - Minimum manning values - water depth

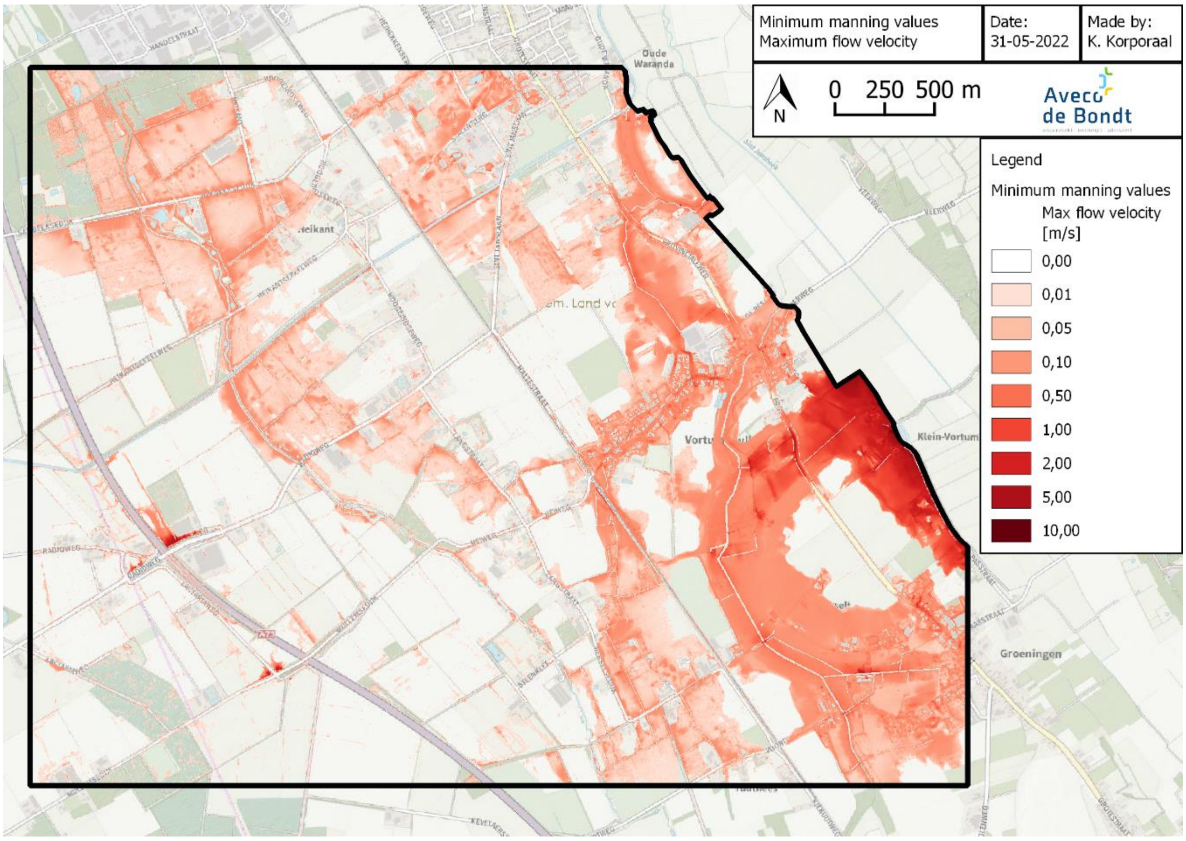


Figure 45 - Vortum Mullem - Minimum manning values - maximum flow velocity

Vortum Mullem Maximum Manning

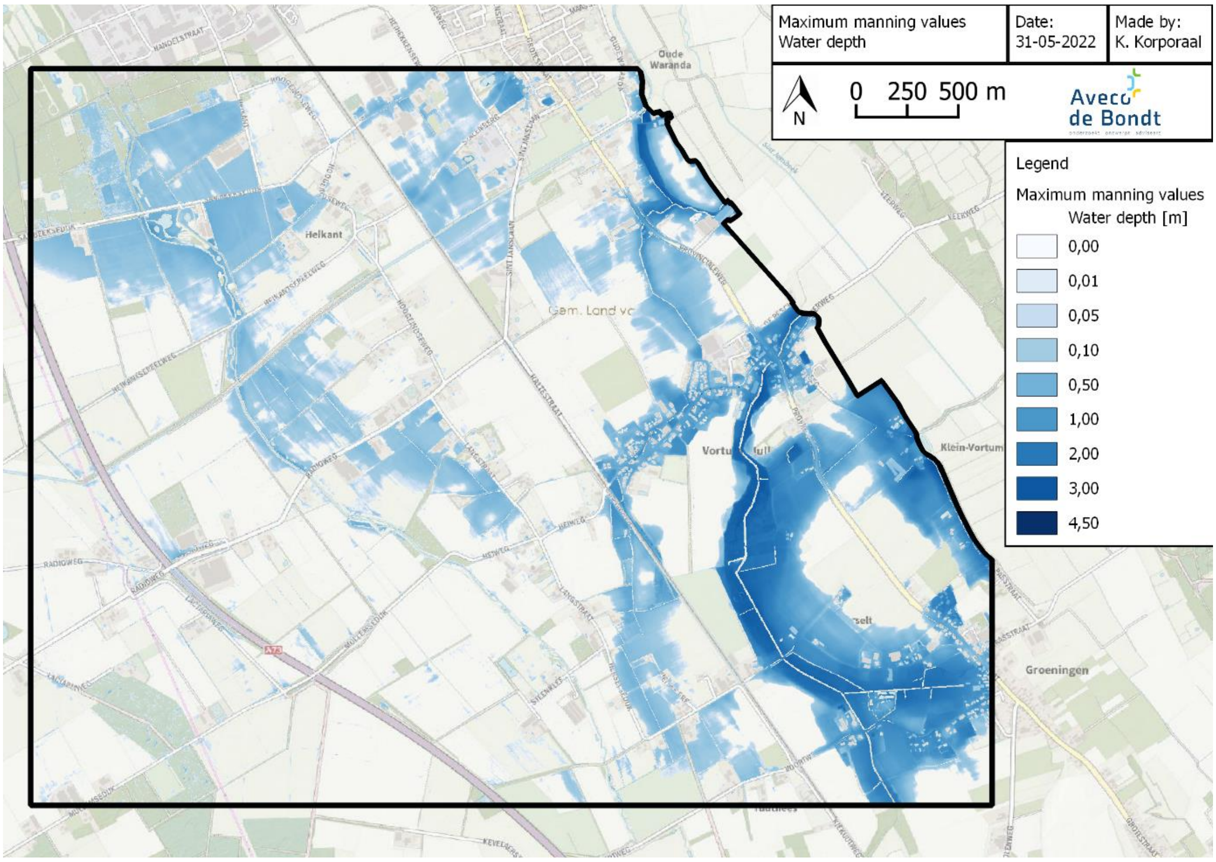


Figure 46 - Vortum Mullem - Maximum manning values - water depth

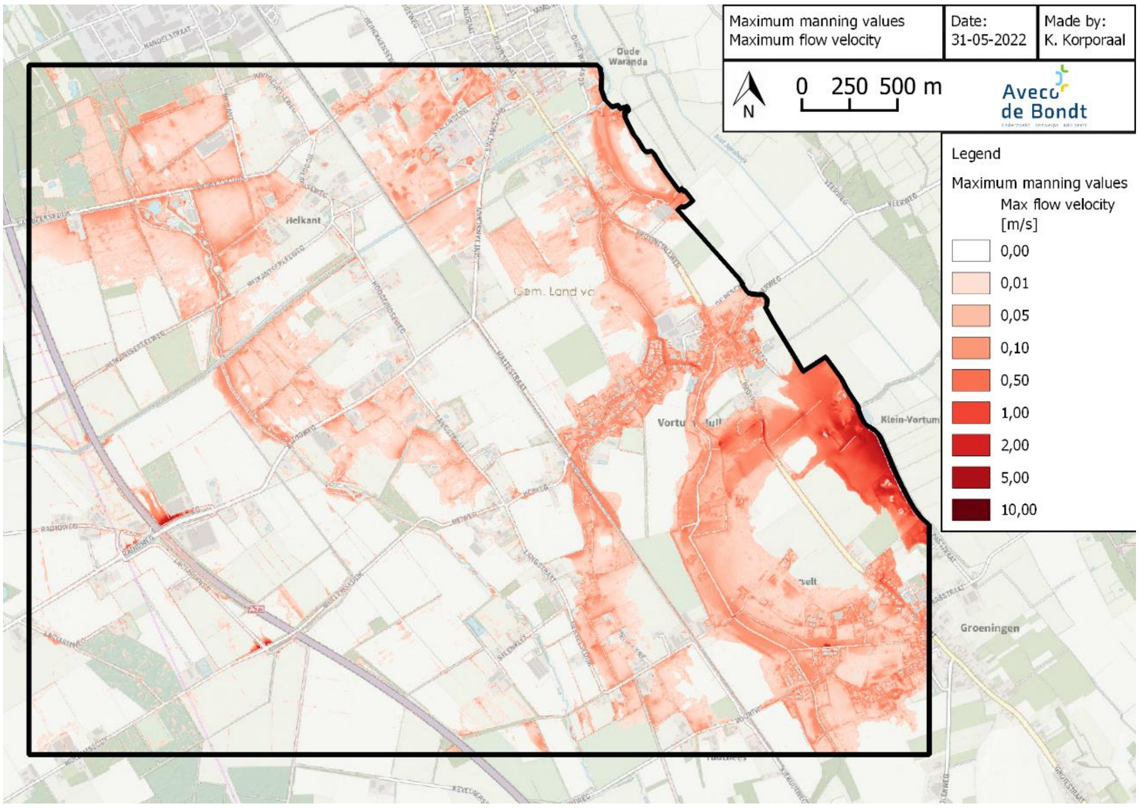


Figure 47 - Vortum Mullem- Maximum manning values - maximum flow velocity

Appendix 3 MT-Polder

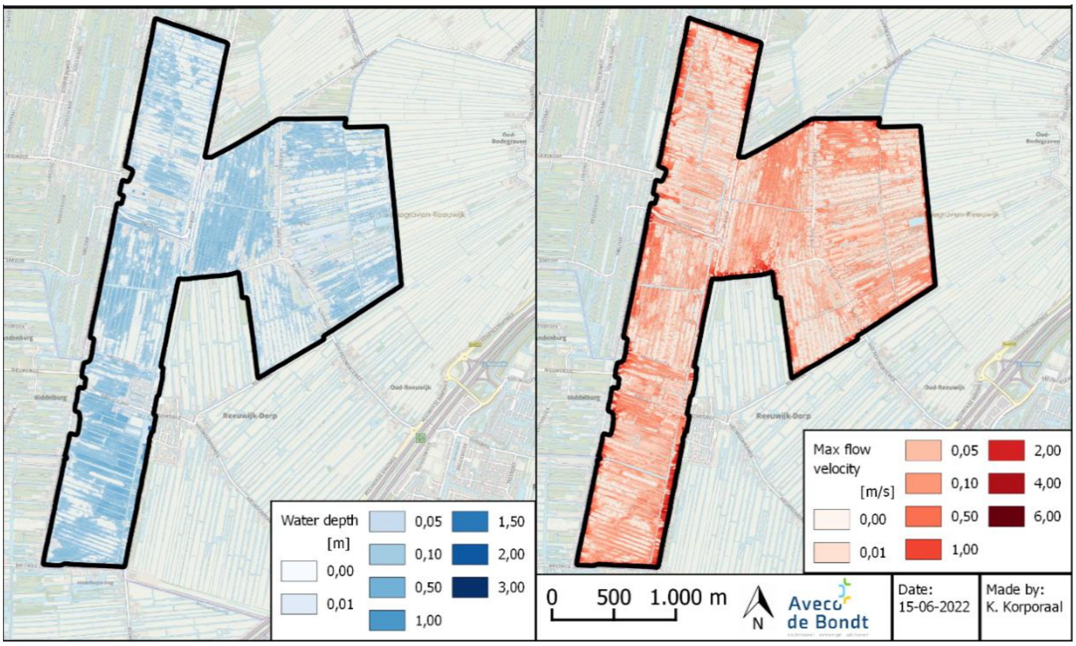


Figure 48 - MT-Polder a=40 mm, t=0 min, d=60 min

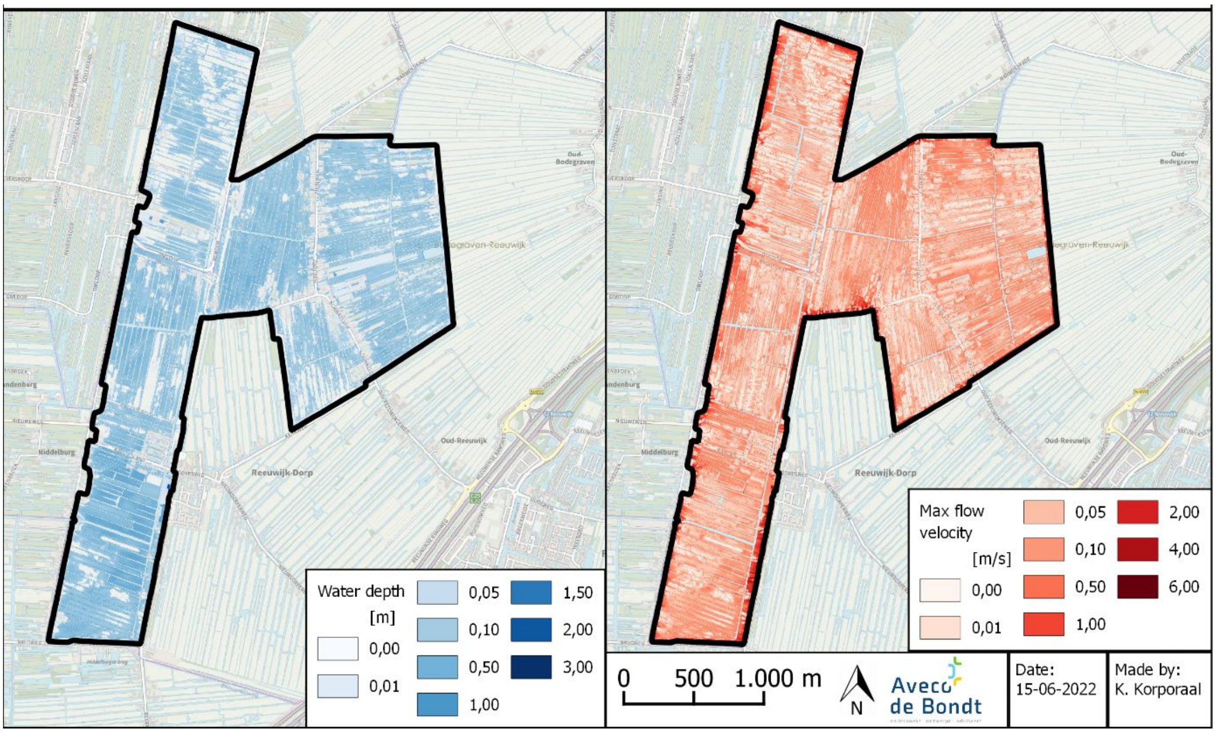


Figure 49 - MT-Polder a=70 mm, t=0 min, d=60 min

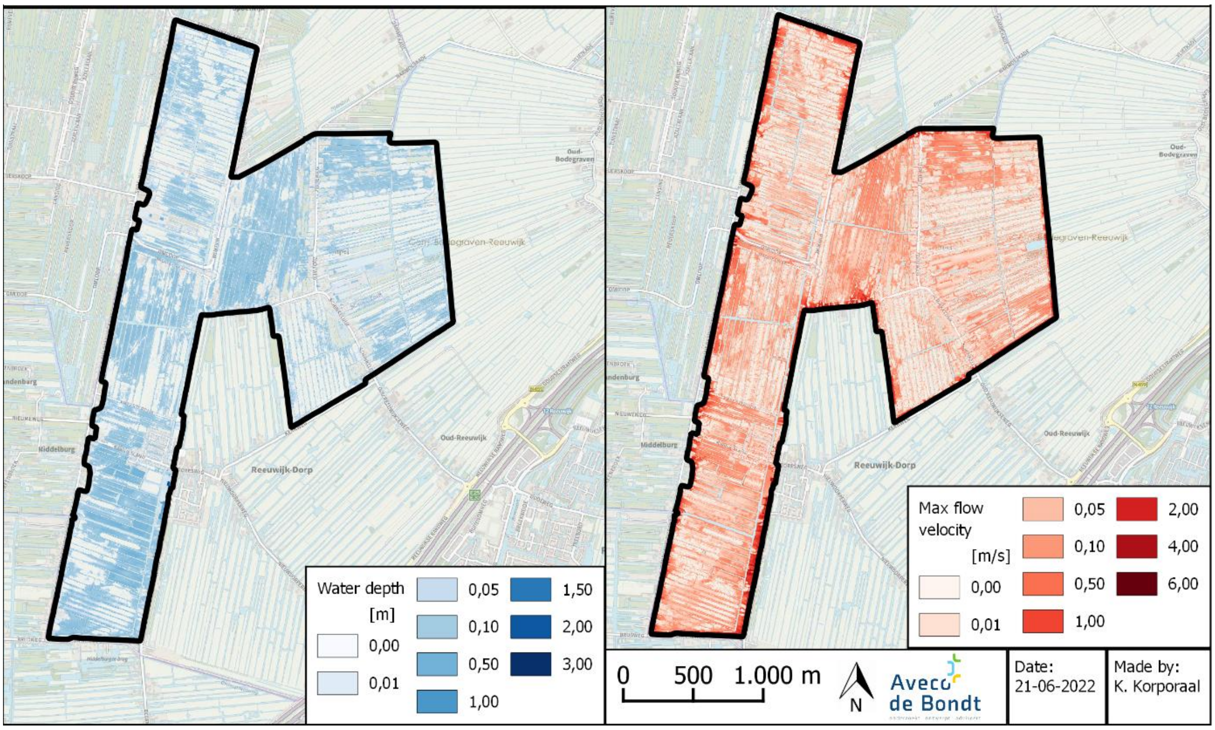


Figure 50 - MT-Polder a=40 mm, t=60 min, d=60 min

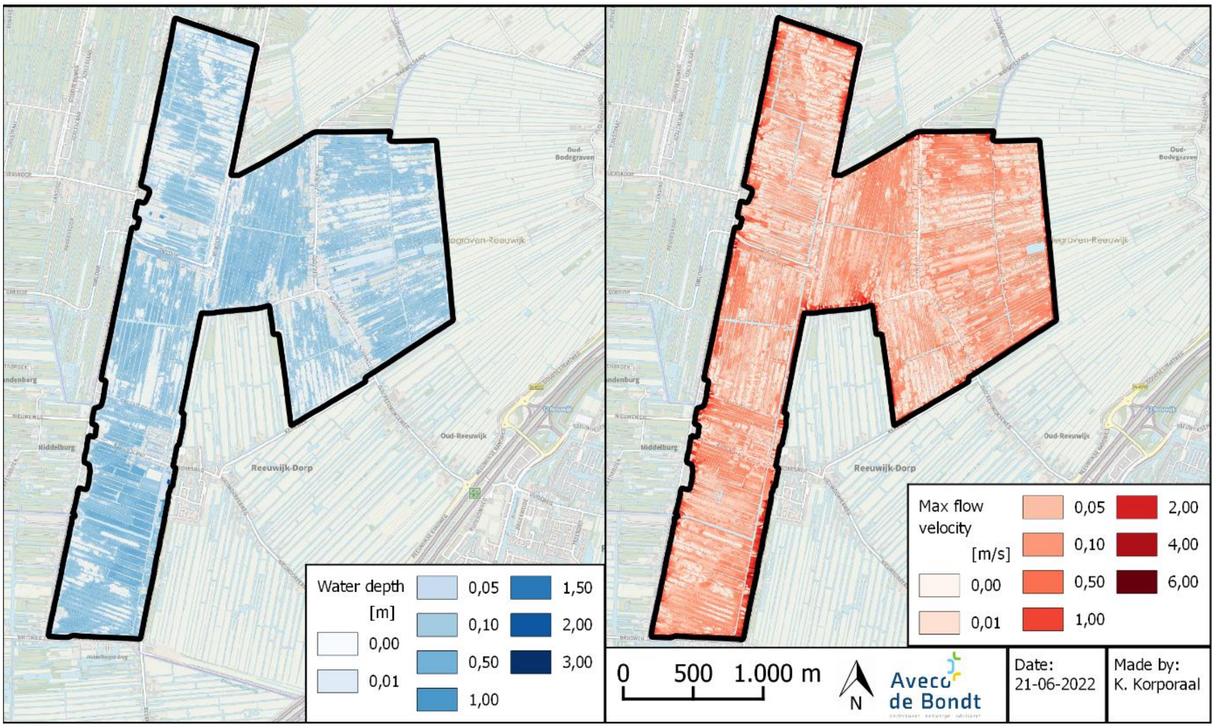


Figure 51 - MT-Polder a=70 mm, t=60 min, d=60 min

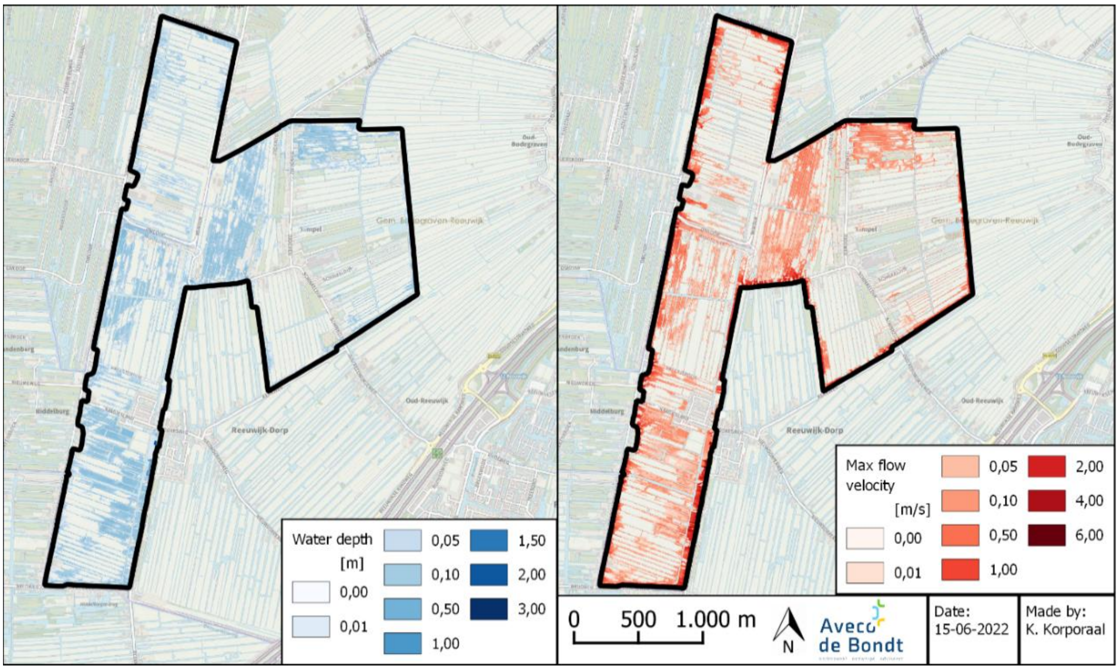


Figure 52 - MT-Polder Manning minimum

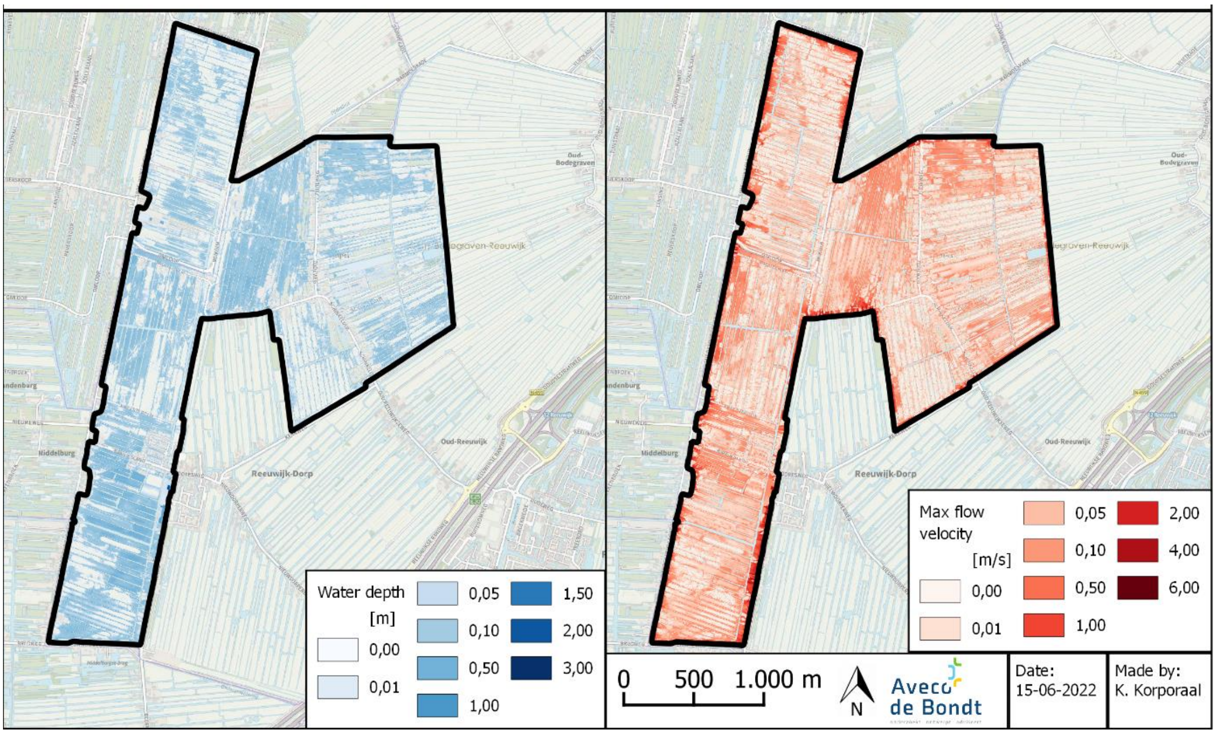


Figure 53 - MT-Polder Manning maximum

Appendix 4 Differences Precipitation

Table 15 - Overview precipitation situations compared (VM = Vortum Mullem, MT = MT-Polder)

Situation	**Compared with**
Intensity	
VM a=40 mm, t=0 min, d=60 min	VM Reference situation
VM a=40 mm, t=8640 min, d=60 min	VM Reference situation
VM a=70 mm, t=0 min, d=60 min	VM Reference situation
VM a=70 mm, t=8640 min, d=60 min	VM Reference situation
