MASTER THESIS

Assessment of 1D and 2D model choices on model accuracy and computation time in D-Hydro

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Preface

Before you lies the thesis "Assessment of 1D and 2D model choices on model accuracy and computation time in D-Hydro", which I wrote as the last step to finish my master programme Civil Engineering and Management at the University of Twente.

Writing my thesis would not have been possible without the support of supervisors and parents. First, I would like to thank Maarten Krol and Anouk Bomers for their feedback during my thesis. I liked the way you provided feedback, which helped me to write my thesis.

I would also like to thank Arjon Buijert and Robbert de Lange for their support during my thesis. The weekly meetings helped me structure my research, and the feedback was always useful. You were always available for questions and had some tips that will also help me in the future.

Finally, I would like to thank my parents for their support during my thesis. The conversations I had with you motivated me to finish my thesis.

Jan Berend Mooijaart,
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Summary

Hydraulic models are used for different purposes, such as real-time flood forecasting, flood risk mapping, and flood damage assessment. Over the years, hydraulic models' performance has improved because of better computers, improvement in details of the input data, and the possibility to couple 1D models with 2D models. However, the computation time can still be high for a large study area.

This study investigates the effect of model choices on model accuracy and computation time in D-Hydro. The goal of this study is to understand the effect of mesh properties on breach discharge and to what extent line elements can compensate for a lower grid resolution. Dike ring area 49, located in Gelderland, the Netherlands, with an area of 12000 ha is used as a realistic case.

Model accuracy is measured in three different ways; mean absolute error (MAE) of water depth, a measure of fit of inundation extent, and flood arrival times. The breach discharge is compared in two different ways, the peak discharge, and the cumulative discharge.

The study shows that grid size and grid schematization affect the breach outflow hydrographs. Models with a coarser grid have a higher peak discharge and cumulative breach discharge. A model with a coarser grid has a peak breach discharge of up to 70% higher than a model with a fine grid resolution and the cumulative breach discharge is up to 50% higher from 3 days after the dike breach. Models with a coarse grid resolution artificially remove local backwater effects near the breach, easing throughflow to the hinterland and increasing breach inflow.

The second part of the study is related to the schematization of higher line elements. Higher line elements, such as roads, are relatively small compared to the cell size and might not be correctly schematized in the 2D grid. For this analysis, roads are schematized as fixed weirs, and the breach outflow hydrograph of the reference model is used as a boundary condition. The study shows that schematizing roads as fixed weirs improves model accuracy significantly. If roads are not schematized correctly, the area will be flooded faster and a larger area inundates. Adding roads as fixed weirs increases model accuracy even in models with a fine grid resolution.

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1 Introduction

1.1 Background

Flooding is one of the most frequent natural disasters affecting society and can be caused by for example rising sea levels, heavy rainfall, or a dike breach. Hydraulic models are developed to predict and assess the impact of flood events. These models are used for different purposes, such as real-time flood forecasting, flood risk mapping, and flood damage assessment, and give information about inundation extent, flood depth, velocities, and flood arrival times (Chu et al., 2020). For each model, a trade-off must be made between the accuracy and the computational efficiency that depends on the purpose of the model. Real-time flood forecasting models require a short computation time and real-time data, whereas models that are used for flood risk mapping maximum flood extent and water depths must be simulated accurately (Teng et al., 2017).

Flooding events can be distinguished into different groups. The most common types are fluvial flooding and pluvial flooding. Pluvial floods occur when rainfall exceeds the infiltration capacity which results in overland flooding (Betsholtz, 2017). Pluvial flooding occurs more frequently than fluvial flooding. Fluvial flooding can occur in two different ways. The first way is water levels rising above the riverbanks of the main channel and is also called overtopping. The second way in which a fluvial flood can occur is when a dike breaches. In general, fluvial flooding causes larger economic and human damage than pluvial flooding (Tanaka et al., 2020).

Hydraulic models are used to predict the consequences of fluvial flooding. The most common hydrodynamic models that are used to predict flooding are 1D-, 2D-, and coupled 1D/2D models (Teng et al., 2017). In the Netherlands, commonly used flood models are made in Sobek1D2D, Delft-FLS, 3Di, and Waqua (Deltares, 2018).

The simplest way to model a river channel is with a 1D model. 1D models can be used to simulate water depths and flow velocities in rivers when a more detailed solution is unnecessary. The results of a 1D model are less accurate at bends, or locations where the river suddenly widens or narrows (Deltares, 2018). Pure 1D models are not suitable for flood mapping when the flow is expected to spread, 2D models are required to simulate overland flow (Pasquier et al., 2019). The advantage of 1D models is that the computation time of these models is lower than 2D models (Deltares, 2018).

The advantage of 2D models is that they can simulate the timing and duration of inundation with high accuracy (Teng et al., 2017). The accuracy of 2D models is affected by the accuracy of the boundary conditions, such as the upstream flow and downstream flow, the accuracy of the roughness parameter, and the topographical data that is used to create the DEM of the study area (Pappenberger et al., 2006; Yu and Lane, 2006a; Horritt and Bates, 2001). The grid size can affect the accuracy of the model and the computation time (Bomers et al., 2019). A disadvantage of 2D models is a high computation time when a fine grid size is used.

The performance of hydraulic models has been improved over the years, because of better computers, improvement in details of the input data, and the possibility to couple 1D models with 2D models. In coupled 1D/2D models that are used to model fluvial flooding, rivers are modeled in 1D, and the hinterland is modeled in 2D (Betsholtz, 2017). By using a 1D/2D model, the advantages of both a 1D model (low computation time) and a 2D model (high accuracy) can be combined (Teng et al., 2017). Coupled 1D/2D models have a lower computation time than fully 2D models. However, for a large study area, the computation time of a coupled 1D/2D model can still be high.

1.2 Problem statement

Coupled 1D/2D models have a shorter computation time than 2D models. When a dike breaches evacuation decisions must be made in time. However, the computation time of 1D/2D models is still high for large study areas. Therefore, they cannot be used as a flood forecasting model since it takes too long to run the model. Various model choices can be made to reduce the computation time, such as altering mesh properties, parallelization, and increasing the time step.

Several studies analyzed the effect of mesh resolution in hydraulic models. Structural features and topography are not as accurately represented in a coarser grid which accelerates the speed at which the area floods and changes the flow direction (Yu and Lane, 2006a). On the other hand, a coarser grid leads to a higher numerical friction and results in a delay of the peak flow (Caviedes-Voullième et al., 2012). The model can be calibrated by changing the roughness parameter. The roughness parameter can be increased to reduce the flow velocity (Yu and Lane, 2006a). However, this does not affect the direction of the flooding. A coarser grid lacks topographical details, which can be compensated for by refining the grid locally (Yu and Lane 2006b). Yu and Lane (2006b) analysed this by representing the topographical data on a sub-grid level. The sub-grid treatment divides the terrain into small cells and considers the effects of small-scale terrain features. The study showed that using a sub-grid improves the model performance when grid cells of 8m were used with a sub-grid of 4m. The effect of a sub-grid treatment reduces for larger grid sizes (Yu and Lane, 2006b). A disadvantage of the sub-grid treatment is that the computation time increases compared to using a coarse grid.

Small structural features can be schematized by either refining the grid throughout the study area, or by refining it locally. Grid refinement increases model accuracy but also increases the computation time. Local grid refinement will result in less of an increase in computation time than refining the entire study area, but the computation time can still be high. An alternative approach is to schematize higher line elements such as roads as so-called “fixed weirs”. Fixed weirs are 1D line elements that are placed on top of a grid with a predefined height value that can vary over space and water can only flow over the height of the fixed weir. These fixed weirs are used to increase the accuracy of the model, whilst maintaining a coarse grid. This results in a lower computation time compared to using a finer grid. So far, it has not been analysed to what extent these fixed weirs can contribute to model accuracy.

In addition, uncertainty of boundary conditions can have a significant effect on model results (Pappenberger et al., 2006). The consequences of a flood after a dike breach depend on the amount of water that flows into the dike ring. Factors that affect breach discharge are the water level outside the dike, the moment the dike breach, breach growth, characteristics of the hinterland, and the dike breach location (De Bruijn et al., 2018). There are guidelines to model a dike breach, but little research has been done into the effect of grid properties on breach discharge.

1.3 Research objective and question

The objective of this research is as follows: *To understand the effect of mesh properties on breach discharge and to what extent line elements can compensate for a lower grid resolution.*

To achieve this goal, the effect of mesh properties, line elements, and courant number is analysed. This study is relevant for researchers, modelers of inundation, and water authorities, as it may provide them with new insights to establish a time efficient flood model.

Based on the research objective, the following research question has been formulated:

What is the effect of mesh properties and line elements on model accuracy and computation time, and can it be used to create a flood forecasting model?

To answer this research question, four sub-questions have been formulated. The first question is related to grid resolution and breach discharge. The amount of water that flows into the dike ring affects the consequences of flooding and depends on water level outside the dike, the breach growth, and the characteristics of the hinterland. This study analyzes the effect of grid resolution on dike breach discharge. To make a fair comparison between the different models, the effect of model choices on dike breach discharge will be analyzed. The first sub question provides insight into the effect of grid resolution on breach discharge, which is used to answer the other sub questions and is as follows:

1) What is the effect of grid resolution on breach discharge?

The second and third question are related to mesh properties and model performance. The computation time can be reduced by increasing the grid size but decreases model accuracy. Higher line elements, such as roads can be added to the model as fixed weirs to compensate for a lower grid resolution. Adding higher line elements as fixed weirs is analyzed both with and without grid refinement around roads. The second and third sub-questions are as follows:

2) *What are the effects of grid resolution on model accuracy and computation time, and to what extent can line elements compensate for a lower grid resolution?*

3) *What is the effect of local grid refinement on model accuracy and computation time?*

The fourth subquestion is related to the courant number. The courant number ensures stable model results. The courant number reduces the time step so that the maximum courant number is not exceeded. By increasing the courant number, the computation time can be reduced but can decrease model accuracy. The fourth sub-question is as follows:

4) *What is the effect of the courant number on computation time and model accuracy?*

1.4 Thesis outline

The remainder of this thesis is structured as follows. In chapter 2 the theoretical framework is described. The study area and model data are explained in chapter 3. The research methodology is described in chapter 4, which consists of a description of the reference model, an overview of the model characteristics that are used in the analysis, and the evaluation criteria that are used to assess the performance of the models. The results of the analyses are presented in chapter 5. After that, the discussion of the results and a conclusion with recommendations is provided in chapters 6 and 7 respectively.

2 Theoretical framework

2.1 Model description

For this study, the software D-Hydro Suite 2022.04 1D2D is used. D-Hydro Suite 1D2D has been developed by Deltares and can be considered the successor of Sobek. Within D-Hydro it is possible to create either coupled or separate 1D, 2D, and 3D models. With the flexible mesh feature in D-Hydro, it is possible to create a grid with different grid sizes and shapes, which makes it possible to create models that are more detailed in specific areas.

1D2D models are analyzed in this study, where rivers and waterways are modeled in 1D, and the hinterland is schematized in 2D. D-Hydro solves the 2D Shallow Water equations that are derived from the Navier-Stokes equations (Deltares, 2022). The continuity equation and the momentum equation in the x and y directions are given below:

$$2D\ continuity\ equation = \frac{\delta h}{\delta t} + \frac{\delta hu}{\delta x} + \frac{\delta hv}{\delta y} = Q \qquad (1)$$

With h the water depth in meters, u and v the depth-averaged velocities in x- and y-directions in meters per second, and Q the contribution per unit area due to discharge in m^3.

$$2D\ momentum\ Equation = \frac{\delta u}{\delta t} + u\frac{\delta u}{\delta x} + v\frac{\delta u}{\delta y} + w\frac{\delta u}{\delta z} - fv = -\frac{1}{\rho} * \frac{\delta P}{\delta x} + F_x + \frac{\delta}{\delta z}\left(v_v \frac{\delta u}{\delta z}\right) + M_x \qquad (2)$$

$$2D\ momentum\ Equation = \frac{\delta v}{\delta t} + u\frac{\delta v}{\delta x} + v\frac{\delta v}{\delta y} + w\frac{\delta v}{\delta z} + fv = -\frac{1}{\rho} * \frac{\delta P}{\delta y} + F_y + \frac{\delta}{\delta z}\left(v_v \frac{\delta v}{\delta z}\right) + M_y \qquad (3)$$

With u and v velocity in x and y direction (m/s), w vertical velocity (m/s), z the water depth (m), f the Coriolis frequency, the ρ the density of water, F_x and F_y the forces that represent the unbalance of horizontal Reynold Stresses and M_x and M_y the contribution to momentum from external forces (Deltares, 2022).

One feature within D-Hydro is fixed weirs. A fixed weirs contains x, y, and z values that can be placed on top of a 2D grid. The fixed weirs are snapped to the nearest 2D grid edge (Figure 1). The z value is the crest level that can vary over space, but not over time. Water flows over the fixed weir when the water level exceeds the crest level of the fixed weir (Deltares, 2022). This feature can be used to schematize dikes, quays, and other line elements such as roads.

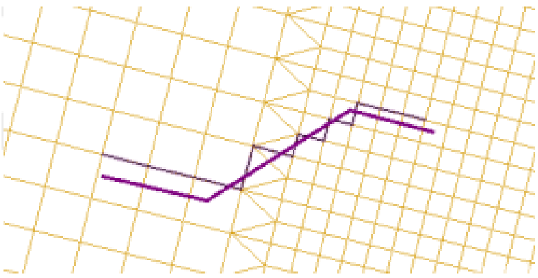

Figure 1: Fixed weir on top of 2D grid and snapped with 2D grid.

Simulation of a dike breach

The dike breach affects the model results because the width of the dike breach in combination with the water levels in both the river (1D) and the hinterland (2D) close to the dike breach location determines the discharge through the dike breach. The breach growth consists of two phases. In the first phase, the lowering phase, the breach level decreases from the initial dike level to the minimal crest level, where the breach width is constant. During the second phase, the breach width increases, and the crest level is at a minimal level. For breach growth, the Verheij and Van der Knaap formula is used (Verheij, 2003):

$$B = 1{,}2\frac{g^{0{,}5}H^{1{,}5}}{u_c}\log\left(1 + \frac{0{,}04 * g}{u_c}t\right)$$

B is the width of the dike breach (meter), g is the gravitational constant, H is the difference between the upstream water level and downstream water level (meter) and u_c is the critical flow velocity (m/s).

The breach growth is affected by the difference in upstream and downstream water levels and depends on the moment of the dike breach and the dike breach location. The critical flow velocity also affects the breach growth and depends on the dike material. The critical flow velocity depends on the material of the dike, the breach growth of a clay dike is slower than a sand dike. The moment of the dike breach influences dikes breach growth because water levels in river change over time. The location of the dike breach also affects breach growth development because it affects the downstream water level (de Bruijn et al., 2018).

2.2 Mesh properties

In coupled 1D2D models, rivers and waterways are schematized in 1D, and overland flow is modeled in 2D. The computation time of 1D2D models can be high, even though parts are modeled in 1D. Several studies have analyzed the effects of 2D mesh properties on model performance. These studies have varying conclusions regarding mesh properties.

Yu and Lane (2006a) analyzed the effects of mesh resolution on inundation extent and the timing of flood inundation. They compared four different square grid resolutions (4, 8, 16, and 32m) and found that increasing the grid size increases the rate of inundation and that it changes the direction of the inundation. These differences can be explained by the fact that coarsening the grid reduces the details of structural features, such as buildings and roads, that can have a blocking effect. Besides that, a coarser grid affects the water depth, which might influence the direction the water can flow and flow velocity. Increasing the roughness parameter can compensate for a lower grid resolution, as it can reduce the flow velocity, but does not affect the direction of the flow (Yu and Lane, 2006a). On the other hand, it might be possible that coarsening a grid might reduce the rate of inundation, this occurs for example when narrow flow pathways are not schematized at a coarser grid size.

In another study, Yu and Lane (2006b) developed a model in which topographical data is represented on a sub-grid scale. When a sub-grid is used, a cell consists of multiple sub-grid cells, and each sub-grid cell has a bed level. Without a sub-grid-scale treatment, the bed levels of a grid cell are calculated by the average bed level in that grid cell. As a result, structural features such as buildings can be better represented with a coarser grid. Yu and Lane (2006b) also included a porosity factor, that depends on the number of wet sub-grid cells and the water depth in these sub-grid cells. A similar study was conducted by McMillan and Brasington (2007), they compared a model with grid cells of 10m and a sub-grid with a model with grid cells of 2m. McMillan and Brasington (2007) found that a model of 10m with sub-grid shows similar results as a model with a 2m grid and was significantly better than a grid with 10m cells without a subgrid. Moreover, the results in the study of Yu and Lane (2006b) show that a sub-grid approach reduces the rate of inundation compared to a model without a sub-grid scale and showed that a sub-grid is even more effective than increasing the roughness parameter. However, a sub-grid treatment is less effective at coarser mesh resolutions (Yu and Lane, 2006b).

The discussed studies show that coarsening the grids increases the rate of inundation. On the other hand, Caviedes-Voullième et al (2012) analyzed the effect of mesh properties on rainfall-runoff. They compared models with squared grids and triangular grids and found that a coarser grid reduces the flow velocity and has a damping effect. The hydrographs showed that a coarser grid dampens the discharge wave and delays the time-to-peak. This can be explained by the fact that with a coarser grid the topographical representation is poor, as a result, water cannot flow further because a coarser grid generates numerical diffusion (Caviedes-Voullième et al., 2012).

Altinakar et al (2010) analyzed the effect of grid size on dam break discharge. The discharge through dam break is important for the accuracy of a flood model. In this study dam break discharges in models with grid sizes of 5m, 10m, 20m, and 40m were compared. They found that coarser grid sizes have a higher peak discharge, the peak discharge of the model with 40m cells was 25% higher than the 5m cells (Altinakar et al., 2010). The study does not make any statements about the validity of the breach discharge. Models with a coarse grid have a similar breach outflow hydrograph as a model with grid cells of 5m when the grid is locally refined to 5m near the dam breach location (Altinakar et al., 2010).

2.3 Courant number

The Courant number is the limiting factor that indicates how far water can flow at one timestep. For each grid cell, the Courant number is determined.

The following formula is used to compute the Courant number:

$$C = \frac{u\Delta \mathrm{t}}{\Delta \mathrm{x}}$$

Where C is the Courant number, u is the velocity (m/s), Δt is the time step (s), and Δx is the distance (m) between two adjacent points of the grid in the flow direction. The maximum Courant number is often exceeded in a few grid cells due to differences in flow velocity over time and space. The grid cells that are courant limiting are the grid cells where the flow velocity is high (for example, near a dike breach), or locations where the grid is refined (Sanders, 2008).

If a global time step is used in the model, the time step has to be reduced when the maximum courant number is exceeded in at least one grid cell. For a large part of the model, the courant number is not the limiting factor, but local bottlenecks reduce Δt and increase the computation time significantly.

When the Courant number is smaller than 1, it means that the water cannot flow further than 1 grid cell within a single time step. A Courant number larger than 1 indicates that water can flow more than 1 grid cell at a time step and possibly skip a cell which can lead to inaccurate model results (Figure 2).

In D-hydro, a maximum Courant number can be defined. Based on the max Courant number, D-Hydro determines the max Δt at each time step that is possible without exceeding the max Courant number. The recommended Courant number is <0.7 (Deltares, 2022). A Courant number greater than 0.7 is possible, but may not exceed 1.0, since the results will be inaccurate if a Courant number greater than 1.0 is used (Deltares, 2022).

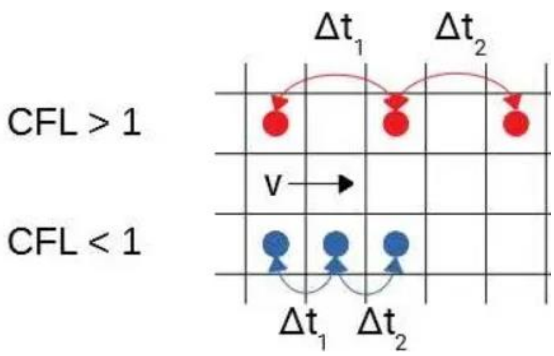

Figure 2: Visualisation of Courant number (Source: IdealSimulations, 2022) [1]

Sanders (2008) used local time stepping (LTS) to reduce the computation time. With LTS, the time step that is used differs for each grid cell. Limiting grid cells that would reduce the time step of the whole model when a global time step is used, have a smaller time step than larger grid cells. As a result, larger grid cells are not updated at every time step which reduces the computation time. Sanders (2008) found that using LTS can reduce the computation time by 50-70% without significantly reducing model accuracy.

[1] IdealSimulations. Courant number. Retrieved from: idealsimulations.com/resources/courant-number-cfd/

3 Study area and data

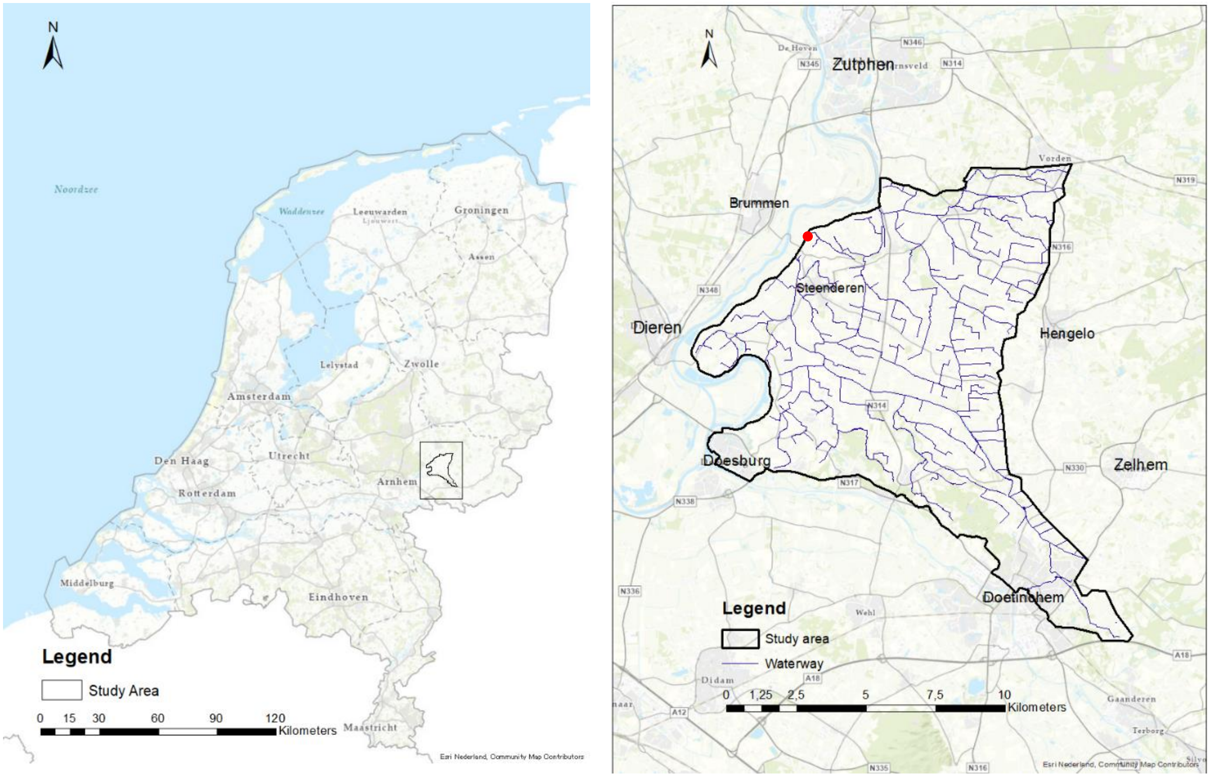

Figure 3: Location of dike ring area 49, the red dot indicates the location of the dike breach.

To determine how the findings in this study can be applied in practice, the study is conducted on a realistic case. The study area is not too large to keep computational times low and to be able to run enough model simulations for this study. The study area contains roads with a bed level that is higher than the surrounding area, which enables the usage of fixed weirs. For this study, dike ring area 49 will be used as the study area. This study area has also been chosen because an existing D-Hydro model of this area is available, which is used to validate and create the models used in this study.

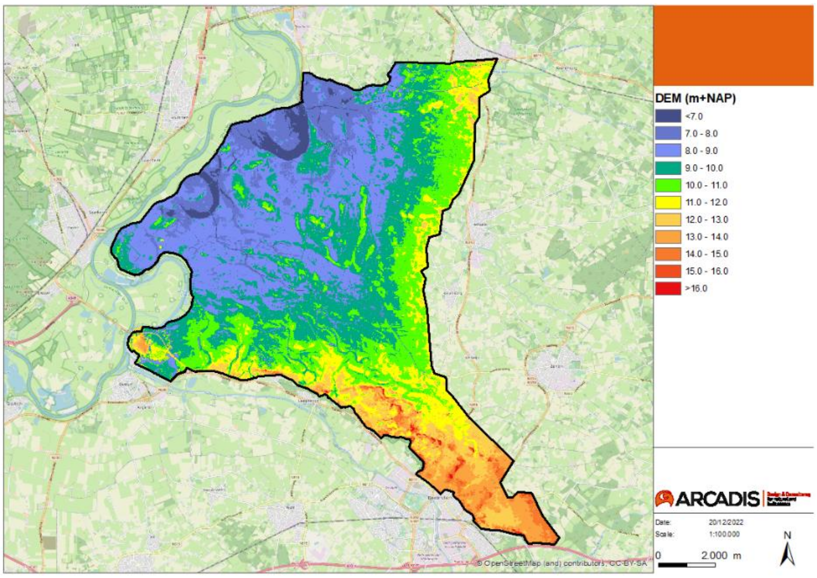

Figure 4: Bed levels in study area

Dike ring 49 has an area of about 12000 ha and is in Gelderland, the Netherlands (Figure 3). The study area consists mainly of rural areas and the largest urban areas are Doetinchem, Doesburg, and Bronckhorst. The IJssel is a distributary of the Rhine and flows in a northern direction on the west side of the study area. The Oude IJssel is located on the south side of the study area and flows in a western direction passing Doetinchem and Doesburg into the IJssel. The water system within the dike ring consists of several small waterways. Water flows through these waterways in the direction of the IJssel, where pumping stations are used to drain the water into the IJssel.

The ground levels vary between 7.0m NAP and 16.0m NAP (Figure 4). The ground levels are higher in the southern and eastern parts of the area. The ground levels decrease towards the northeast as can be seen in Figure 4.

3.1 Data

Building a hydraulic model can be done by starting from scratch. In this study, the D-Hydro models are build using a Sobek model, a 1D D-Hydro model and several datasets with properties of the area. An overview of the datasets that are used is given below and the data is provided by Arcadis and Waterschap Rijn en IJssel (WRIJ):

- 1D Sobek model that consists of the waterways within the dike ring. The waterways in this model contain information about the dimensions of the waterways, such as the bed level, the width, and the slope. In addition, underpasses, culverts, tunnels, and weirs are included in this model. Furthermore, three outflow structures are included in this model that consist of a combination of a pumping station and weirs to drain water into the IJssel.
- 1D D-Hydro model that consists of the main Rhine branches (Neder-Rijn, Waal, Lek, and IJssel). This model consists of four boundary nodes of which one is used to define the upstream boundary condition and the other three to define the downstream boundary condition. Besides that, this model contains information about the dimensions of the waterways and the roughness value.
- Landelijk Grondgebruik Nederland (LGN7). This dataset consists of a raster with a resolution of 25x25m that shows the land use in a specific area. A conversion table has been used to convert the land use to roughness values (de Bruijn et al., 2018). the most common land use and associated roughness factors are shown in Table 1.
- Actueel Hoogtebestand Nederland (AHN3).[2] This dataset consists of a raster with a resolution of 0.5x0.5m that shows the bed levels. This dataset is used to determine the bed levels in the study area.
- Shapefile with initial water levels. These water levels are based on the policy of the waterboard to maintain a certain water level in waterways.
- Nationaal wegenbestand.[3] This dataset contains the locations of the roads in the Netherlands.
- A dataset that contains the locations and dimensions of underpasses (culverts and tunnels). This dataset is provided by Arcadis.
- Shapefile with locations and crest levels of primary and secondary flood defenses.

[2] PDOK. Dataset: Actueel hoogtebestand Nederland AHN3. Retrieved from: pdok.nl/introductie/-/article/actueel-hoogtebestand-nederland-ahn3-

[3] Rijkswaterstaat. Nationaal wegenbestand en weggegevens. Retrieved from: downloads.rijkswaterstaatdata.nl/nwb-wegen/geogegevens/shapefile/

- 1D2D D-Hydro model of dike ring area 49 that has been created by Arcadis. This model is used to validate the reference model.

Table 1: Conversion table Land use to roughness value (Source: De Bruijn et al., 2018)

Land use	**Nikuradse roughness (m)**
Grassland	0.25
Cornland	0.40
Grain	0.40
Other agricultural crops	0.40
Forest	5.0
Water	0.1
Built-up area	10.0
Main roads and railways	1.0

4 Methodology

In this chapter, the methodology that is used to answer the research questions is explained. This chapter is structured as follows. First, a description of the reference model is given. Second, an overview of the model characteristics that are used in the analysis is presented. After that, the boundary conditions that are used in the simulations are explained. Finally, the model performance criteria that are used to compare the models to the reference model are described. A schematic overview of the research methodology is shown in Figure 5.

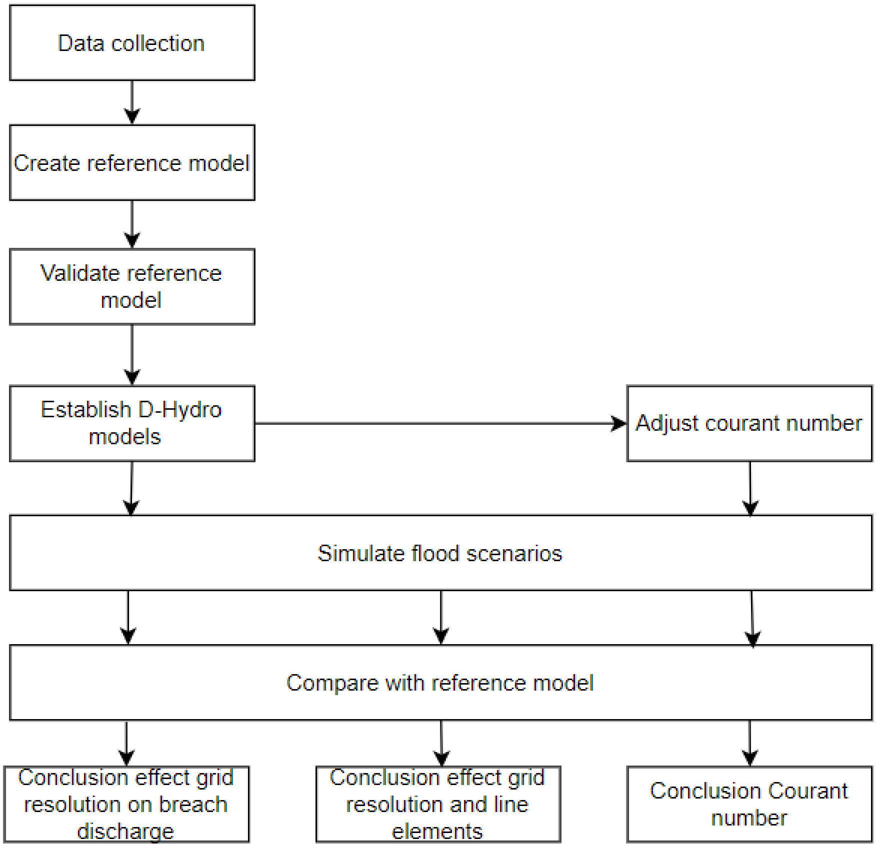

Figure 5: Schematic overview research method

4.1 Reference model

A reference model is created because an existing D-Hydro model of the study area cannot be used as a reference model. This model is not suitable as a reference model because the grid sizes used in this model are 40m with local grid refinement to 20m. A finer grid resolution is needed for the reference model to analyze the effects of model adjustments on performance and computation time. The model with 40m and 20m grid cells is used to validate the reference model. This chapter explains the characteristics and boundary conditions that are used in the reference model.

1D model

The 1D model consists of the Rhine River branches (Rijn, Waal, Lek, and IJssel) and the waterways within the dike ring that are wider than 5 meters. Water can flow out of the dike ring area to the IJssel through three different waterways. In the 1D model, calculation points are located 100 meters from each other. Calculation points are placed 10m in front and behind weirs and culverts. The 1D model is optimized by moving and removing calculation points that reduce the time step and is not Courant limiting for a time step of 30 seconds.

The waterways within the dike ring have a Strickler value of 23 $m^{1/3}/s$. The roughness values of the Rhine River branches are imported from the provided 1D model of the Rhine River branches (Section 3.1). The Rhine branches have an initial water depth of 5.0 meters and the waterways within the dike ring have an initial water depth of 1.5 meters.

2D model

In the reference model, squared grids are used with a grid size of 10 meters. Fixed weirs are used to schematize flood defenses and roads that have a surface level that is at least 0.25 meter higher than surrounding area. The dataset Nationaal Wegenbestand is used to define the location of the roads. AHN3 is used to define the surface level of the roads. The maximum surface level over a length of 5 meters is used as the surface level of the roads. Underpasses are added to the model where roads are schematized as fixed weirs. The bed levels are based on AHN3 and the land use map is used (LGN7) to determine roughness values. Average values are used to determine the roughness and bed level in a grid cell. The interpolation method that is used is simple averaging, and after that triangulation for grid cells that do not have a value.

1D2D links

The waterways within the dike ring area and underpasses are linked to the 2D grid with embedded links. Embedded links are used because the 1D waterways overlap with the 2D grid and can be used when waterways are relatively small (Deltares, 2022). Lateral links are used to connect the IJssel with the 2D grid.

Boundary conditions

Boundary conditions are required to run the model. Boundary conditions are defined for the upstream and the downstream location of the 1D model. For the upstream location, a discharge wave (Q-t) is used as a boundary condition. A Q-h relation is used for the downstream location near IJsselmond (Figure 6). The boundary condition is further explained in section 4.3.

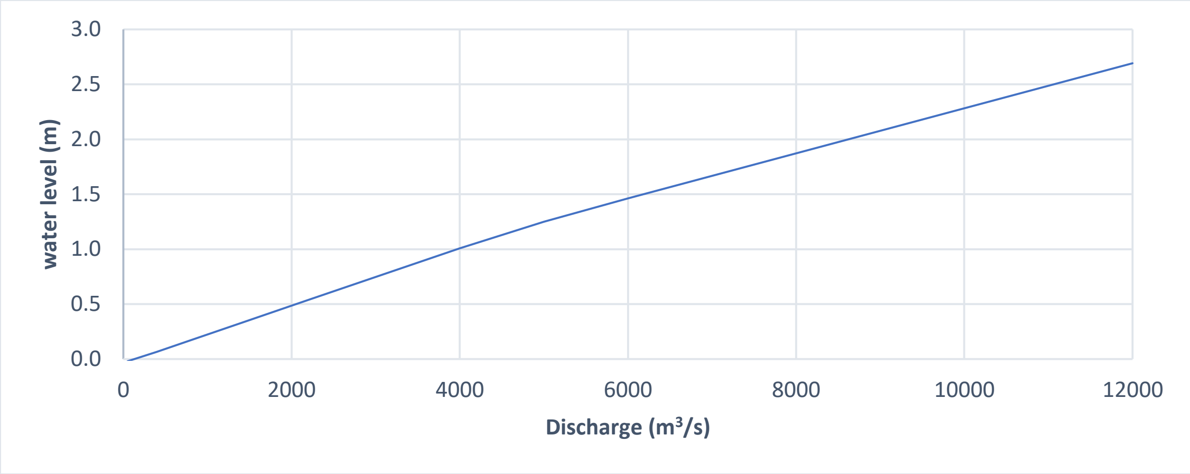

Figure 6: Q-h relation at IJsselmond

Dike breach

The crest width in combination with the difference in upstream water level and inland water level (downstream water level) determines the discharge through the dike breach. The location of the dike breach might affect the consequences of the dike breach. In literature, different breach locations are analyzed when the flood impact of an additional dike breach is significantly different (de Bruijn et al., 2014). For this study, it is important that roads are present in the flooded area to analyze the effect of schematizing roads as fixed weirs. The location of the dike breach is near Bronckhorst (Figure 3).

Table 2: Dike breach parameters

Parameter	
Start breach growth	17/11/2010 7:00
Initial crest level (m NAP)	11.1
lowest crest level (m NAP)	8.3
Initial crest width (m)	20
Period to reach lowest crest level (minutes)	10
Critical flow velocity (m/s)	0.2
Downstream water level (m from 2D grid cell)	240

An overview of the dike breach parameters is shown in Table 2. The crest level of the dike (11.1 m +NAP) is used as the initial crest level. The bed level of the hinterland near the dike breach location is 8.3m +NAP and is used as the lowest crest level. The critical flow velocity of a sand dike is 0.2 m/s (de Bruijn et al., 2014). The breach growth starts on 17/11/2010 at 7:00, as the water level at the breach location is at its highest at that time. The water level within the dike ring at 240 meters from the breach is used as the downstream water level. The water level at this location is lower than in the 2D grid cell that is linked to the IJssel and leads to a larger crest width, that corresponds to the expected crest width (Arcadis, 2022).

4.2 Model simulations

This chapter gives an overview of the model setups that are used in the study. Different grid resolutions are used to analyze the effect of grid size on model accuracy and computation time. The smallest grid size that is used in this study is 10 meters, because the computation time of a 10m model for this study area is about 60 hours. The computation time of a model with grid cells of 5m increases the computation time by about a factor of 4, which would be too long for this study. The coarsest grid resolution that is used is grid cells of 80m, to avoid analyzing too many models.

Three different options are used to analyze the effect of schematizing roads as fixed weirs; 1) roads are not schematized as fixed weirs, 2) roads that have surface level that is at least 0.25m higher than the surrounding area are schematized as fixed weirs, and 3) all roads are schematized as fixed weirs.

Local grid refinement is applied on models with grid cells of 80m. The grid is locally refined to 40m, to 20m, and 10m around roads that are schematized as fixed weirs. This is only applied on models with grid cells of 80m, to avoid analyzing too many models. Grid refinement does not replace the fixed weirs because roads are not correctly schematized with the refinement that is used.