VM a=89 mm, t=0 min, d=2880 min	VM Reference situation
VM a=89 mm, t=8640 min, d=2880 min	VM Reference situation
VM a=70 mm, t=0 min, d=60 min	VM a=40 mm, t=0 min, d=60 min
VM a=70 mm, t=8640 min, d=60 min	VM a=40 mm, t=8640 min, d=60 min
MT a=40 mm, t=0 min, d=60 min	MT Reference situation
MT a=40 mm, t=60 min, d=60 min	MT Reference situation
MT a=70 mm, t=0 min, d=60 min	MT Reference situation
MT a=70 mm, t=60 min, d=60 min	MT Reference situation
MT a=70 mm, t=0 min, d=60 min	MT Reference situation
MT a=70 mm, t=60 min, d=60 min	MT Reference situation
Short and high intensity vs long and low intensity	
VM a=89 mm, t=0 min, d=2880 min	VM a=40 mm, t=0 min, d=60 min
VM a=89 mm, t=8640 min, d=2880 min	VM a=40 mm, t=8640 min, d=60 min
Moment	
VM a=40 mm, t=8640 min, d=60 min	VM a=40 mm, t=0 min, d=60 min
VM a=70 mm, t=8640 min, d=60 min	VM a=70 mm, t=0 min, d=60 min
VM a=89 mm, t=8640 min, d=2880 min	VM a=89 mm, t=0 min, d=2880 min
MT a=40 mm, t=60 min, d=60 min	MT a=40 mm, t=0 min, d=60 min
MT a=70 mm, t=60 min, d=60 min	MT a=70 mm, t=0 min, d=60 min

Intensity Vortum Mullem

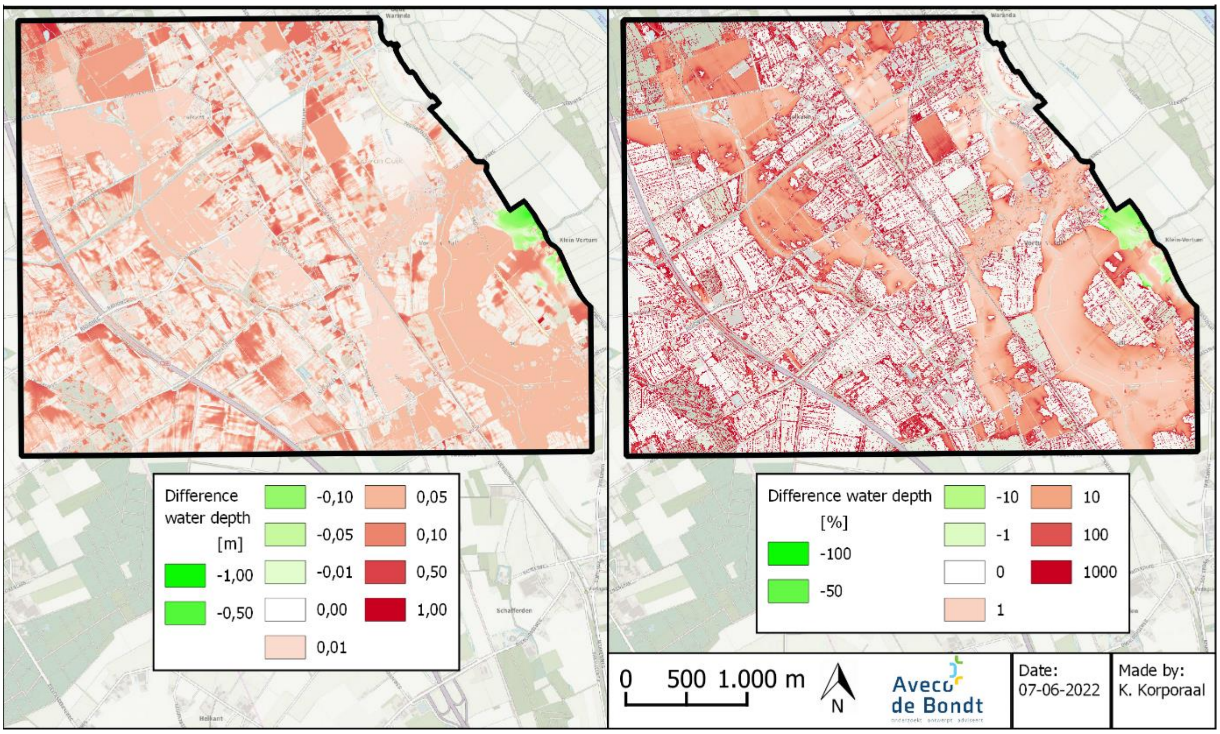


Figure 54 – Water depth differences for the precipitation situation a=40 mm, t=0 min, d=60 min in comparison with the reference situation without precipitation at Vortum Mullem. With on the left the absolute differences and on the right the relative differences.

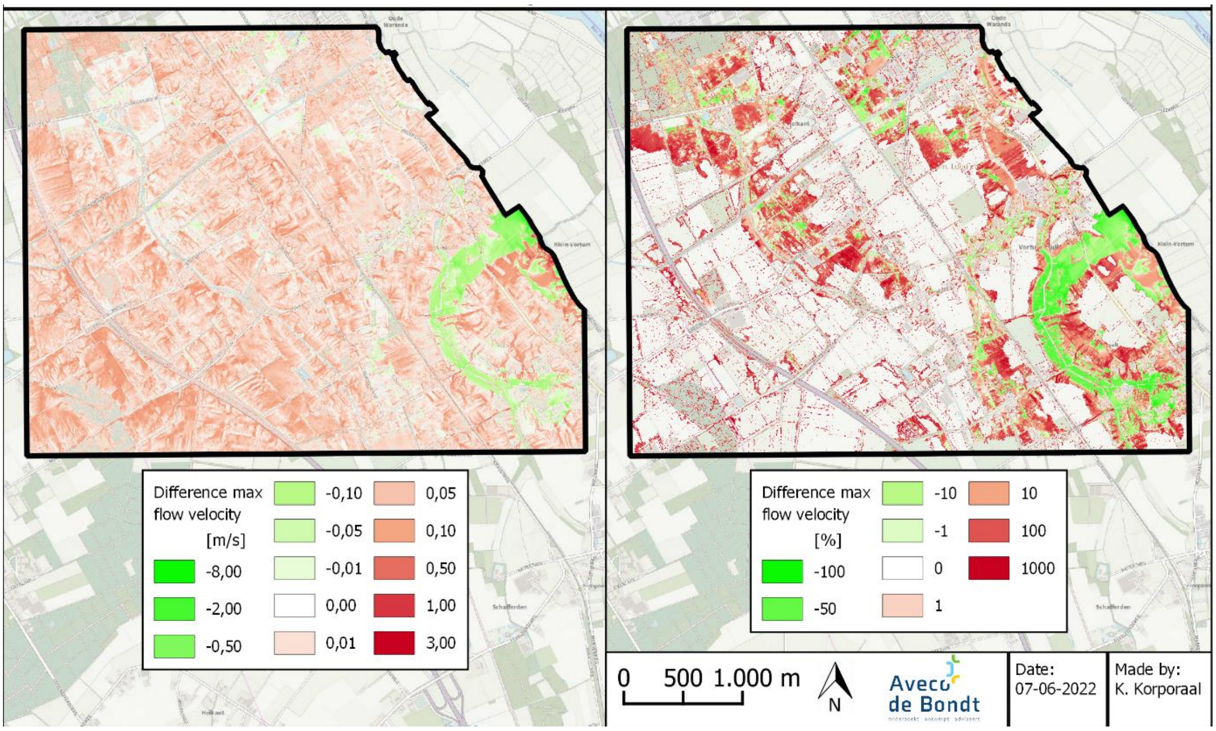


Figure 55 – Flow velocity differences for the precipitation situation a=40 mm, t=0 min, d=60 min in comparison with the reference situation without precipitation at Vortum Mullem. With on the left the absolute differences and on the right the relative differences.

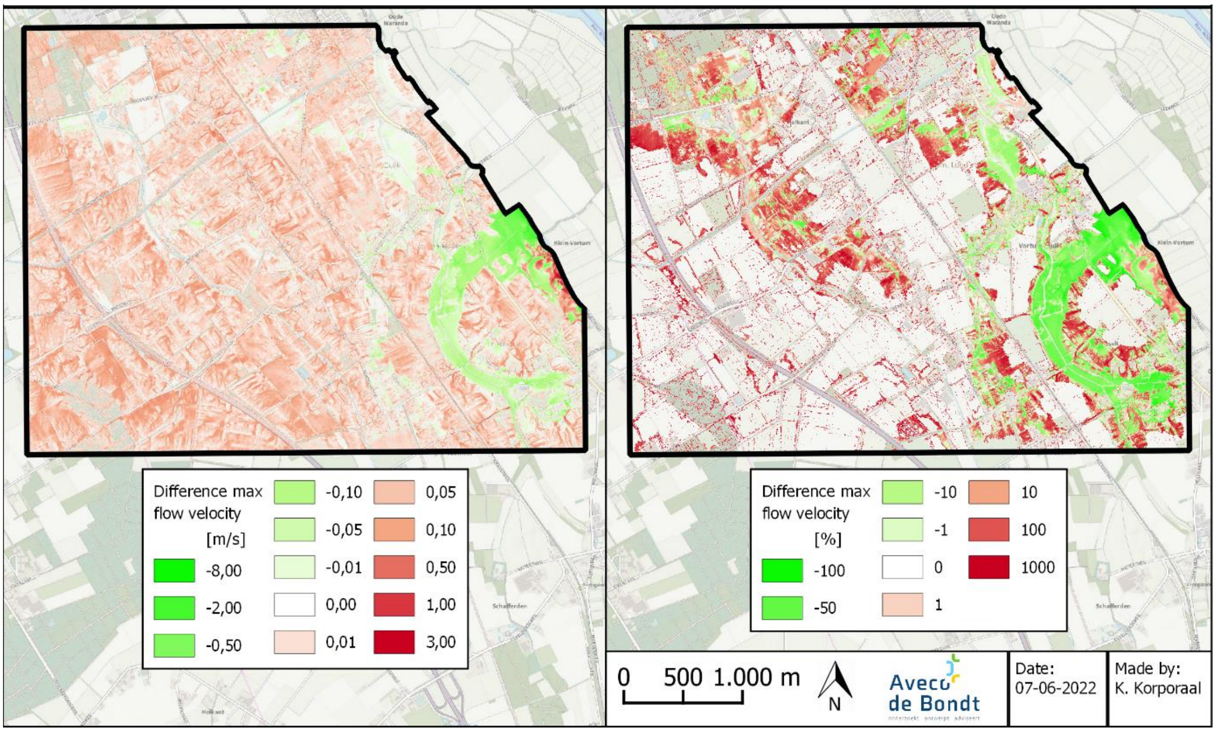


Figure 56 – Flow velocity differences for the precipitation situation a=40 mm, t=8640 min, d=60 min in comparison with the reference situation without precipitation at Vortum Mullem. With on the left the absolute differences and on the right the relative differences.

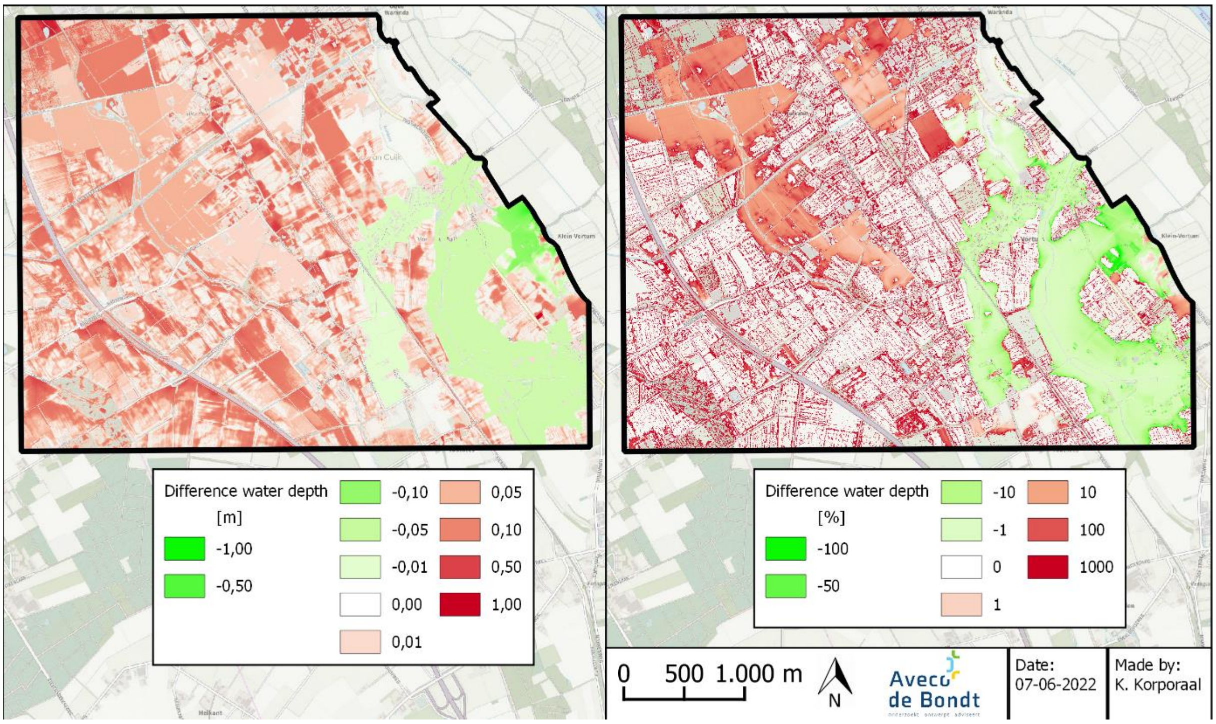


Figure 57 – Water depth differences for the precipitation situation a=70 mm, t=0 min, d=60 min in comparison with the reference situation without precipitation at Vortum Mullem. With on the left the absolute differences and on the right the relative differences.

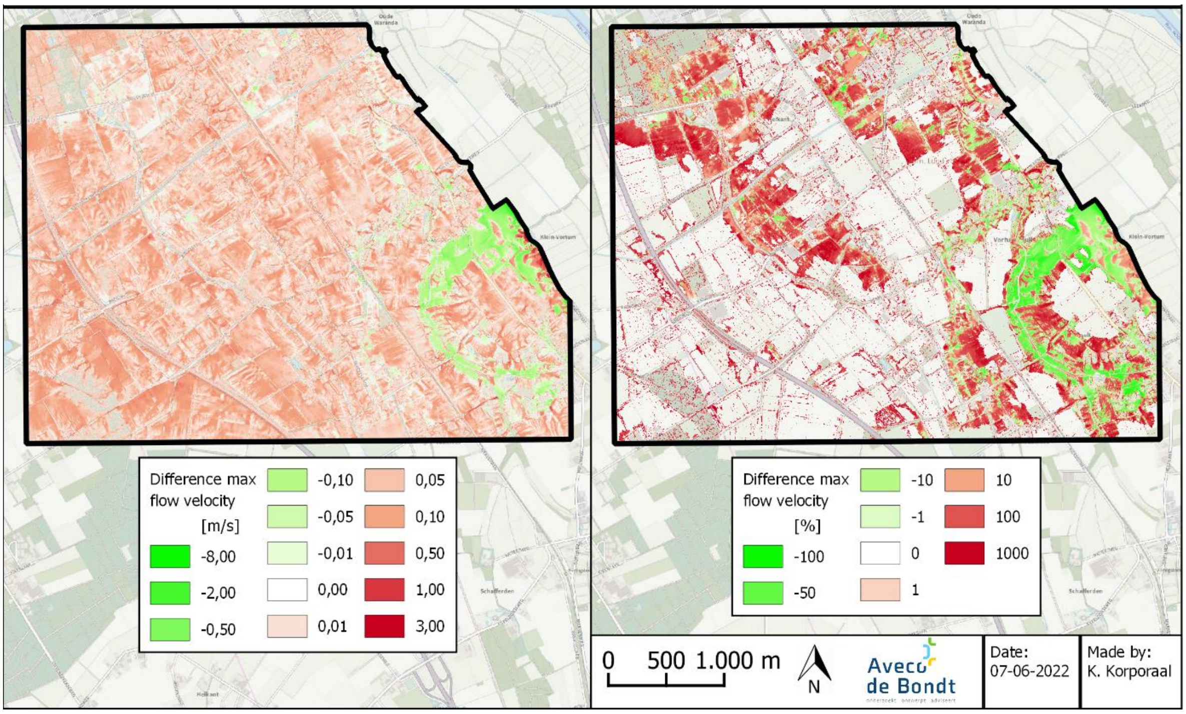


Figure 58 – Flow velocity differences for the precipitation situation a=70 mm, t=0 min, d=60 min in comparison with the reference situation without precipitation at Vortum Mullem. With on the left the absolute differences and on the right the relative differences.

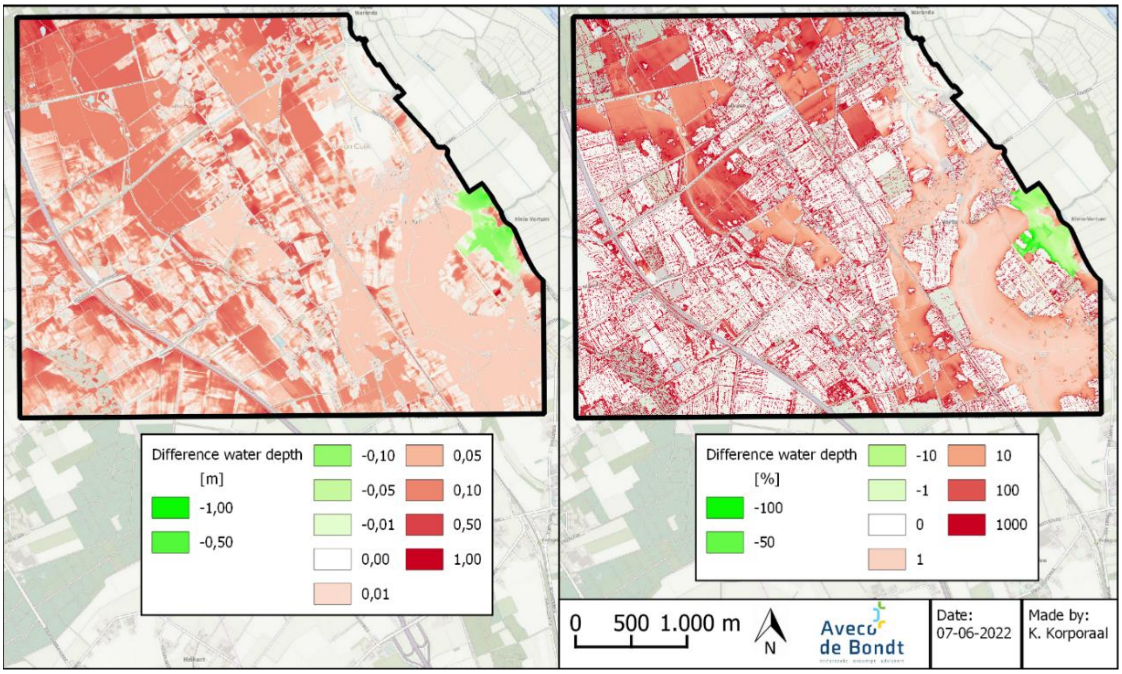


Figure 59 – Water depth differences for the precipitation situation a=70 mm, t=8640 min, d=60 min in comparison with the reference situation without precipitation at Vortum Mullem. With on the left the absolute differences and on the right the relative differences.