Models 1, 4, 7, and 10 are used to analyze the effect of grid resolution on breach discharge (Table 3). These are used because the only difference between these four models is the grid resolution. Models 1 to 11 are used to analyze the effect of grid resolution and fixed weirs on model accuracy and computation time. Models 12 to 14 are used to analyze the effect of grid refinement on model accuracy and computation time.

Table 3: Overview model characteristics

Model	Grid cells	Grid refinement	Roads as fixed weirs
1 (reference)	10x10m	No	Roads that have a surface level of >0.25m than the surrounding area
2	10x10m	No	No roads as fixed weirs
3	20x20m	No	No roads as fixed weirs
4	20x20m	No	Roads that have a surface level of >0.25m than the surrounding area
5	20x20m	No	All roads as fixed weirs
6	40x40m	No	No roads as fixed weirs
7	40x40m	No	Roads that have a surface level of >0.25m than the surrounding area
8	40x40m	No	All roads as fixed weirs
9	80x80m	No	No roads as fixed weirs
10	80x80m	No	Roads that have a surface level of >0.25m than the surrounding area

11	80x80m	No	All roads as fixed weirs
12	80x80m	Local grid refinement to 40x40m	Roads that have a surface level of >0.25m than the surrounding area
13	80x80m	Local grid refinement to 20x20m	Roads that have a surface level of >0.25m than the surrounding area
14	80x80m	Local grid refinement to 10x10m	Roads that have a surface level of >0.25m than the surrounding area

Courant number

The default value for the Courant number is 0.7. The Courant number is the limiting factor and cannot be exceeded. After the dike breaches, the grid cells near the dike breach are Courant limiting, and the time step will be reduced. Increasing the Courant number leads to a lower simulation time because the time step will be larger after the dike breaches. A Courant number larger than 1.0 might lead to inaccurate results. However, it is possible that the results of a model with a fine grid resolution using a Courant number >1.0 are more accurate than using a model with a coarser grid using a Courant number of 0.7. The Courant number will be varied between 0.7 and 2.0. This is only done for model 1 and 10 since it takes too much time to test this on all models (Table 3).

4.3 Flood analysis

Each model is simulated for a period of one month, the simulation starts on 01/11/2010 at 00:00:00 and ends on 02/12/2010 at 00:00:00. The dike breach starts on 17/11/2010 at 7:00:00, and has model has an initialization period of 17 days.

To analyze the effect of grid resolution on breach outflow, a T100 discharge hydrograph is used as a boundary condition. The T100 discharge is a flood event with a 100-year return period. The T100 discharge hydrograph is used as the upstream boundary condition and is shown in Figure 7.

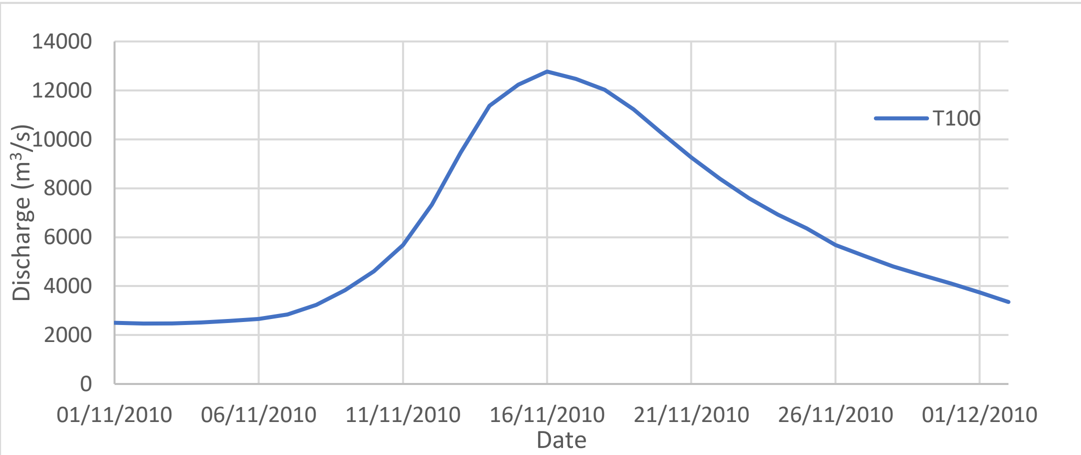

Figure 7: T100 discharge hydrograph Lobith

The breach outflow hydrograph of the reference model used as a boundary condition for the other analyses of this study since breach outflow affects model results. To simulate the breach outflow, a time series with discharge is placed directly on the 2D grid (Figure 8).

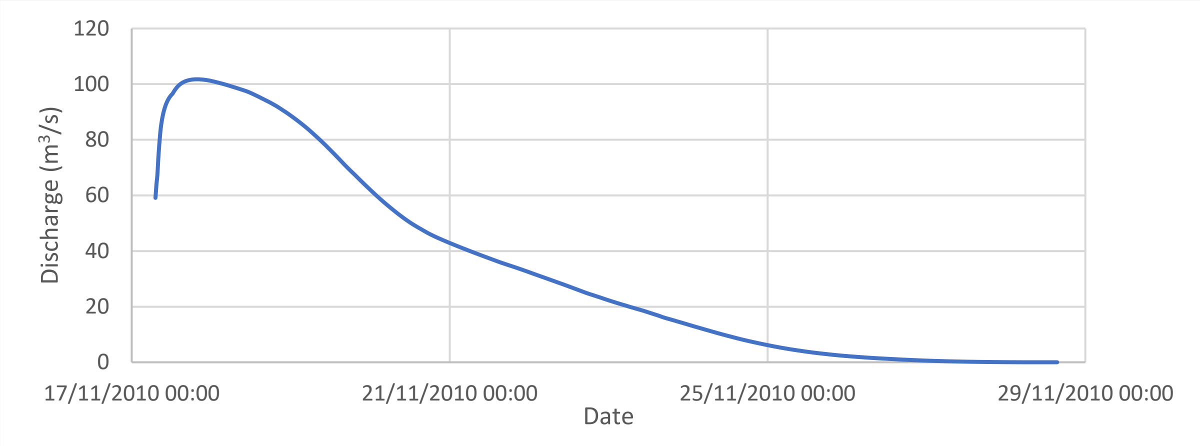

Figure 8: Breach outflow hydrograph reference model

4.4 Model performance assessment

The way to assess model performance depends on several factors, such as model characteristics, available data, and the objective of the model application. Several model performance criteria are used to assess the model performance since one criterion only assesses a specific aspect of the model, which may result in choosing a model that is not the most suitable (Bennet et al., 2012). A flood forecasting model requires a short computation time. In addition, water depths, the rate that water level rises, arrival times, and inundation extent must be simulated accurately (Teng et al., 2017).

Model performance can be assessed by comparing the model output to observational data. However, when observational data is not available, results can be compared to a reference model (Bennet et al., 2012). In this study, results are compared to a reference model that has been validated with an existing model.

Several performance criteria are used to evaluate model performance. The first way the models are evaluated is by comparing the breach outflow. The relative volume error (RVE) is used as the goodness of fit indicator for breach outflow. The RVE is calculated with the following formula (Krause et al., 2005).

$$RVE = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)}{\frac{1}{n}\sum_{i=1}^{n}(x_i)} \qquad (1)$$

Where x_i is the (cumulative) discharge in the reference model and y_i is the (cumulative) discharge in the adjusted model.

The other criteria that are used to assess the performance are comparing water levels, the inundation extent, and arrival times. For flood forecasting models, the first hours after a dike breach must be simulated accurately. Therefore, water levels and inundation extent are compared 3 hours, 6 hours, 12 hours, and 24 hours after the dike breaches and when the maximum water level is reached.

The mean absolute error is used in previous studies to compare water levels (Juan and Luis, 2019; Afshari et al., 2017). The mean absolute error is calculated with the following formula:

$$MAE = \frac{1}{N}\int_{i=1}^{N} |x_i - y_i| \qquad (2)$$

Where x_i is the water surface elevation simulated by the reference model and y_i is the water surface elevation simulated by the adjusted models, N is the total number of locations where the water levels are compared.

Inundation maps will be generated to compare the inundation extent of different models. Previous studies use the measure of fit to compare inundation extents (Juan and Luis, 2019; Afshari et al., 2017). The measure of fit (F) is calculated with the following formula:

$$F = \frac{M_1 \cap M_2}{M_1 \cup M_2} \qquad (3)$$

Where M1∩M2 is the area (in m2) that is inundated in both the reference model and the adjusted model and M1∪ M2 also includes the area that is only inundated in the reference or adjusted model (Juan and Luis, 2019).

The last way the models are evaluated is by comparing the arrival times. Therefore, arrival maps are created that show the first moment a cell has been inundated and the difference in arrival times between the reference model and the adjusted model.

Computation time

The simulated time is compared in two different ways. First, the total time to simulate a period of one month is measured in simulated hours/hour. The model is optimized so that the time step before the dike breaches is 30 seconds. After the dike breaches, it is expected that the time steps reduces because the 2D grid near the dike breach is courant limiting. Therefore, the computation time before and after the dike breach is compared separately. The second way the simulation time of different models is compared is the average time step, which is measured in seconds.

5 Results

The results of the analysis are discussed in this chapter. First, the reference model is validated by comparing the results with the model that has been established by Arcadis (Section 5.1). The results of the models with a T100 discharge hydrograph are described in section 5.2. The effect of grid resolution on breach outflow is analyzed in section 5.2. The effect of fixed weirs, grid refinement, and courant number are described in sections 5.3, 5.4, and 5.5 respectively.

5.1 Validation reference model

A validation model is used to validate the reference model. The only difference between the validation model and the reference model is the size of the grid cells. The reference model has grid cells of 10x10 meters, and the validation model has grid cells of 40x40 meters with local grid refinement to 20x20 meters. A T100 discharge hydrograph is used as a boundary condition. The results of the reference model are compared with the validation model in three different ways. First, the peak discharge and cumulative breach discharge are compared. Secondly, an inundation map is created to compare the inundation extent. Third, the maximum water levels in the hinterland are compared.

Figure 9 shows the breach outflow hydrograph of the reference and validation models. The validation model has a higher breach outflow during the first days after the dike breaches. The peak discharge in the reference model is 112 m^3/s compared to 153 m^3/s in the validation model, which is 27% lower than in the validation model. As a result, the cumulative breach outflow is also lower in the reference model (Figure 10). The cumulative discharge is 37.1 million m^3 in the reference model compared to 43.3 million m^3 in the validation model. The cumulative breach outflow is 13% lower than the reference model.

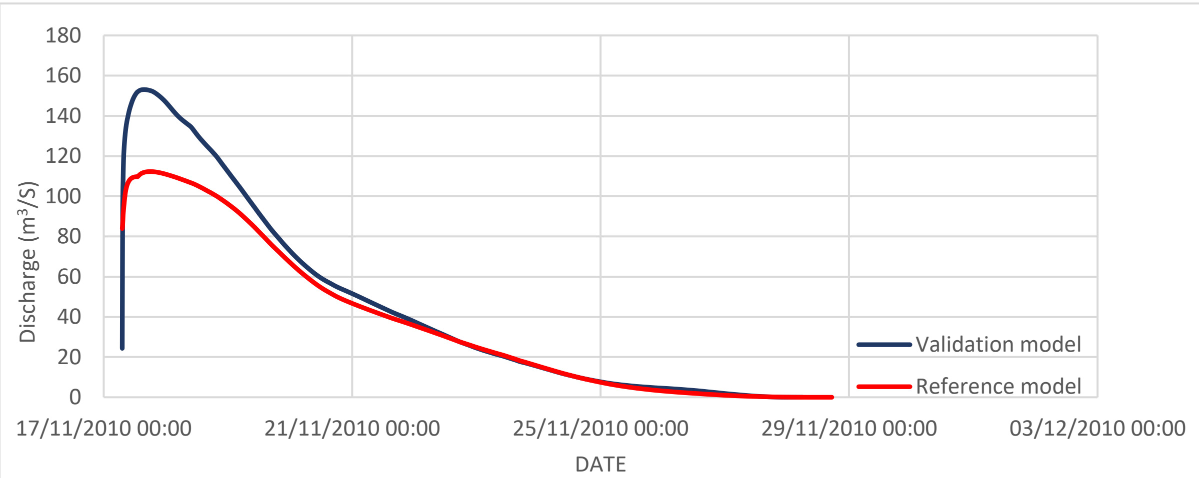

Figure 9: Breach discharges of reference model and validation model with T100 discharge boundary

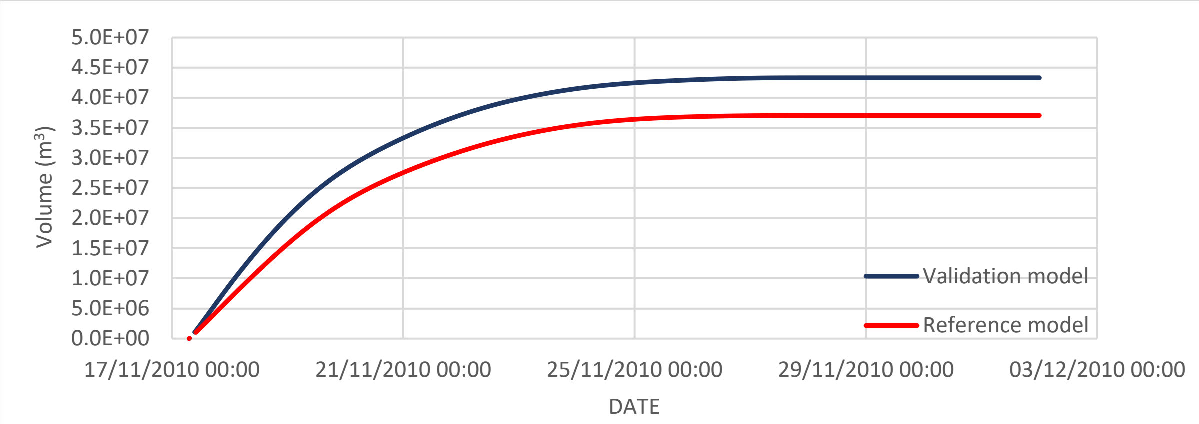

Figure 10: Cumulative breach discharges of reference model and validation model for T100

Differences in breach outflow can be caused by several factors, such as a difference in water level outside the dike and inland water level, dike breach width, bed level of the breach, and flow velocity. The bed level of the breach is in both models the same. The dike breach width of the reference model (72 meters) is larger than the validation model (65 meters). However, this does not explain the difference in breach outflow since a wider breach should lead to a higher breach outflow.

The upstream water levels of both models differ by less than 5 centimeters and this difference decreases over time (Figure 10). However, there are differences in water levels within the dike ring near the dike breach location. In the reference model, water levels inside the dike rise to 9.52 m +NAP and in the validation model the water level inside the dike increases to 9.27 m +NAP (Figure 12). In the reference model, water accumulates in the grid cells that are directly linked to the 1D model (see Section 5.2) and water levels inside the dike rise to the same water level as the water level in the IJssel. In the validation model, water levels are 0.25m lower in the grid cells that are directly linked to the IJssel. In the validation model, there is a large difference between the water levels inside the dike and outside the dike, as a result more water flows through the breach into the dike ring. Due to higher water levels inside the dike in the reference model, water cannot flow easily through the breach and the flow velocity through the breach decreases faster than in the validation model (Figure 13).

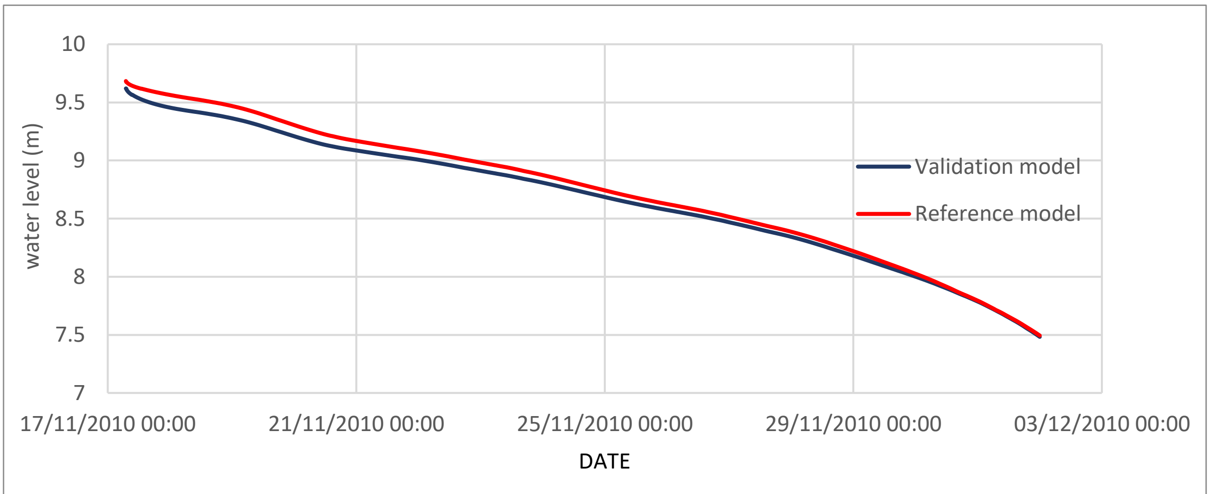

Figure 11: Water levels in IJssel near dike breach location

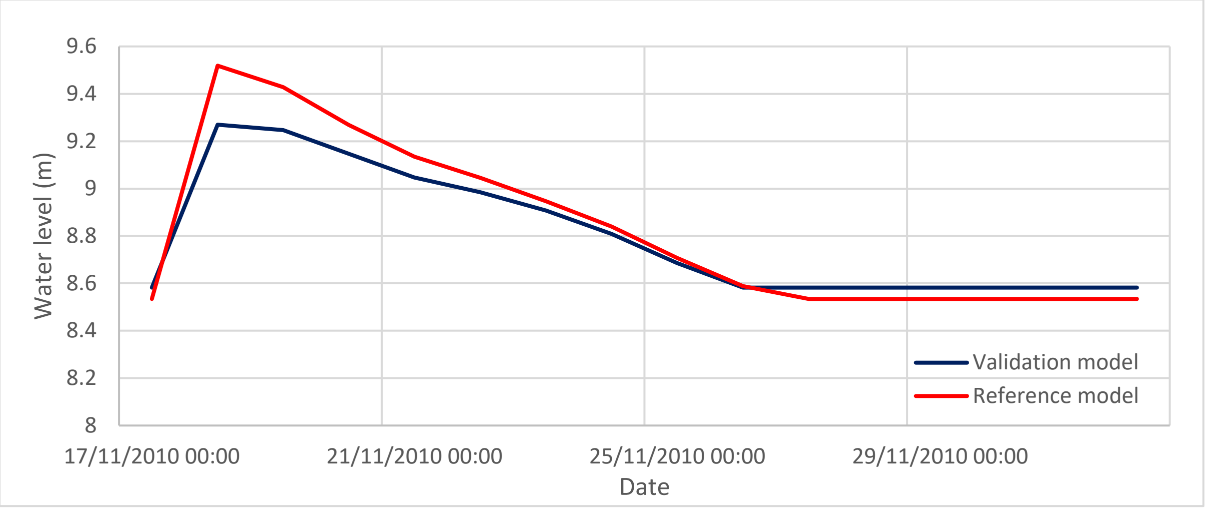

Figure 12: Water level inside the dike near dike breach location

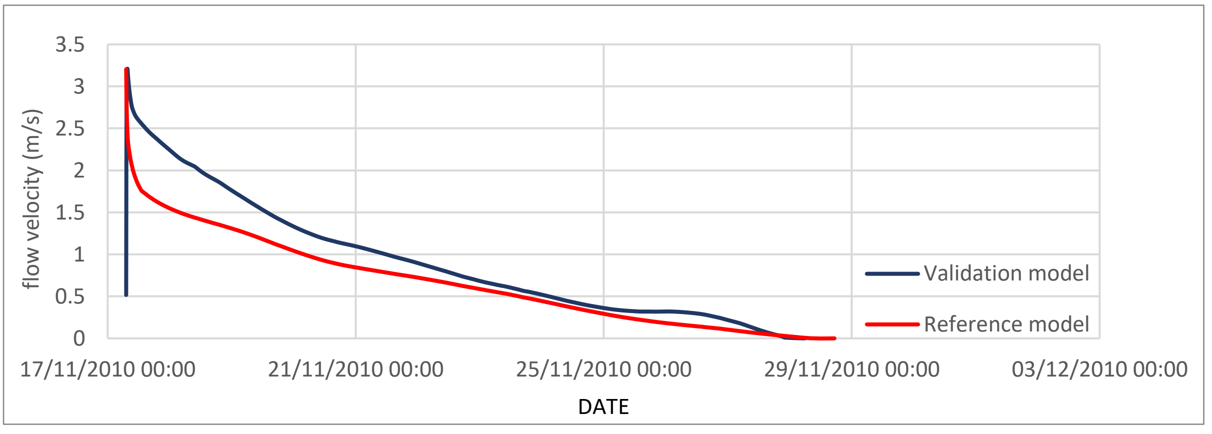

Figure 13: Flow velocity through dike breach

Figure 14 shows the maximum water levels in the reference model. This inundation map is used to compare the inundation extent and water depths of the models. The maximum water levels are higher in the validation model than in the reference model with a mean absolute error (MAE) of 0.24 meters. Locations near the dike breach show a smaller difference in water level than locations further away from the dike breach. Furthermore, only 72% of the area that has been inundated in the validation model is inundated in the reference model. This can be explained by the difference in breach outflow since a higher breach outflow leads to higher water levels and a larger area that inundates. Differences in breach outflow must be further analyzed before the model can be used as a reference model.

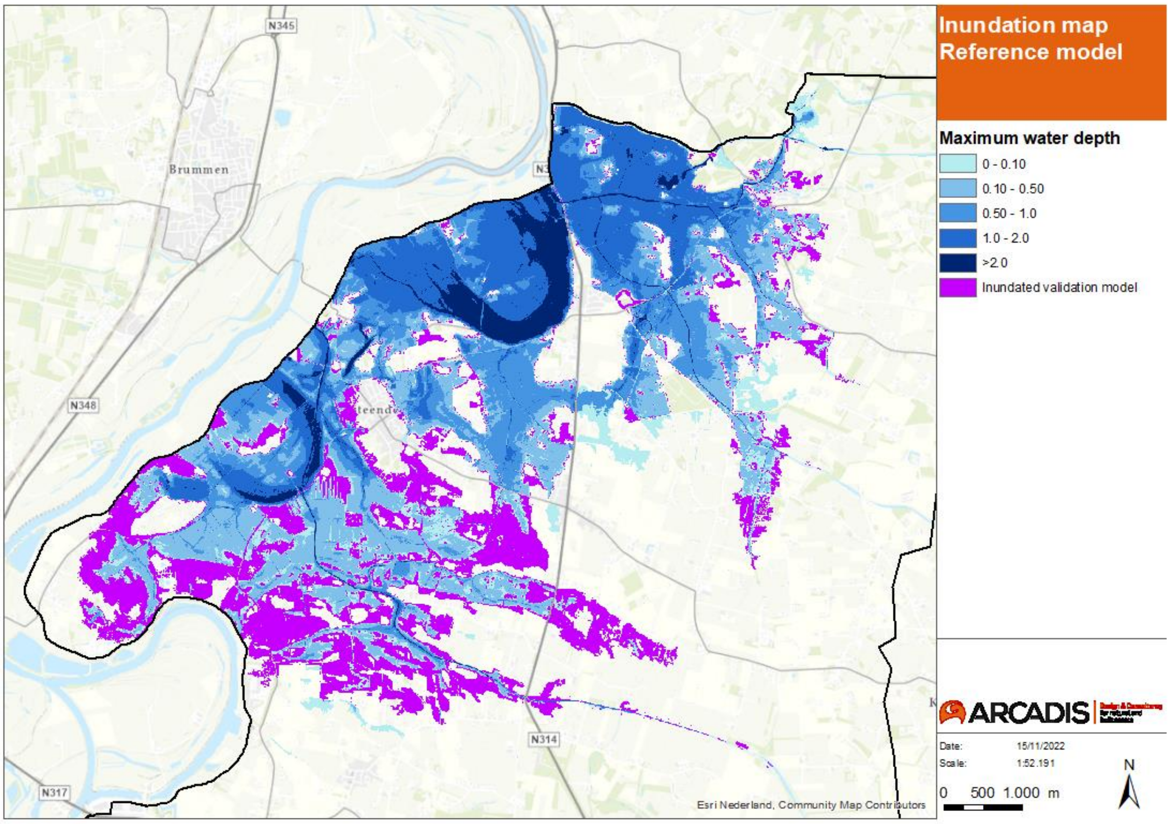

Figure 14: Inundation map of reference model for T100. Purple shows the areas that are inundated in the validation model but not in the reference model.

5.2 Analysis breach outflow

This subchapter describes the model simulation results in which a T100 hydrograph is used as a boundary condition. For this analysis, the models with grid cells of 20m, 40m, and 80m are compared with the reference model that has grid resolution of 10m. In these models, fixed weirs are used to schematize roads that are more than 0.25 meters higher than the surrounding area (see Section 4.2). The breach outflow, water levels, inundation extent, and arrival times are compared with the reference model.

Figure 15 shows an overview of the breach outflows and cumulative breach outflows. The peak discharge of the 40m- and 80m- models are 58% and 71% higher respectively compared to the reference model. The cumulative discharges of the 20m-, 40m, and 80m- models are 4%, 45%, and 51% higher respectively than in the reference model. The bed

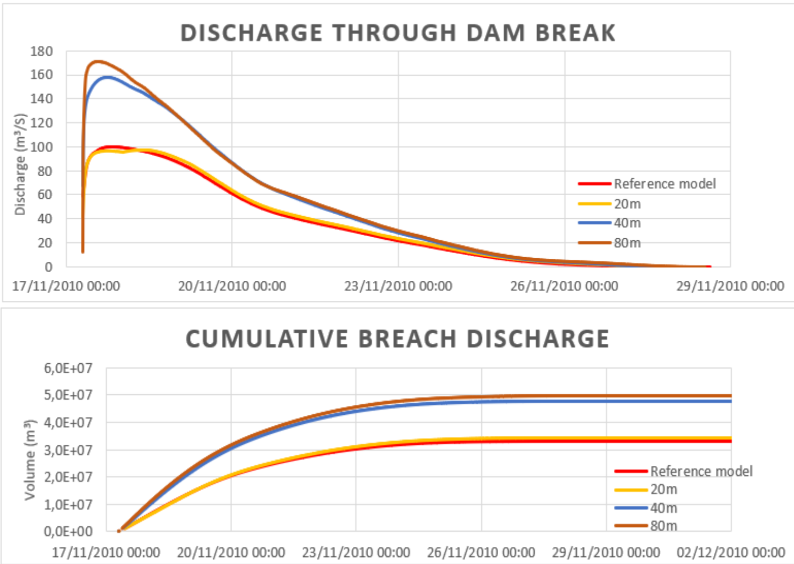

Figure 15: Discharge and cumulative discharge through dike breach of models with grid cells of 10m, 20m, 40m, and 80m for T100

levels are lower in the grid cells directly linked to the IJssel in the models with a coarser grid. 8.30 meter in the model with 80m grid cells compared to 8.53m in the reference model. In a model with grid cells of 80m, surface levels of up to 80 meters from the dike are included to determine the average bed level in the grid cell directly linked to the IJssel, while in the 10m model, surface levels up to 10m from the dike are included. Surface levels are lower at a greater distance from the dike. The bed levels near the dike breach location may be overestimated in the models with grid cells of 10m and 20m because the grid cells that are linked to the IJssel are too close to the dike. As a result, the surface level of the hinterland is not correct in the grid cells directly linked to the IJssel. The grid cell may also be partly on top of the dike in models with a coarser grid. However, only a small part of the grid cell lies on top of the dike, and surface levels of up to 40 meters and 80 meters away from the dike are included to determine the bed level. As a result, the bed levels near the dike breach location are closer to the lowest crest level of the dike (8.3 meters) in models with a coarser grid.

Besides that, water spreads easier to surrounding cells in models with grid cells of 40m and 80m. Therefore, water levels inside the dike near the dike breach location are lower than in models with a fine grid (Figure 16). As a result, more water can flow through the breach into the dike when a coarser grid resolution is used. The cumulative breach outflow is higher in models with a coarser grid because of the higher breach outflow during the first days (Figure 15). The model with 20m grid cells had similar discharges as the 10m model.

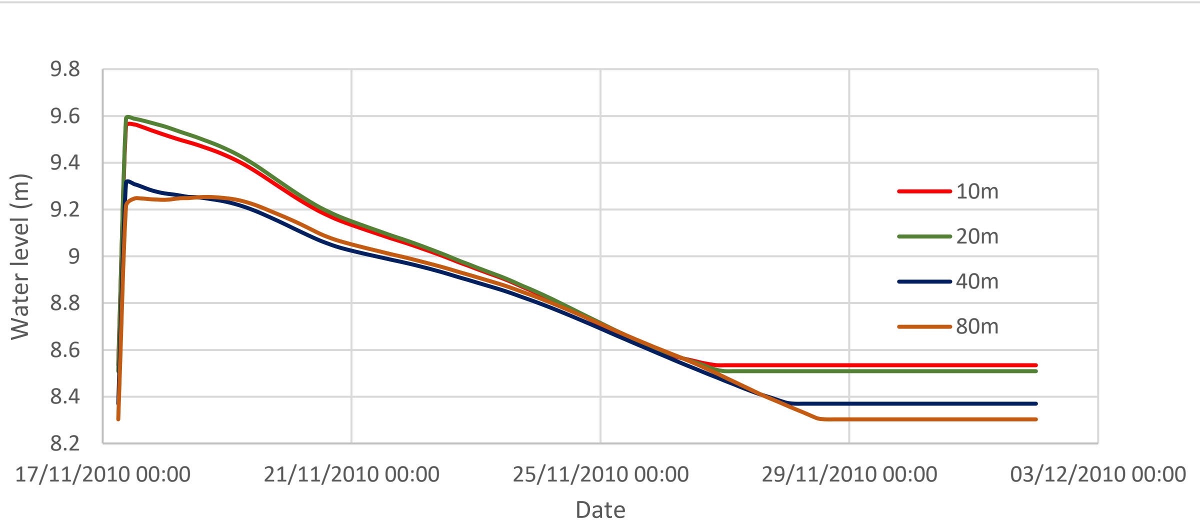

Figure 16: Water level inside dike near dike breach location

An explanation for the difference in breach outflows is the 2D grid schematization near the dike breach. The schematization affects the length through which water can flow to neighbor cells. The red arrows in Figure 17 are the 1D2D links through which water flows from the IJssel to the 2D grid. The total length through which water can flow to surrounding cells depends on the schematization and grid size. The brown line shows the cell edges through which water can flow to surrounding cells. In the reference model, five cells have one edge, and four cells have two edges through which water can flow to neighboring cells (Figure 17a). When a cell has two edges, more water flows to neighbor cells but reduces the amount of water that can flow from another cell that shares an edge with this cell. Water can flow over 1x the length of a grid cell when a grid cell has one cell edge through which water can flow to a surrounding cell and 2x the length when a grid cell has two brown cell edges. However, if a grid cell has a cell edge and another cell has also a cell edge to this grid cell, the length counts as 0.5x the length of a grid cell.

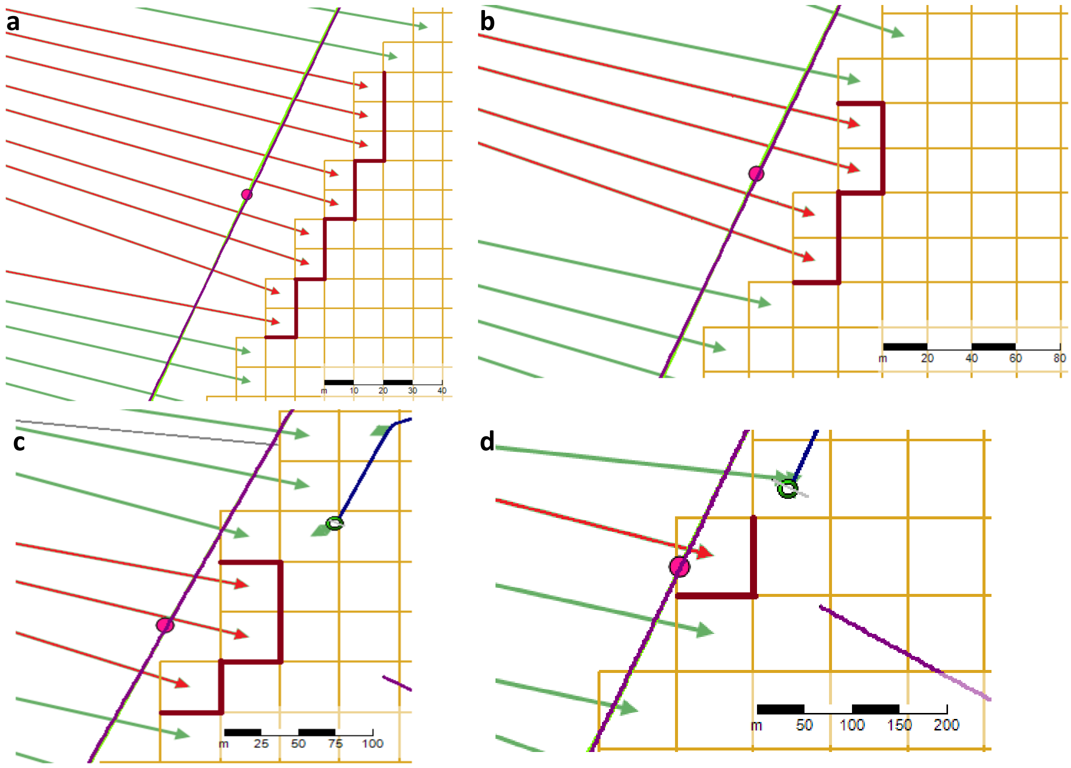

Figure 17: Schematization at dike breach location of different models. a) reference model b) 20m cells c) 40m cells, and d) 80m cells

Therefore, the length over which water can flow to neighboring cells is 100 meters in the reference model, since three cells share one edge with another cell. The model with 20m grid cells has a length of 120 meters over which water can flow to surrounding cells. Water can flow from the upper grid cell to two neighboring cells. One of these neighbor cells is in a corner and water cannot flow easily to other grid cells from this cell. Therefore, the available length through which water can flow to neighboring cells is also 100 meters. In the model with grid cells of 40m and 80m, water can flow over a length of 160 meters to surrounding cells.

To conclude, grid size and schematization affect the breach outflow. Models with a coarser grid have a higher breach outflow, because of the lower surface level in the grid cell near the dike breach location and the lower water level inside the dike.

Inundation extent and water levels

The inundation extent and water levels are compared with the reference model after five time periods: 3 hours, 6 hours, 12 hours, and 24 hours after the dike breach, and when maximum water levels are reached.

The mean absolute error (MAE) is larger in the 40m and 80m models than in the 20m model (Table 4). The large difference between the 40m and 80m model can mainly be explained by the higher breach outflow of the models with grid cells of 40m and 80m. Due to a higher breach outflow, more water flows into the dike ring area, which results in higher water levels and a larger inundated area.

The inundation map of the 20m model shows small differences in water depths compared to the reference model, whereas the inundation maps of the 40m and 80m models have higher water depths in a large part of the inundated area than in the reference model (Appendix A). Near the dike breach, all models have a lower water depth than the reference model in the first 6 hours after the dike breach.

In the 20m model, the MAE is small for all time steps and measure of fit for inundation extent increases over time (Table 4). The accuracy of the 40m and 80m models does not increase over time. The 40m and 80m models were most inaccurate 6 hours after the dike breach with a measure of fit is 51% and 49%, which means that about 50% of the inundated area is simulated correctly. The area that has been inundated in the 40m and 80m models is significantly larger than in the reference model. The cumulative discharge of the 40m and 80m models is 63% and 85% higher, respectively, than that of the reference model six hours after the dike breach.

Table 4: Overview of MAE and inundation extent for 20m, 40m, and 80m models

Grid size	Roads as line elements	MAE [m]					Measure of fit inundation extent				
		3h	6h	12h	24h	Max	3h	6h	12h	24h	Max
20x20m	Roads >0.25m	0.03	0.03	0.05	0.02	0.06	0.86	0.91	0.93	0.96	0.88
40x40m	Roads >0.25m	0.26	0.15	0.34	0.4	0.27	0.68	0.51	0.67	0.71	0.69
80x80m	Roads >0.25m	0.26	0.15	0.35	0.45	0.29	0.69	0.49	0.62	0.69	0.68

The differences between the reference model with the 40m and 80m model are mainly caused by a higher breach outflow. The 20m model showed significantly better results than the 40m and 80m models. The effect of grid size on water level and inundation extent can only be fairly compared between the 20m model and the reference model since these models have a similar breach outflow. When comparing water levels and inundation extents, it can be concluded that differences in water depths are quite small. The first hours after the dike breach the inundation extent is simulated less accurately than 24 hours after the breach. At maximum water levels, the inundated area is larger in the 20m model than in the reference model. This can be caused by the fact that the 20m model has a cumulative discharge that is 4% higher than the reference model and bed levels are more flattened at a coarser grid and therefore water can spread over a larger area.

Flood arrival times

The results of the 20m model show that arrival times are correctly predicted in the area that inundates within the first 24 hours after the dike breach (Figure 18 and Figure 19). Differences can be seen at the border of this area; these are mostly inundated earlier in the 20m model (Figure 19). In the reference model, the area near Steenderen inundates more than 24 hours after the dike breach. In the model with 20m grid cells, this area floods 3 to 6 hours earlier. Further away from the breach, differences in arrival times are even larger, with area flooding 6 to more than 24 hours earlier in the 20m model. Differences in arrival times between the 20m model and reference model can mainly be explained by differences in grid size. The difference in arrival times can partly be explained by the difference in cumulative breach outflow. Since more water flows into the 20m model, a larger area inundates. Besides that, the flow velocity through the dike breach is higher in models with a coarser grid. It is likely that the flow velocity over the hinterland is also higher when a coarser grid is used. In addition, bed levels are flattened more, and water can flow more easily to surrounding cells.

The flood arrival times of the 40m and 80m models are similar. Arrival times are only predicted correctly in a small area (Figure 20). The area that floods between 6-12 hours after the dike breach, floods between 3-6 hours earlier of the 40m and 80m models. The results show that Steenderen inundates 12 to 24 hours earlier. The area south of Steenderen floods more than 24 hours earlier in the models with a coarse grid. The higher breach discharge of models with a coarser grid can mainly explain the large difference in flood arrival times.