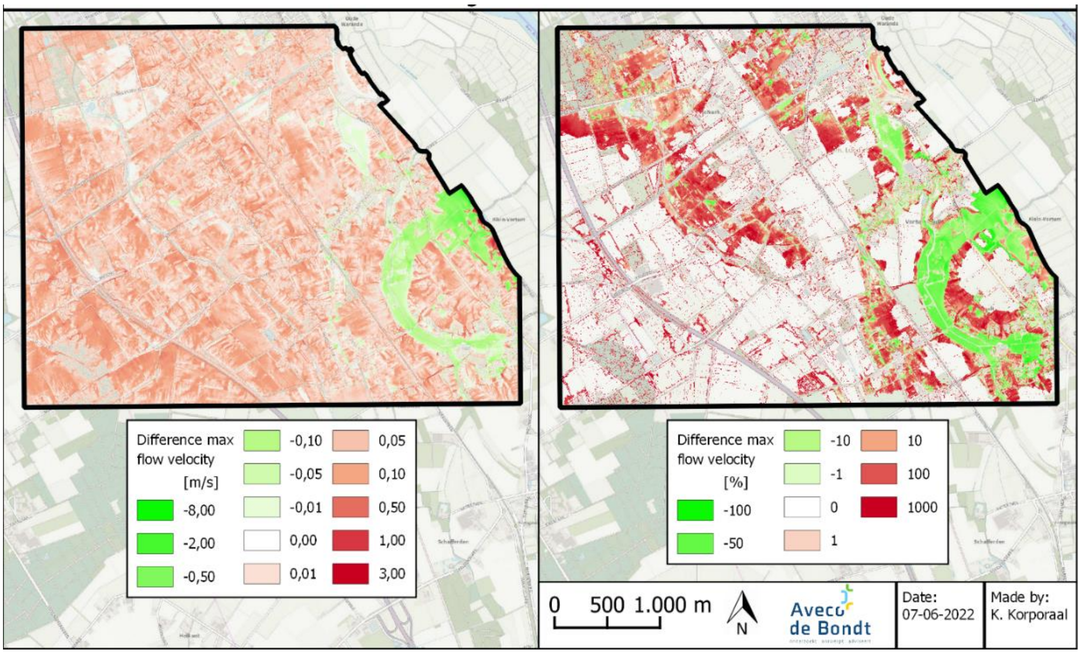


Figure 60 – Flow velocity differences for the precipitation situation a=70 mm, t=8640 min, d=60 min in comparison with the reference situation without precipitation at Vortum Mullem. With on the left the absolute differences and on the right the relative differences.

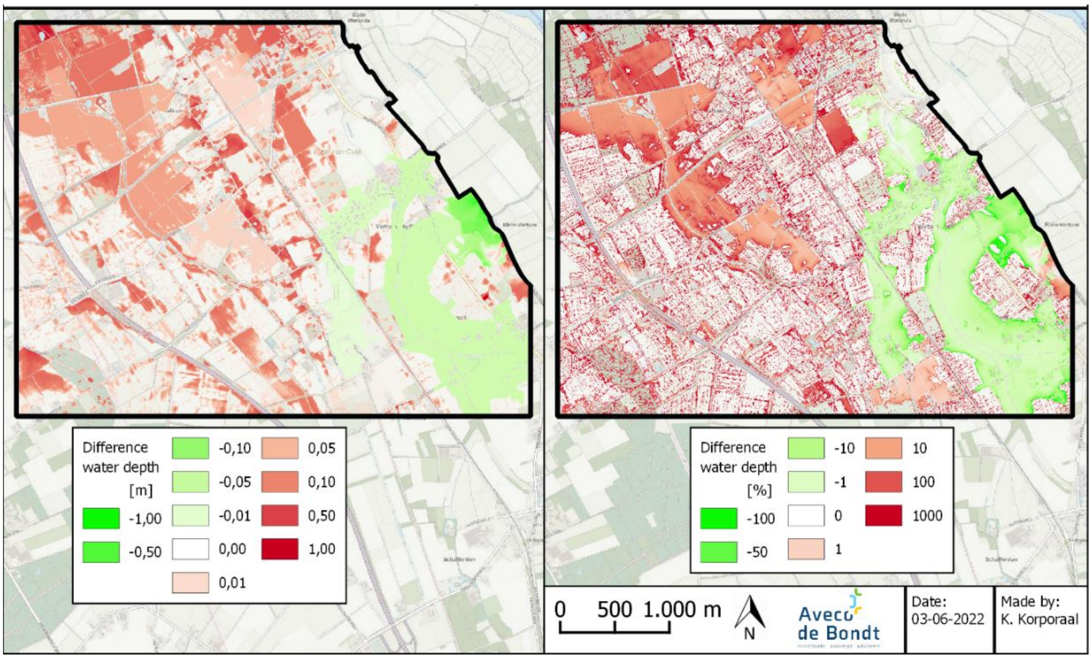


Figure 61 – Water depth differences for the precipitation situation a=89 mm, t=0 min, d=2880 min in comparison with the reference situation without precipitation at Vortum Mullem. With on the left the absolute differences and on the right the relative differences.

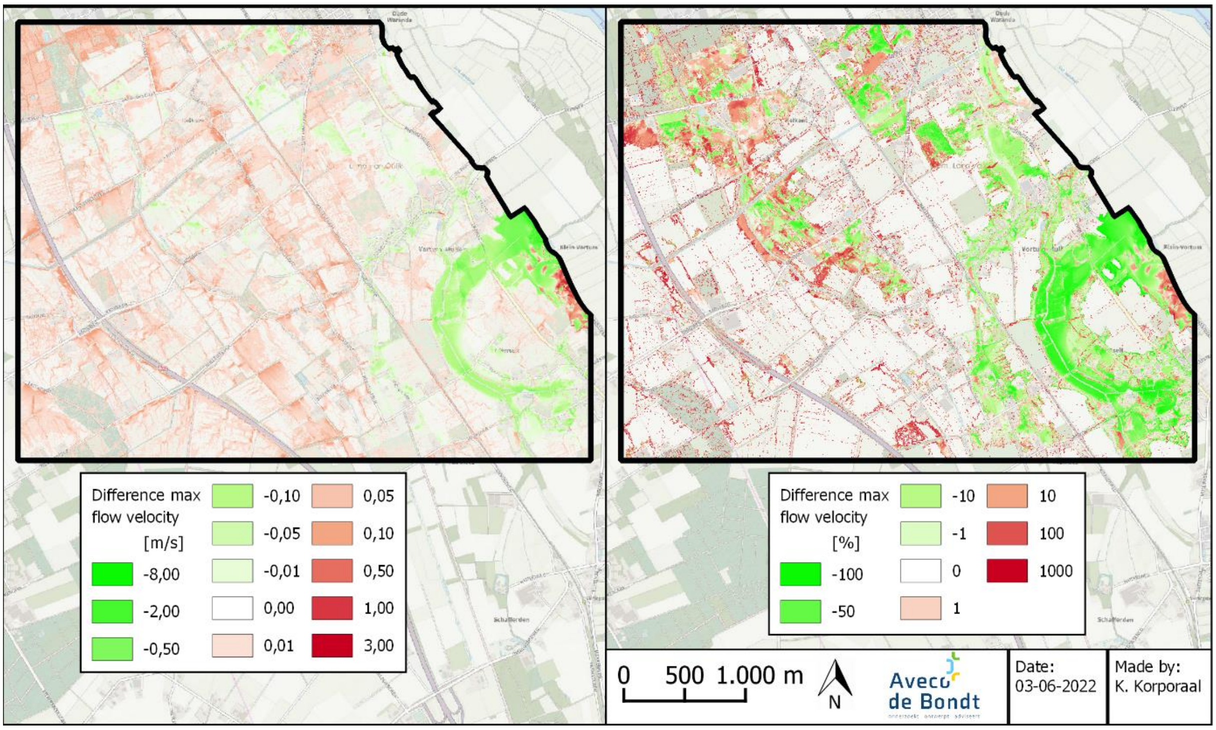


Figure 62 – Flow velocity differences for the precipitation situation a=89 mm, t=0 min, d=2880 min in comparison with the reference situation without precipitation at Vortum Mullem. With on the left the absolute differences and on the right the relative differences.

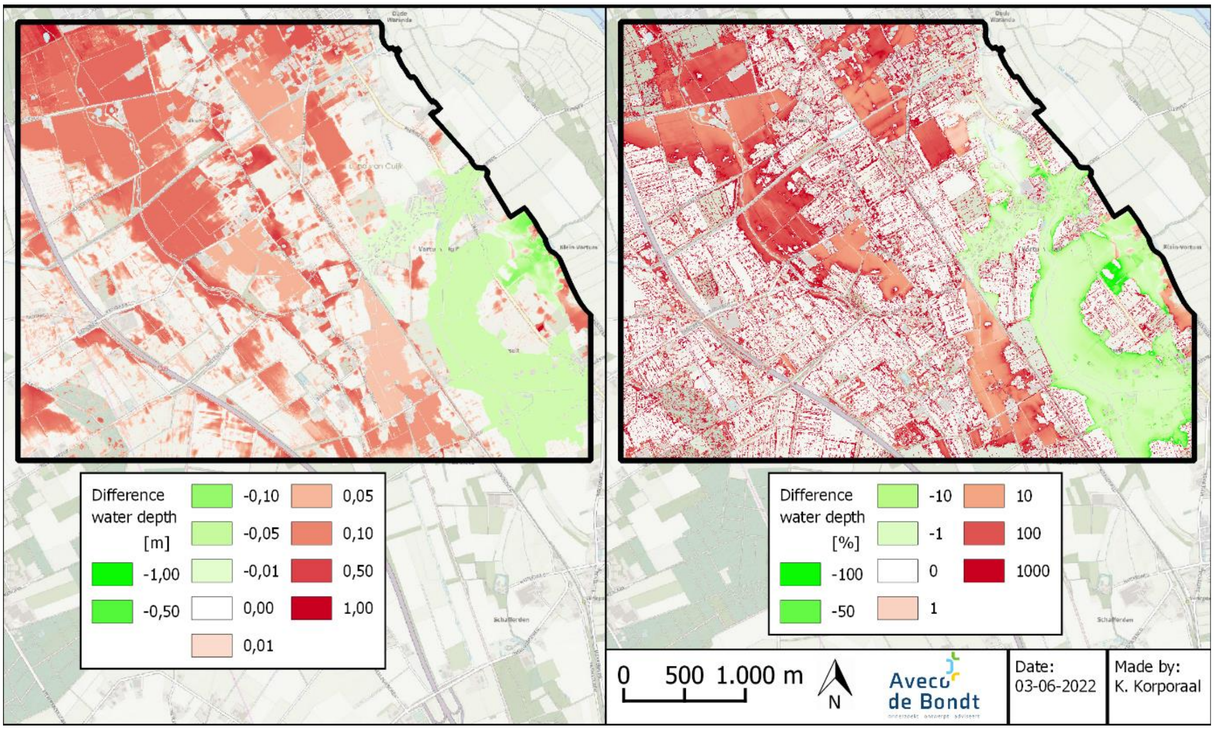


Figure 63 – Water depth differences for the precipitation situation a=89 mm, t=8640 min, d=2880 min in comparison with the reference situation without precipitation at Vortum Mullem. With on the left the absolute differences and on the right the relative differences.

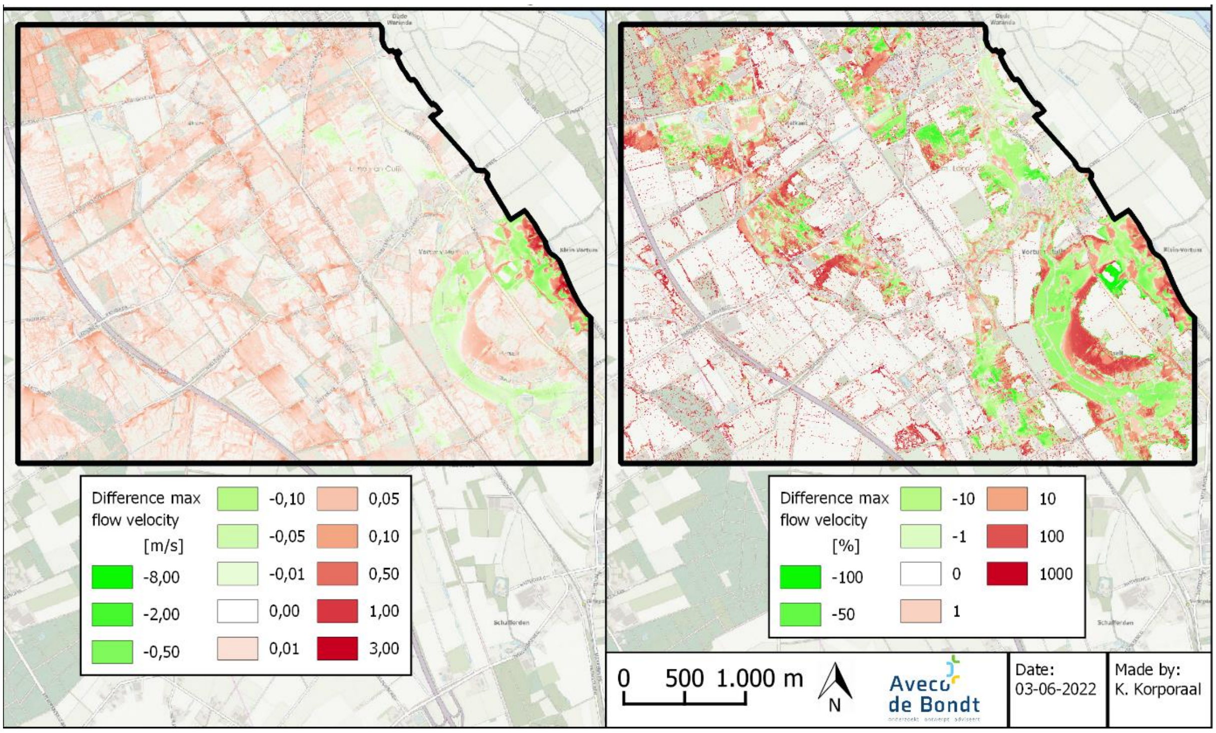


Figure 64 – Flow velocity differences for the precipitation situation a=89 mm, t=8640 min, d=2880 min in comparison with the reference situation without precipitation at Vortum Mullem. With on the left the absolute differences and on the right the relative differences.