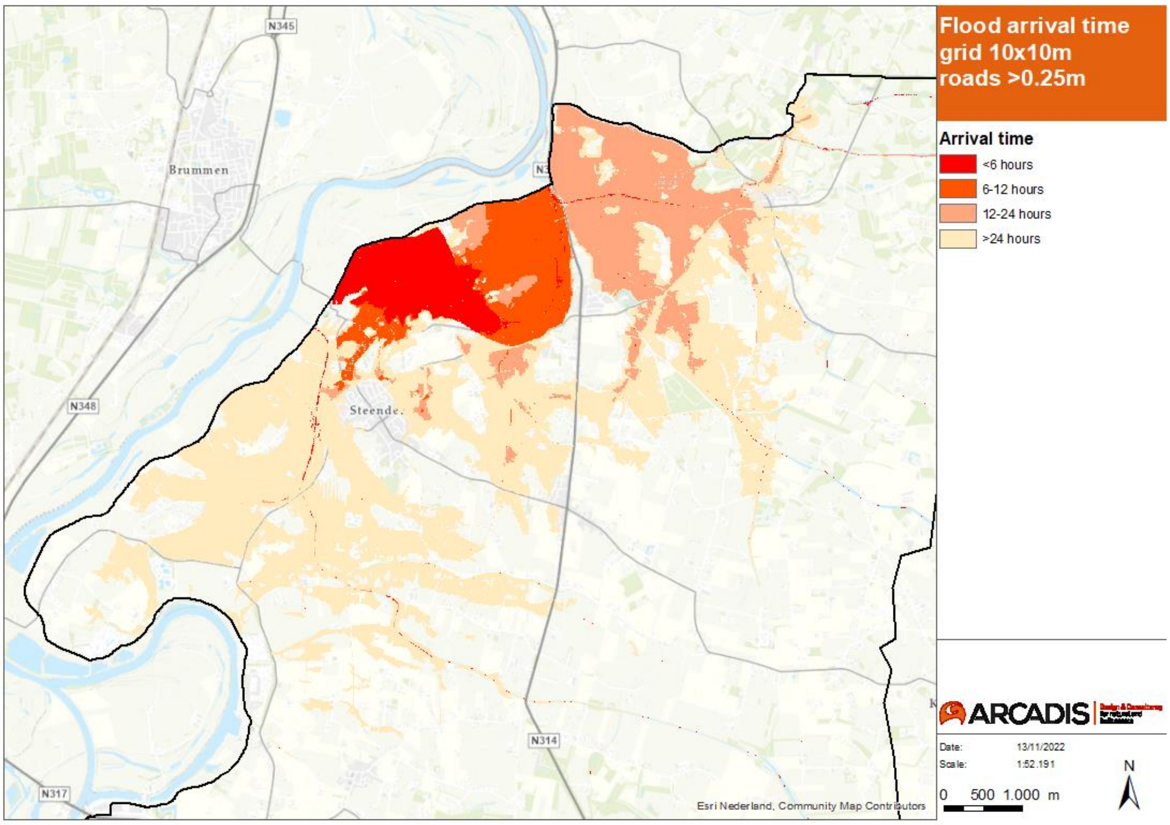

Figure 18: Flood arrival times of the reference model

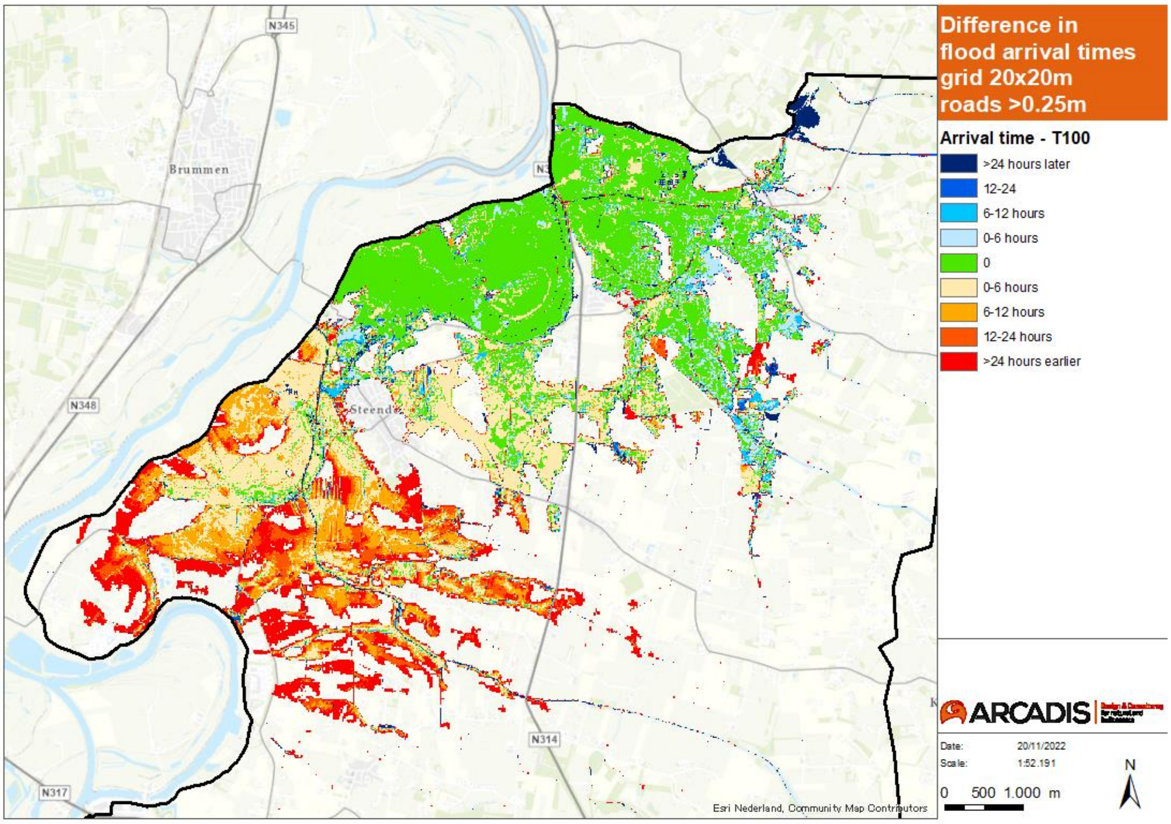

Figure 19: Difference in flood arrival times between 20m model and reference model

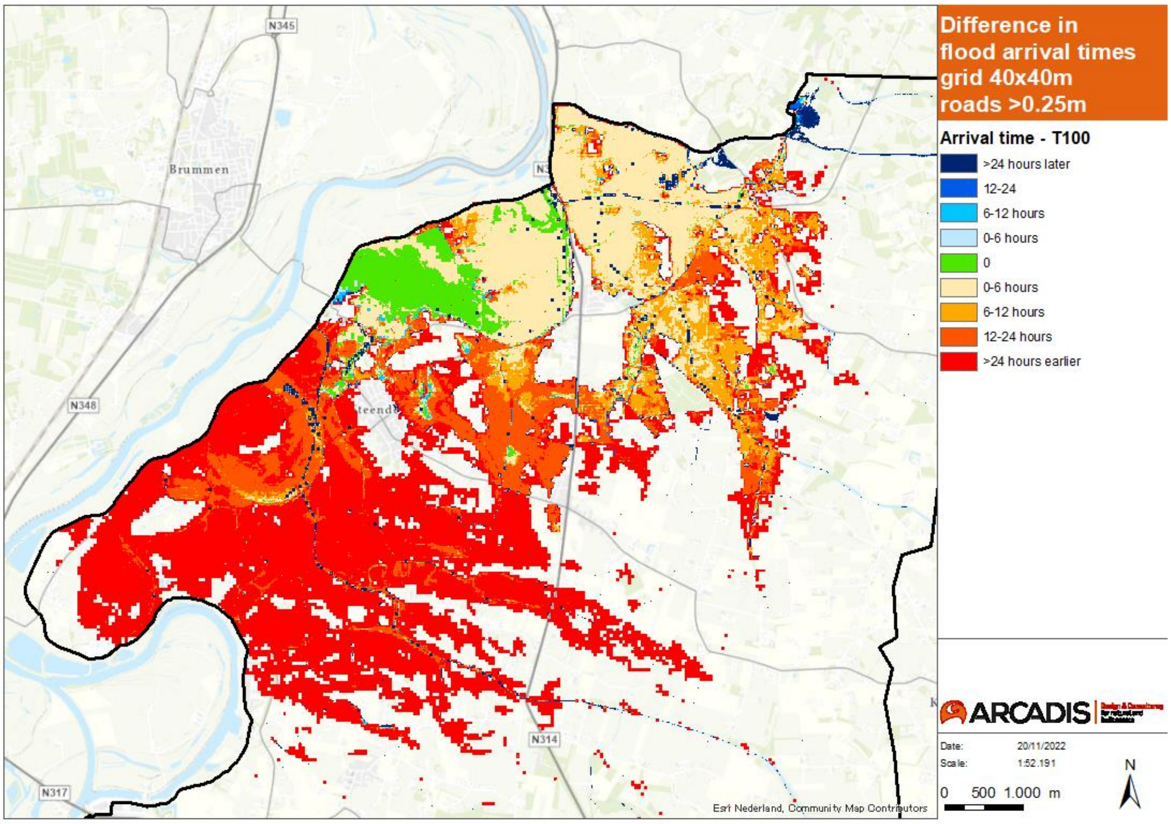

Figure 20: Difference in flood arrival times between 40m model and reference model

5.3 Effect of fixed weirs

This section describes the model simulation results in which the breach outflow hydrograph of the reference model is used as a boundary condition, so that breach outflow does not affect the model results. For this analysis, the models with grid sizes 10m, 20m, 40m, and 80m are compared with the reference model. In the reference model, roads with a surface level that are at least 0.25m higher than surrounding areas are schematized as fixed weirs. In the models with grid cells 20m, 40m, and 80m, three different fixed weirs options are analyzed; 1) roads are not schematized as fixed weirs, 2) roads that have a surface level that is at least 0.25m higher than the surrounding area are schematized as fixed weirs, and 3) all roads are schematized as fixed weirs.

Inundation extent and water level comparison

Water levels and inundation extent are compared with the reference model 3 hours, 6 hours, 12 hours, and 24 hours after the dike breach and maximum water levels are compared.

The results show that adding fixed weirs increases model accuracy significantly for all grid resolutions (Table 6). For example, the average inundation depth is 0.86 meters in the reference model 12 hours after the dike breach, the 20m model has a MAE of 0.31 meter and decreases to 0.06 meter when fixed weirs are added (Table 5 and Table 6). The measure of fit for inundation extent increases from 0.72 to 0.93. This indicates that roads are not correctly schematized in the grid. Roads have a blocking effect; a larger area inundates when roads are not schematized as fixed weirs (Figure 21 and Figure 22).

Table 5: Results of reference model

Grid size	Roads	Average inundation depth (m)					Inundated area (ha)					Simulation time
		3h	6h	12h	24h	Max	3h	6h	12h	24h	Max	Hours
10x10	Roads >0.25m	0.44	0.82	0.86	0.9	0.82	115	177	394	780	2384	61.1

Table 6: Overview model results

Grid size	Roads	MAE (m)					Measure of fit inundation extent					Simulation time
		3h	6h	12h	24h	Max	3h	6h	12h	24h	Max	Hours
10x10	No	0.00	0.07	0.12	0.05	0.07	0.99	0.9	0.93	0.96	0.89	62.9
20x20	No	0.02	0.42	0.31	0.06	0.17	0.87	0.58	0.72	0.9	0.78	12.1
20x20	Roads >0.25m	0.02	0.02	0.06	0.03	0.06	0.87	0.9	0.93	0.96	0.88	12.0
20x20	All	0.02	0.02	0.06	0.03	0.06	0.87	0.9	0.93	0.96	0.88	12.0
40x40	No	0.05	0.45	0.31	0.08	0.16	0.8	0.56	0.74	0.87	0.79	3.3
40x40	Roads >0.25m	0.05	0.04	0.11	0.02	0.07	0.8	0.83	0.9	0.94	0.88	3.2
40x40	All	0.05	0.04	0.11	0.02	0.07	0.8	0.84	0.9	0.94	0.88	3.3
80x80	No	0.06	0.47	0.29	0.1	0.16	0.75	0.56	0.7	0.87	0.79	1.6
80x80	Roads >0.25m	0.06	0.06	0.12	0.06	0.06	0.75	0.84	0.89	0.91	0.88	1.6
80x80	All	0.06	0.06	0.12	0.06	0.06	0.75	0.84	0.89	0.91	0.88	1.6

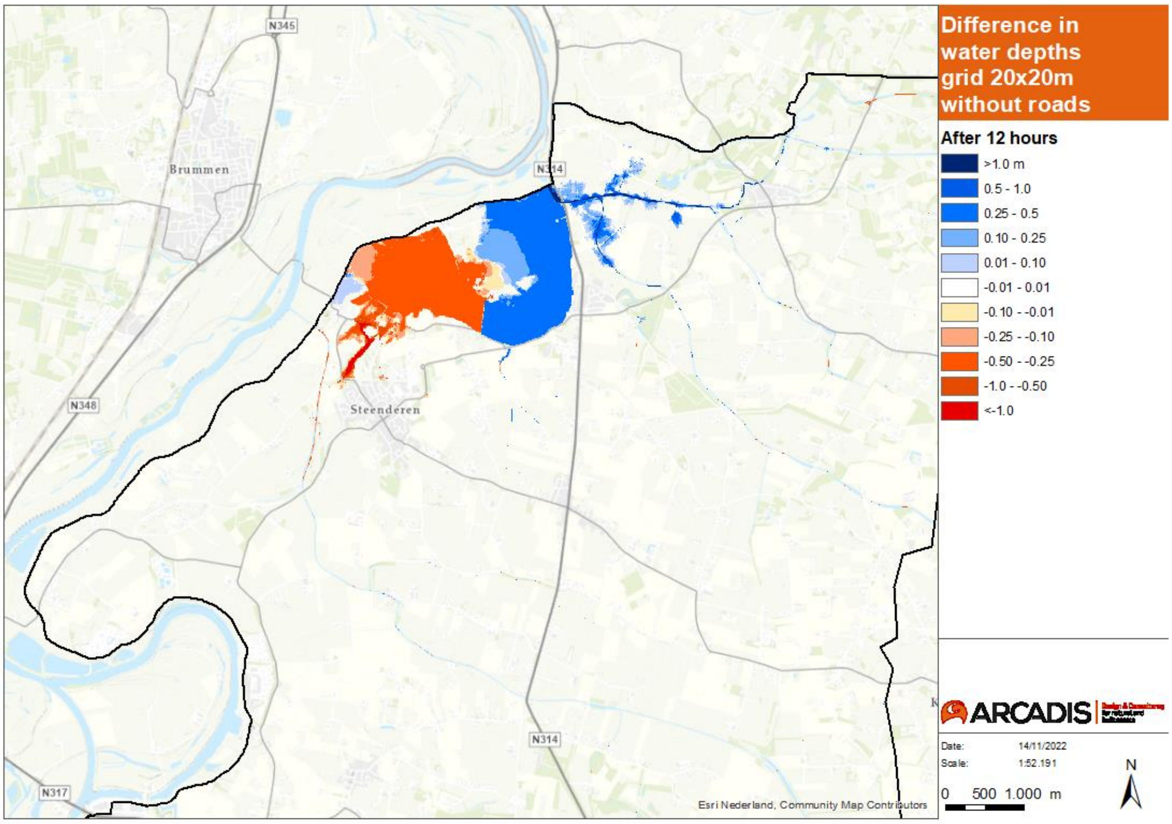

Figure 22: Difference in water depth between 20m model without roads as fixed weirs and reference model

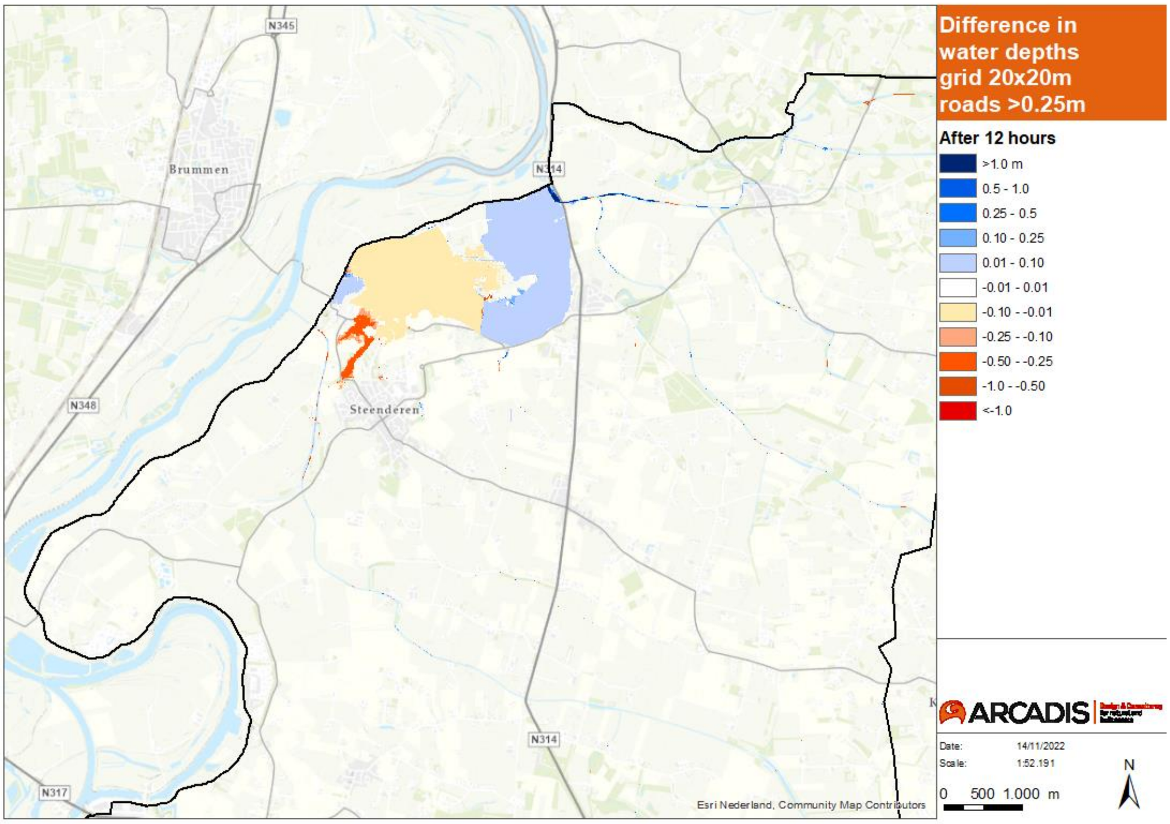

Figure 21: Difference in water depth between 20m model with roads as fixed weirs and reference model

The models without fixed weirs show large differences in inundation extent and water levels compared to the reference model, especially between 6 and 12 hours after the dike breach. Adding roads with a surface level less than 0.25m higher than the surrounding area does not improve model accuracy compared to only adding roads with a surface level more than 0.25m higher than the surrounding area (Table 6). All models with fixed weirs are found to be equally accurate in simulating the maximum water level of inundation. Differences in model accuracy during the first 24 hours after the dike breach can be explained by the fact that bed levels are flattened more when a coarser grid is used, and water can spread more easily over a larger area.

The 10m model without roads does not show a significant difference 3 hours after the dike breach. 6 hours after the dike breach a larger area inundates in the 10m model without roads as fixed weirs, because water is not blocked by a fixed weir, whereas at the same time artificial holes in elevated road elements are created in the digital elevation model by averaging elevation over 10m grid cells. As a result, the water levels are higher on the east side and lower on the west side of this road (Figure A.7 and Figure A.8). 24 hours after the dike breach, water depths are higher on the east side and lower on the west side of N314. In the reference model, the N314 is schematized as a fixed weir and the highest surface level of the road determines whether water can flow over the road. Whereas at the 10m model without fixed weirs, the average height is taken over an area of 100 m^2. As a result, the height of the road is lower, and water can flow over the road at a lower water level. At maximum water depths, the 10m model without roads has lower water depths in the northern part of the dike ring and higher water levels in the southern area (Figure A.10). 89% of the inundated area is correctly simulated in the model without fixed weirs. A larger area has been inundated when fixed weirs are not included. Roads that are schematized as fixed weirs have a better blocking effect than in a model that does not include roads as fixed weirs. Even in models with grid cells of 10m, roads are not schematized correctly because the average bed levels are used (Section 4.1). This is because grid cells are not exactly on top of a road and roads are in general smaller than 10 meters, for example, the N314 has a width of 7.5 meters.

Flood arrival times

Schematizing roads as fixed weirs improves the prediction of arrival times significantly for all grid resolutions. When roads are schematized as fixed weirs, flood arrival times are correctly predicted on locations that inundate within first 24 hours after the dike breach, whereas flood arrival times are only correctly predicted near the dike breach location when roads are not schematized as fixed weirs (Figure 23 and Figure 24).

It takes more than 24 hours after the dike breach before Steenderen floods in the reference model. In the 20m model with roads as fixed weirs, this area inundates 3 hours earlier and locations south of Steenderen are flooded at least 6 hours earlier than in the reference model. The flood arrival maps of the 40m and 80m model show similar differences in flood arrival times as the 20m model (Figure B.10 and B.13). However, south of Steenderen are a few locations that are flooded 12 hours earlier in the 20m model and 6 hours earlier in the 40m and 80m models. The arrival map of the 80m model shows that the area east of

Steenderen floods 6 hours later than in the reference model, whereas this area inundates earlier in the model with grid cells of 20m and 40m.

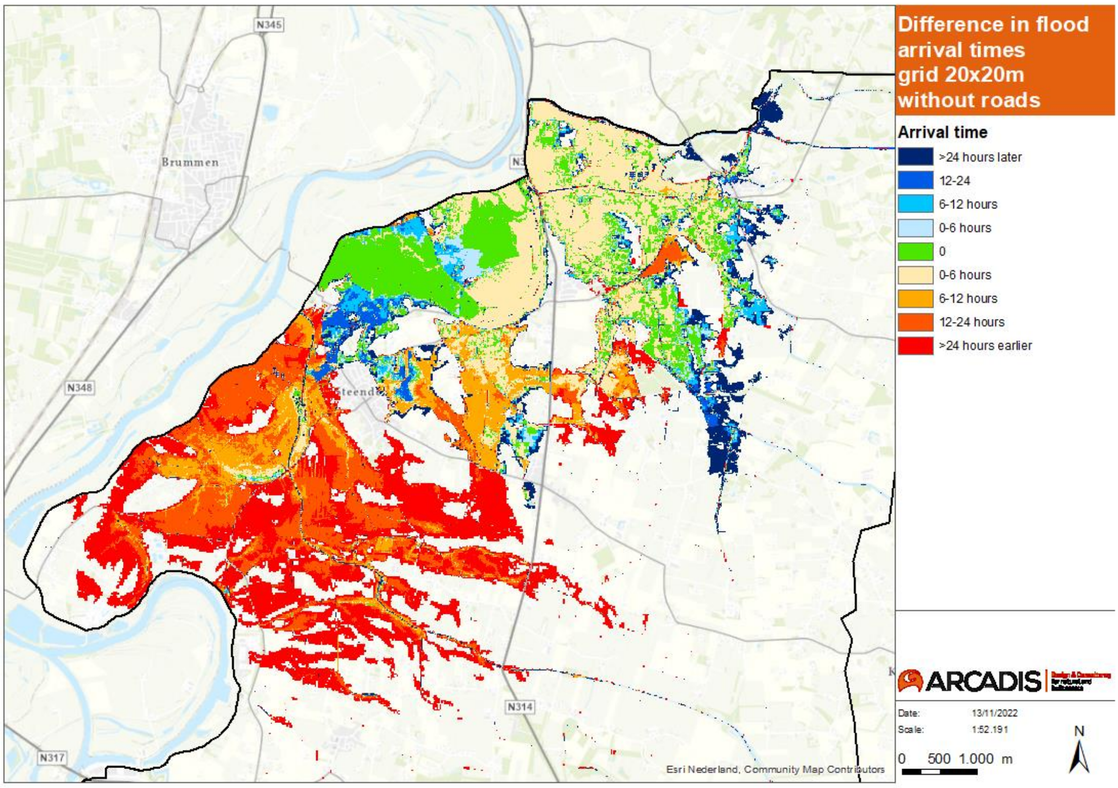

Figure 23: Difference in flood arrival times between 20m model without roads and reference model

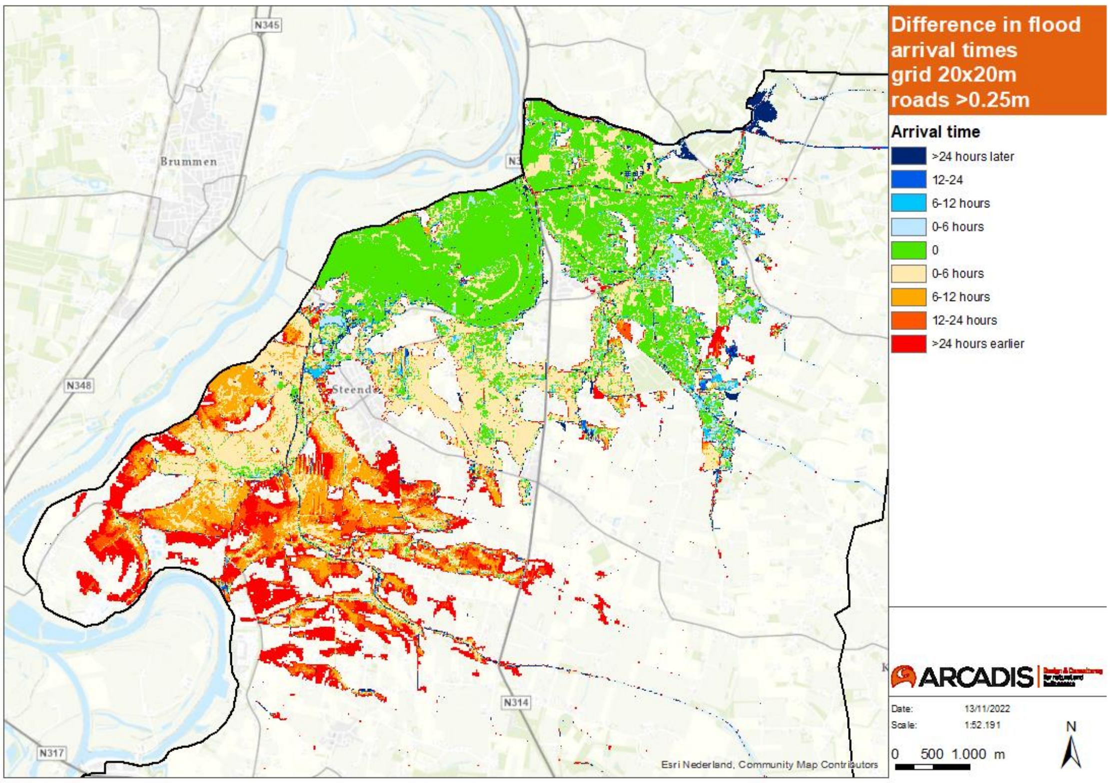

Figure 24: Difference in flood arrival times between 20m model with roads as fixed weirs and reference model

The arrival maps of the 20m, 40m, and 80m without fixed weirs show that arrival times are only correctly predicted in a small area near the dike breach. Locations near the N314 inundate at least 3 hours earlier than in the reference model. The area that is located northwest of Steenderen inundates at least 6 hours later because the water flows to the eastern part of the N314 before it reaches the northwest of Steenderen, whereas in the reference model this area inundates within the first 12 hours after the dike breach. South of Steenderen inundates at least 6 hours earlier, and large parts inundate even 12 to more than 24 hours earlier. The difference in flood arrival times is larger in the 40m and 80m models without fixed weirs. Locations that flooded at least 6 hours earlier when roads are schematized as fixed weirs flood at least 12 hours earlier in the 40m model when roads are not schematized as fixed weirs. Locations that flooded 12 hours earlier in the 20m model than in the reference model, are flooded 24hours earlier in the 40m and 80m models.

So, when looking at arrival times it can be concluded that fixed weirs have a significant effect on flood arrival times. The flood arrives earlier in a large part of the inundated area, when roads are not schematized as fixed weirs. Grid size also affects the flood arrival times, since flood arrives earlier in models with a coarser grid. Arrival times are correctly predicted near the dike breach and differences in arrival times become larger as the distance from the breach increases.

5.4 Effect of local grid refinement

This subchapter describes the results of the models in which the grid is locally refined. For this analysis, three different models are compared with the reference model. The basic grid size is 80m and is locally refined to 40m, 20m, and 10m around the roads that are 0.25m higher than surrounding areas. In these models, roads are schematized as fixed weirs.

Inundation extent and water level comparison

The results show that grid refinement around roads improves model accuracy (Table 7). With local grid refinement, similarly accurate results can be obtained in a shorter simulation time compared to models that have finer grid cells in the entire area. For example, an 80m model with grid refinement to 20m is similarly accurate as a model with 20m grid cells (Table 6 and Table 7). The computation time of an 80m model with grid refinement to 20m increases with 1 hour compared to using a model with only 80m grid cells, whereas the computation time of a model with only 20m grid cells is 10.4 hours longer than the reference model. The 80m model with local grid refinement does not show improvements in accuracy during the first 3 hours after the dike breach. The difference in model accuracy can be explained by the fact that areas with differences in surface levels, for example near roads, are schematized more accurately in the model with local grid refinement.

However, it should be mentioned that an 80m model with local grid refinement to 10m, is not as accurate as a model with only grid cells of 10m. The results of a model with grid cells of 80m with local grid refinement to 10m, are similarly accurate as a model with grid cells of 10m in which roads are not schematized as fixed weirs. Increasing the grid locally to 10m increases the computation time by a factor of 4.2.

To conclude, the improvements in model accuracy due to grid refinement do not outweigh the increase in computation time. The results of a model with 80m with roads as fixed weirs are accurate. The model with 80m grid cells is inaccurate in the first hours after the dike breach when considering the measure of fit for inundation extent. Refining the grid around roads hardly improves the results in the first hours after the dike breach.

Table 7: Results of grid refinement

Grid size	Grid refinement	**Roads**	**MAE (m)**					**Measure of fit inundation extent**					**Simulation time**
			3h	**6h**	**12h**	**24h**	**Max**	**3h**	**6h**	**12h**	**24h**	**Max**	**Hours**
80x80	40x40	Roads >0.25m	0.06	0.04	0.1	0.03	0.03	0.75	0.82	0.9	0.93	0.91	1.8
80x80	20x20	Roads >0.25m	0.06	0.04	0.04	0.03	0.03	0.75	0.85	0.92	0.94	0.91	2.6
80x80	10x10	Roads >0.25m	0.06	0.03	0.02	0.02	0.02	0.77	0.86	0.94	0.95	0.94	6.7
80x80	No	Roads >0.25m	0.06	0.06	0.12	0.06	0.06	0.75	0.84	0.89	0.91	0.88	1.6

5.5 Effect of Courant number

In this section, the effects of the Courant number on model are described. The Courant number is explained in section 2.3. To analyze the effect of the Courant number, the Courant number of the reference model is adjusted from 0.7 to 0.95 and 2.0. It is not recommended to use a Courant number >1.0, because results might become inaccurate. However, the maximum time step increases when a larger Courant number is used. A model with a fine grid resolution and a Courant number >1.0 may be more accurate than model with a coarse grid and a Courant number <1.0. The T100 discharge is used as a boundary condition, which means that breach discharge depends on the water level in the IJssel (Section 4.3).

Increasing the Courant number from 0.7 to 0.95 reduces the simulation time of the reference model by 30%. The results do not show a difference in MAE and inundation extent (Table 8). The model is Courant limiting in the grid cells near the dike breach. So, differences in results are expected to be at the dike breach location. However, even in the grid cells near the dike breach the water depths are the same. The breach outflow of the reference model with a Courant number of 0.7 is similar as that of the reference model with a Courant number of 0.95.

With a Courant number of 2.0, water can flow through more than one grid cell within a single time step. It is expected that model results become unstable when a Courant number >1.0 is used. The breach outflow hydrograph is however not affected when the Courant number is increased from 0.7 to 2.0. The results do not show a difference in MAE and the inundation extent is hardly affected by a Courant number of 2.0. There is no difference in water depths in the grid cells near the dike breach location. Increasing the Courant number reduces the computation time by 47%. Despite having a Courant number of 2.0, the computation time of the reference model is still 32.5 hours.

The effect of increasing the Courant number was also tested on the model with 80m grid cells. However, the model was hardly Courant limiting for a maximum time step of 30 seconds, meaning increasing the Courant number had no effect on computation time or model accuracy.

Table 8: Results courant number

Grid size	Courant	Roads	MAE					Measure of fit inundation extent					Simulation time
			3h	6h	12h	24h	Max	3h	6h	12h	24h	Max	Hours
10x10	0.95	Roads >0.25m	0.00	0.00	0.00	0.00	0.00	1	1	1	1	1	43.1
10x10	2.0	Roads >0.25m	0.00	0.00	0.00	0.00	0.00	0.995	0.998	1	1	0.99	32.5

6 Discussion

The goal of this study was to understand the effect of mesh properties on breach discharge and to what extent line elements can compensate for a lower grid resolution. This study has some limitations. First, the grid size of the reference model is 10m and has a computation time of 60 hours. This grid size is mainly chosen because the computation time of the reference model would be too long if grid cells of 5m were used. The computation time of the reference model would at least be a factor four higher if grid cells of 5m were used. A model with grid cells of 5m is more suitable since roads are not correctly schematized in a model with grid cells of 10m. In the reference model, roads were therefore schematized as fixed weirs.

Second, the reference model is validated with a similar model that already was validated and has grid cells of 40m with local grid refinement to 20m. There were some differences in results between the reference model and the validation model (See section 5.1). These differences were caused by the difference in breach outflow and were not due to a modelling error. At the end of the study, it was noticed that there is a leak in the reference model, which is also in the validation model. This leak was previously not noticed in the validation model, as it did not affect model results. In the reference model water flows over 2D grid cells that are located on top of a 1D waterway because the water level in this waterway is higher than the bed level in the grid cells on top of the waterway. This does not occur in the model with 40m grid cells, since the bed level on top of this waterway are about 2 meters higher. The average surface level of a grid cell is used as the bed level, and the waterway is relatively small compared to the 40m grid cell. The bed level of the 40m is higher than the water level in the 1D model and water does not flow over the 2D grid. This leak in the reference model influences model results, as more water flows out of the dike ring towards the IJssel. It is important to mention that this leak is far away from the dike breach location, and water does not flow out of the dike ring area until 2 days after the dike breach due to this leak. Most of the results of this study can be used because they are not affected by the leak. The only results that are affected by this are the comparison at maximum water levels and flood arrival times at location further away from the dike breach since this is more than 2 days after the dike breach.

The breach outflow hydrograph of the reference model is used as a boundary condition to make a fair comparison between the models with different grid resolutions. However, it is important to consider this assumption when interpreting the results and answering the research question, as the study does not show whether the breach discharge of the reference model is correct. It is possible that the breach discharge is overestimated in models with a coarser grid, but it is also possible that the breach discharge is underestimated in the reference model. The first part of the study shows that a coarser grid resolution increases breach discharge, and a higher breach discharge leads to inaccurate model results. Consequently, it is assumed that the breach discharge of the reference model is correct, upon which this conclusion is based. The second part shows that the results of a model with a coarse grid are accurate when roads are schematized as fixed weirs.

The time step settings that are chosen in the analysis are a maximum timestep of 30 seconds and a Courant number of 0.7. The 1D model is optimized so that it is hardly courant limiting with a time step of 30 seconds. Analyzing the effect of the Courant number showed that the model is hardly Courant limiting with the time step of 30 seconds when a coarse grid resolution is used. Increasing the Courant number has no effect on the calculation time and results. As a result, no well-founded conclusions can be drawn from the effect of the Courant number. In order to draw a well-founded conclusion, a larger maximum time step could be used, or to let the model determine the time step based on the Courant number.

When comparing the results of this study to existing literature, many similarities can be found. This study showed that a coarser grid resolution leads to a higher breach outflow, with a peak discharge that is 58% and 71% higher than the reference model when grid cells of 40m and 80m are used. The results of Altinakar et al. (2010) also concluded that a coarser grid leads to a higher breach outflow. The differences between the two studies can possibly be explained by the fact that Altinakar et al. (2010) used a fully 2D model, whereas this study used a coupled 1D2D model. In a fully 2D model, the grid cells of the hinterland are better aligned to the river than in a 1D2D model. Model schematization near the dike breach affects the breach outflow. One of the grid cells near the dike breach in the 20m model is in a corner and water cannot flow easily to neighboring cells, which limits the breach outflow. This might explain why the breach outflow of the 10m and 20m model is similar, and it is likely that if the grid cell in the 20m model was not located in a corner, the breach outflow of the 20m would be higher.

The results of the models with 40m and 80m grid cells were inaccurate, with higher water depths, a larger area inundates, and the area inundates faster. A higher breach outflow ensures that more water flows to the hinterland in a shorter time. As a result, water levels rise faster, increasing the speed at which the area floods, and a larger area inundates. Other studies used a breach outflow as a boundary condition and therefore breach outflow does not affect model results (e.g., Yu and Lane, 2006a; Yu and Lane, 2006b). For the other analyses in this study, the breach outflow hydrograph of the reference model was used.

Previous studies found different results regarding the effect of grid resolution on model accuracy. Caviedes-Voullième et al. (2012) concluded that a coarser grid leads to higher numerical friction and results in a delay of the peak flow. Yu and Lane (2006a) mention that structural features and topography are not as accurately represented in a coarser grid which accelerates the speed at which the area floods and changes the flow direction (Yu and Lane, 2006a). This study confirms that a coarser grid without adding additional approaches to capture spatial features as fixed weirs or local grid refinement increases the flooding speed (Section 5.4). Line elements are not schematized correctly if a coarser grid is used.

By schematizing roads as fixed weirs, model accuracy improves significantly, and differences in flood arrival times between a model with a coarse grid and a small grid become smaller. Adding roads as fixed weirs delays the flood, even in models with grid cells of 10m. With 10m grid cells, roads are partly schematized in the grid, but the highest surface level of the roads is not schematized well, since the average bed level within the grid cell is used. Moreover, grid cells are not exactly on top of the roads. Grid cells finer than 10m are required to correctly schematize roads within the grid. Within this study, roughness parameters of the hinterland are based on land use. The roughness parameter can be increased in models with a coarse grid to delay the flood which was done by Yu and Lane (2006a) but is not further analysed within this study.