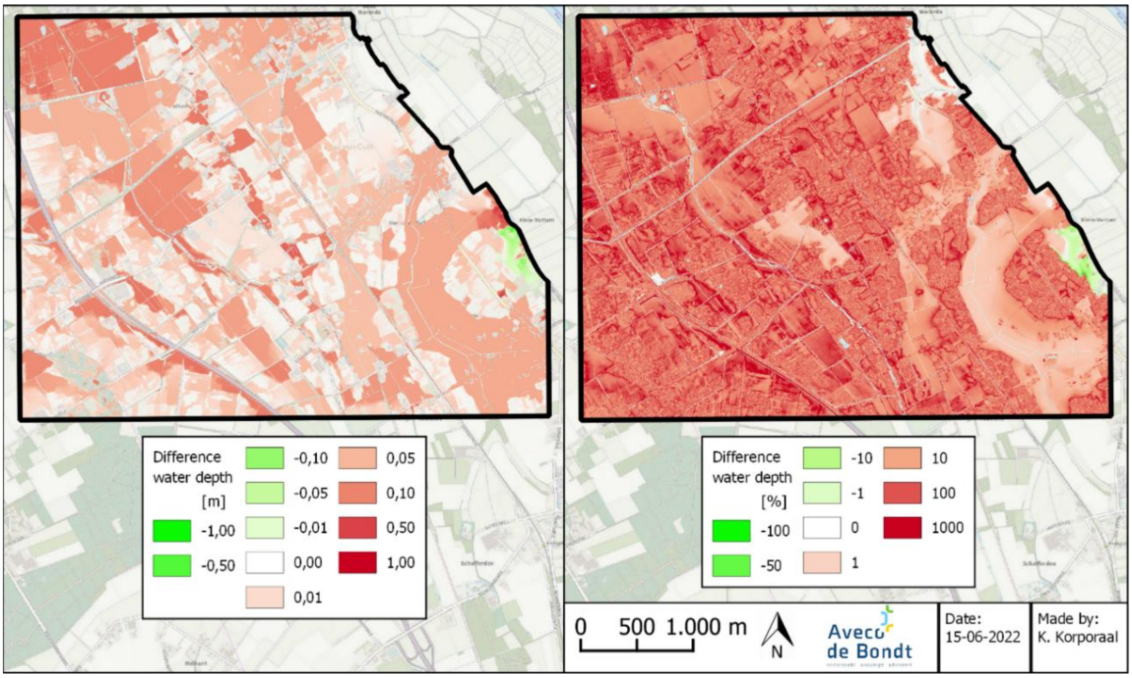


Figure 65 – Water depth differences for the precipitation situation a=70 mm, t=8640 min, d=60 min in comparison with the precipitation situation a=40 mm, t=8640 min, d=60 min at Vortum Mullem. With on the left the absolute differences and on the right the relative differences.

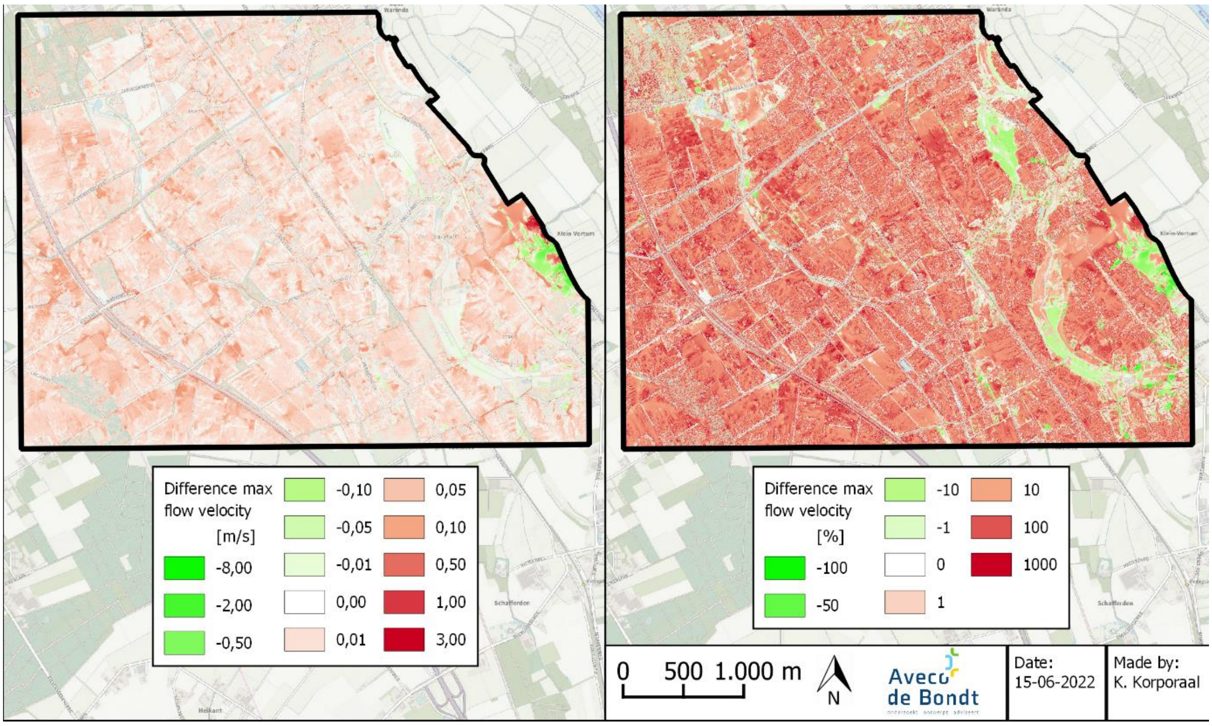


Figure 66 – Flow velocity differences for the precipitation situation a=70 mm, t=8640 min, d=60 min in comparison with the precipitation situation a=40 mm, t=8640 min, d=60 min at Vortum Mullem. With on the left the absolute differences and on the right the relative differences.

Intensity MT-Polder

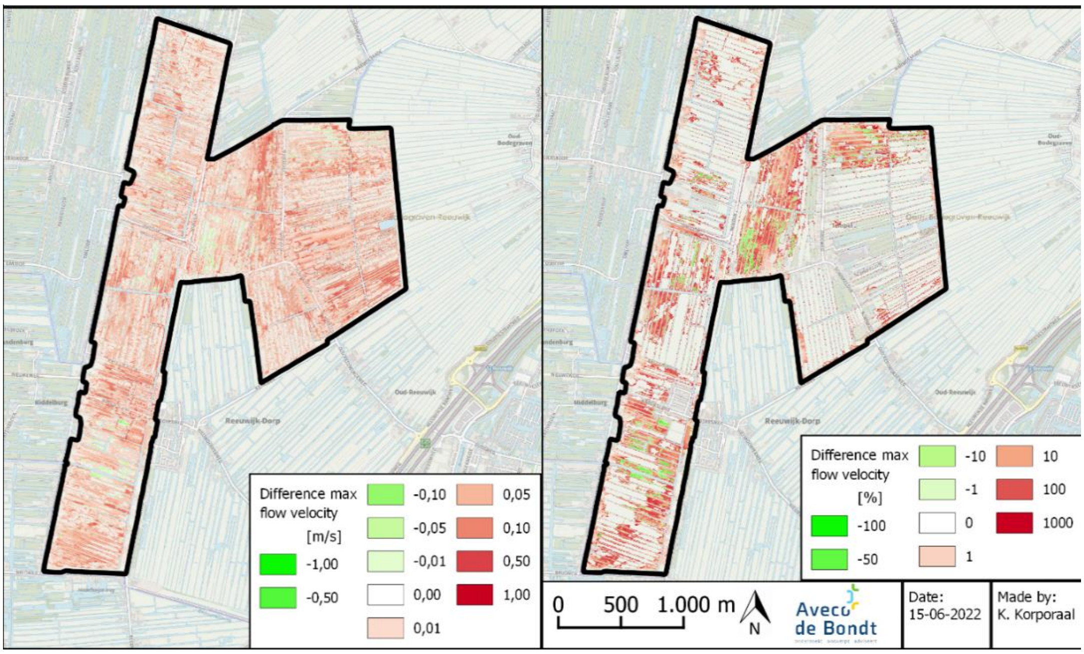


Figure 67 – Flow velocity differences for the precipitation situation a=40 mm, t=0 min, d=60 min in comparison with the reference situation without precipitation at MT-Polder. With on the left the absolute differences and on the right the relative differences.

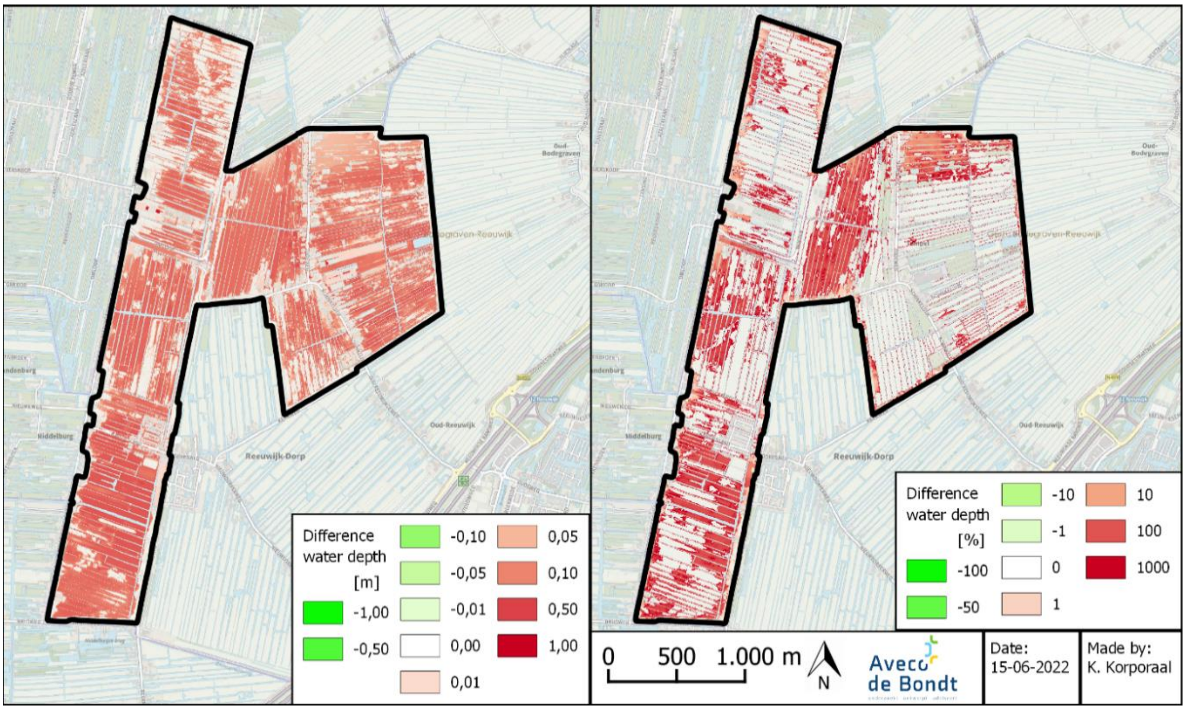


Figure 68 – Water depth differences for the precipitation situation a=70 mm, t=0 min, d=60 min in comparison with the reference situation without precipitation at MT-Polder. With on the left the absolute differences and on the right the relative differences.

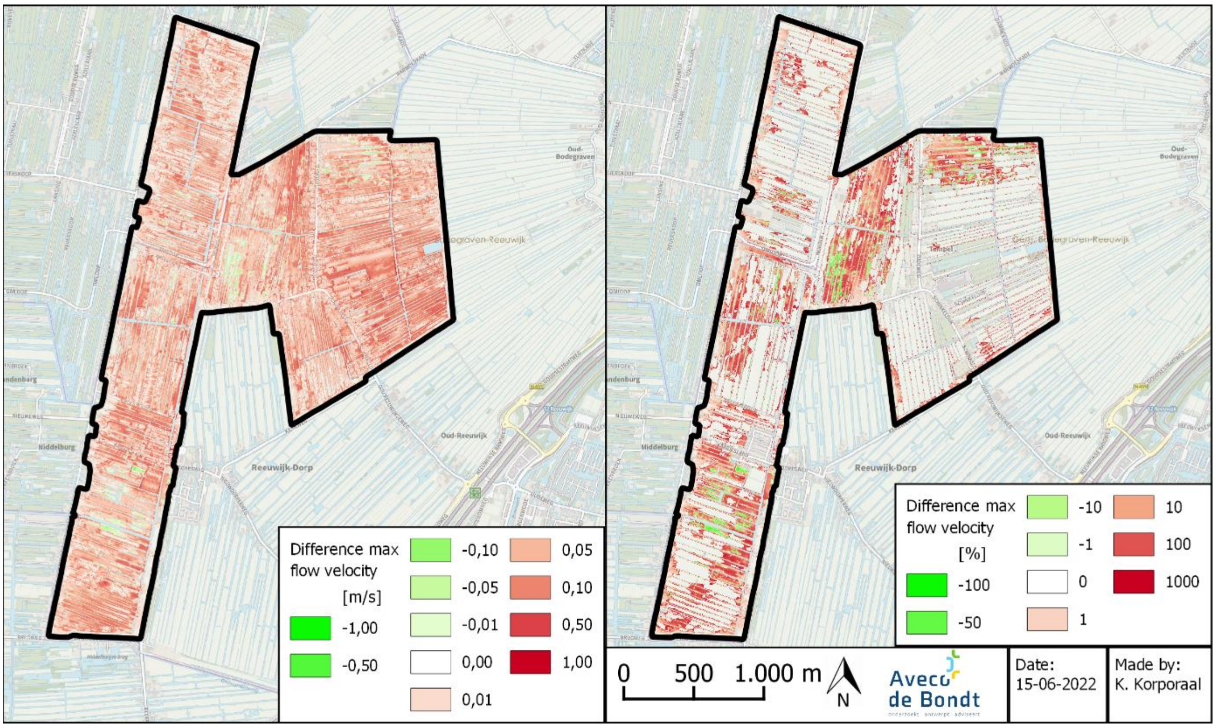


Figure 69 – Flow velocity differences for the precipitation situation a=70 mm, t=0 min, d=60 min in comparison with the reference situation without precipitation at MT-Polder. With on the left the absolute differences and on the right the relative differences.

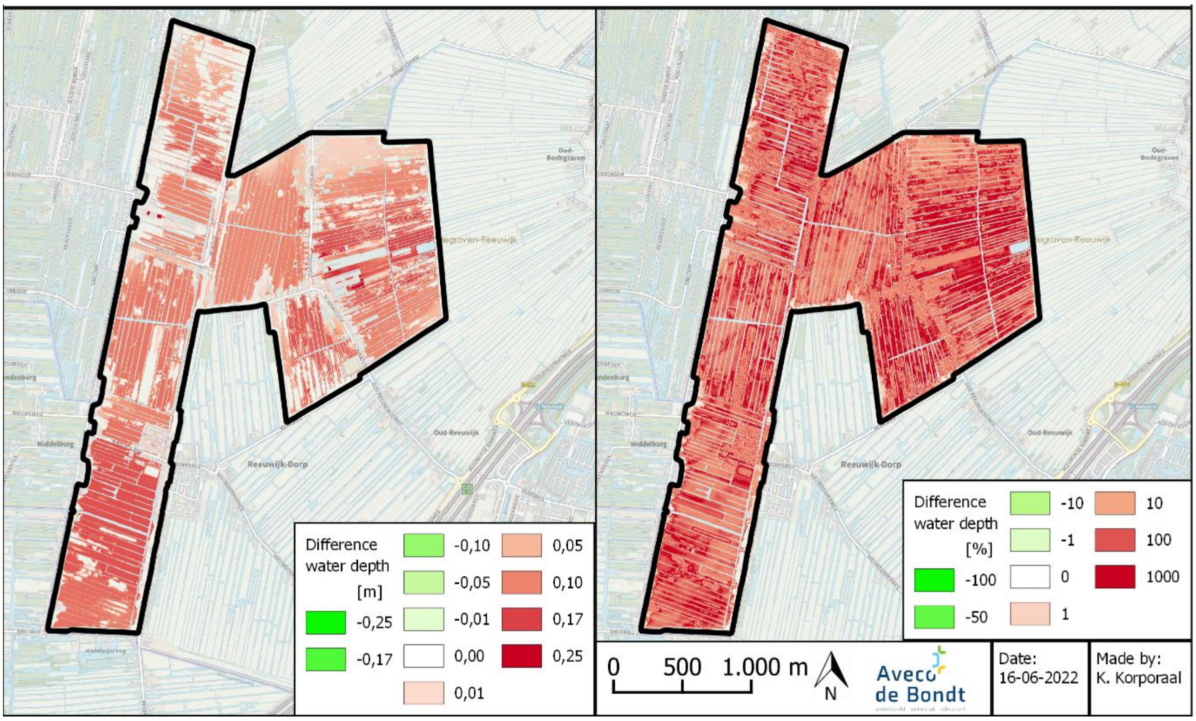


Figure 70 – Water depth differences for the precipitation situation a=70 mm, t=0 min, d=60 min in comparison with the precipitation situation a=40 mm, t=0 min, d=60 min at MT-Polder. With on the left the absolute differences and on the right the relative differences.