The breach outflow of a flood forecasting model depends on several factors, such as the location of the dike breach, the moment of the dike breach, and the characteristics of the hinterland. When a different dike breach location is used. The model with grid cells of 80m and roads schematized as fixed weirs are expected to be accurate when a breach outflow hydrograph is used as a boundary condition. However, it is not possible to know in advance where the breach location exactly is. For a flood forecasting model, the model should be able to correctly estimate the breach outflow, based on the location of the breach, in which it considers the characteristics of the hinterland and water level in the river. This model is not yet suitable as flood forecasting because it not able to correctly estimate breach outflow.

7 Conclusion

The goal of this study is to determine if D-Hydro can be used to create a flood forecasting model for large study areas. To achieve this goal, 1D2D D-Hydro models of dike ring area 49 are created to analyze the effects of model choices on a realistic case. For this study, the following research question has been formulated:

What is the effect of model choices on model accuracy and computation time, and can it be used to create a flood forecasting model?

The first sub question that is answered is: *What is the effect of grid size on breach discharge?*

The grid sizes used in these models are 10m, 20m, 40m, and 80m. Grid size and grid schematizations affect breach outflow. The grid schematization at the breach location resulted in bed levels in the hinterland being higher than the minimum crest level of the dike in the reference model. This is because the grid cells are close to the dike. As a result, the reference model may underestimate the breach discharge. Grid schematization also affects breach outflow because the drainage of water to surrounding cells is limited if a grid cell is in a corner. The peak discharge and cumulative discharge are significantly higher in the models with a coarse grid. Models with a coarse resolution artificially remove local backwater effects near the breach, easying throughflow to the hinterland and increasing breach outflow. Therefore, models with a coarse grid resolution overestimate the breach discharge. The high breach outflows for coarse-resolution models resulted in consistently inaccurate results for water depth, inundation extent, and flood arrival times.

The second sub question that is answered is: *To what extent can line elements compensate for a lower grid resolution?*

Adding roads as fixed weirs significantly improved model accuracy. Even with a resolution of 10m, roads are not schematized correctly without adding them as fixed weirs. Without adding roads as fixed weirs, model accuracy decreases when using a coarser grid resolution. Adding roads as fixed weirs with a surface level that is more than 0.25m higher than the surrounding area makes a model with grid cells of 80m accurate. Adding roads with a surface level that is less than 0.25m higher than the surrounding area does not further improve model accuracy.

The third sub-question is: *What is the effect of local grid refinement on model performance?*

The results of a model with grid cells of 80m, with roads added as fixed weirs are inaccurate in the first hours after the dike breach. By locally refining the grid around the fixed weirs to 10m, the computation time significantly increases with a factor of 4.2 but has only 10% of the computation time of a model with only 10m grid cells. Model accuracy improves as a result of grid refinement. However, the results are not as accurate as a 10m model with roads as fixed weirs and the results do not improve in the first hours after the dike breach. Refining the grid of an 80m model to 20m is similarly accurate as a model with only 20m grid cells. However, it does not improve the model accuracy in the first hours after the dike breach. The improvements in model accuracy due to grid refinement do not outweigh the increase in computation time.

The fourth sub question that is answered: *What is the effect of the courant number on model performance and computation time?*

Increasing the Courant number in a model with grid cells of 10m from 0.7 to 0.95 and 2.0 reduced the computation time of a model with 30% and 45% respectively and does not affect the breach outflow, the water depth, and inundation extent, or arrival times.

To answer the main research question, the model cannot yet be used as a flood forecasting model. It is possible to simulate a study area of 12000 ha for a period of 31 days within 1.6 hours with accurate results in D-Hydro. This can be done by using grid cells of 80m, and schematizing roads as fixed weirs. Model accuracy depends on the boundary condition that are used. The results are accurate when the breach outflow hydrograph of the reference is used as a boundary condition but is inaccurate when breach outflow is based on water levels in the IJssel. For a flood forecasting model, a simulation time of 1.6 hours is long. The computation time can be reduced by shortening the simulation period or by increasing the maximum time step. Moreover, the 1D model consists of the main Rhine-branches and the waterways within the dike ring. Simulating only the 1D Rhine-branches for a period of 31 days already takes about an hour. By not including all the Rhine-branches, but only the IJssel, the computation time can also be further reduced. However, a large part of the Rhine branches cannot be simply removed, since water levels in the IJssel might not be accurate anymore.

It is important to do more research about breach discharge because this study shows that grid resolution affects breach discharge which leads to inaccurate results. A follow-up study may focus on model schematization choices that can be made to accurately determine the breach discharge. For D-Hydro users, a trade-off between computation time and model accuracy must be made, which depends on the purpose of the model. For a policy model, a fine grid resolution should be used. Schematizing roads as fixed weirs, improves model accuracy and has little to no effect computation time. For models with a coarser grid resolution, higher line elements must be added as fixed weirs. If fixed weirs are used, underpasses must also be added to the model. The output of the model includes water depths/water levels. An inundation map and a map with flood arrival times provides a good insight, however, post-processing has been done to make this map, which takes time. In case of evacuation, decisions must be made quickly. Post processing steps can be further automated with scripting, so that inundation maps and food arrival maps can be made more quickly.

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Appendix A – Inundation maps

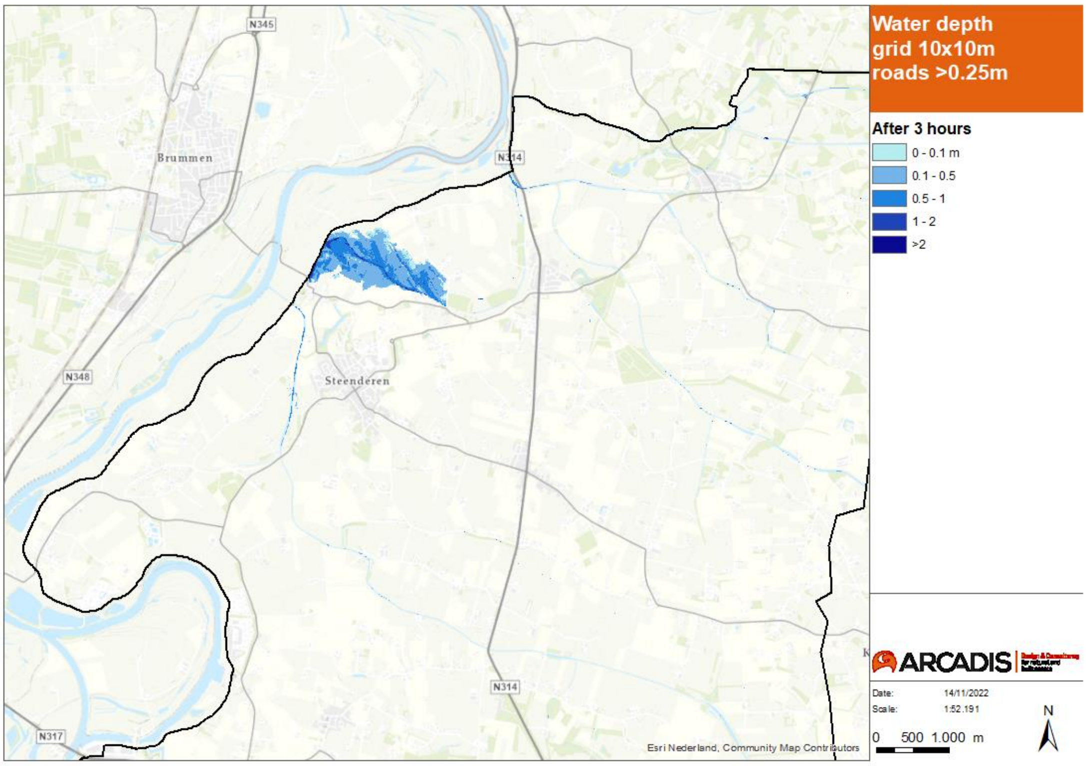

Figure A. 1: Water depth reference model 3 hours after dike breach

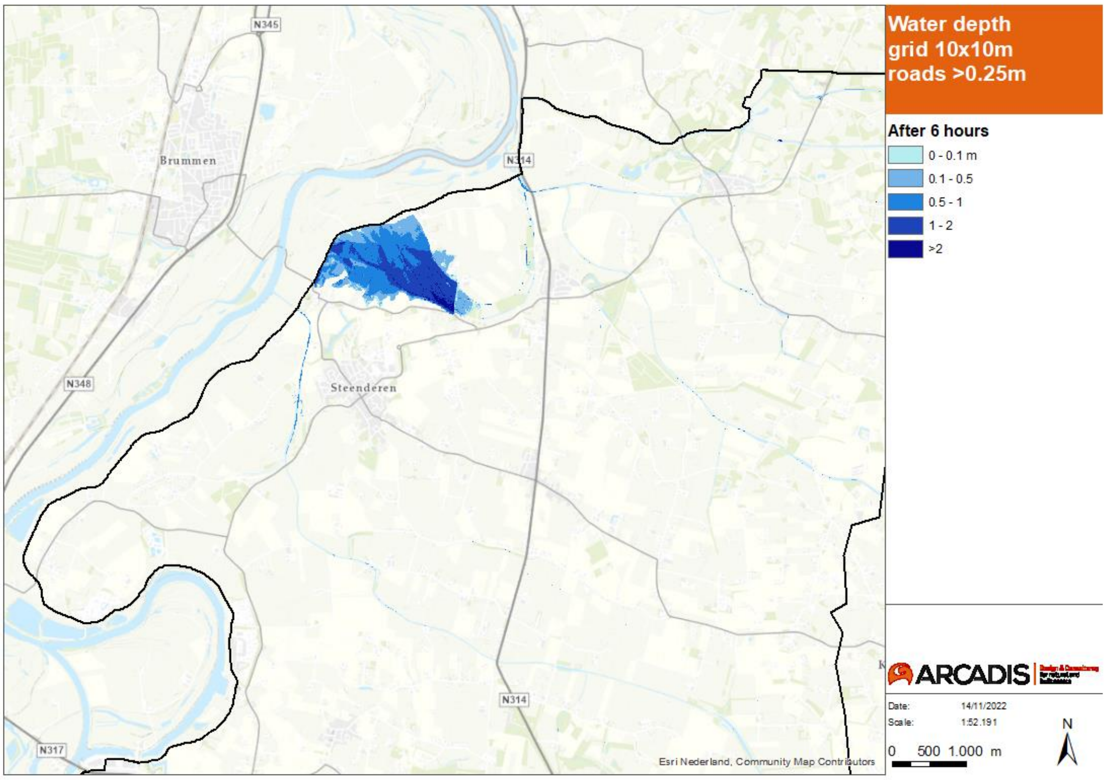

Figure A. 2: Water depth reference model 6 hours after dike breach

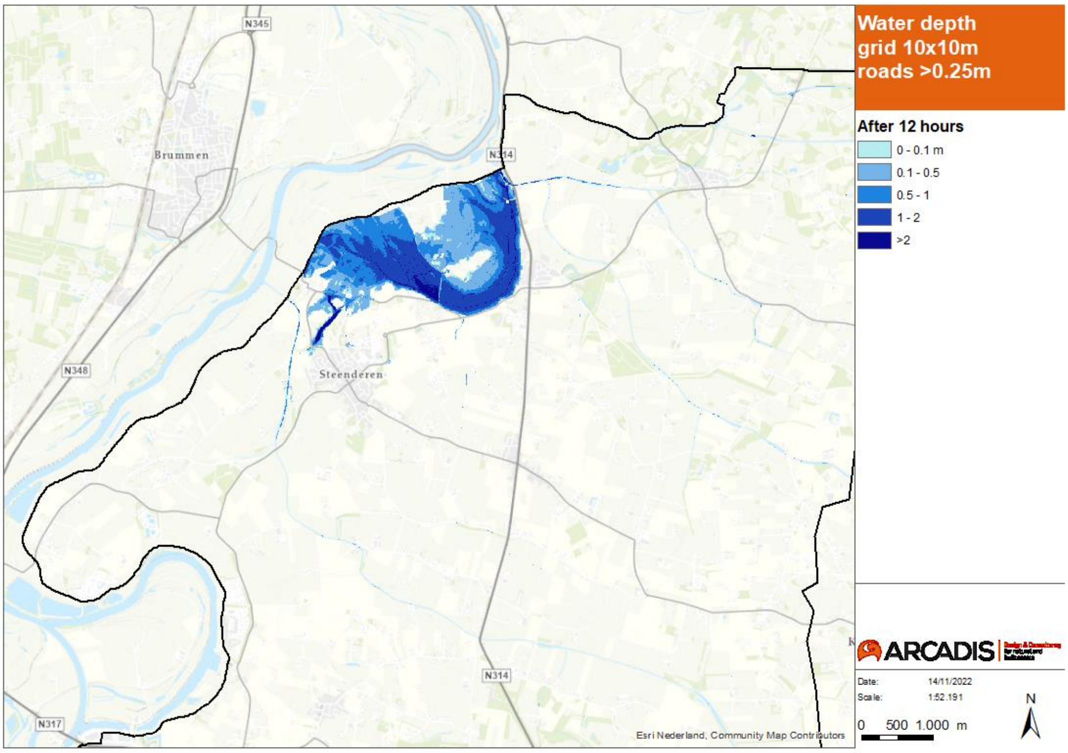

Figure A. 3: Water depth reference model 12 hours after dike breach

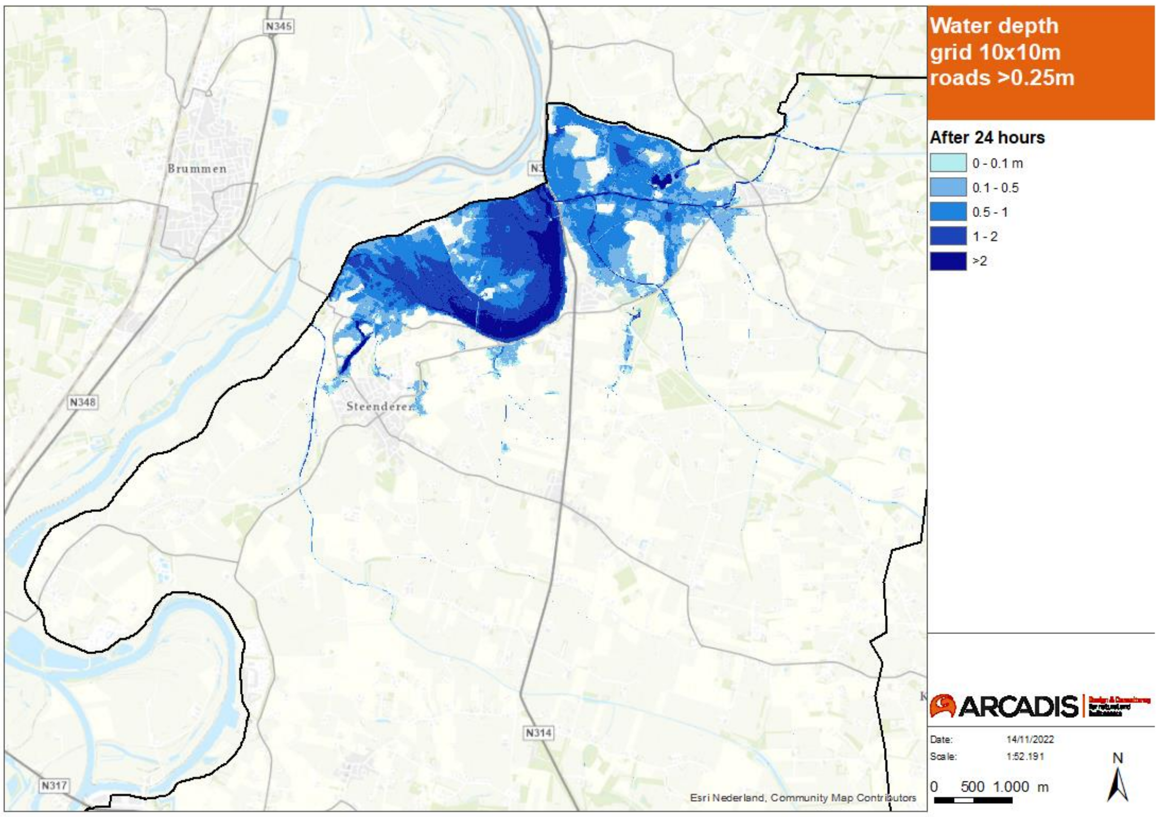

Figure A. 4: Water depth reference model 24 hours after dike breach

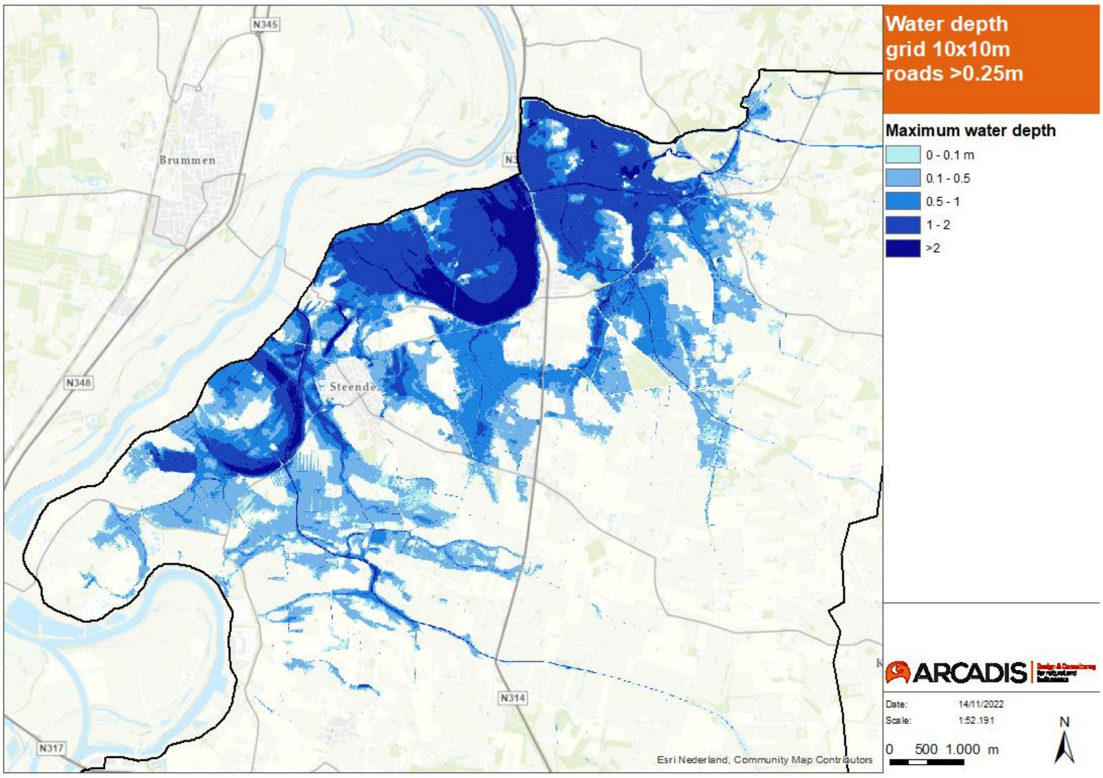

Figure A. 6: Maximum water depth reference model

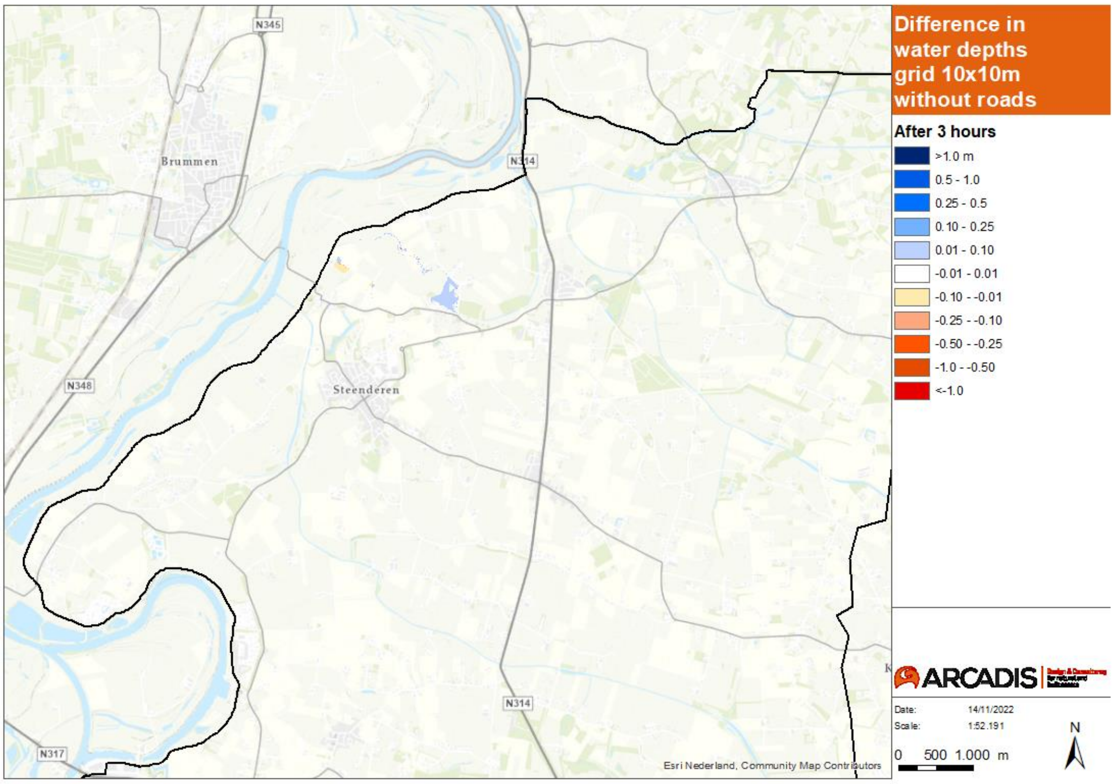

Figure A. 5: Difference in water depths between 10m model without roads as fixed weir and reference model 3 hours after dike breach

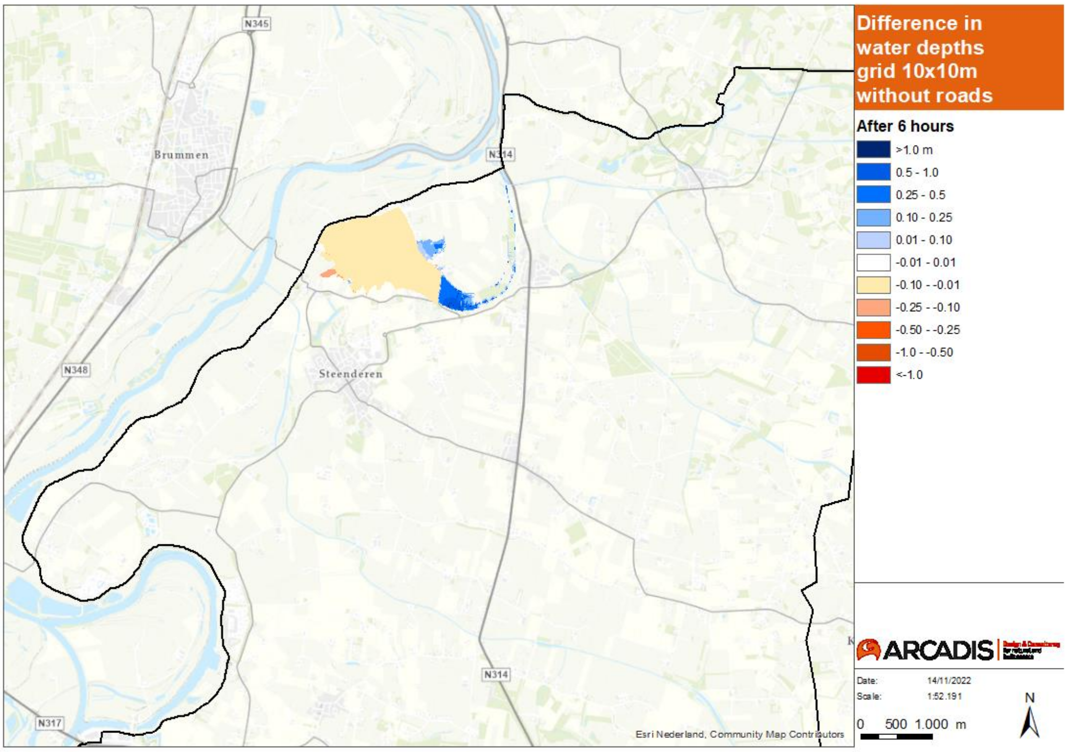

Figure A. 7: Difference in water depths between 10m model without roads as fixed weir and reference model 6 hours after dike breach

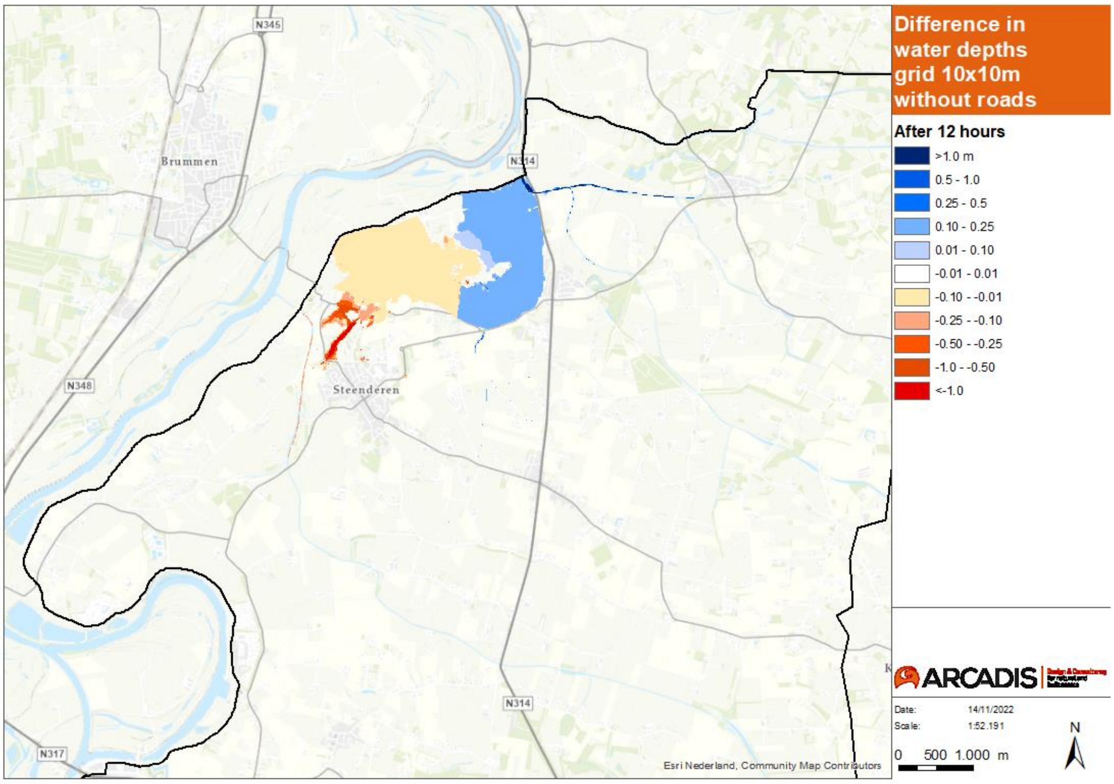

Figure A. 8: Difference in water depths between 10m model without roads as fixed weir and reference model 12 hours after dike breach

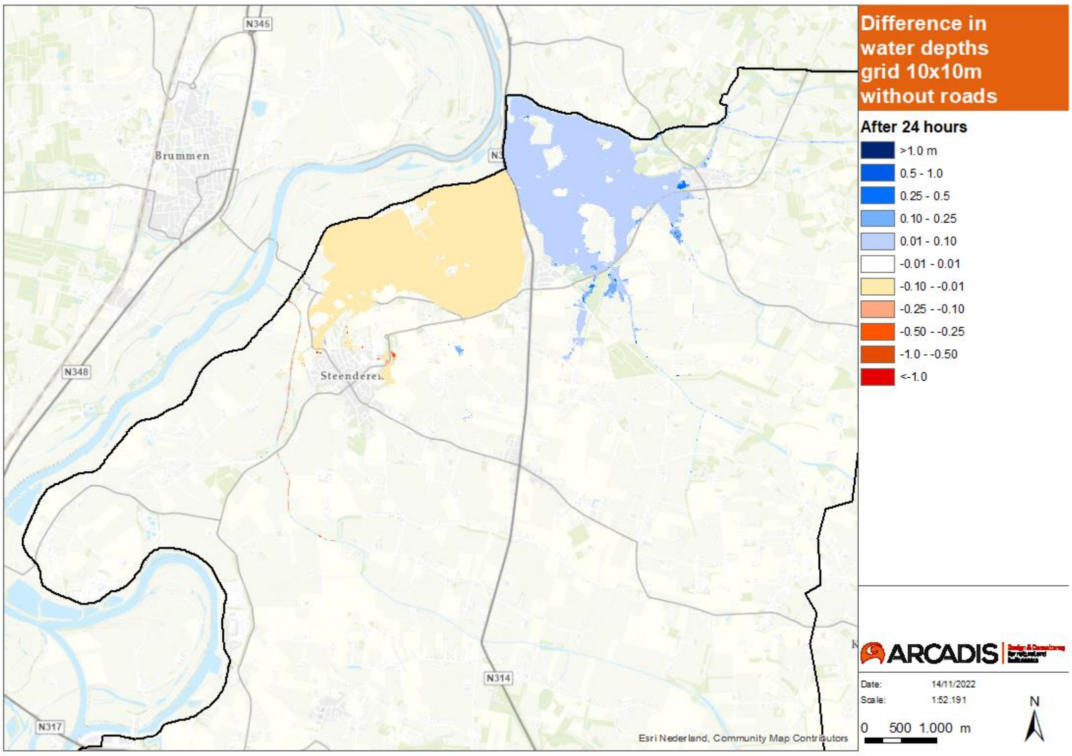

Figure A. 9: Difference in water depths between 10m model without roads as fixed weir and reference model 12 hours after dike breach

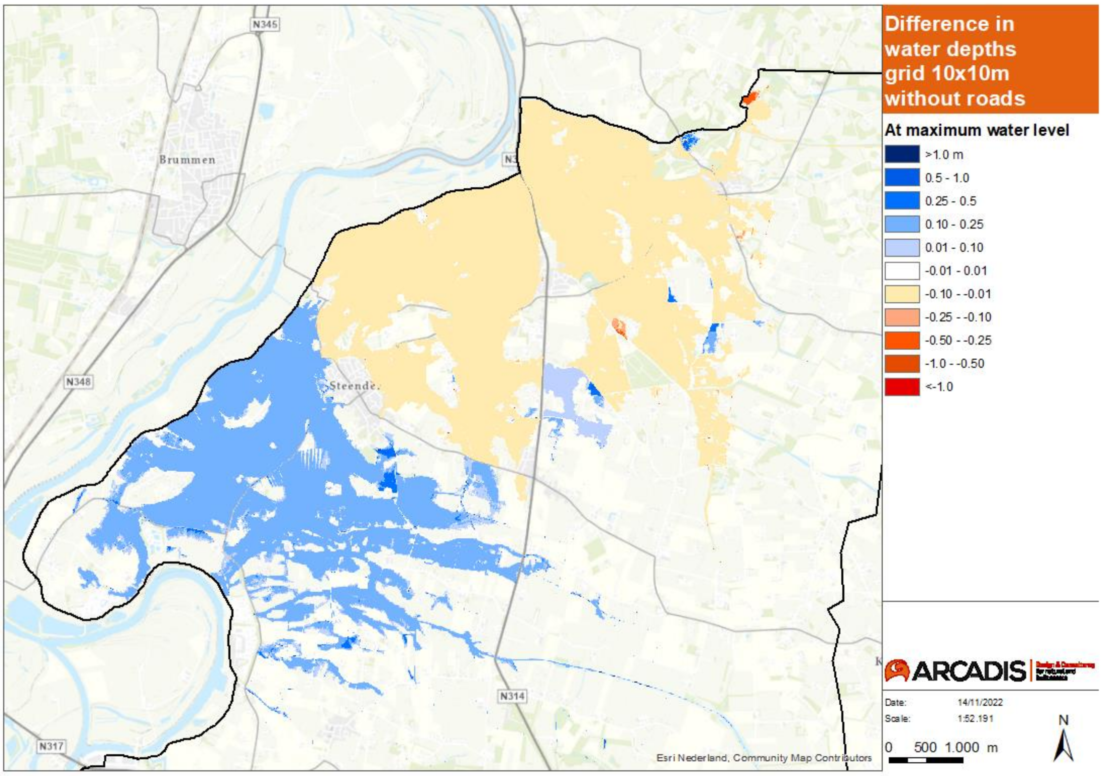

Figure A. 10: Difference in water depths between 10m model without roads as fixed weir and reference model at maximum water level

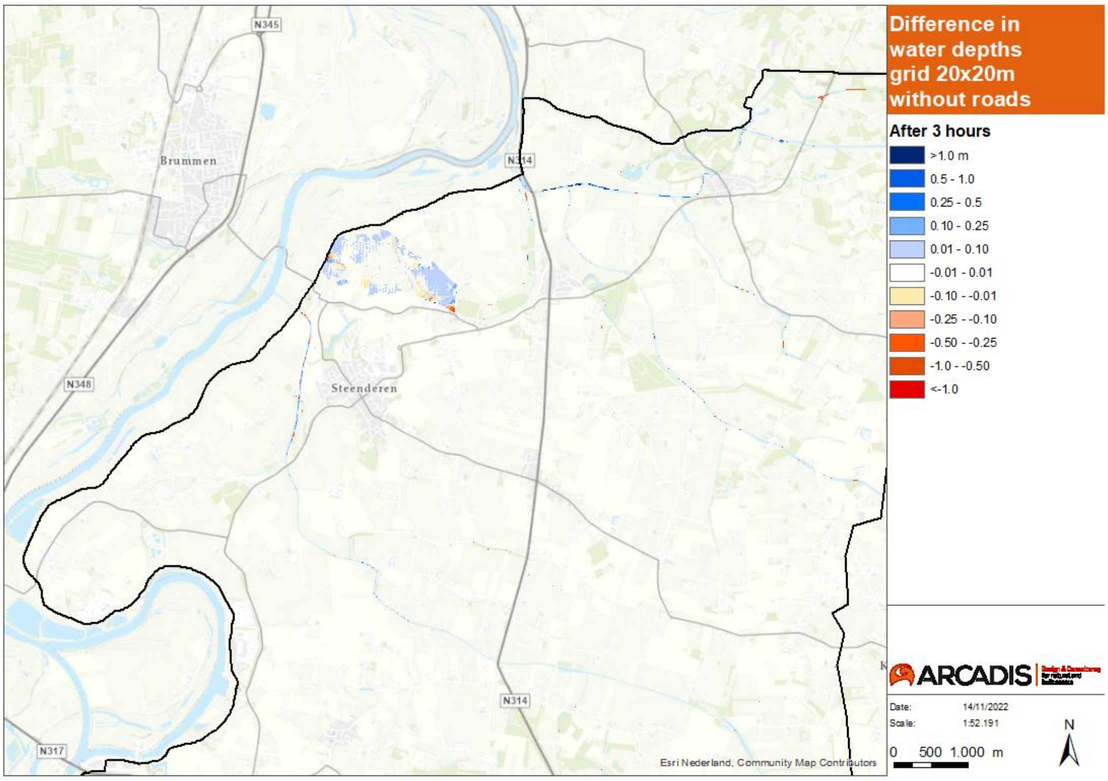

Figure A. 12: Difference in water depths between 20m model without roads as fixed weir and reference model 3 hours after dike breach

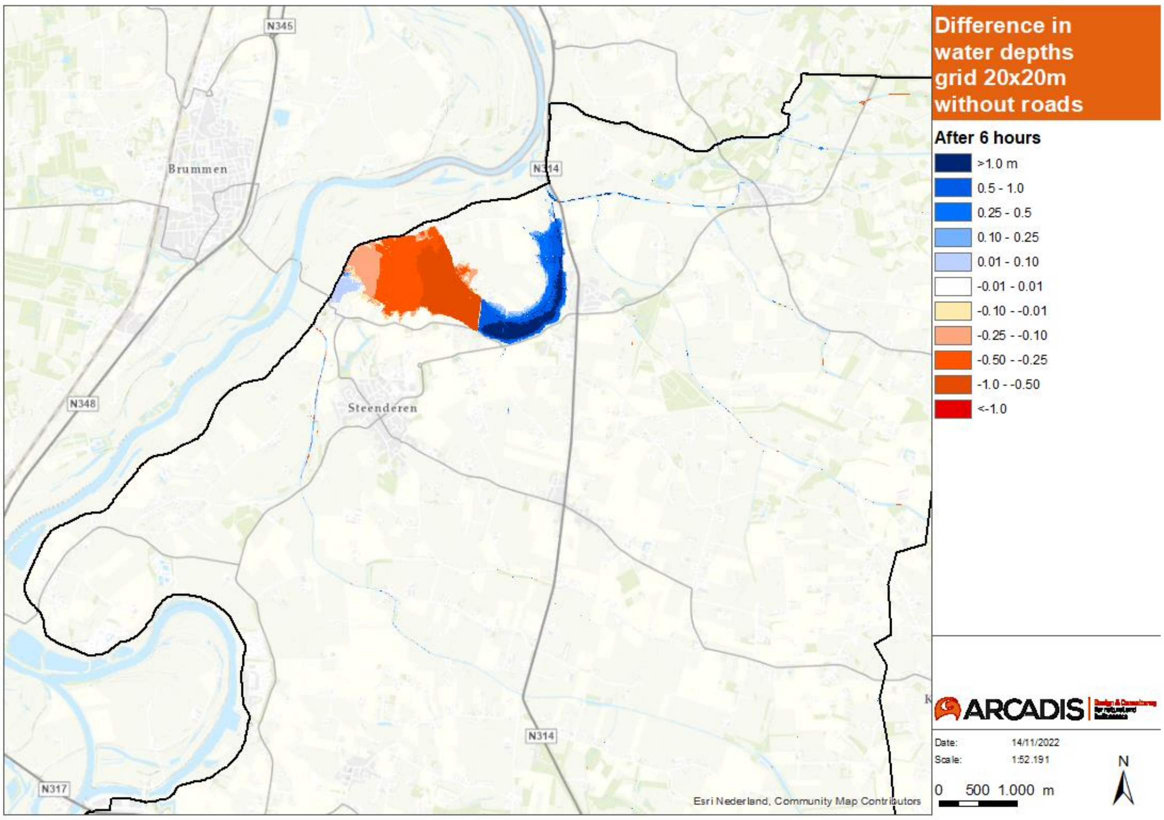

Figure A. 11: Difference in water depths between 20m model without roads as fixed weir and reference model 6 hours after dike breach