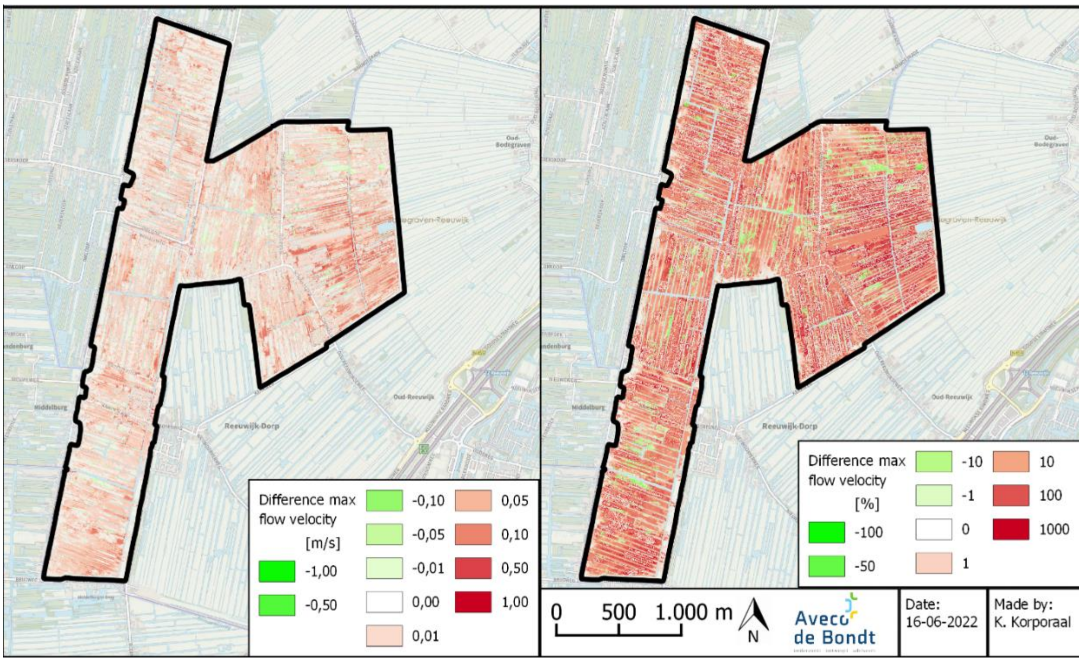


Figure 71 – Flow velocity differences for the precipitation situation a=70 mm, t=0 min, d=60 min in comparison with the precipitation situation a=40 mm, t=0 min, d=60 min at MT-Polder. With on the left the absolute differences and on the right the relative differences.

Short and high intensity vs long and low intensity Vortum Mullem

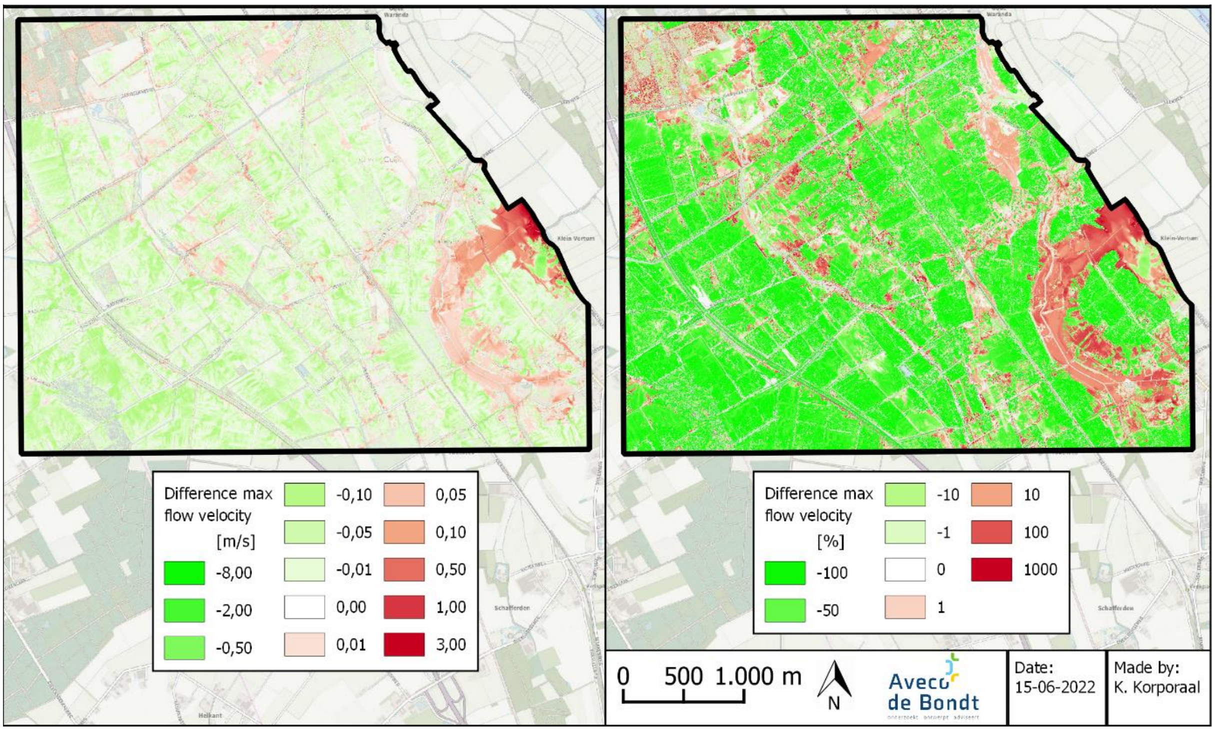


Figure 72 – Flow velocity differences for the precipitation situation a=89 mm, t=8640 min, d=2880 min in comparison with the precipitation situation a=40 mm, t=8640 min, d=60 min at Vortum Mullem. With on the left the absolute differences and on the right the relative differences.

Moment in time – Vortum Mullem

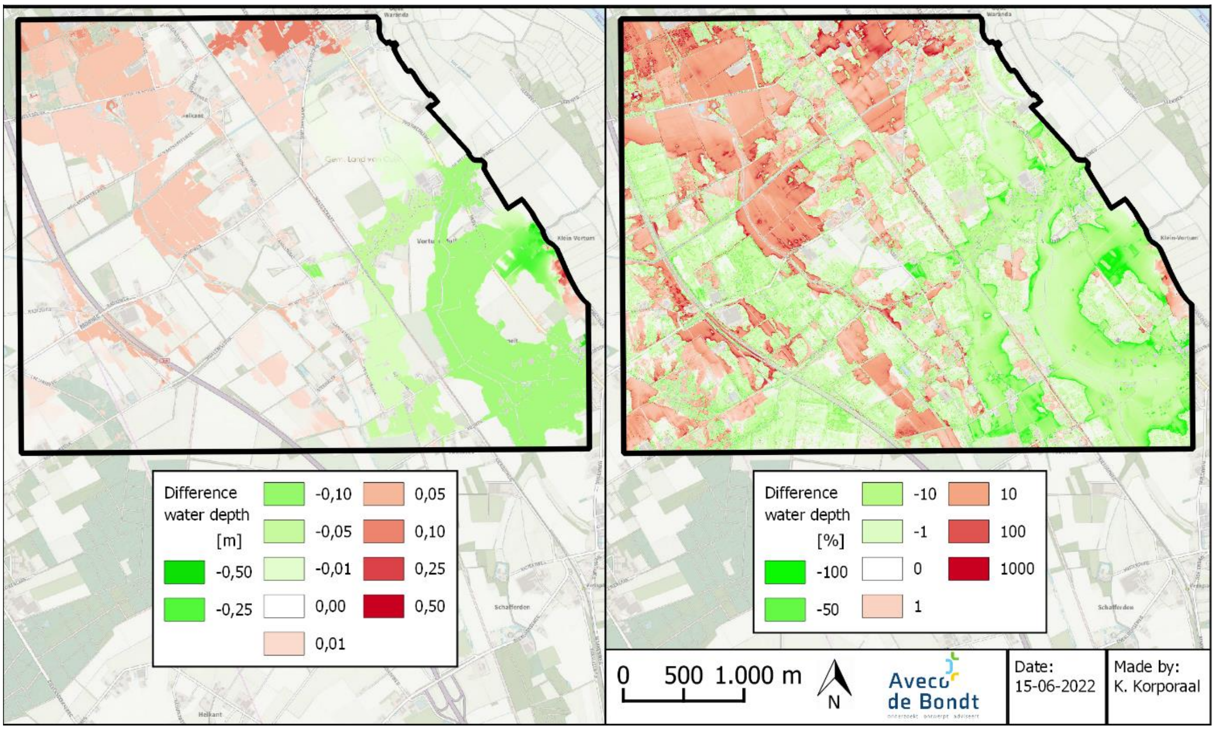


Figure 73 – Water depth differences for the precipitation situation a=40 mm, t=8640 min, d=60 min in comparison with the precipitation situation a=40 mm, t=0 min, d=60 min at Vortum Mullem. With on the left the absolute differences and on the right the relative differences.

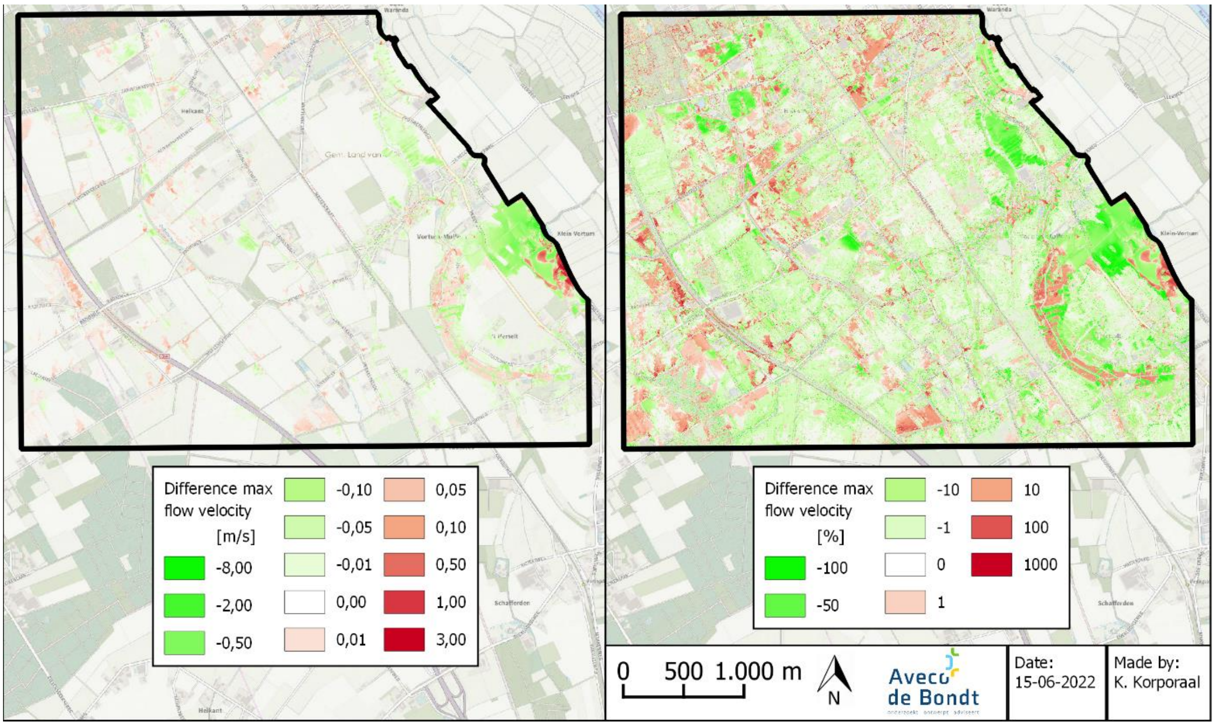


Figure 74 – Flow velocity differences for the precipitation situation a=40 mm, t=8640 min, d=60 min in comparison with the precipitation situation a=40 mm, t=0 min, d=60 min at Vortum Mullem. With on the left the absolute differences and on the right the relative differences.

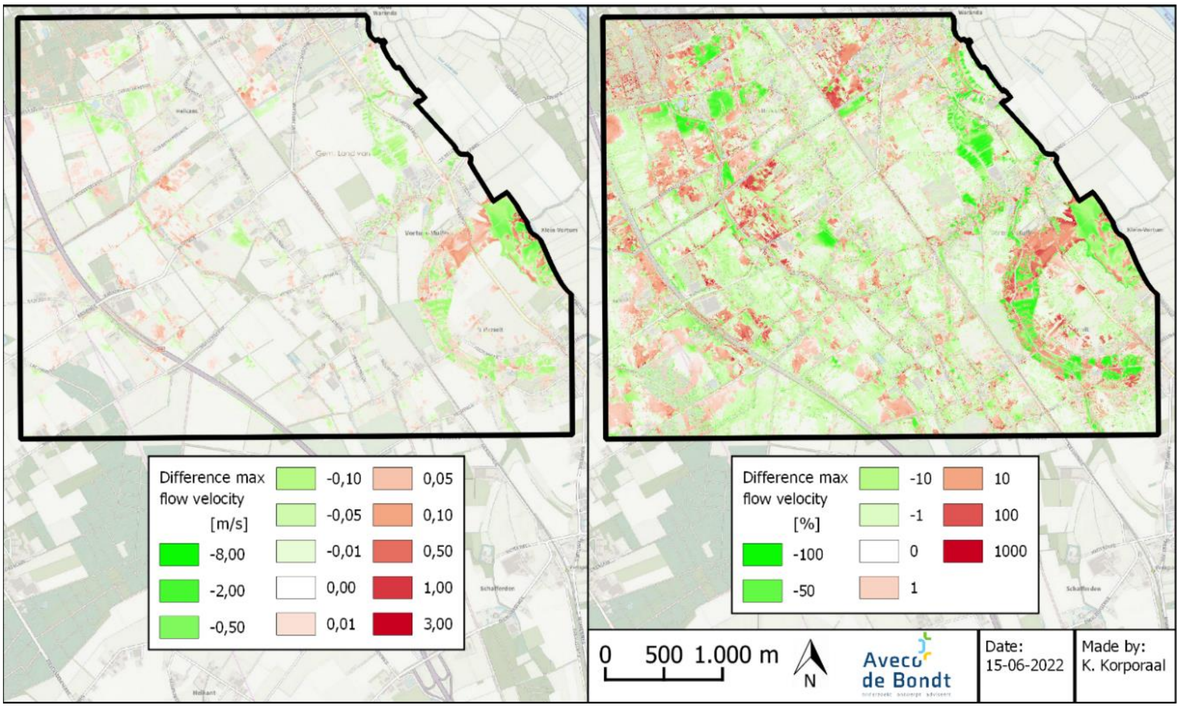


Figure 75 – Flow velocity differences for the precipitation situation a=70 mm, t=8640 min, d=60 min in comparison with the precipitation situation a=40 mm, t=0 min, d=60 min at Vortum Mullem. With on the left the absolute differences and on the right the relative differences.

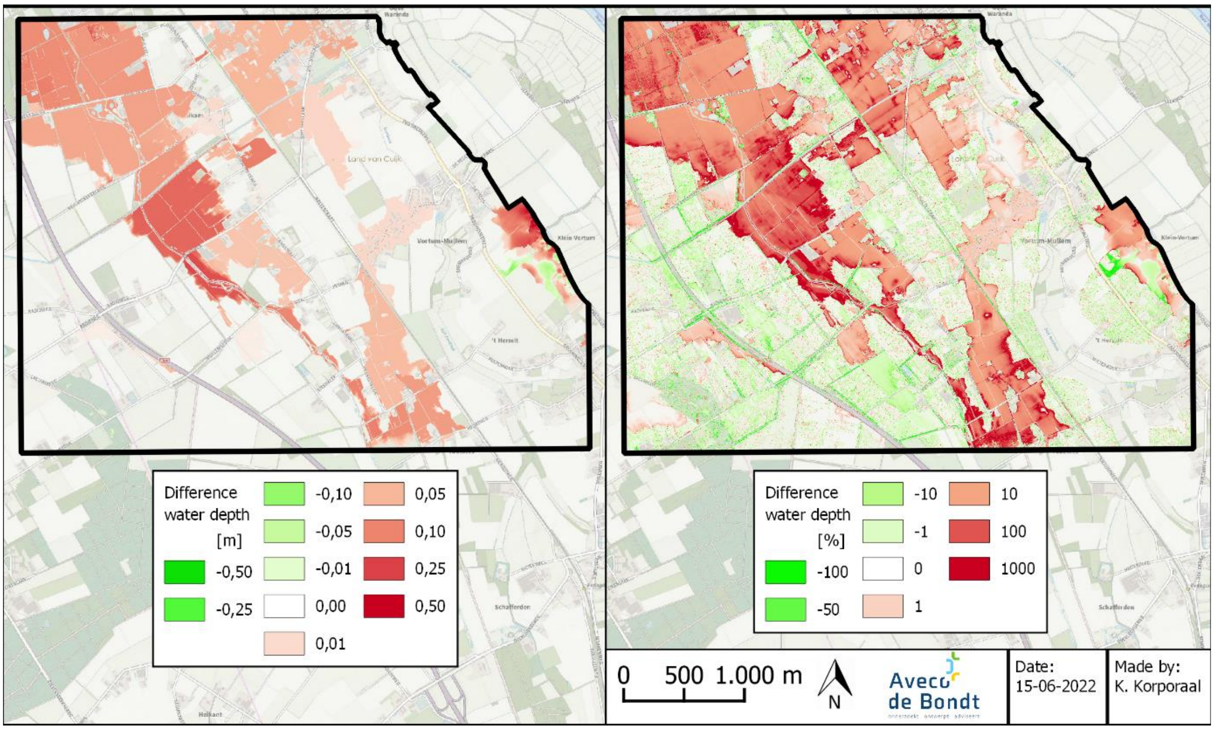


Figure 76 – Water depth differences for the precipitation situation a=89 mm, t=8640 min, d=2880 min in comparison with the precipitation situation a=89 mm, t=0 min, d=2880 min at Vortum Mullem. With on the left the absolute differences and on the right the relative differences.

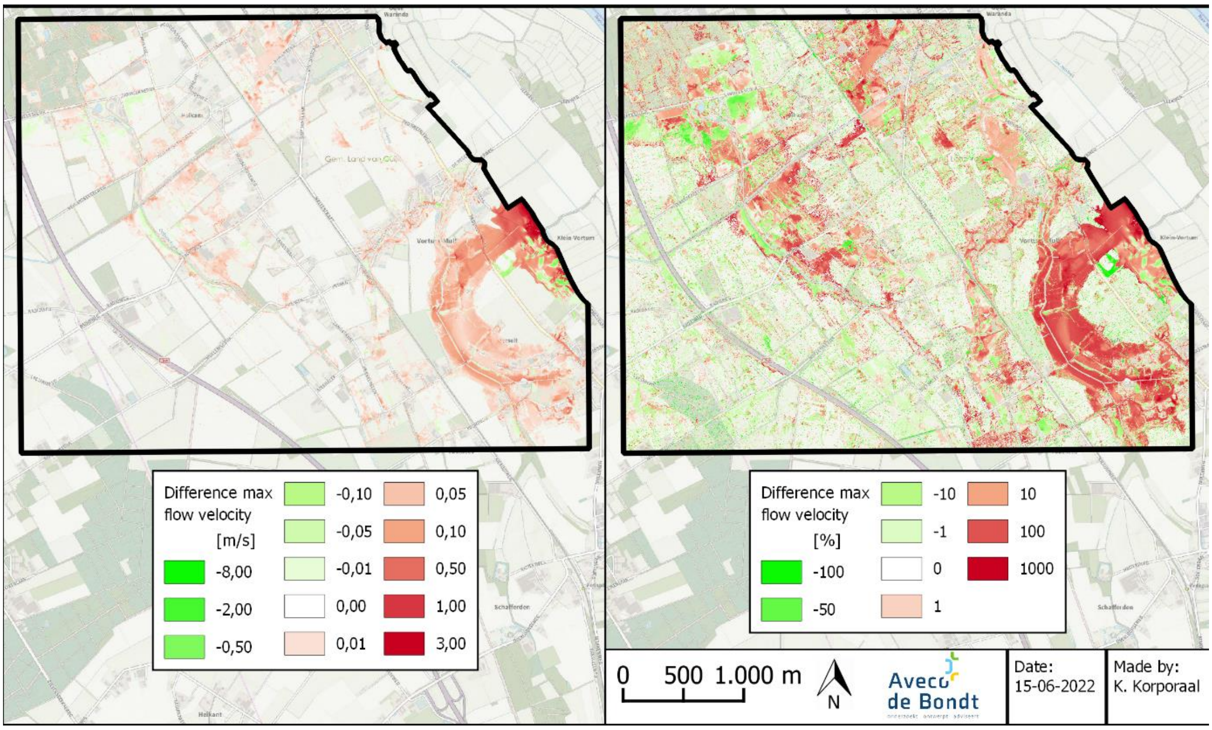


Figure 77 – Flow velocity differences for the precipitation situation a=89 mm, t=8640 min, d=2880 min in comparison with the precipitation situation a=89 mm, t=0 min, d=2880 min at Vortum Mullem. With on the left the absolute differences and on the right the relative differences.

Moment in time – MT-Polder

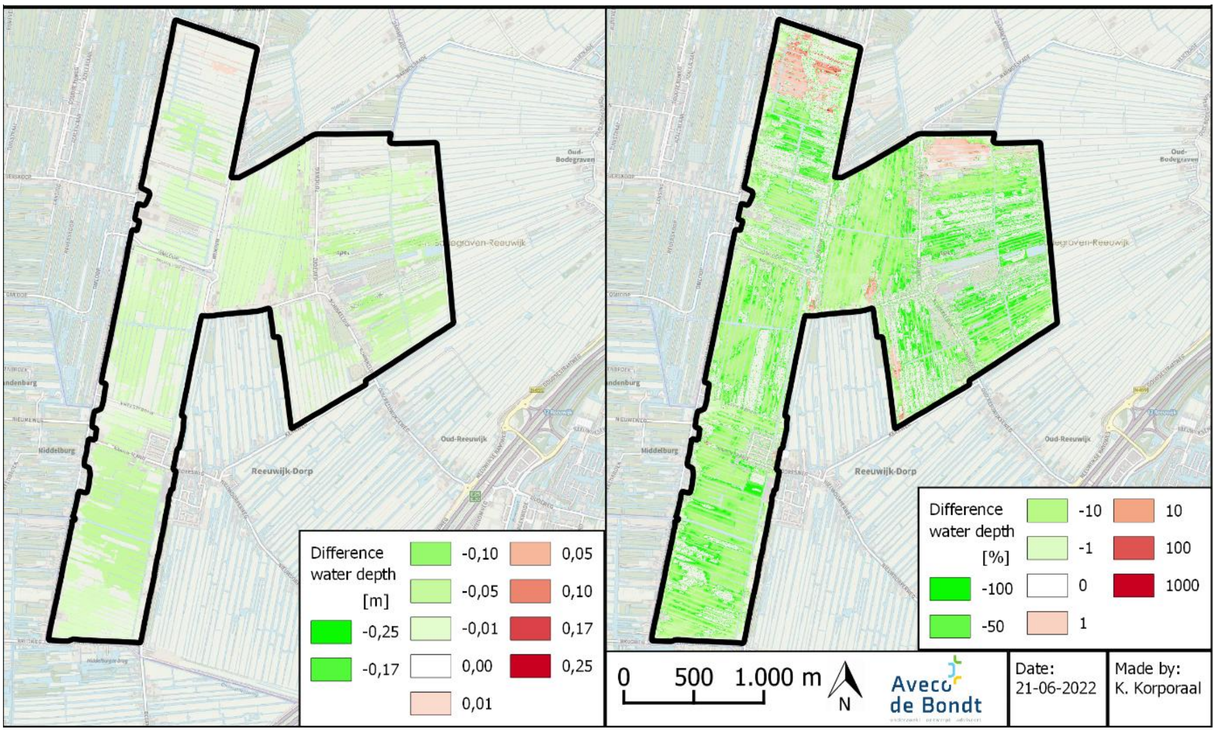


Figure 78 – Water depth differences for the precipitation situation a=40 mm, t=60 min, d=60 min in comparison with the precipitation situation a=40 mm, t=0 min, d=60 min at MT-Polder. With on the left the absolute differences and on the right the relative differences.

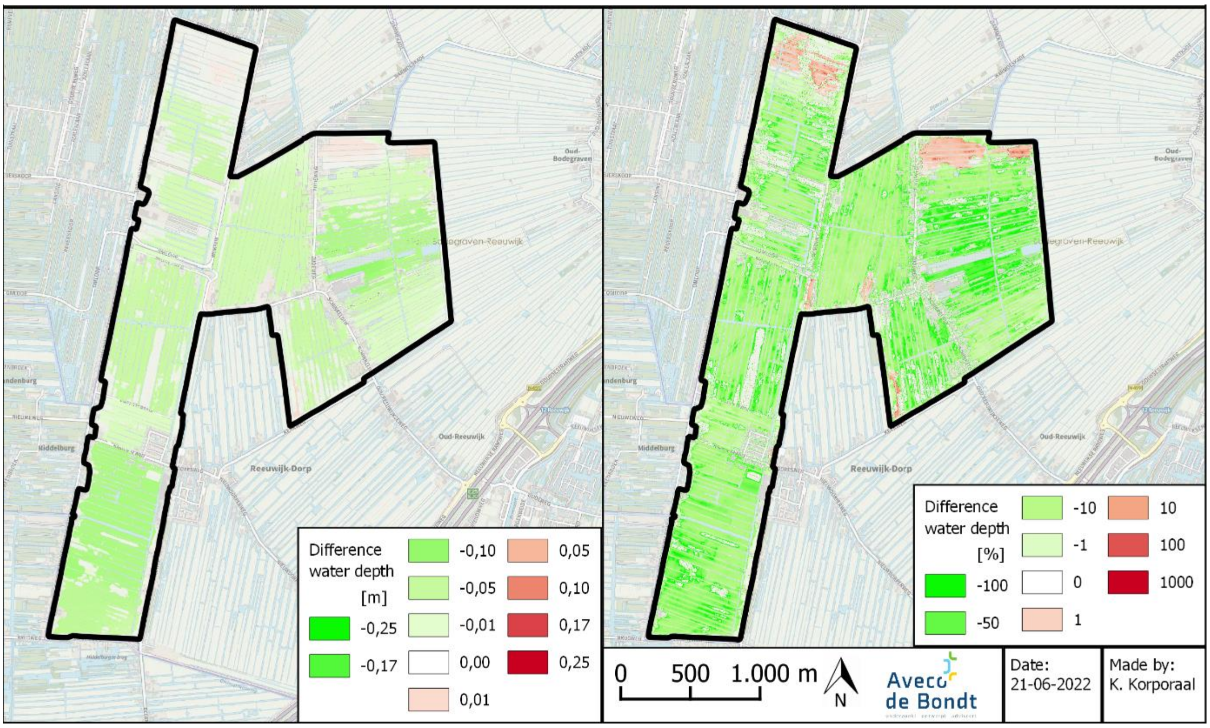


Figure 79 - Water depth differences for the precipitation situation a=70 mm, t=60 min, d=60 min in comparison with the precipitation situation a=70 mm, t=0 min, d=60 min at MT-Polder. With on the left the absolute differences and on the right the relative differences.

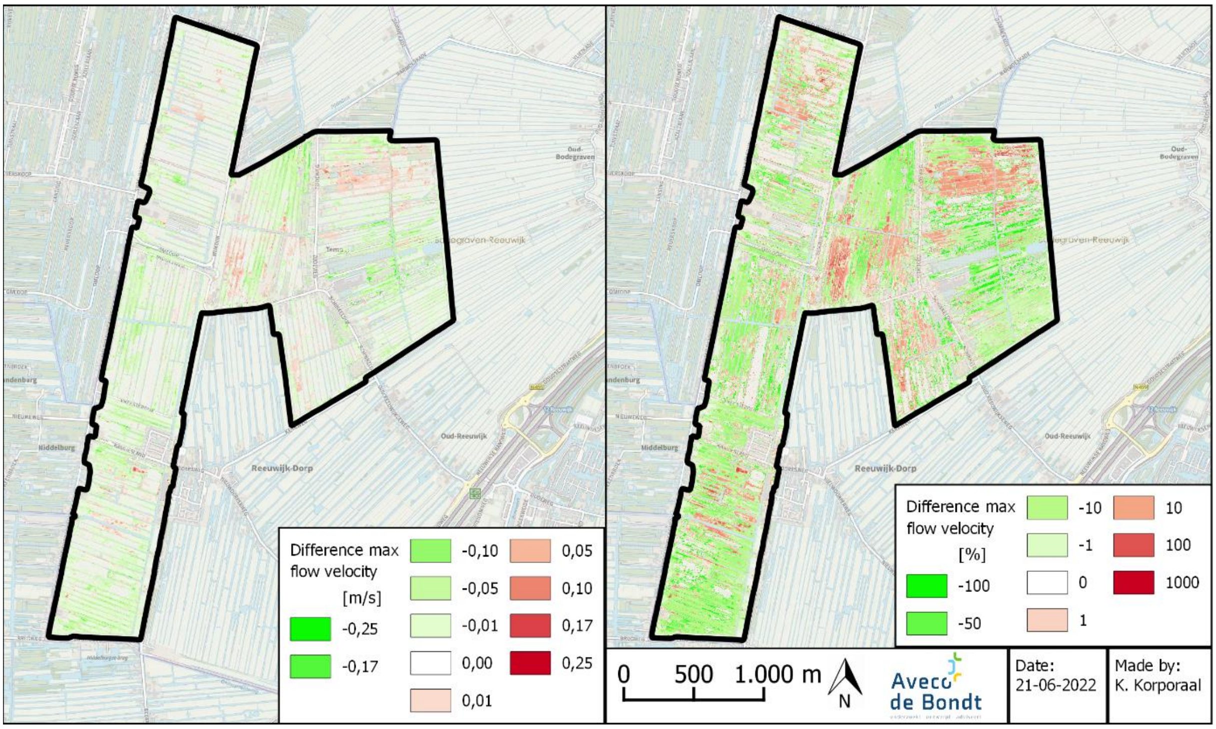


Figure 80 – Flow velocity differences for the precipitation situation a=70 mm, t=60 min, d=60 min in comparison with the precipitation situation a=70 mm, t=0 min, d=60 min at MT-Polder. With on the left the absolute differences and on the right the relative differences.