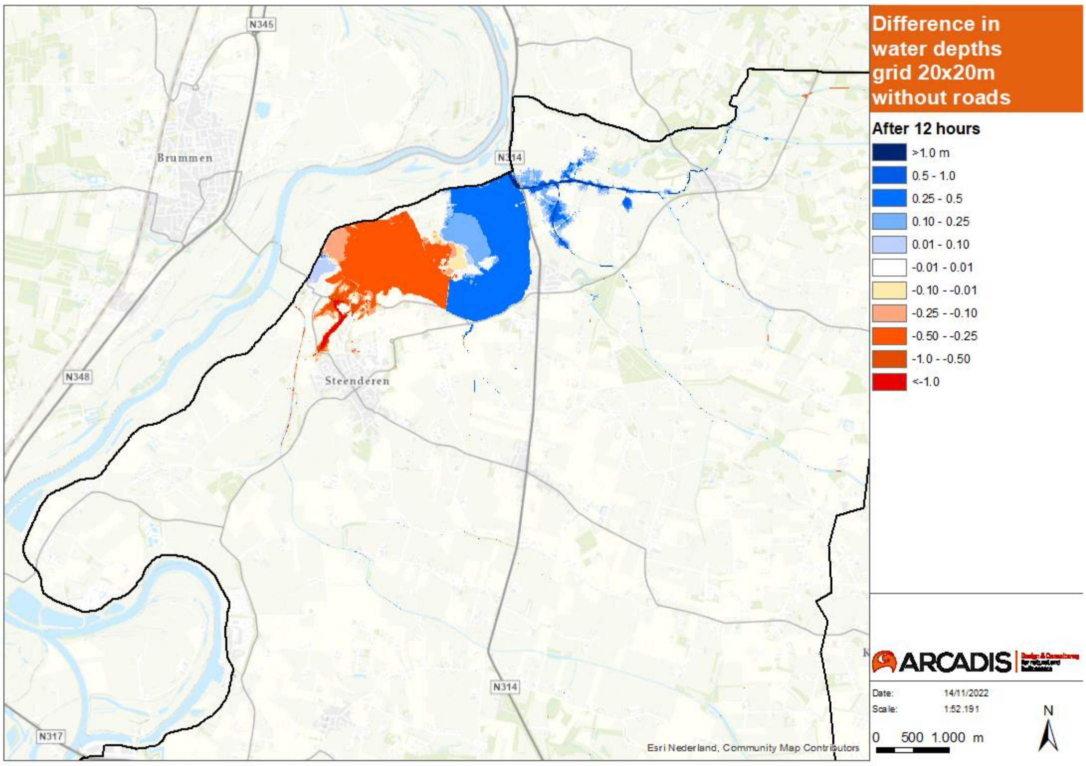

Figure A. 13: Difference in water depths between 20m model without roads as fixed weir and reference model 12 hours after dike breach

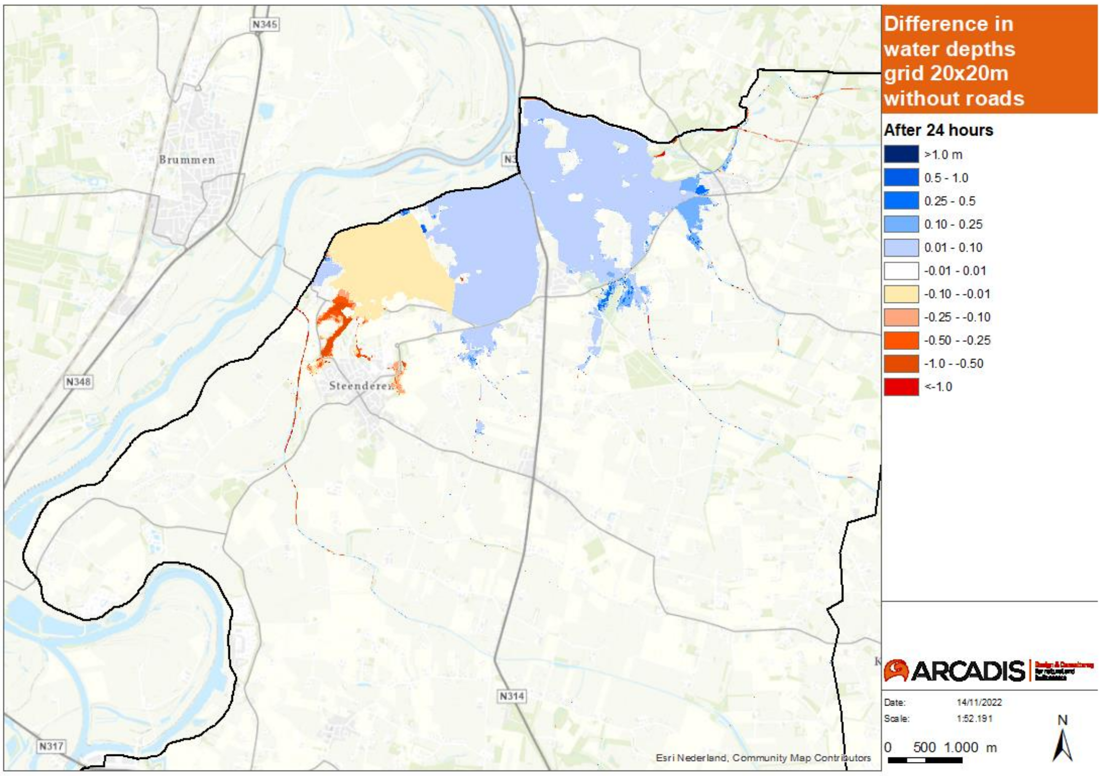

Figure A. 14: Difference in water depths between 20m model without roads as fixed weir and reference model 24 hours after dike breach

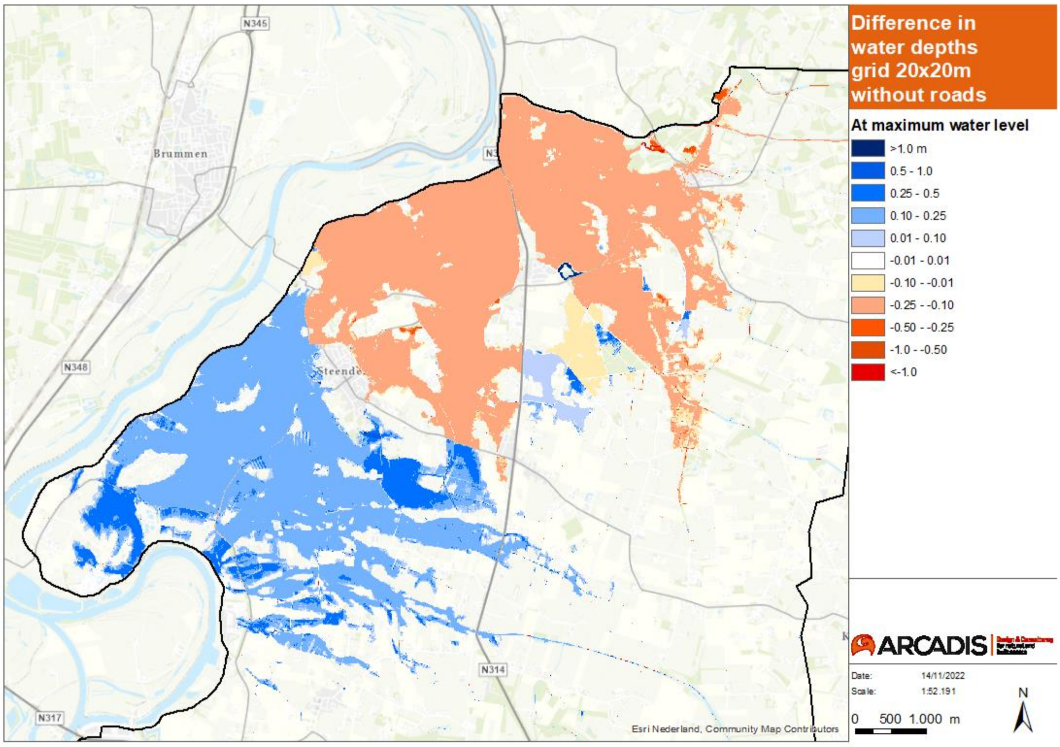

Figure A. 16: Difference in water depths between 20m model without roads as fixed weir and reference model at maximum water depth

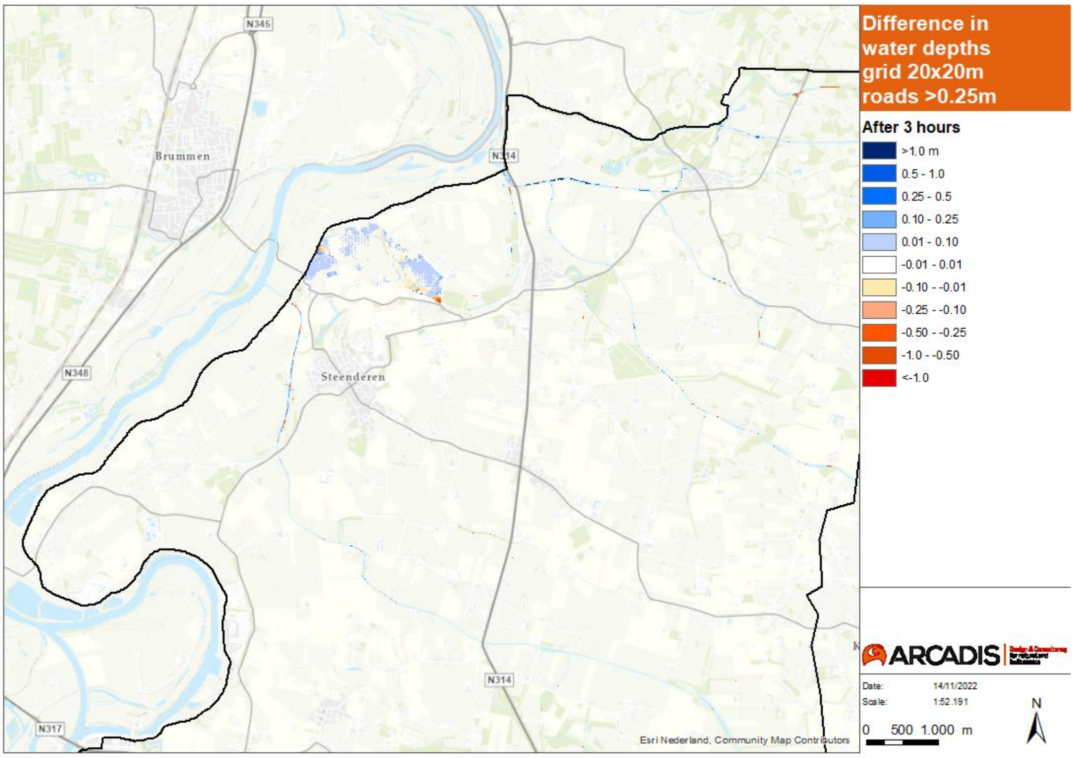

Figure A. 15: Difference in water depths between 20m model with roads as fixed weir and reference model 3 hours after dike breach

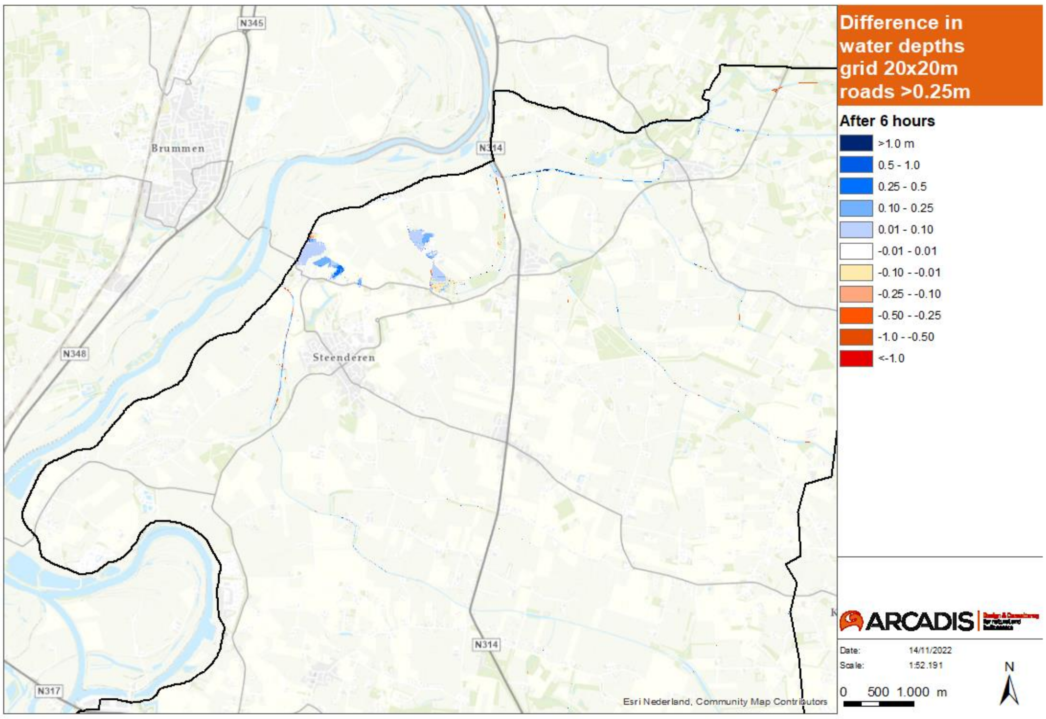

Figure A. 17: Difference in water depths between 20m model with roads as fixed weir and reference model 6 hours after dike breach

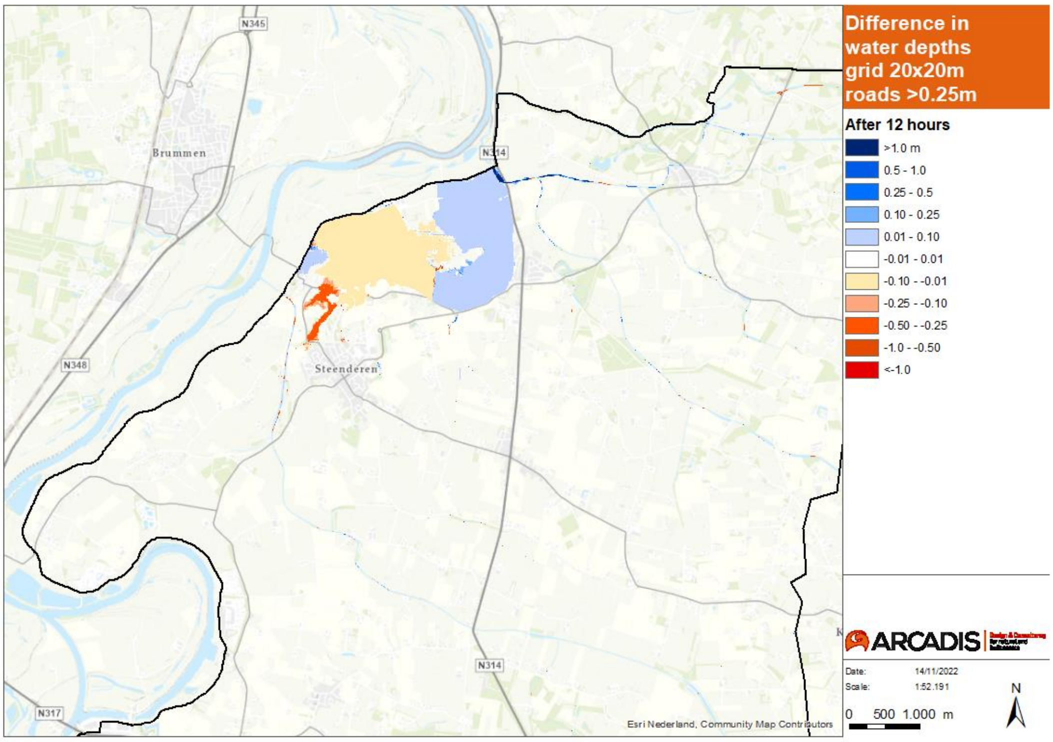

Figure A. 18: Difference in water depths between 20m model with roads as fixed weir and reference model 12 hours after dike breach

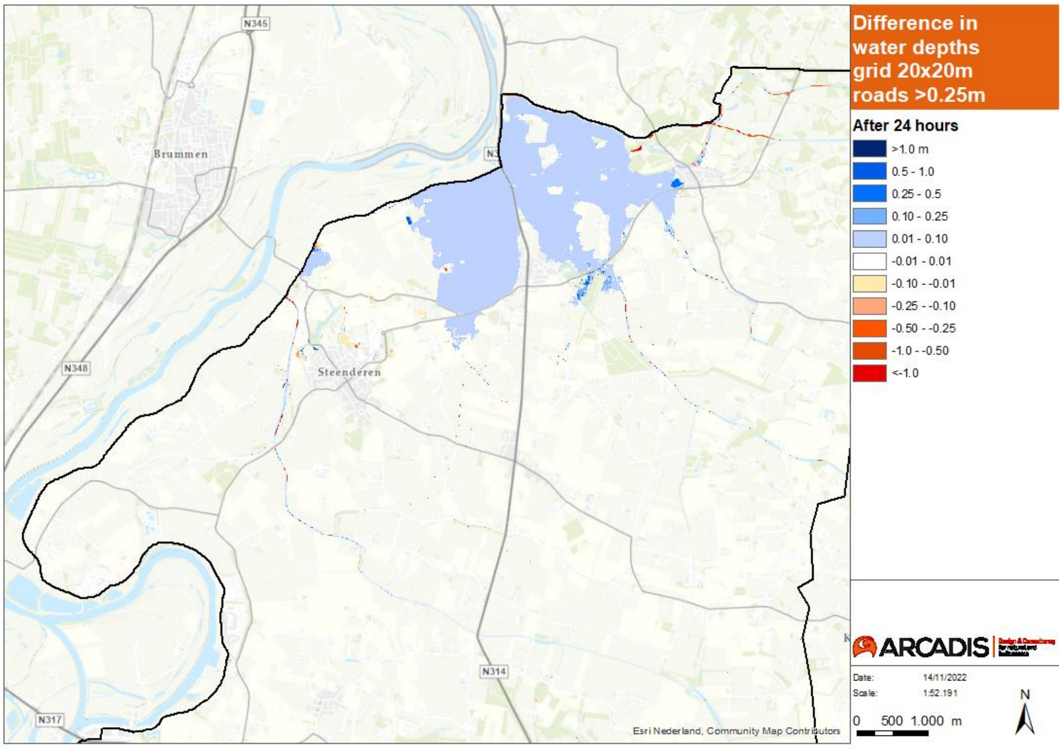

Figure A. 19: Difference in water depths between 20m model with roads as fixed weir and reference model 24 hours after dike breach

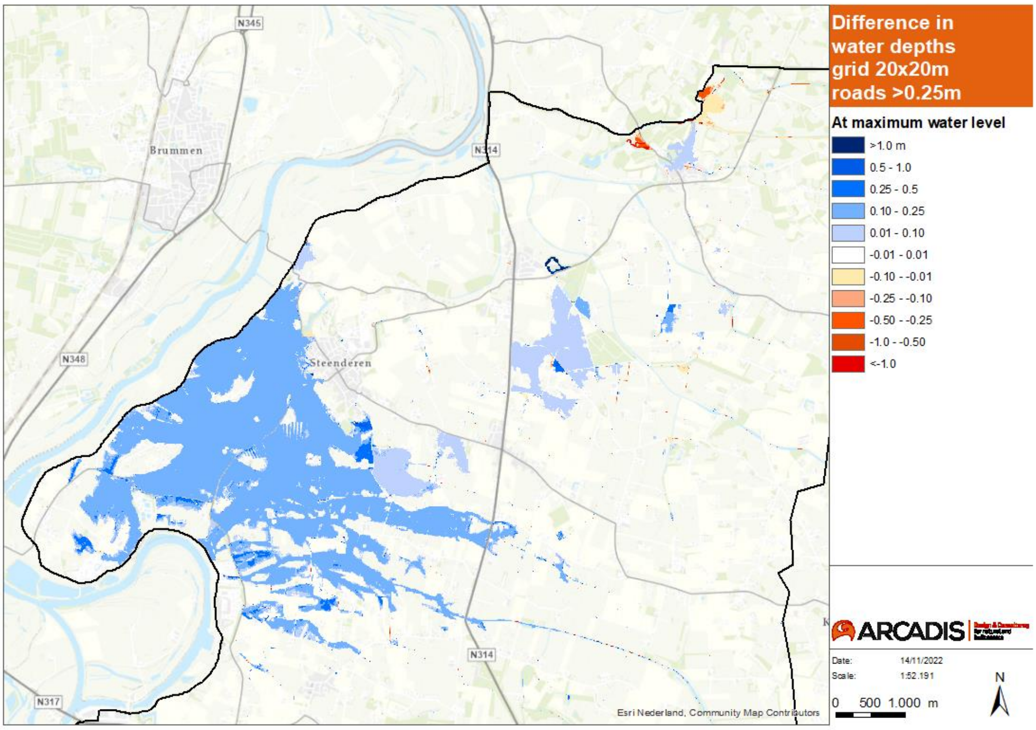

Figure A. 20: Difference in water depths between 20m model with roads as fixed weir and reference model at maximum water level

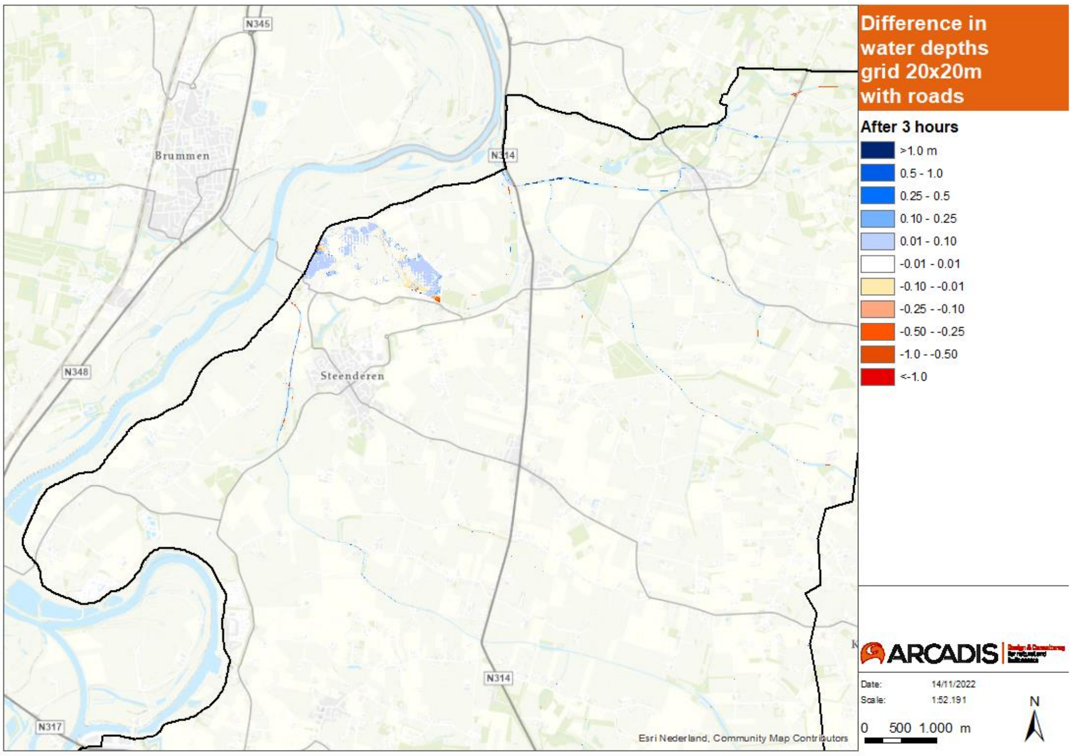

Figure A. 21: Difference in water depths between 20m model with all roads as fixed weir and reference model 3 hours after dike breach

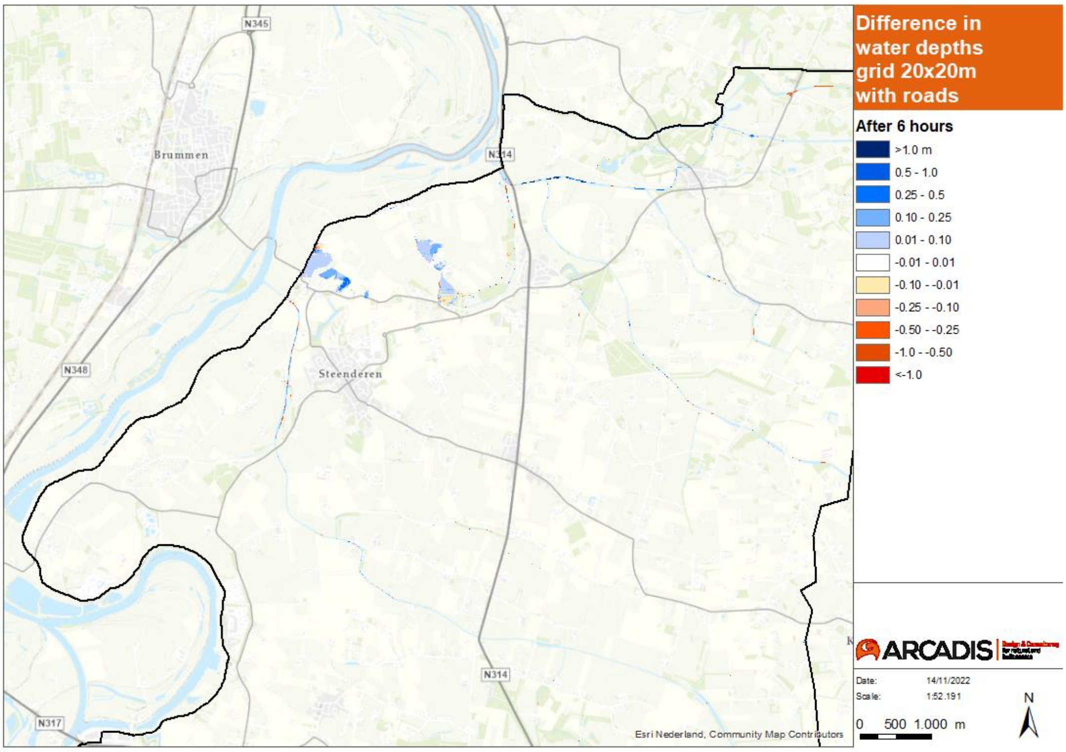

Figure A. 22: Difference in water depths between 20m model with all roads as fixed weir and reference model 6 hours after dike breach

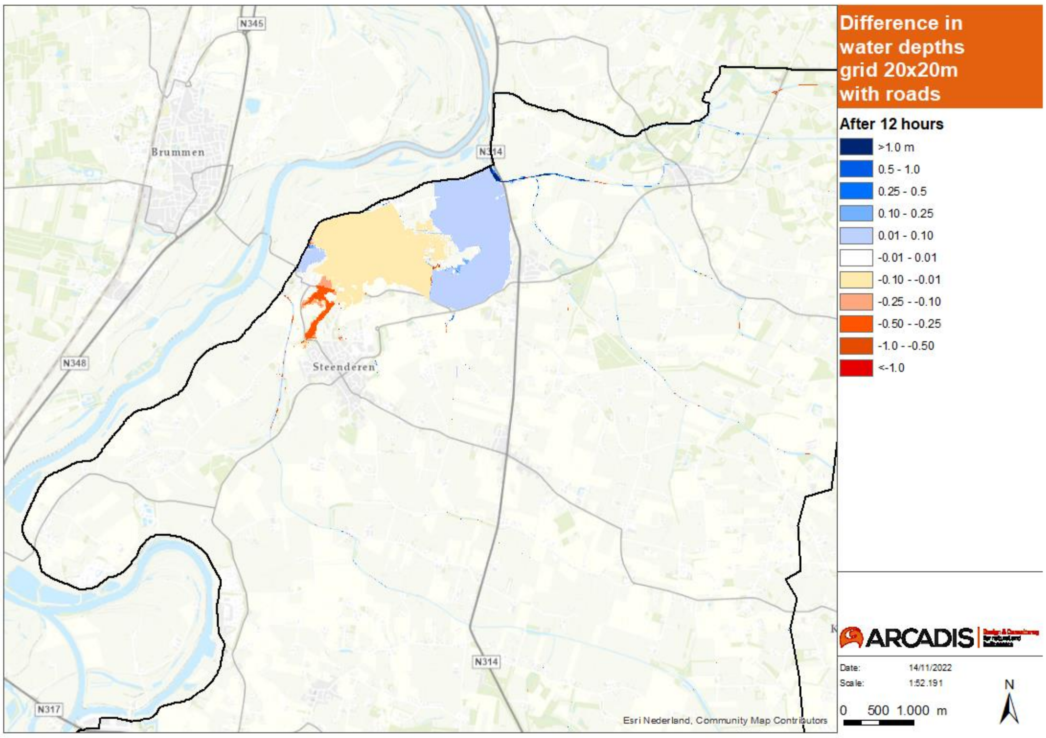

Figure A. 23: Difference in water depths between 20m model with all roads as fixed weir and reference model 12 hours after dike breach

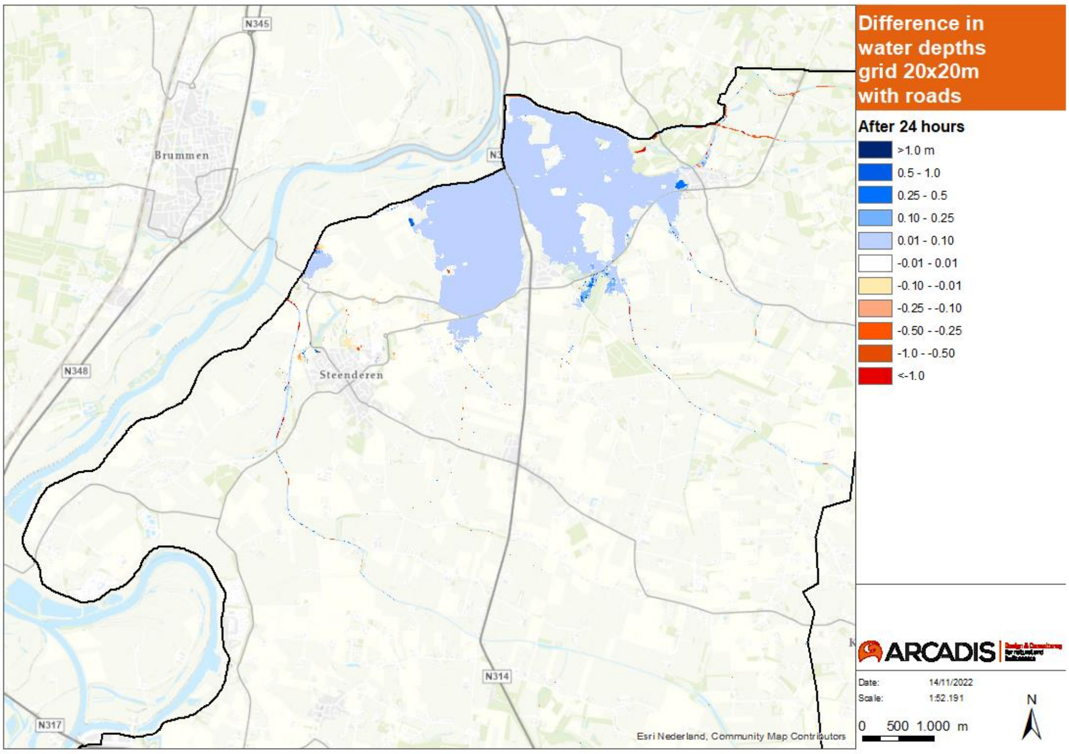

Figure A. 24: Difference in water depths between 20m model with all roads as fixed weir and reference model 24 hours after dike breach

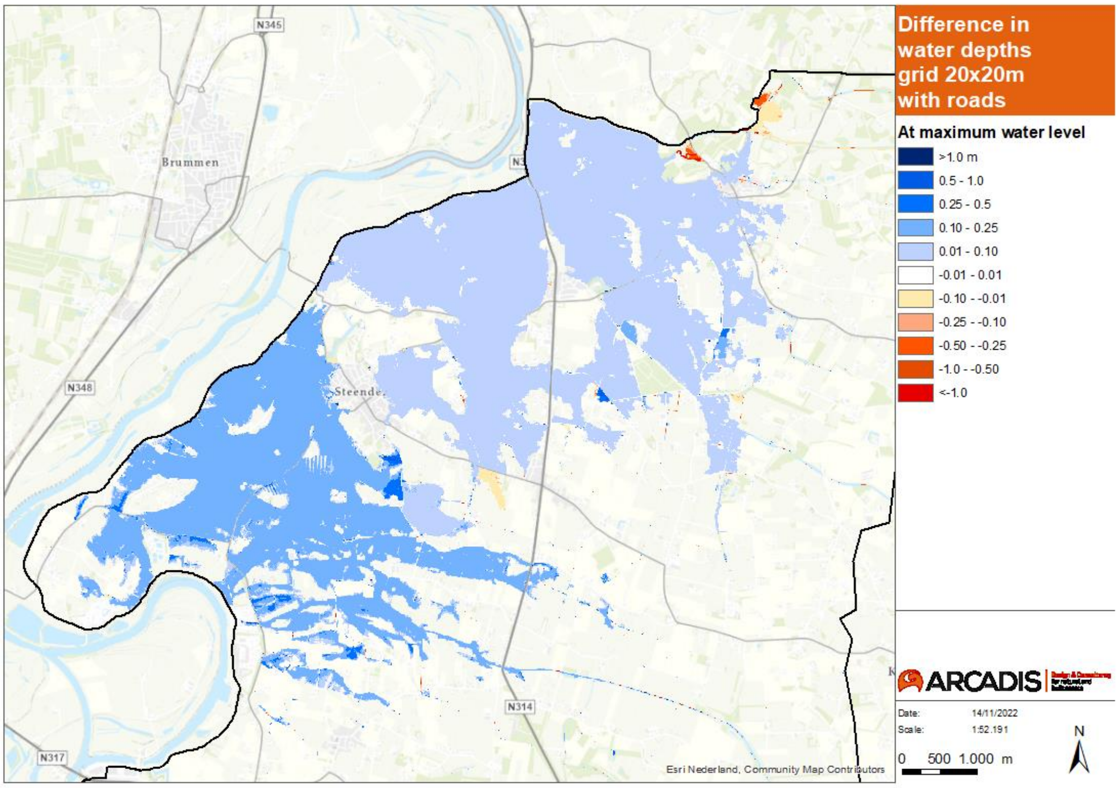

Figure A. 25: Difference in water depths between 20m model with all roads as fixed weir and reference model at maximum water depths

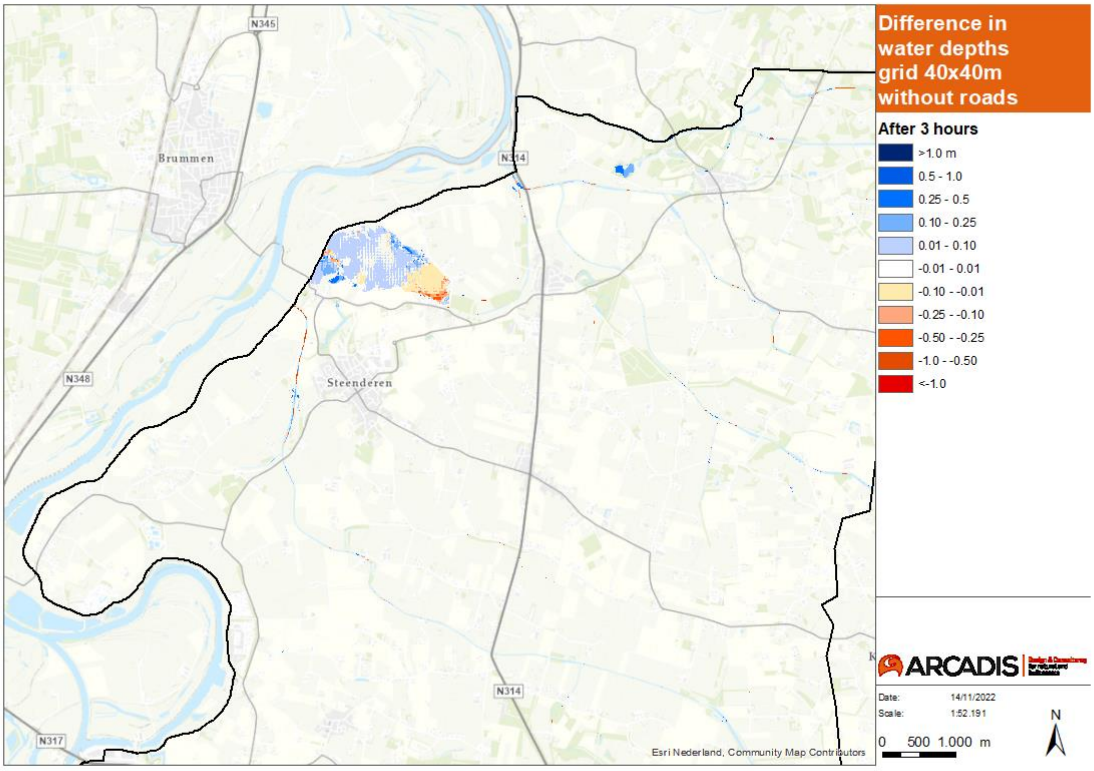

Figure A. 26: Difference in water depths between 40m model without roads as fixed weir and reference model 3 hours after dike breach

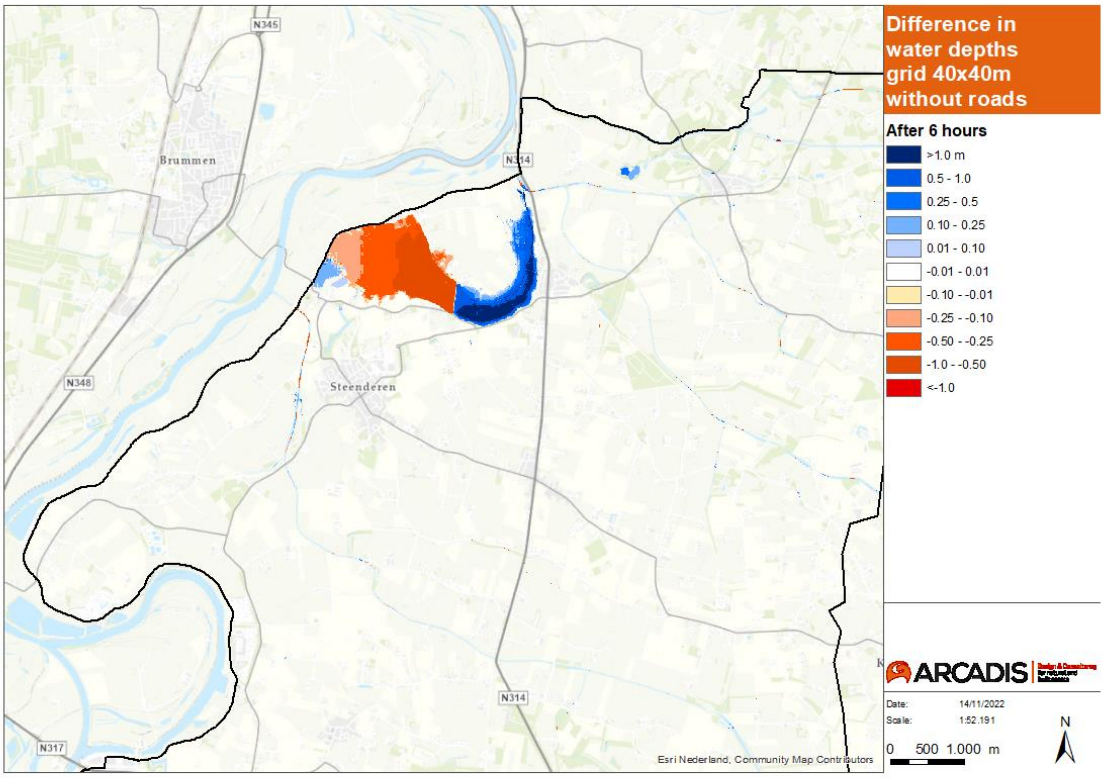

Figure A. 27: Difference in water depths between 40m model without roads as fixed weir and reference model 6 hours after dike breach

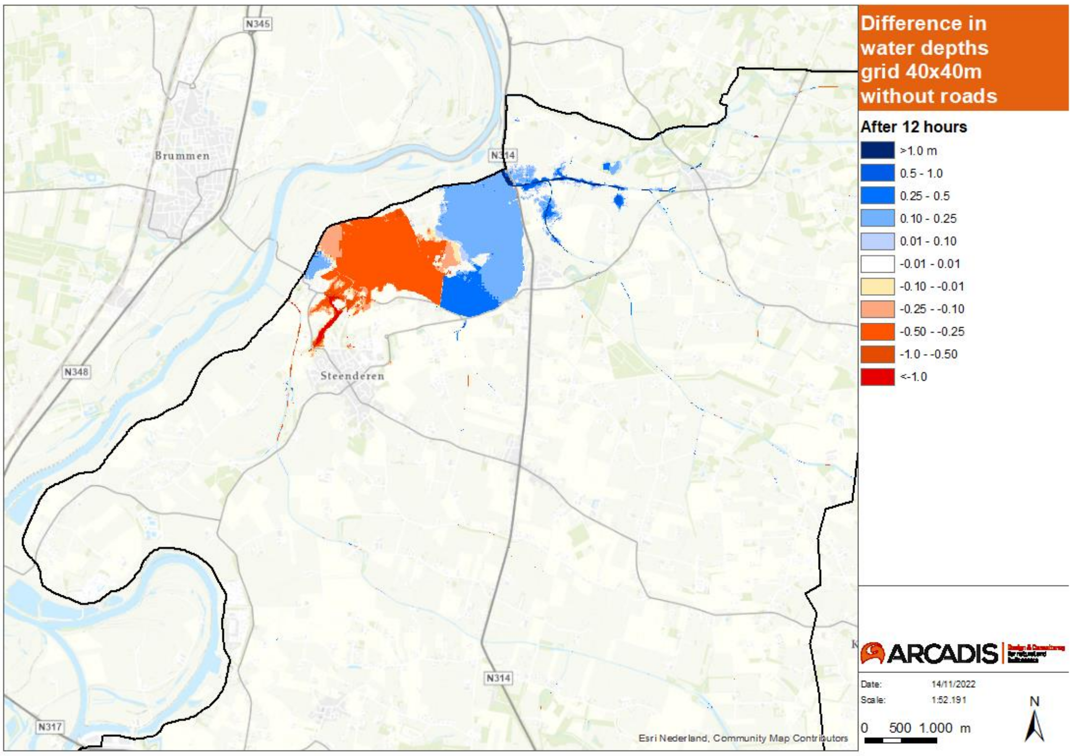

Figure A. 28: Difference in water depths between 40m model without roads as fixed weir and reference model 12 hours after dike breach

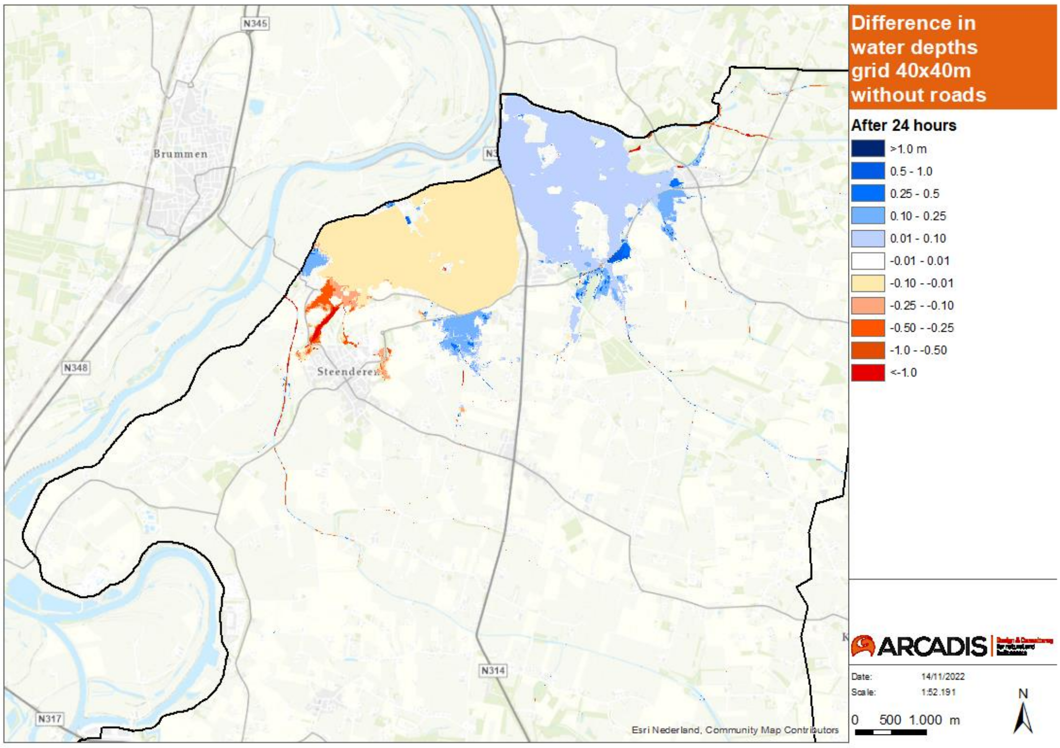

Figure A. 29: Difference in water depths between 40m model without roads as fixed weir and reference model 24 hours after dike breach

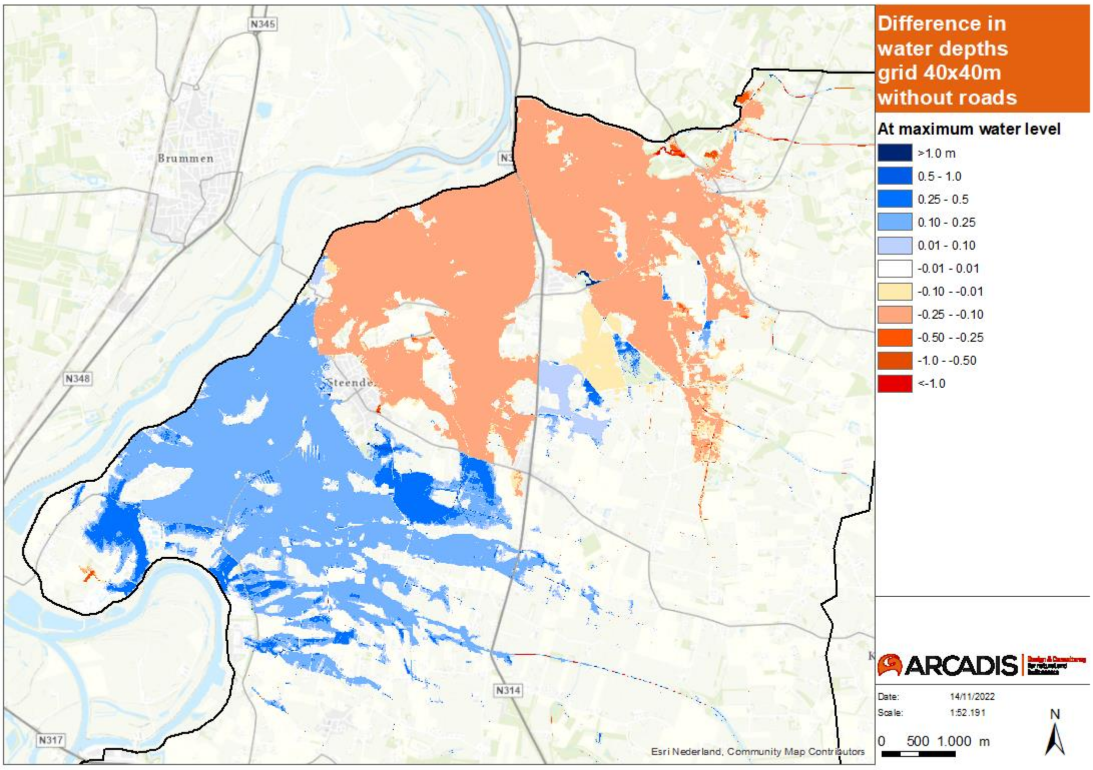

Figure A. 30: Difference in water depths between 40m model without roads as fixed weir and reference model at maximum water depths

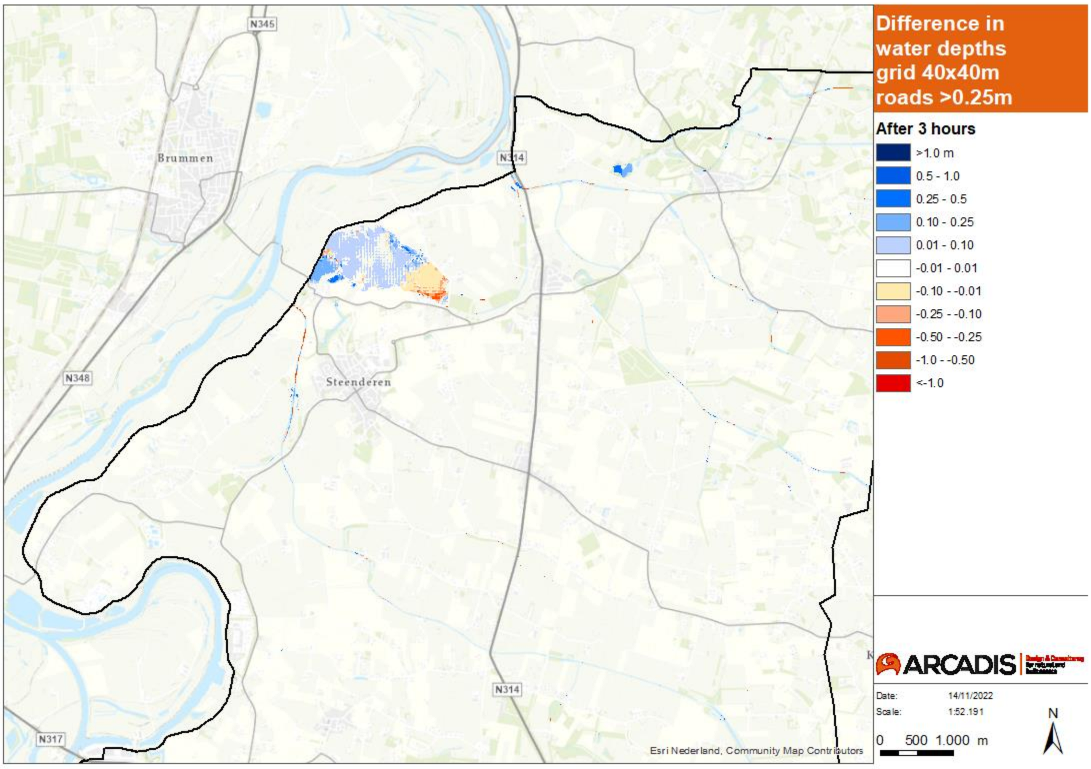

Figure A. 31: Difference in water depths between 40m model with roads as fixed weir and reference model 3 hours after dike breach

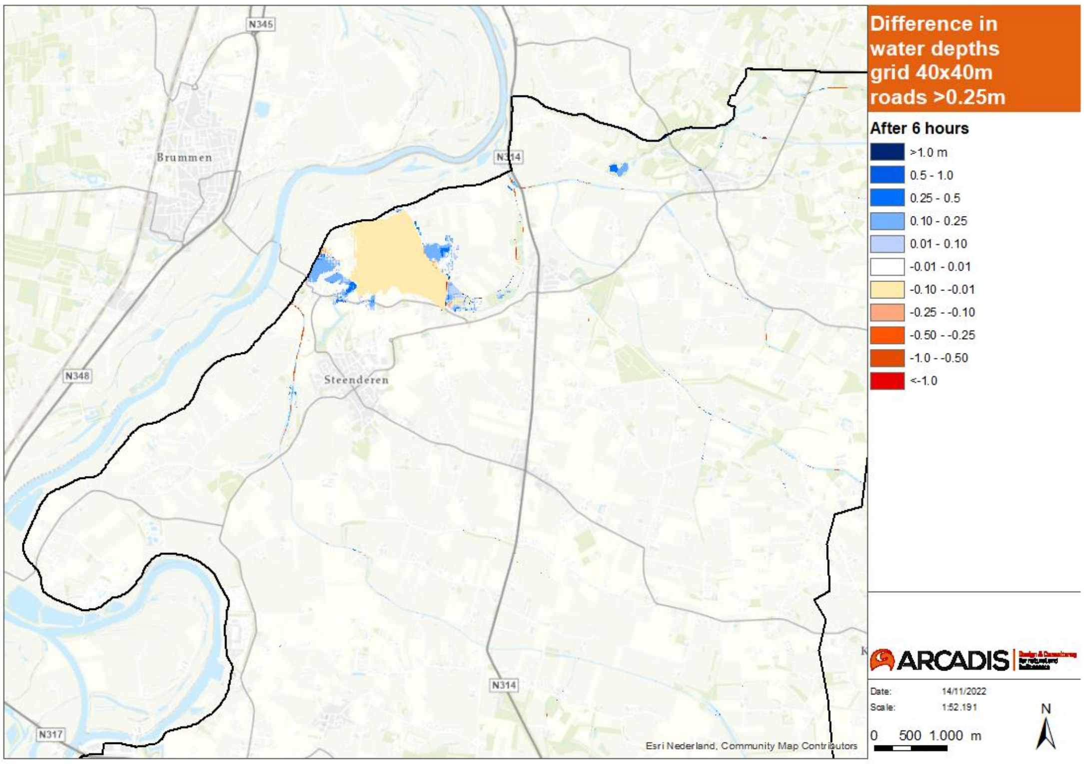

Figure A. 32: Difference in water depths between 40m model with roads as fixed weir and reference model 6 hours after dike breach

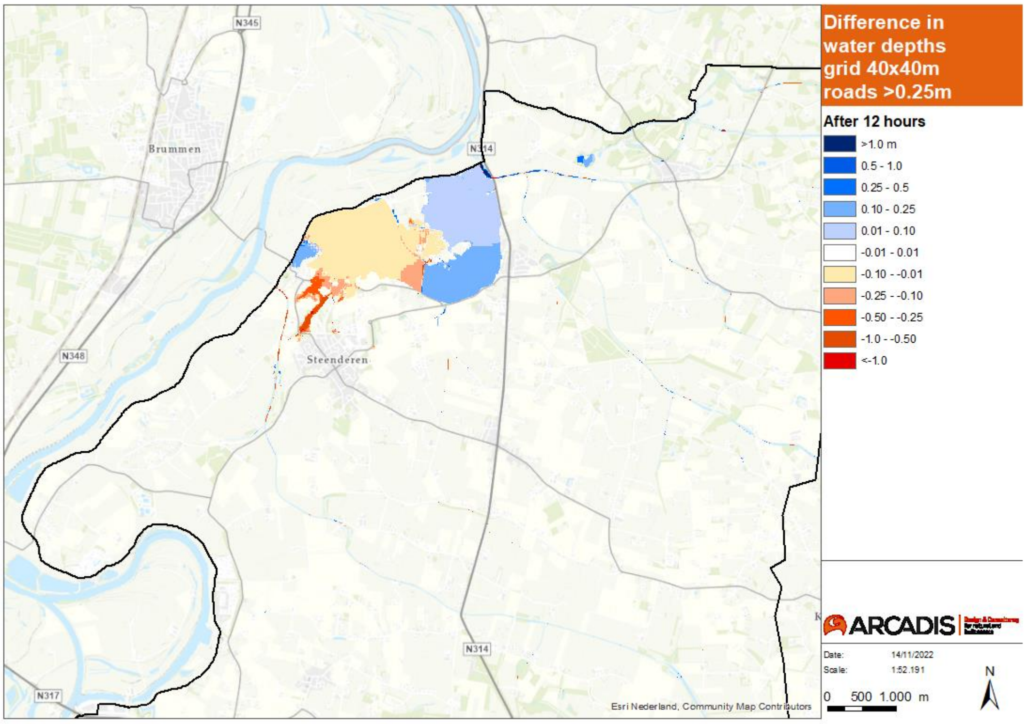

Figure A. 33: Difference in water depths between 40m model with roads as fixed weir and reference model 12 hours after dike breach

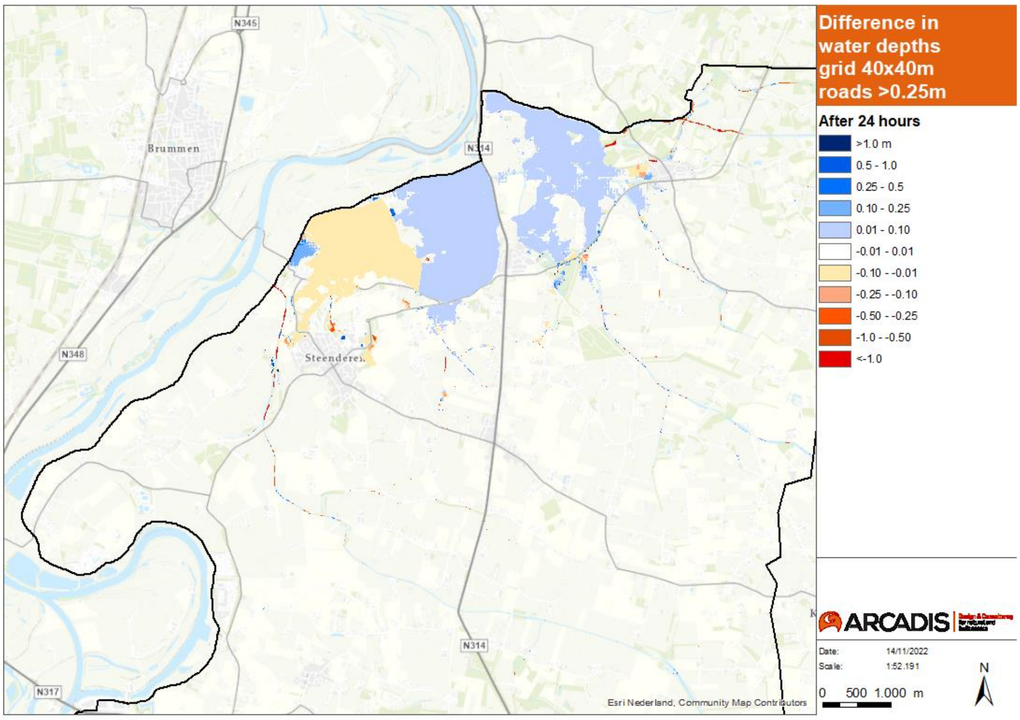

Figure A. 34: Difference in water depths between 40m model with roads as fixed weir and reference model 24 hours after dike breach

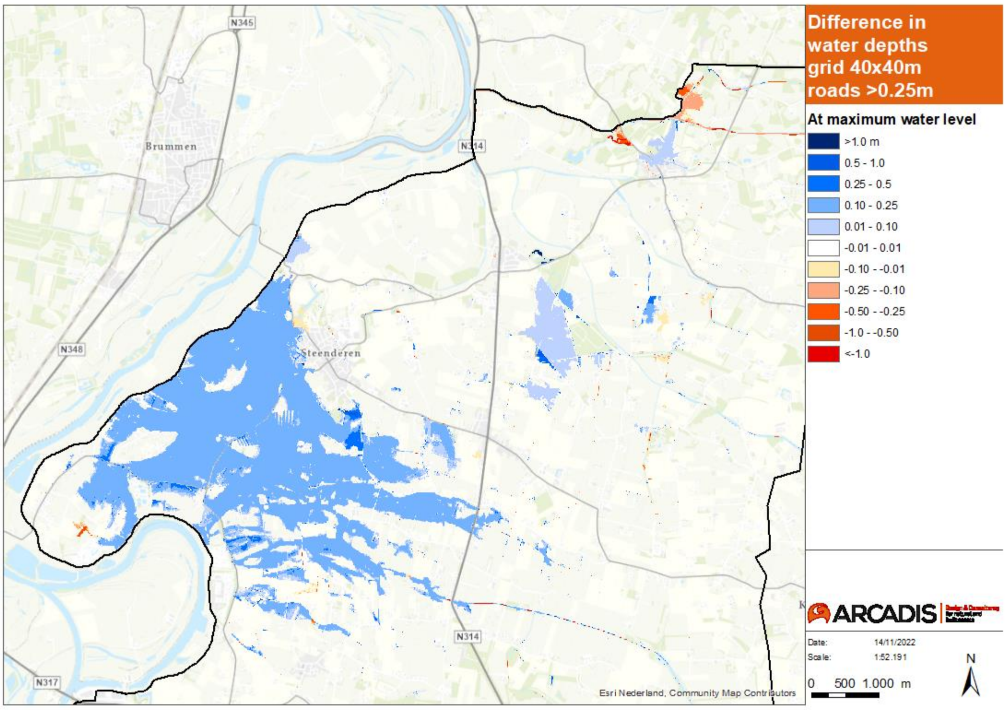

Figure A. 35: Difference in water depths between 40m model with roads as fixed weir and reference model at maximum water depth

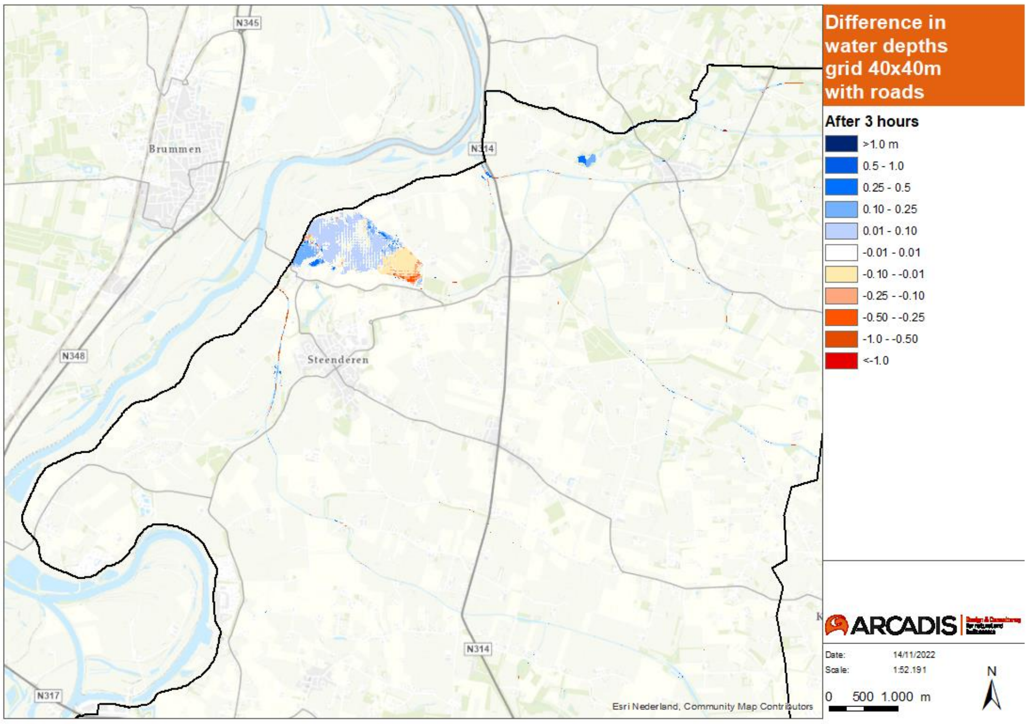

Figure A. 36: Difference in water depths between 40m model with all roads as fixed weir and reference model 3 hours after dike breach

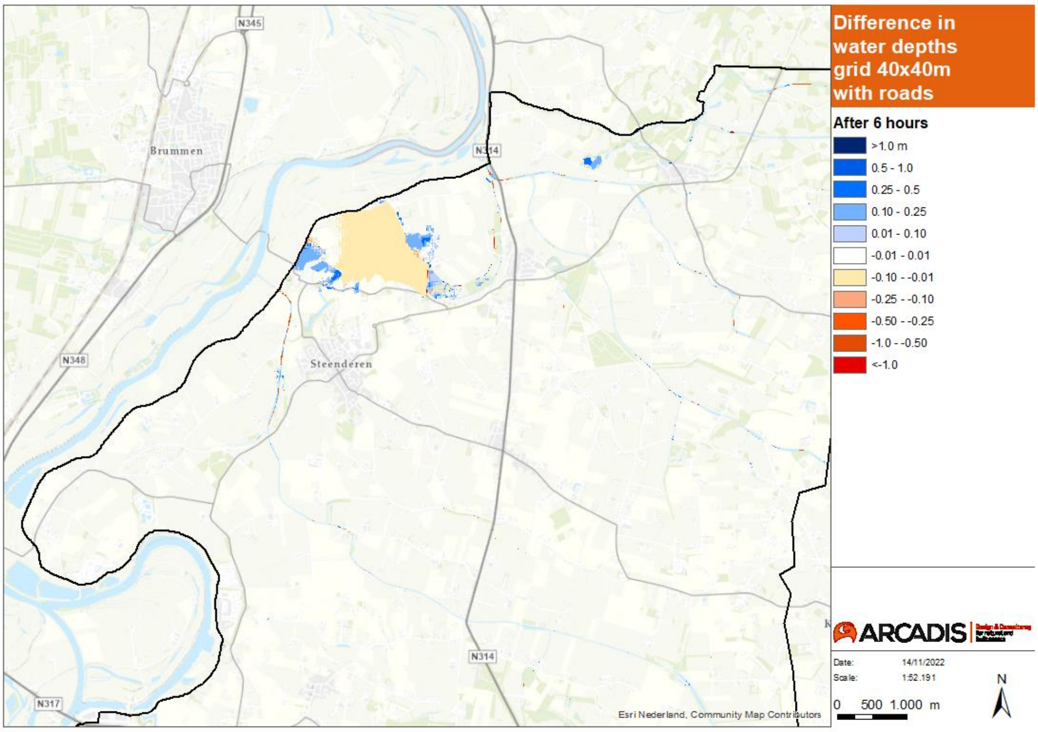

Figure A. 37: Difference in water depths between 40m model with all roads as fixed weir and reference model 6 hours after dike breach

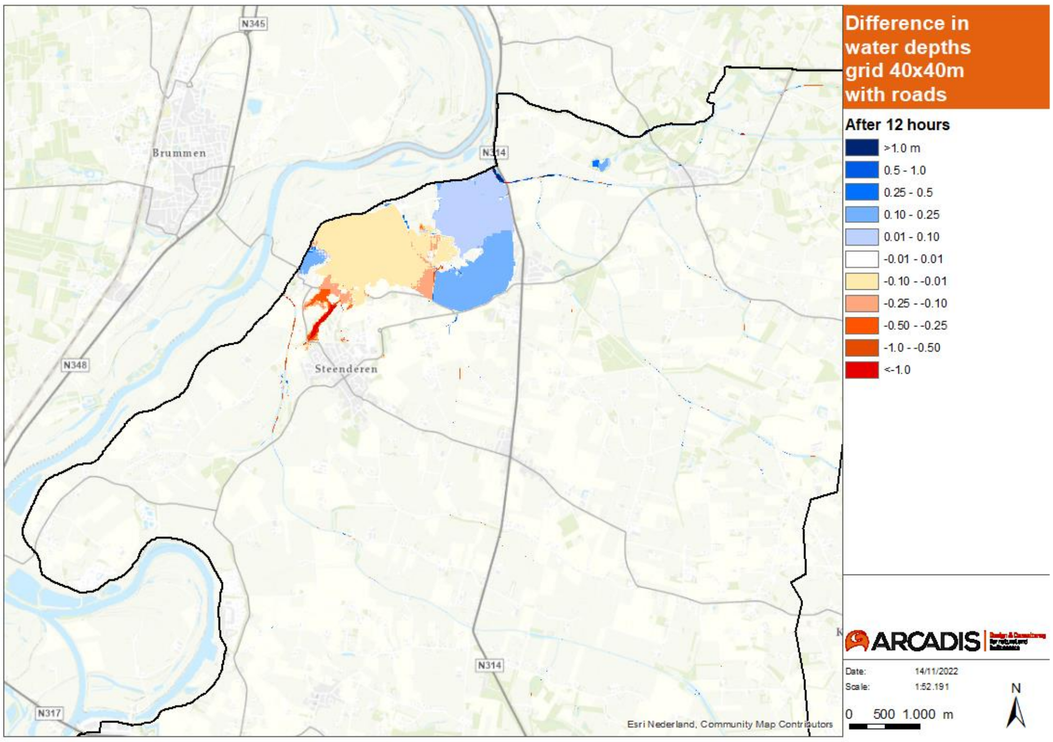

Figure A. 38: Difference in water depths between 40m model with all roads as fixed weir and reference model 12 hours after dike breach

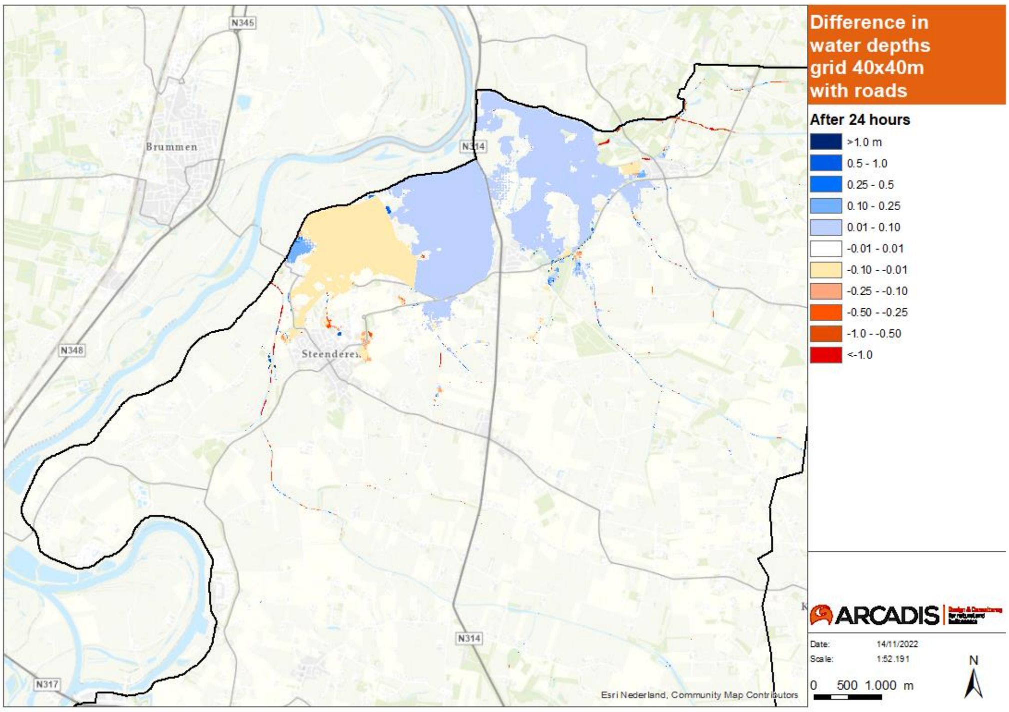

Figure A. 39: Difference in water depths between 40m model with all roads as fixed weir and reference model 24 hours after dike breach

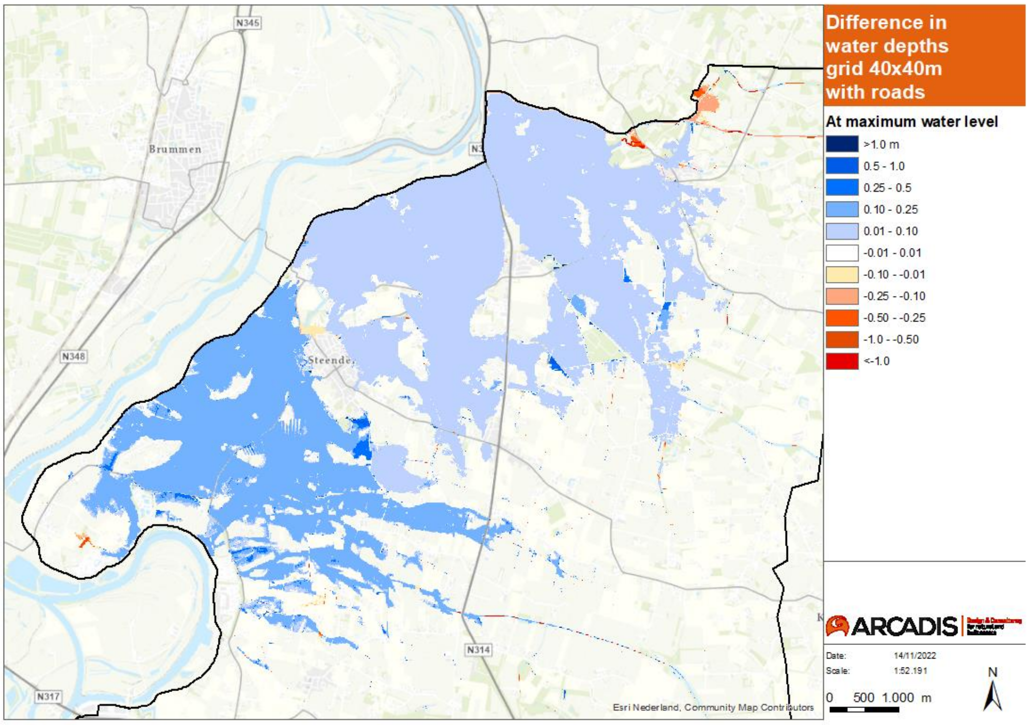

Figure A. 40: Difference in water depths between 40m model with all roads as fixed weir and reference model at maximum water depths

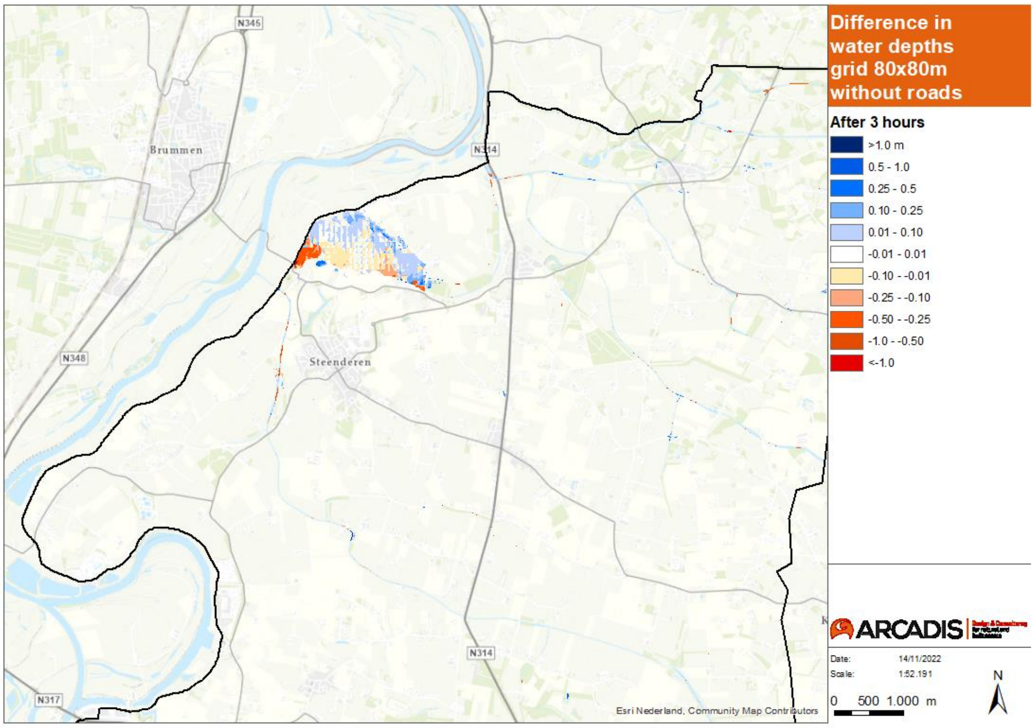

Figure A. 41: Difference in water depths between 80m model without roads and reference model 3 hours after dike breach