Appendix 5 Difference Manning

Table 16 - Overview manning situations compared (VM = Vortum Mullem, MT = MT-Polder)

Situation	Compared with
VM Maximum manning	VM Reference situation
VM Minimum manning	VM Reference situation
MT Maximum manning	MT Reference situation
MT Minimum manning	MT Reference situation

Manning – Vortum Mullem

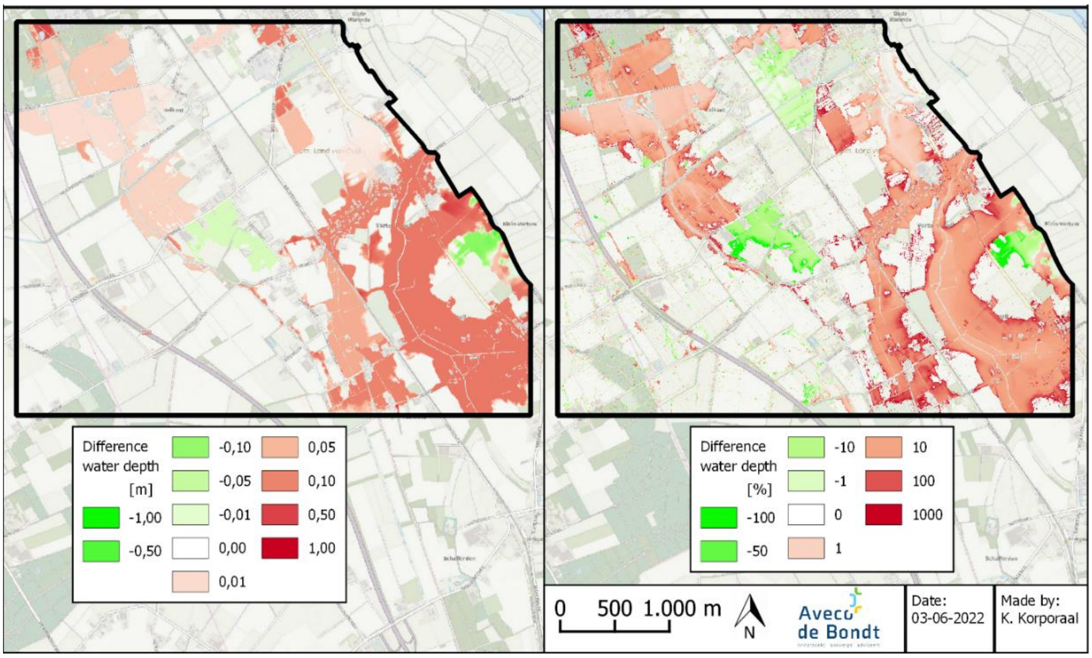


Figure 81 – Water depth differences for the minimum manning in comparison with the reference situation at Vortum Mullem. With on the left the absolute differences and on the right the relative differences.

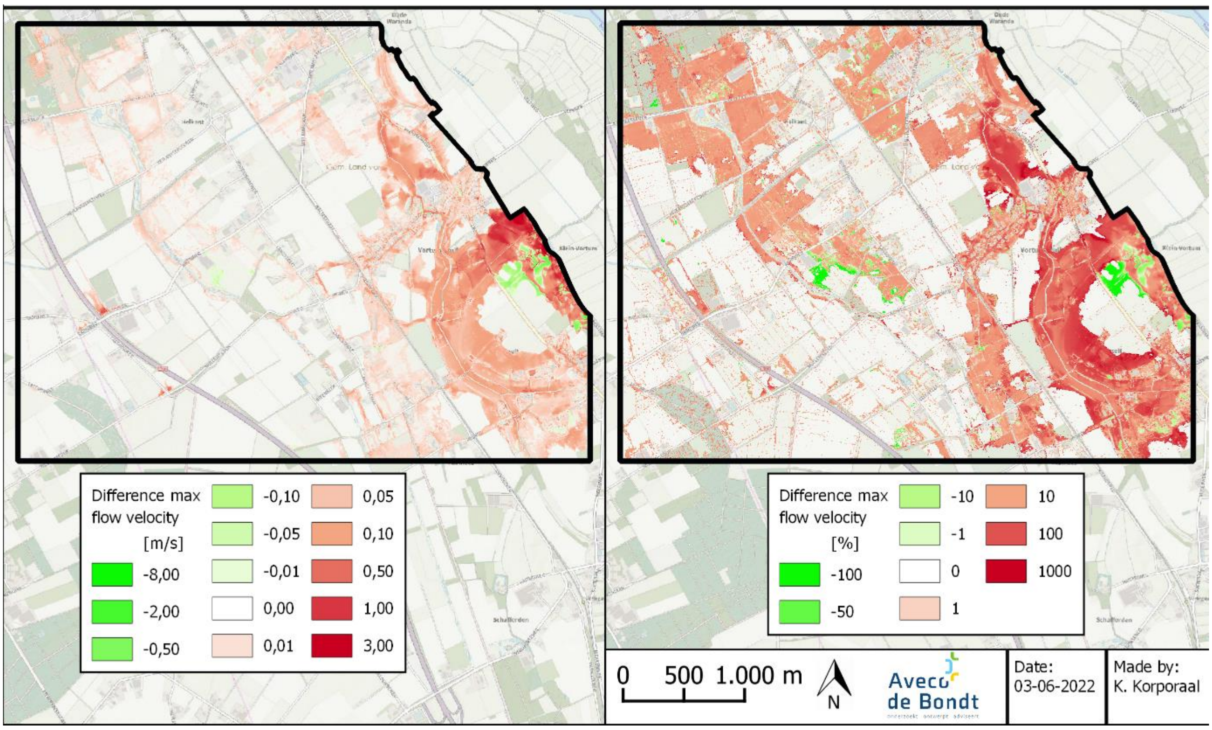


Figure 82 – Flow velocity differences for the minimum manning in comparison with the reference situation at Vortum Mullem. With on the left the absolute differences and on the right the relative differences.

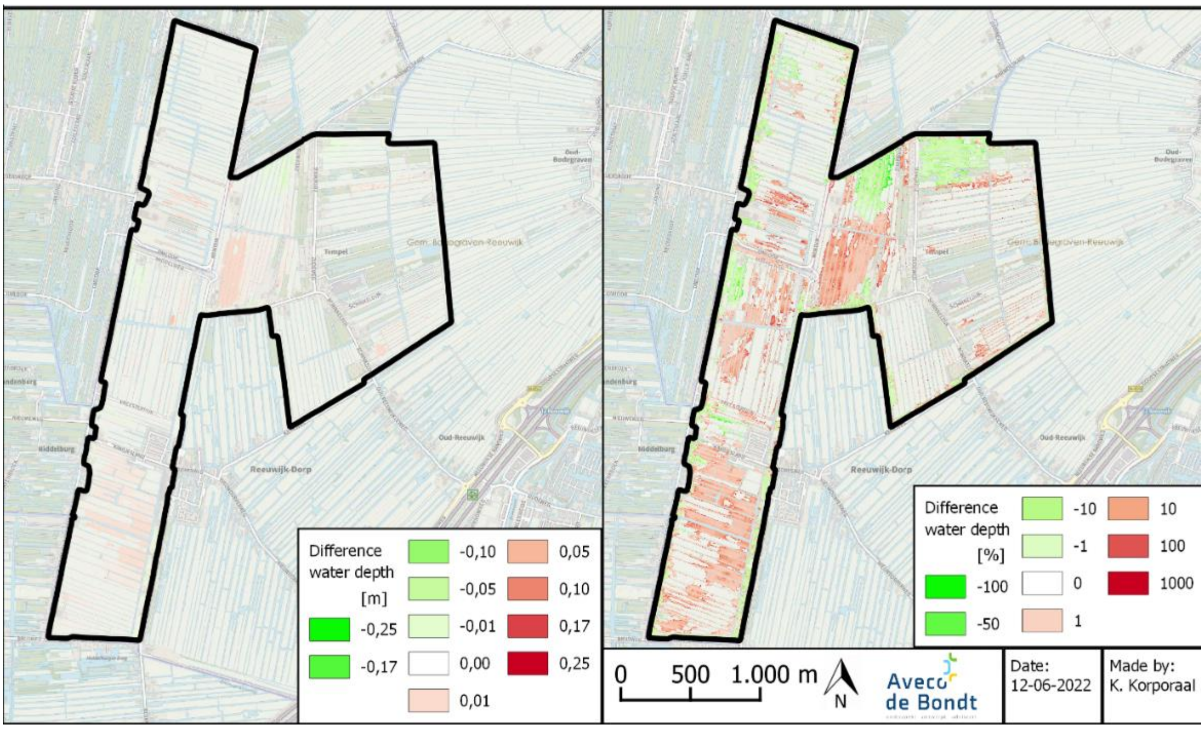


Figure 83 – Water depth differences for the minimum manning in comparison with the reference situation at MT-Polder. With on the left the absolute differences and on the right the relative differences.

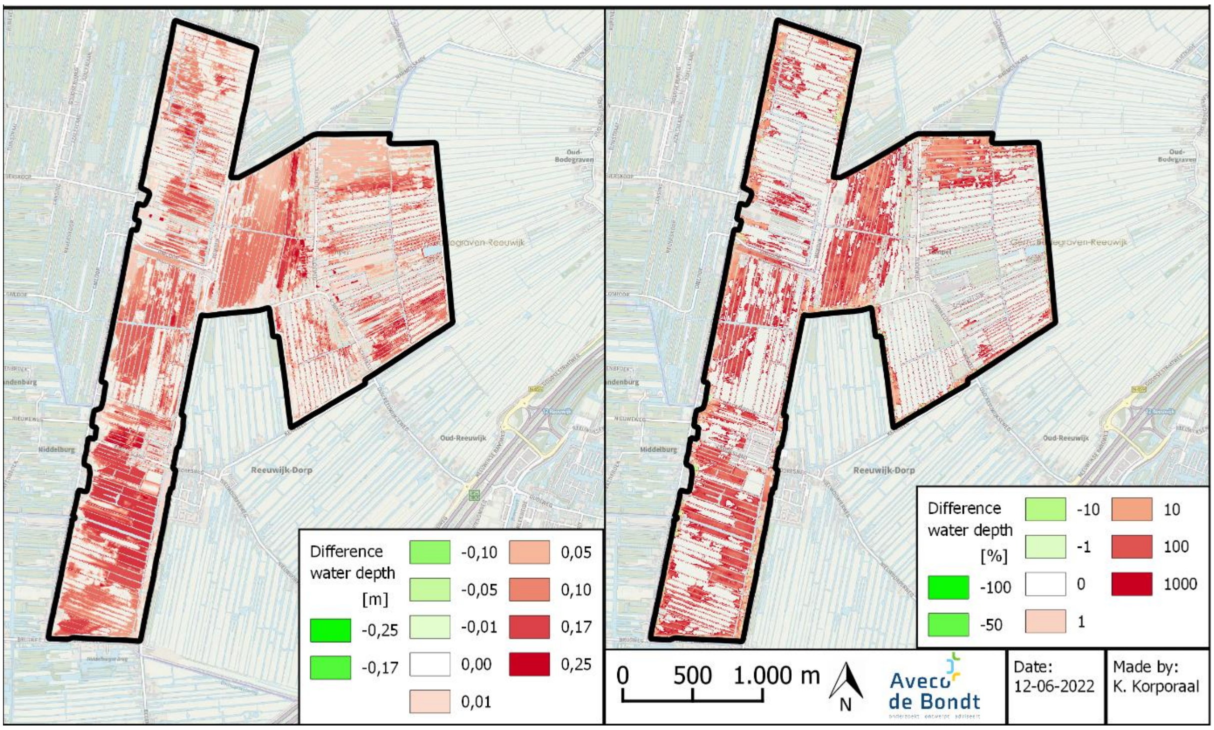


Figure 84 – Water depth differences for the maximum manning in comparison with the reference situation at MT-Polder. With on the left the absolute differences and on the right the relative differences.

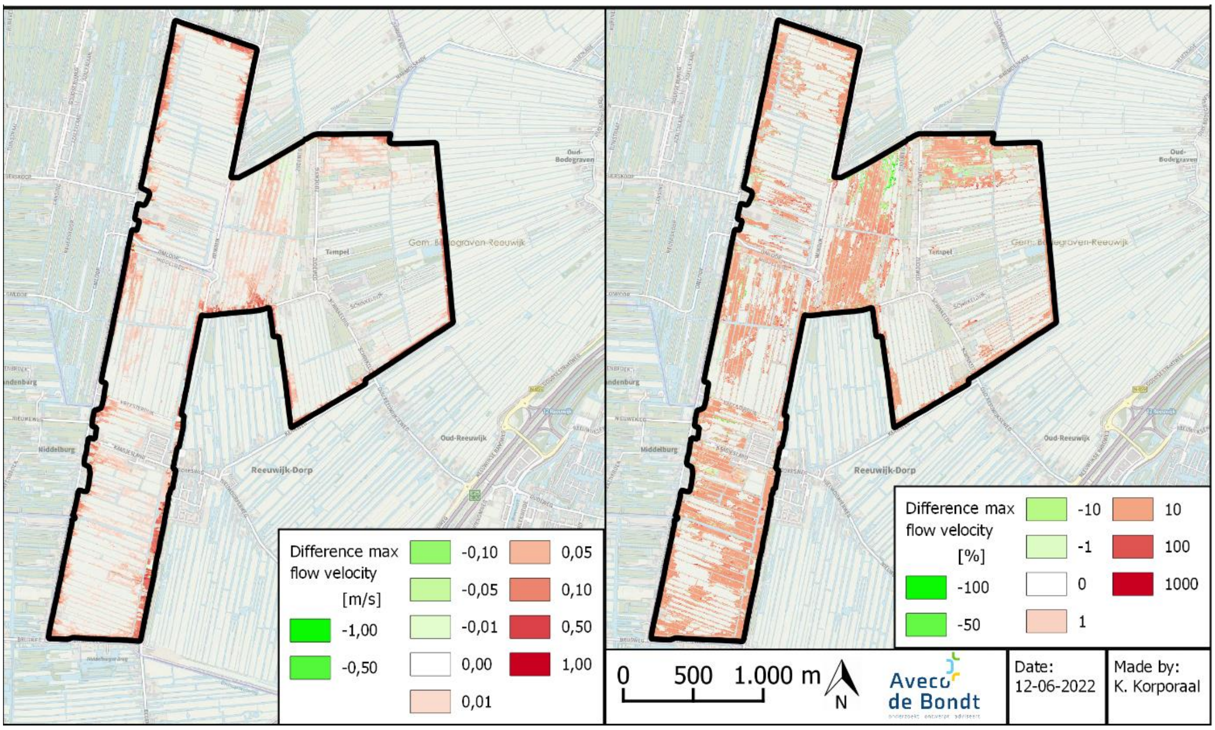


Figure 85 – Flow velocity differences for the minimum manning in comparison with the reference situation at MT-Polder. With on the left the absolute differences and on the right the relative differences.