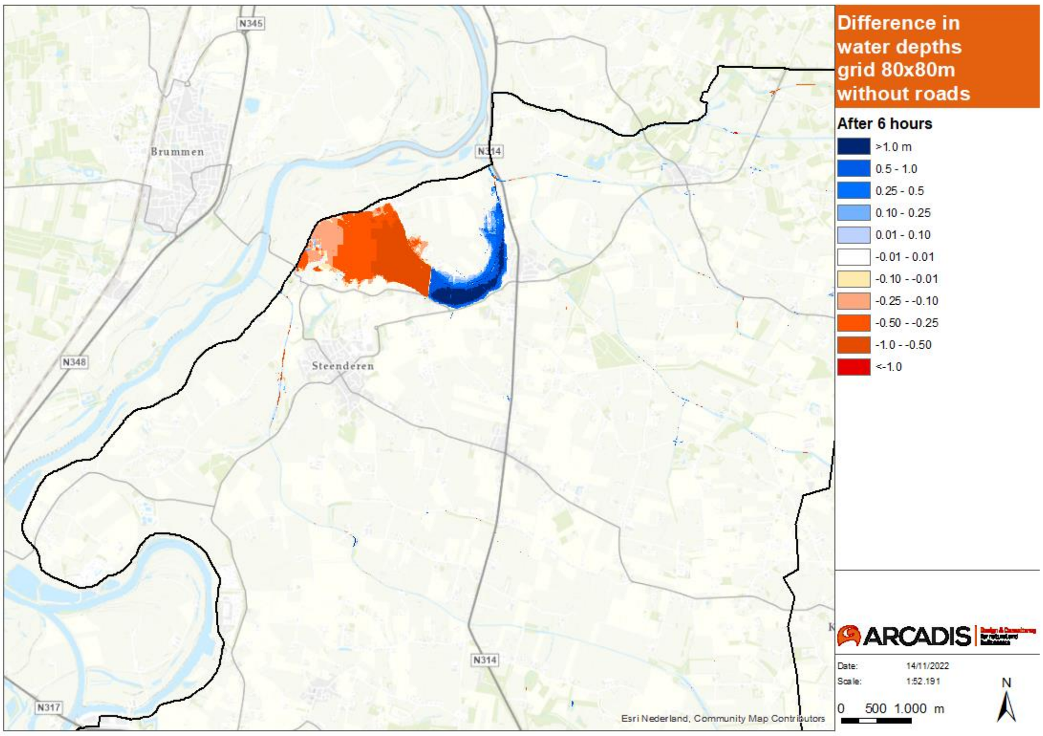

Figure A. 42: Difference in water depths between 80m model without roads and reference model 6 hours after dike breach

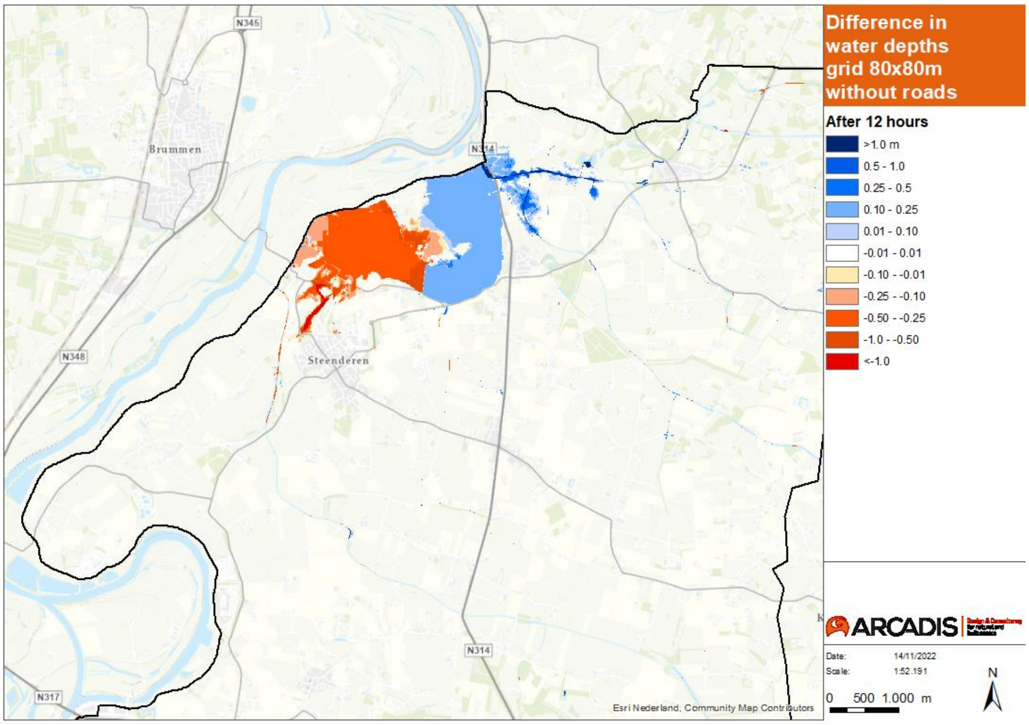

Figure A. 43: Difference in water depths between 80m model without roads and reference model 12 hours after dike breach

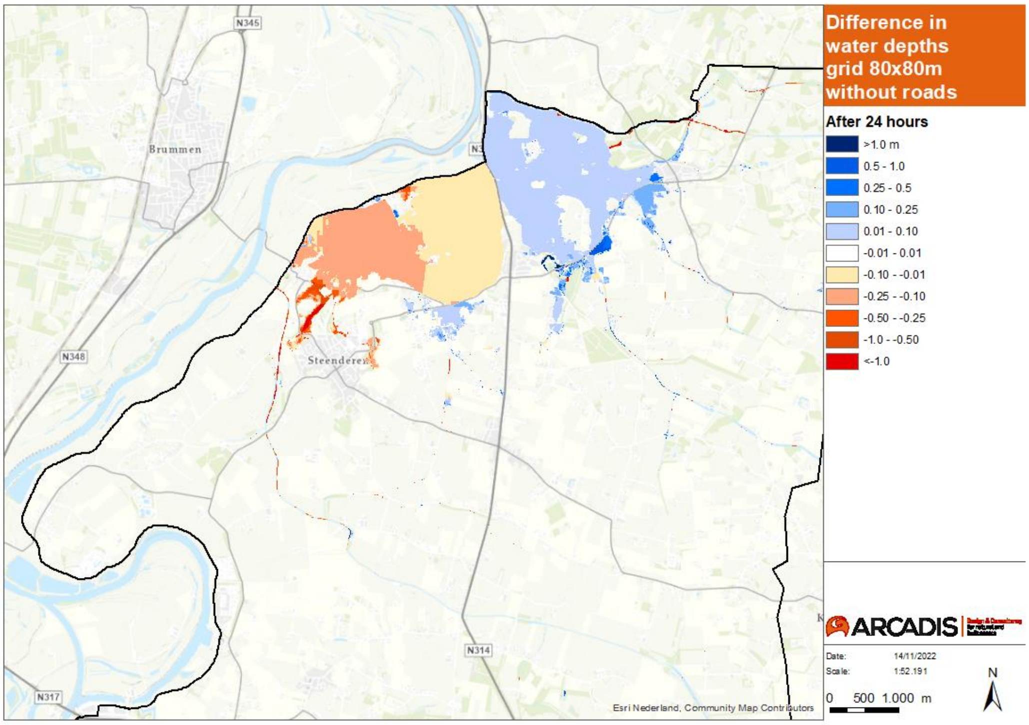

Figure A. 44: Difference in water depths between 80m model without roads and reference model 24 hours after dike breach

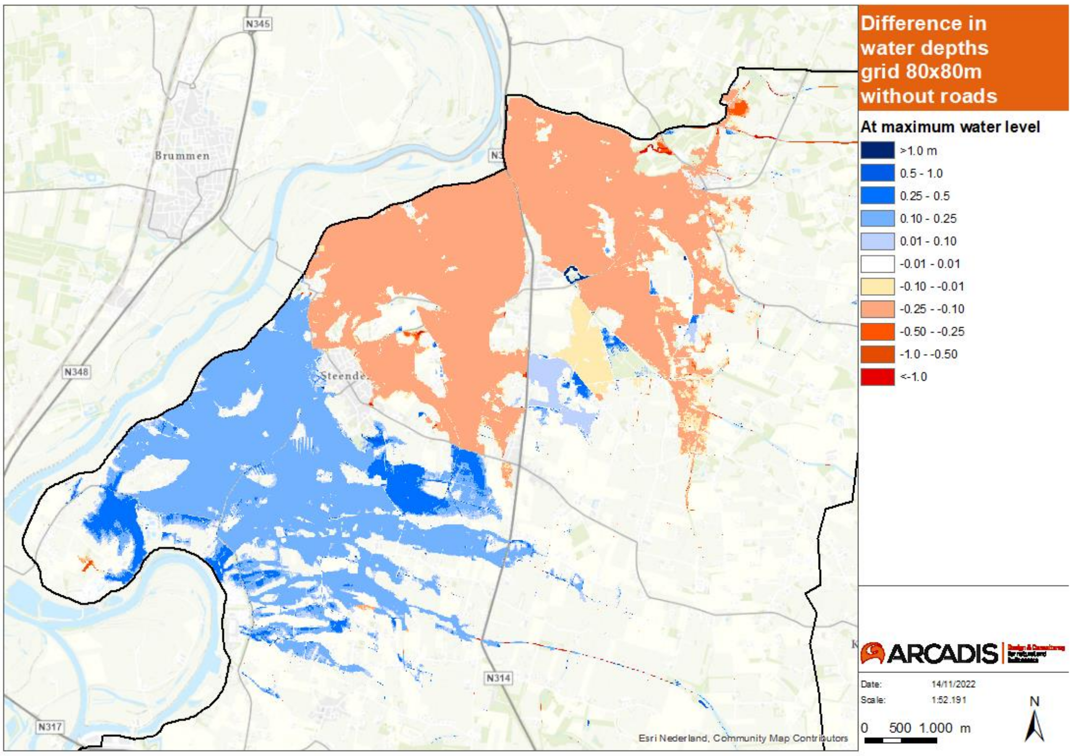

Figure A. 45: Difference in water depths between 80m model without roads and reference model at maximum water depths

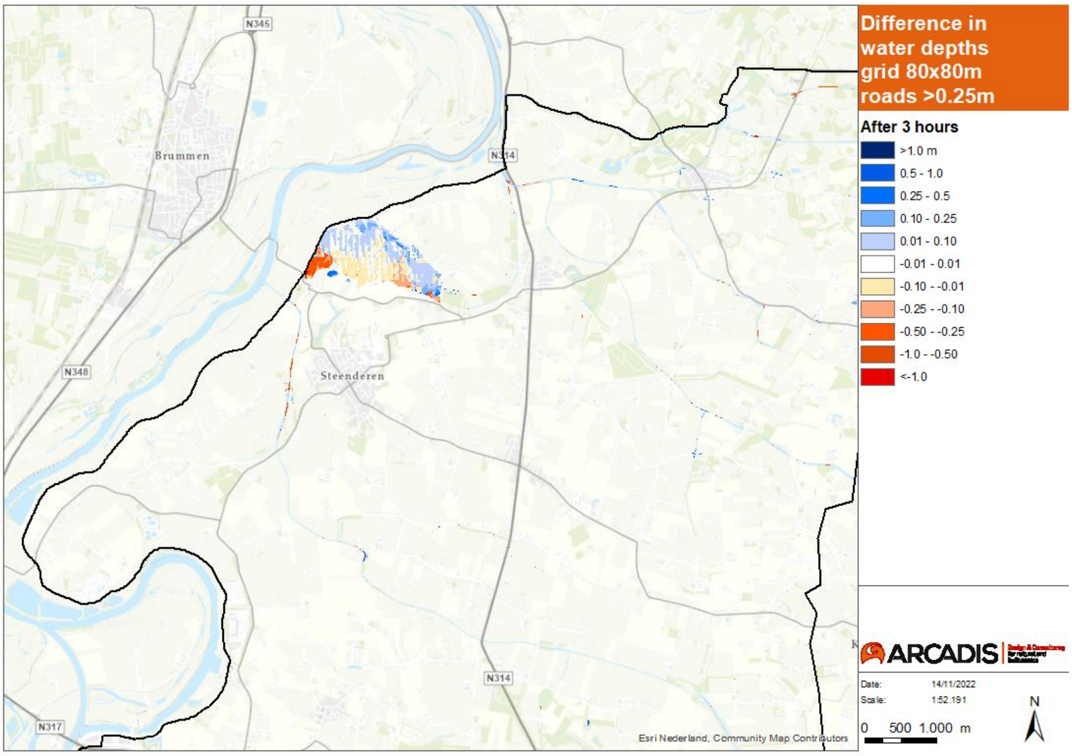

Figure A. 46: Difference in water depths between 80m model with roads as fixed weirs and reference model 3 hours after dike breach

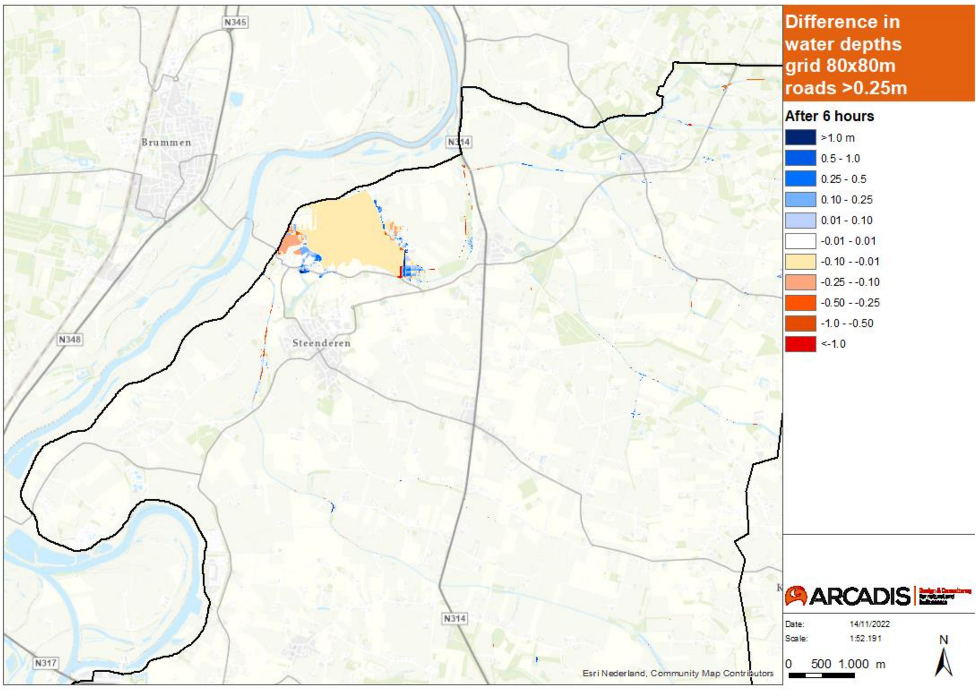

Figure A. 47: Difference in water depths between 80m model with roads as fixed weirs and reference model 6 hours after dike breach

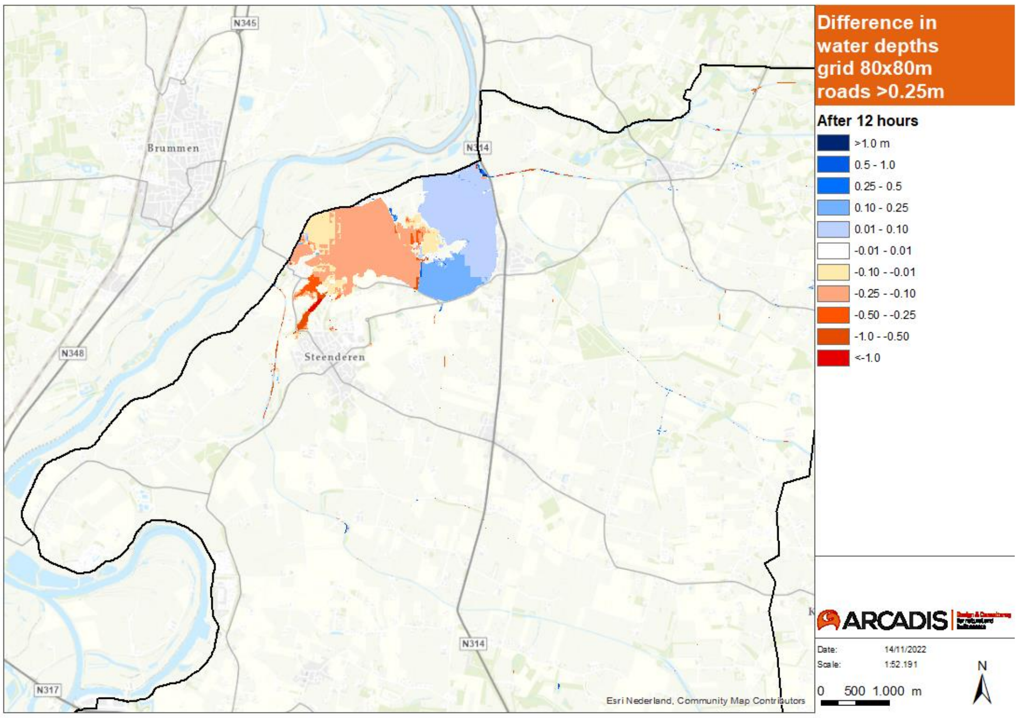

Figure A. 48: Difference in water depths between 80m model with roads as fixed weirs and reference model 12 hours after dike breach

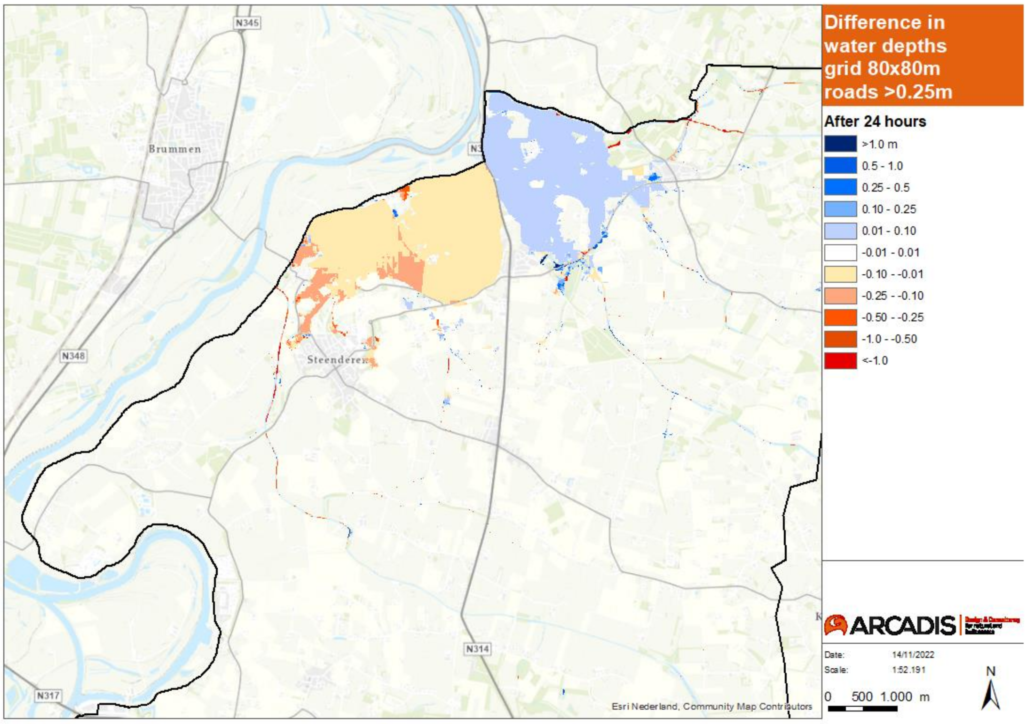

Figure A. 49: Difference in water depths between 80m model with roads as fixed weirs and reference model 24 hours after dike breach

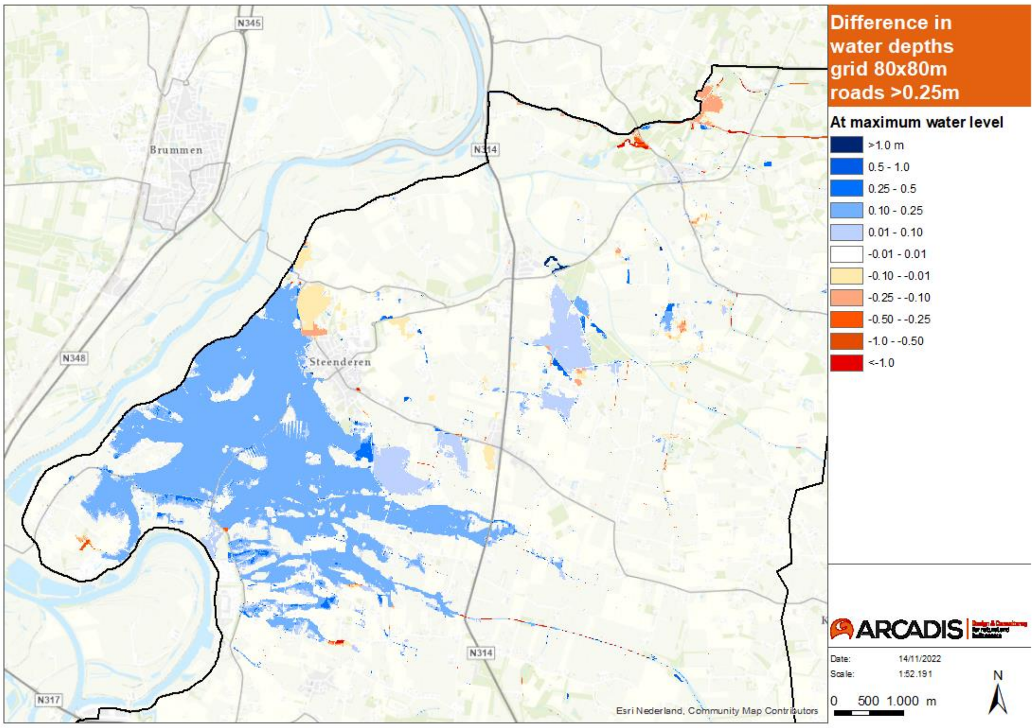

Figure A. 50: Difference in water depths between 80m model with roads as fixed weirs and reference model at maximum water depths

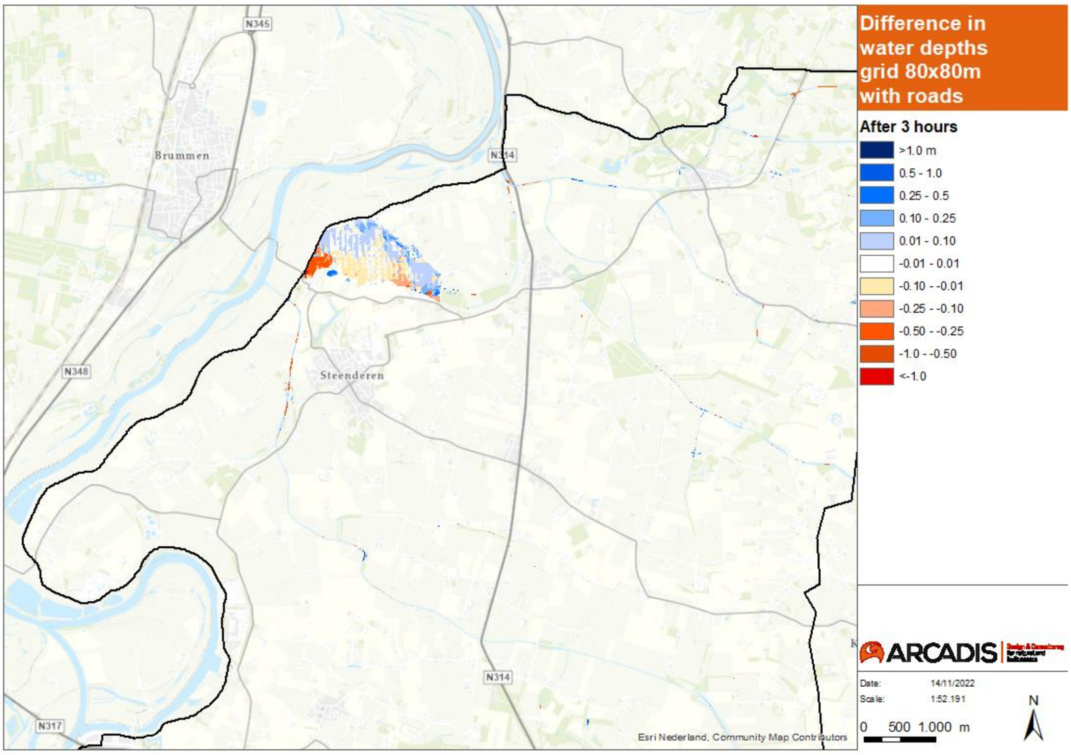

Figure A. 51: Difference in water depths between 80m model with all roads as fixed weirs and reference model 3 hours after the dike breach

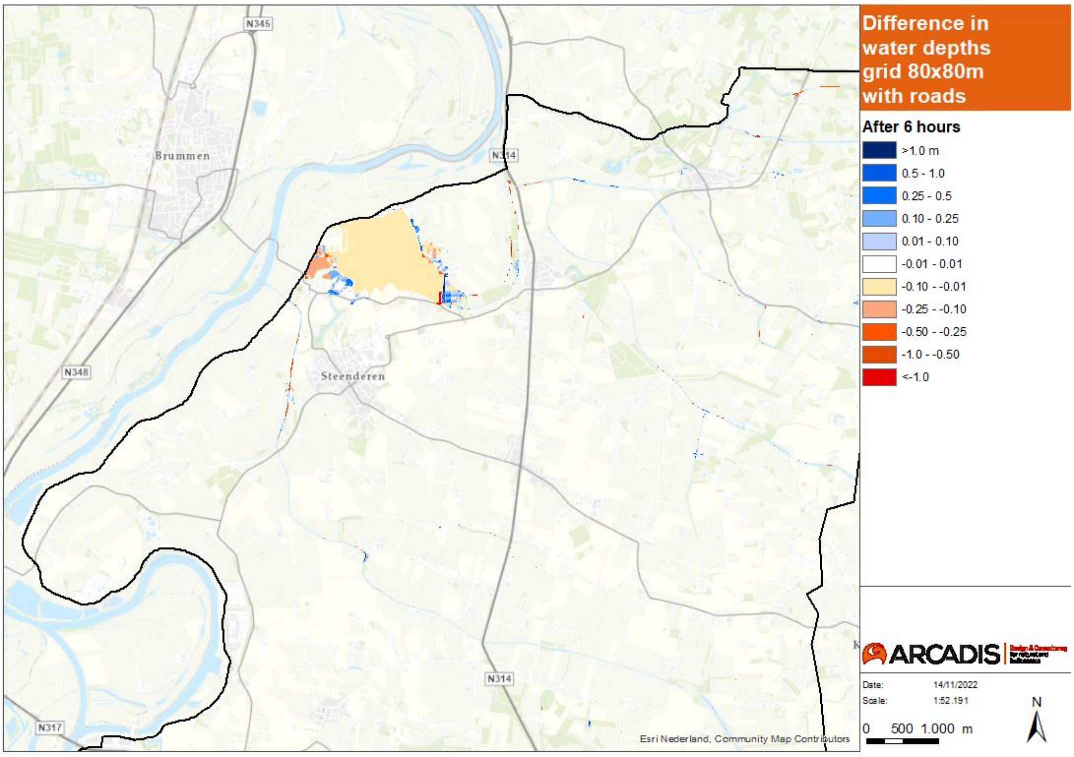

Figure A. 52: Difference in water depths between 80m model with all roads as fixed weirs and reference model 6 hours after the dike breach

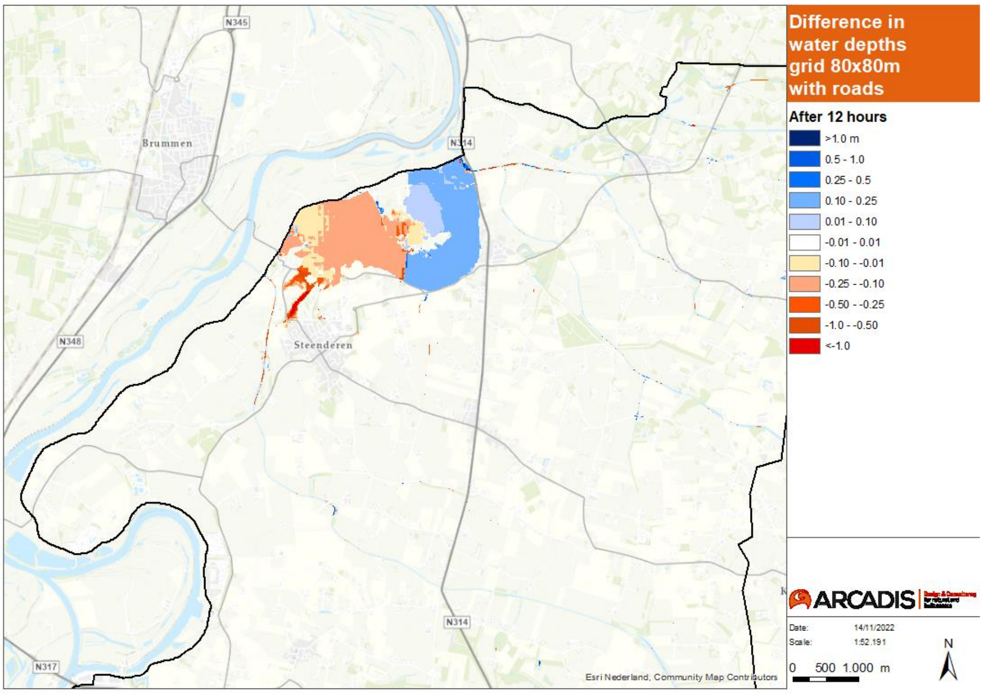

Figure A. 53: Difference in water depths between 80m model with all roads as fixed weirs and reference model 12 hours after the dike breach

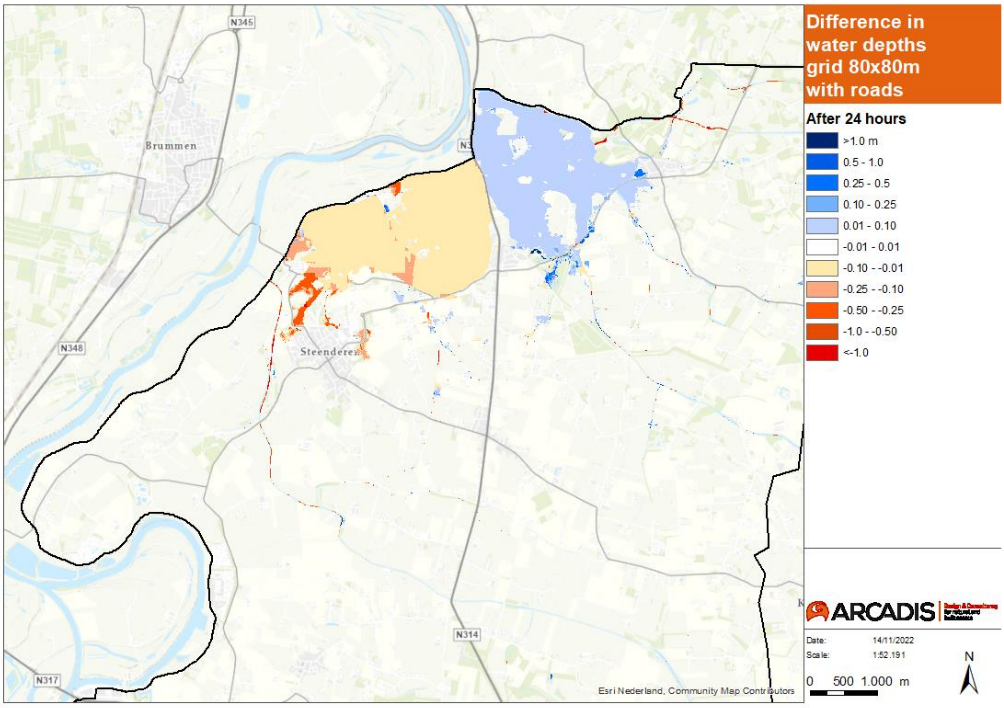

Figure A. 54: Difference in water depths between 80m model with all roads as fixed weirs and reference model 24 hours after the dike breach

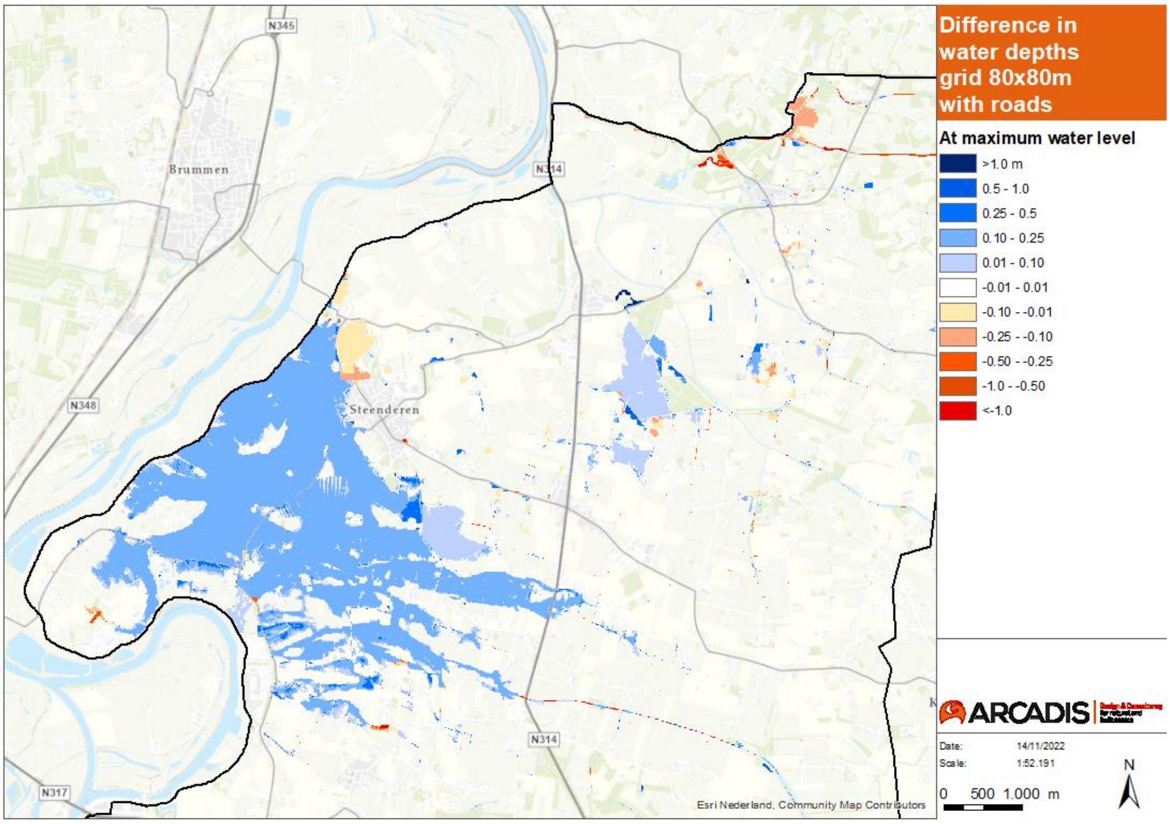

Figure A. 55: Difference in water depths between 80m model with all roads as fixed weirs and reference model at maximum water depths

Appendix B – Flood arrival maps

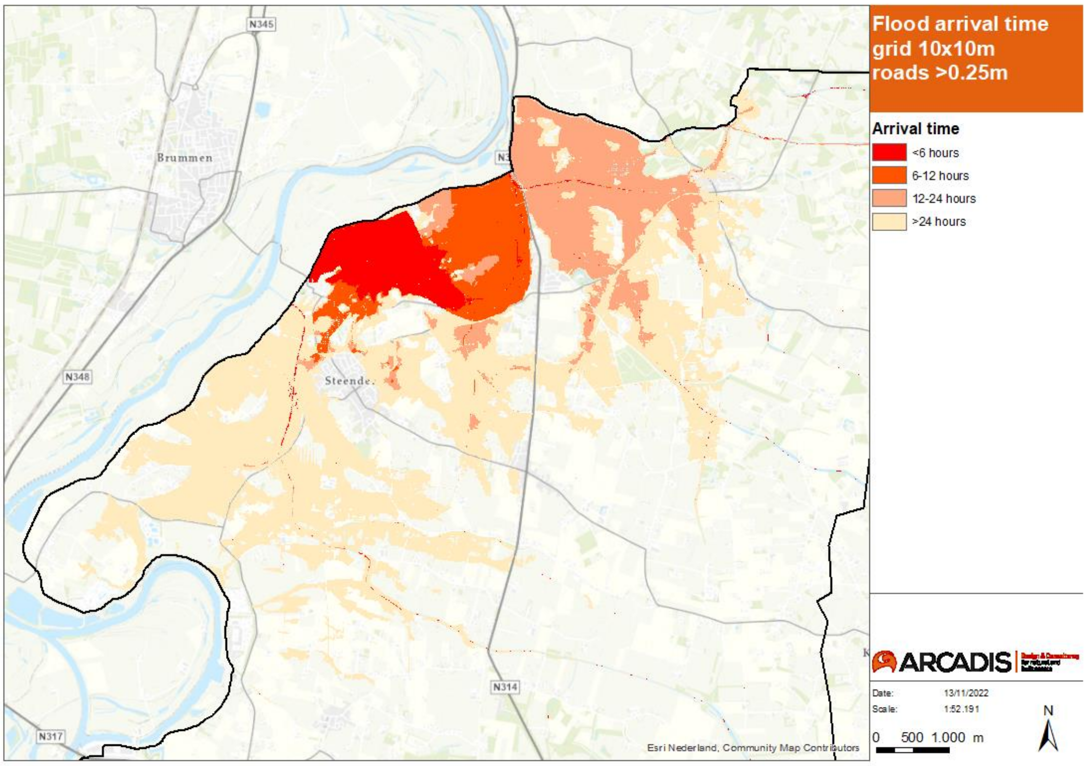

Figure B. 1: Flood arrival times reference model

Figure B. 2: Flood arrival times reference model

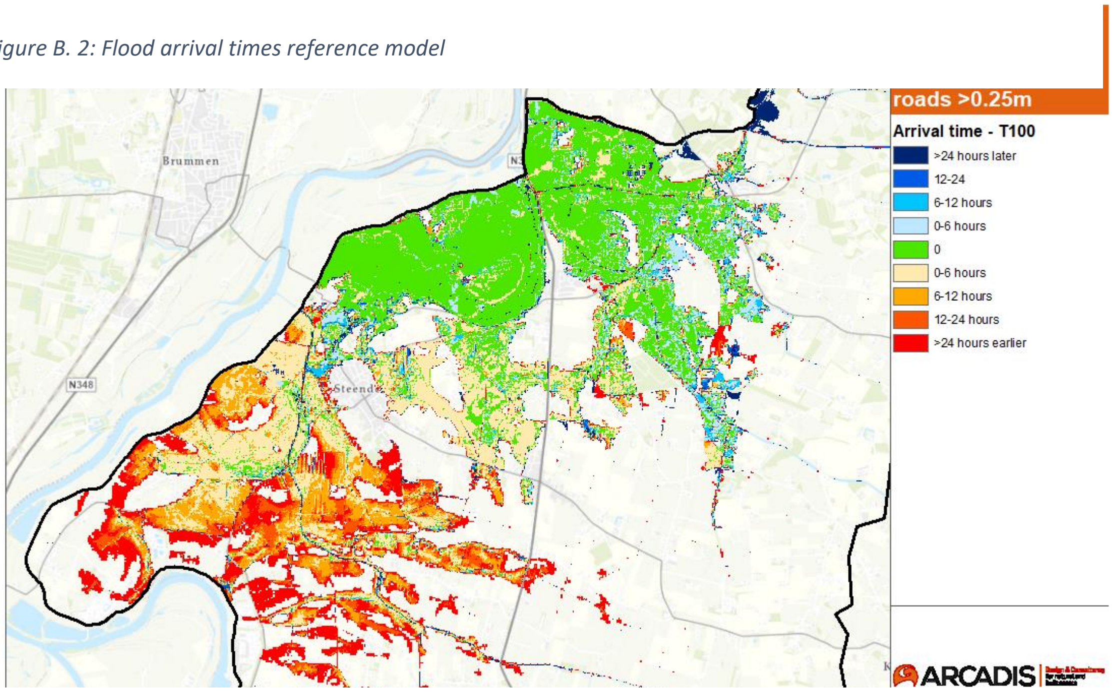

Figure B. 3: Difference in flood arrival times between 20m model with roads as fixed weirs and reference model for T100

Figure B. 4: Difference in flood arrival times between 20m model with roads as fixed weirs and reference model for T100

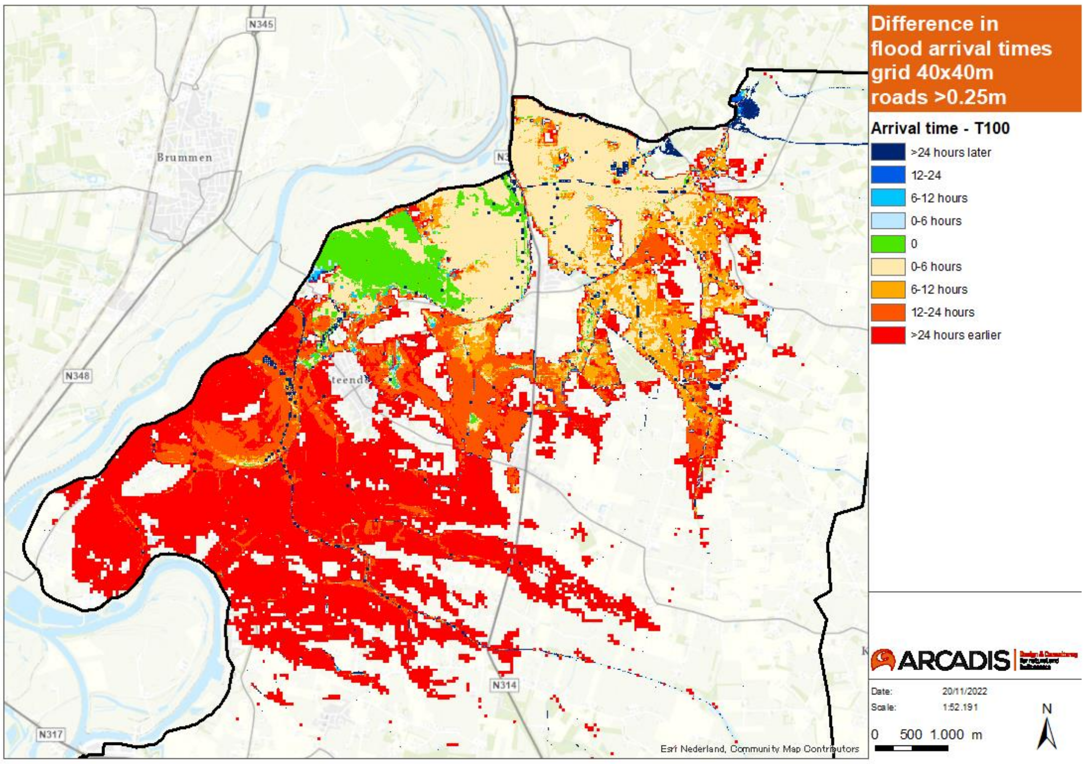

Figure B. 5: Difference in flood arrival times between 40m model with roads as fixed weirs and reference model for T100

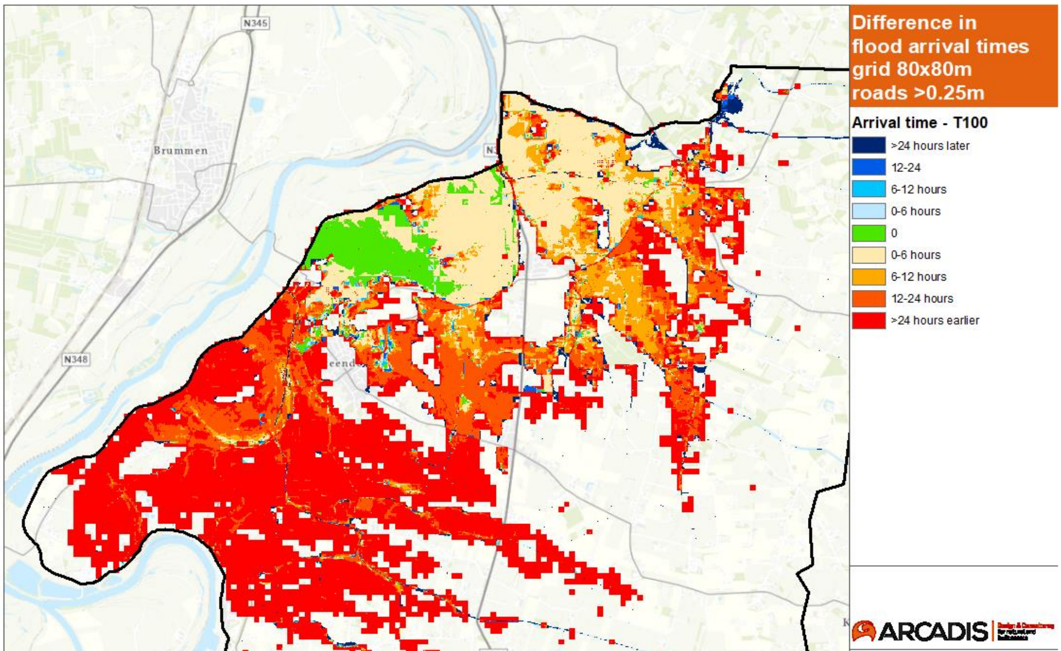

Figure B. 7: Difference in flood arrival times between 20m model with roads as fixed weirs and reference model for T100

Figure B. 8: Difference in flood arrival times between 20m model with roads as fixed weirs and reference model for T100

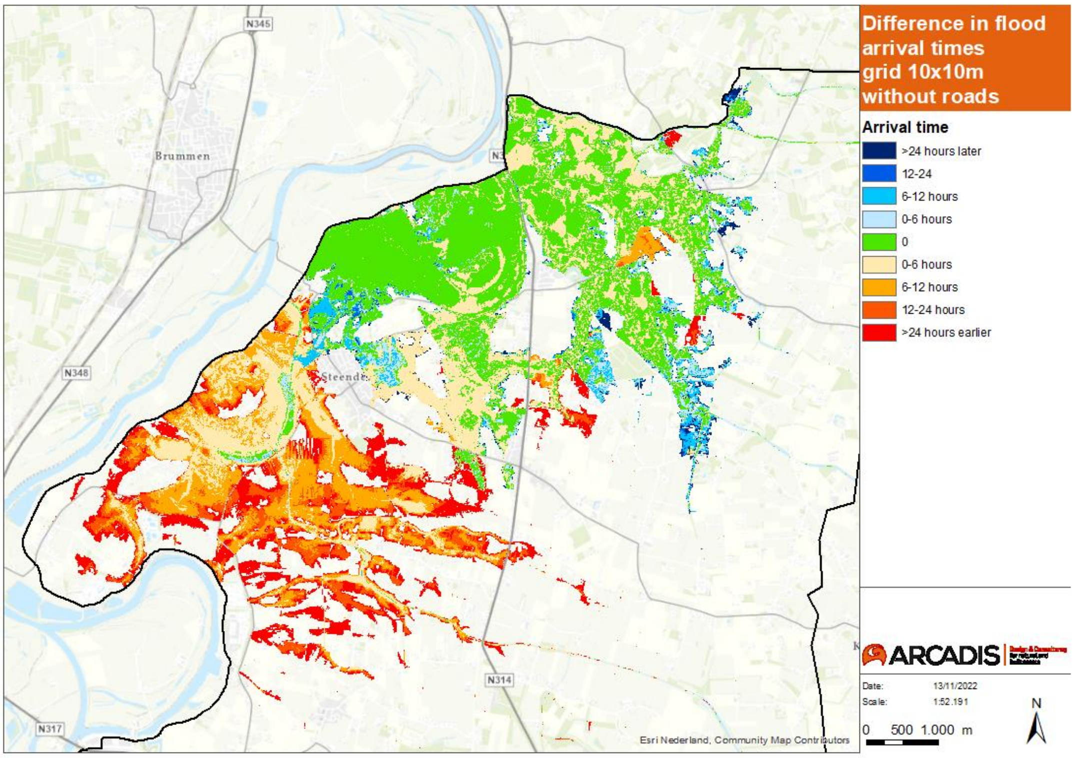

Figure B. 9: Difference in flood arrival times between 10m model without roads and reference model

Figure B. 10: Difference in flood arrival times between 10m model without roads and reference model

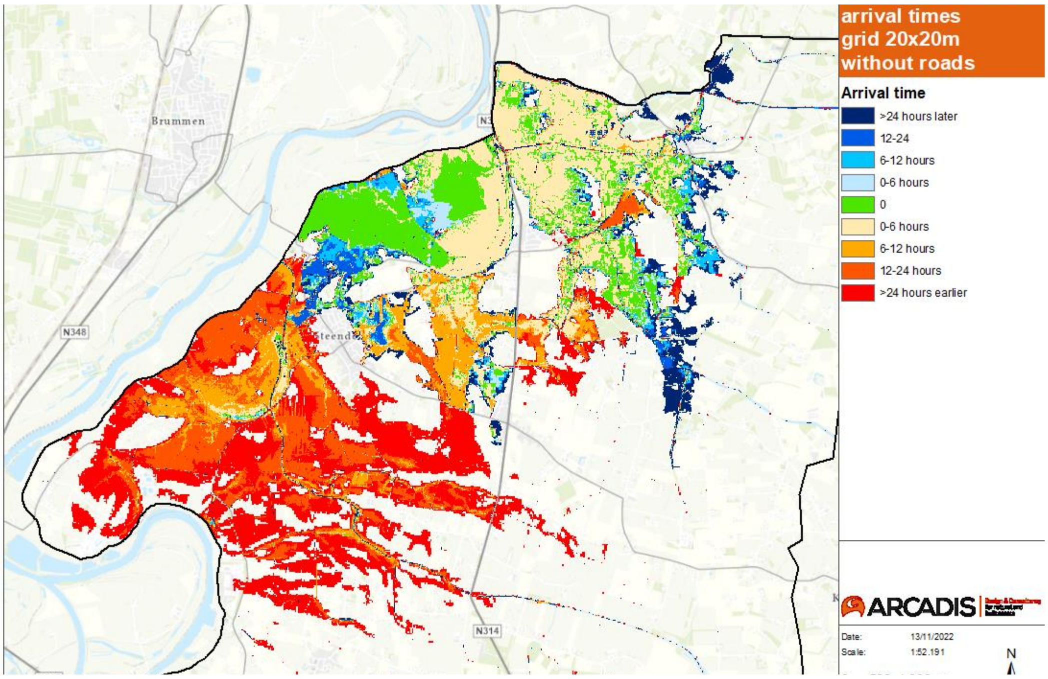

Figure B. 11: Difference in flood arrival times between 20m model without roads and reference model

Figure B. 12: Difference in flood arrival times between 20m model without roads and reference model

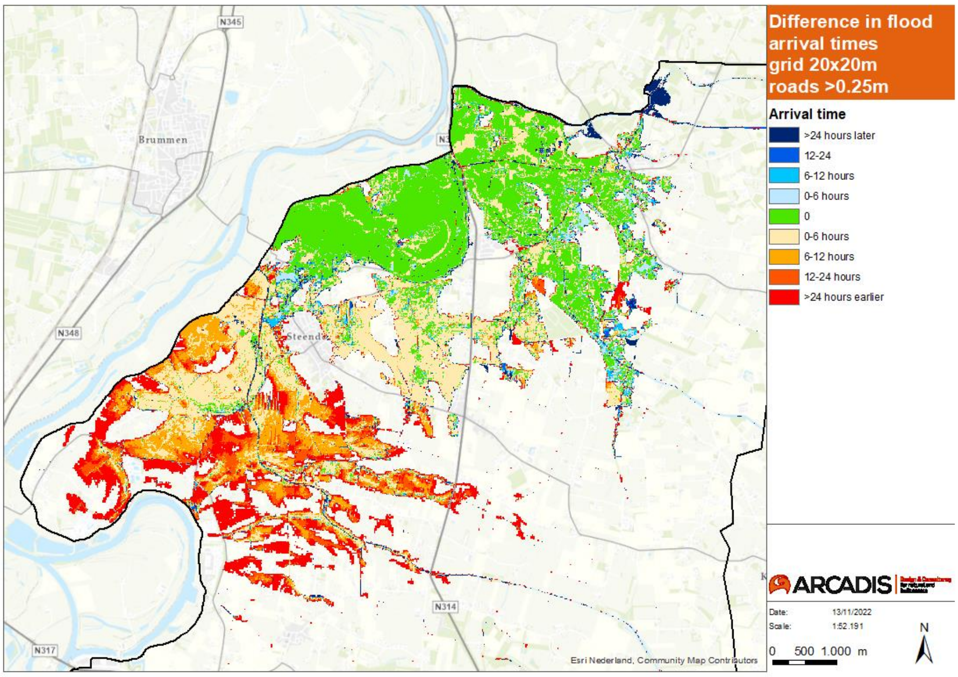

Figure B. 13: Difference in flood arrival times between 20m model with roads as fixed weirs and reference model

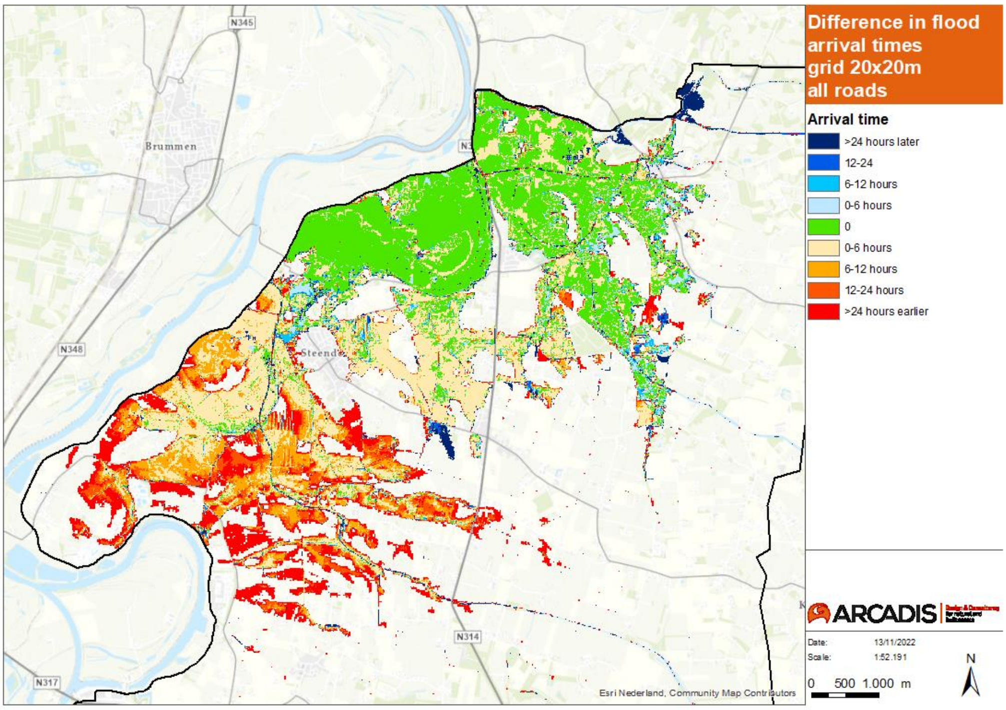

Figure B. 15: Difference in flood arrival times between 20m model with all roads as fixed weirs and reference model

Figure B. 16: Difference in flood arrival times between 20m model with all roads as fixed weirs and reference model

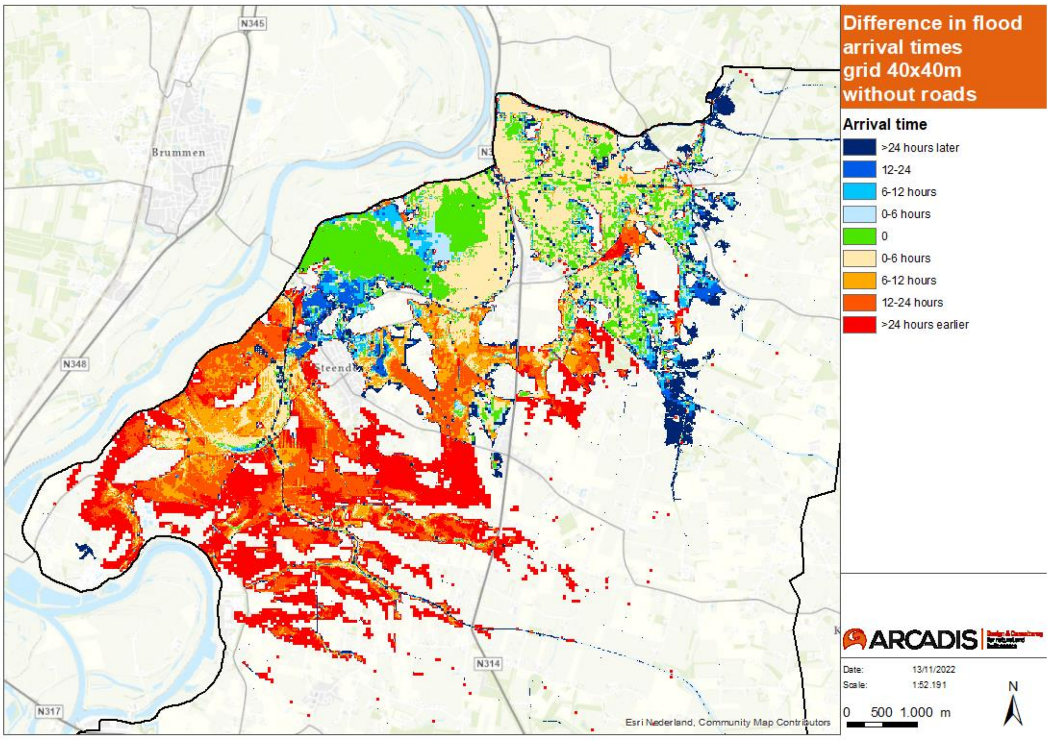

Figure B. 17: Difference in flood arrival times between 40m model without roads and reference model

Figure B. 18: Difference in flood arrival times between 40m model without roads and reference model

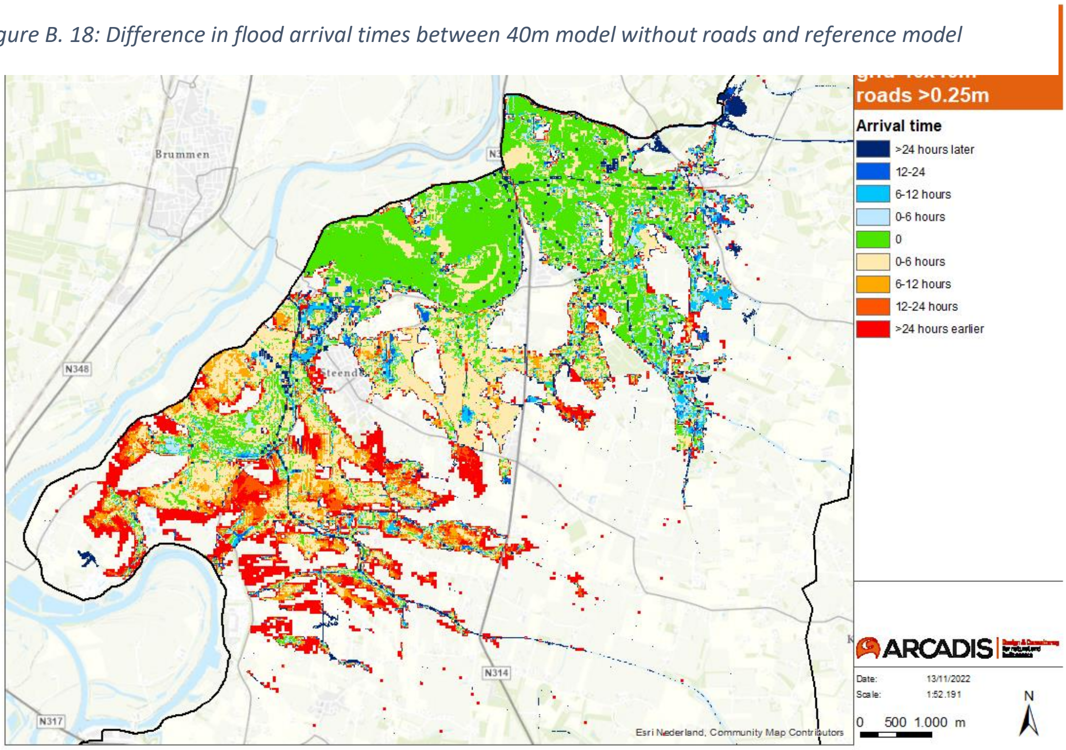

Figure B. 19: Difference in flood arrival times between 40m model with roads as fixed weirs and reference model

Figure B. 20: Difference in flood arrival times between 40m model with roads as fixed weirs and reference model

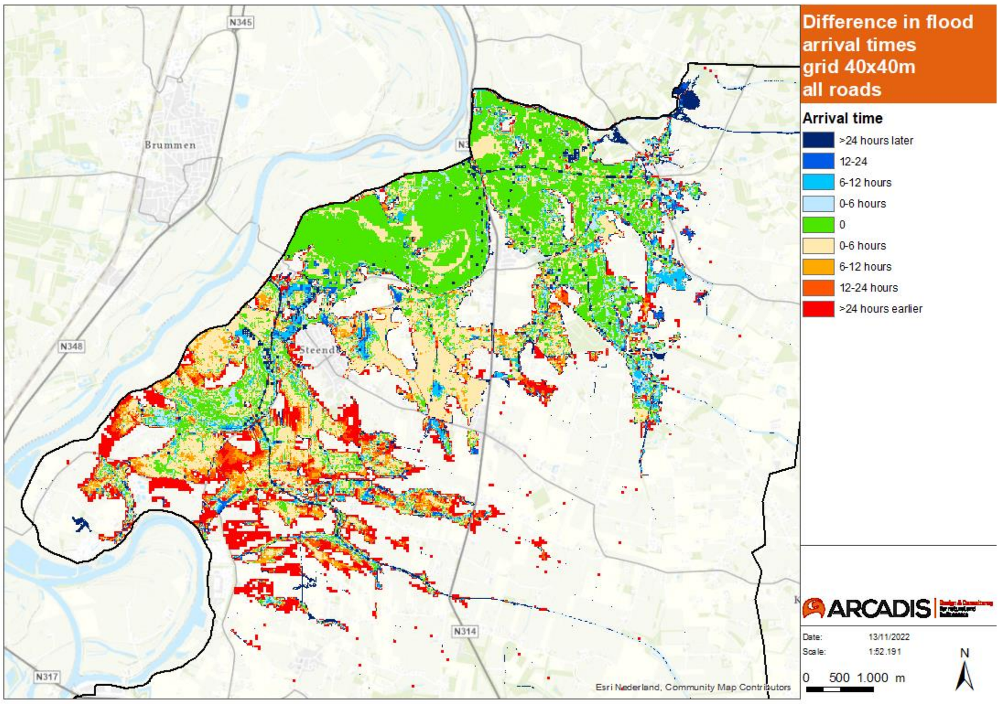

Figure B. 21: Difference in flood arrival times between 40m model with all roads as fixed weirs and reference model

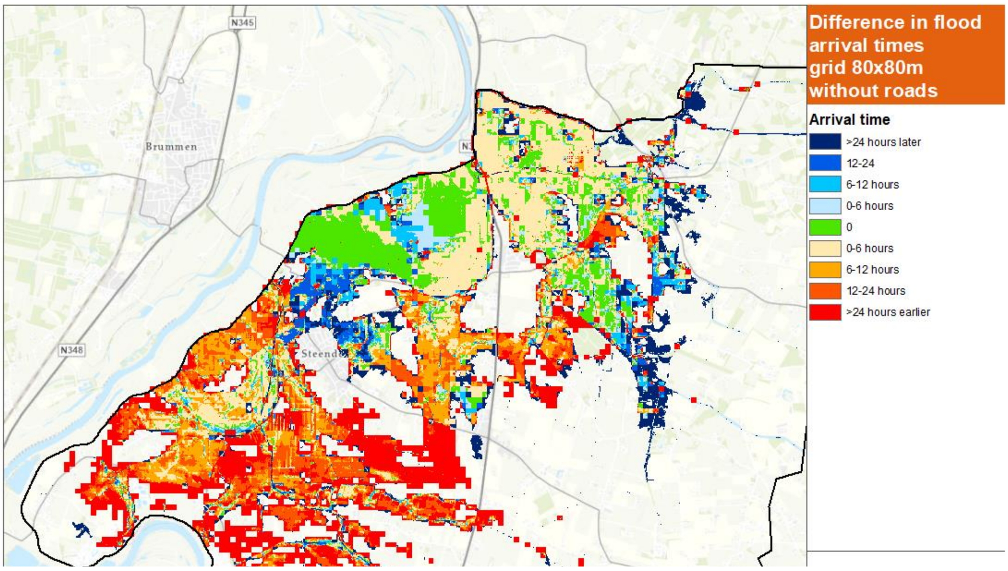

Figure B. 23: Difference in flood arrival times between 80m model without roads and reference model

Figure B. 24: Difference in flood arrival times between 80m model without roads and reference model

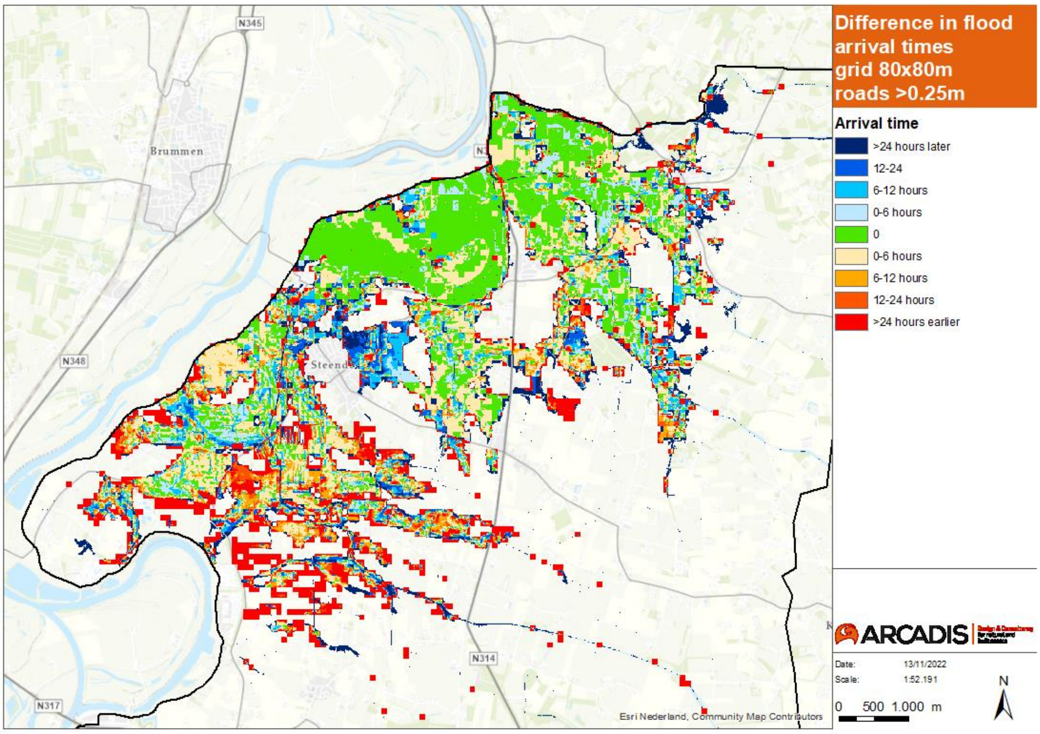

Figure B. 25: Difference in flood arrival times between 80m model with roads as fixed weirs and reference model

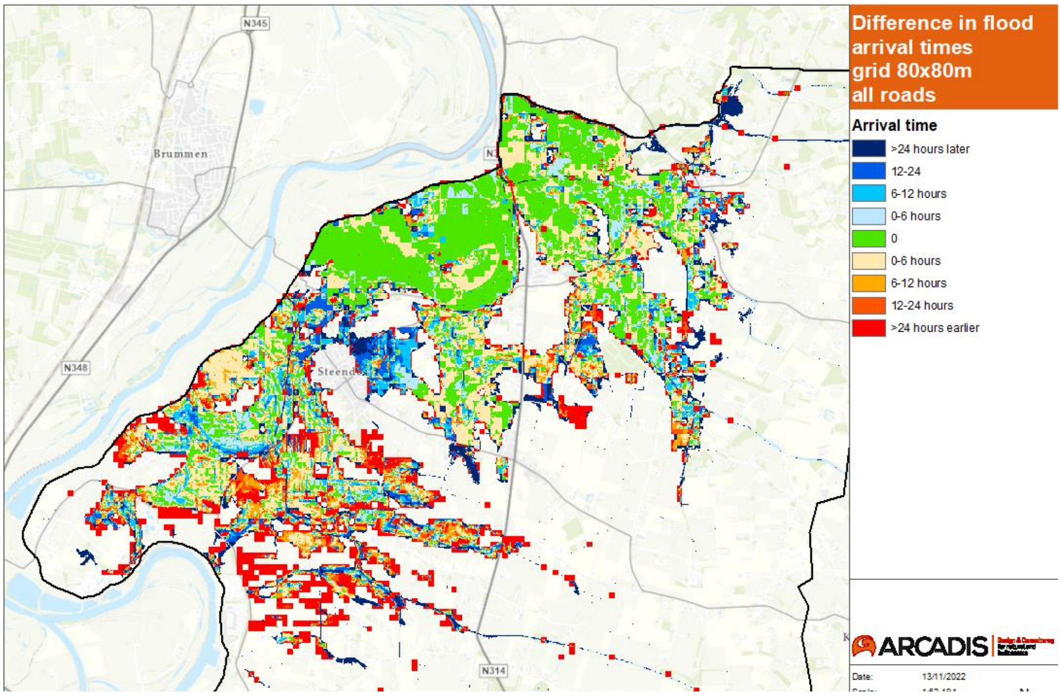

Figure B. 27: Difference in flood arrival times between 80m model with all roads as fixed weirs and reference model

Figure B. 28: Difference in flood arrival times between 80m model with all roads as fixed weirs and reference model

Appendix C – Model creation in D-Hydro

The models that are used in this study are created step-by-step as described below.

The first step is to create the 2D grid and import the 2D grid in D-Hydro. On the imported grid the initial conditions are defined. This is done by interpolating bed levels, initial water levels, and friction coefficients on the 2D grid. The interpolation methods used are simple averaging and triangulation. Simple averaging is the first method used, whereafter triangulation is used for grid cells that contain no data. AHN3 data is used to define bed levels, the land use map (LGN7) is used to define the friction coefficients and the shapefile with initial water levels is used to define water levels.

The second step is to import line elements such as dikes and roads as fixed weirs into the model. Underpasses, bridges, and culverts are imported into the model as so-called pipes and manholes.

Step three is to import the 1D model. The 1D model consists of the main Rhine branches (The Rijn, Waal, Lek, and IJssel) and the waterways within the dike ring area. The 1D model with the Rhine branches and the 1D Sobek model with waterways within the dike ring area has been combined into a 1D model. This has been done to ensure that there are no differences in the 1D model after connecting the two 1D models. After importing the 1D model, the cross sections and roughness data are imported into the configuration files, because this data is not imported correctly into the model. After that, the initial conditions of the 1D model are defined.

Step four is linking the 1D model with the 2D grid. Embedded links are used to connect the waterways within the dike ring to the 2D grid, this is done with a script. Lateral links are used to connect the IJssel with the 2D grid.

Step five is adding the dike breach to the model and after that, the boundary conditions are defined. The last step is to check whether the model parameters are the same as the value in the validation models and are adjusted.

Appendix D – Analysis adjusting 1D2D links

In this section, the results are shown in which some adjustments are made to the 1D2D links. Section 5.2 shows that there are differences in breach outflow. This analysis is done to see whether adjusting the 1D2D links results in a similar breach outflow at different grid resolutions. The breach outflow hydrograph of the model with a fine grid resolution might underestimate the breach discharge. However, it is likely that the models with a coarse grid overestimate the breach discharge since water levels inside the dike near the dike breach location are lower than the water level outside the dike when a coarse grid resolution is used.

The difference in water level inside the dike can be explained by the length over which water can flow to surrounding cells, which results in a lower breach outflow for models with a fine grid resolution. This section analyses how 1D2D affects breach outflow. First models with grid cells of 5m, 10m, and 40m are compared and the model schematizations are shown in Figure D.1. After that, the 1D2D links in the 10m model are moved to the second cell from the edge (Figure D.2a) and the 1D2D links are alternately connected to the 2D grid (Figure D.2b).

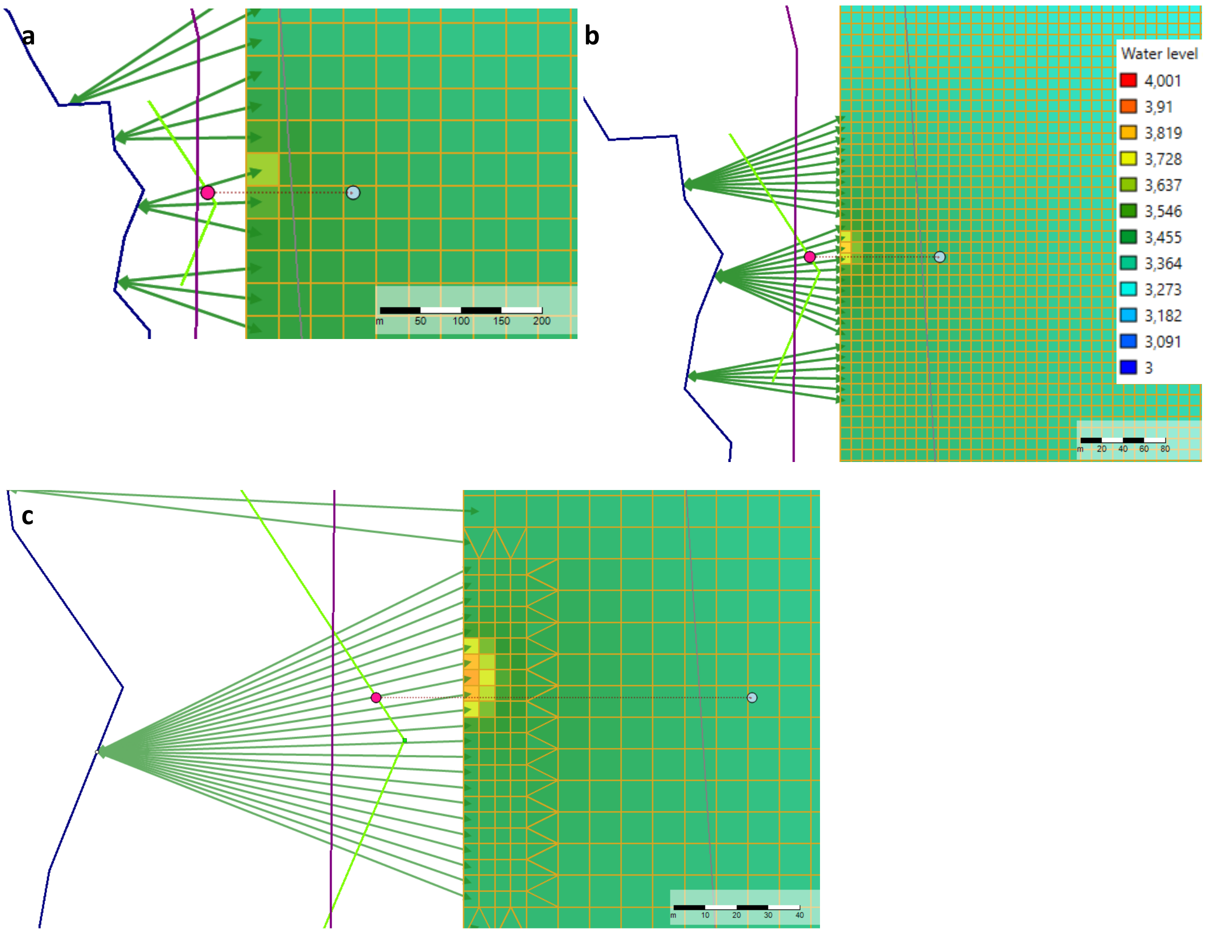

Figure D. 1: Overview test models with a) 40m grid cells, b) 10m grid cells, and c) 5m grid cells

Figure D. 2: Overview test models with a) 40m grid cells, b) 10m grid cells, and c) 5m grid cells

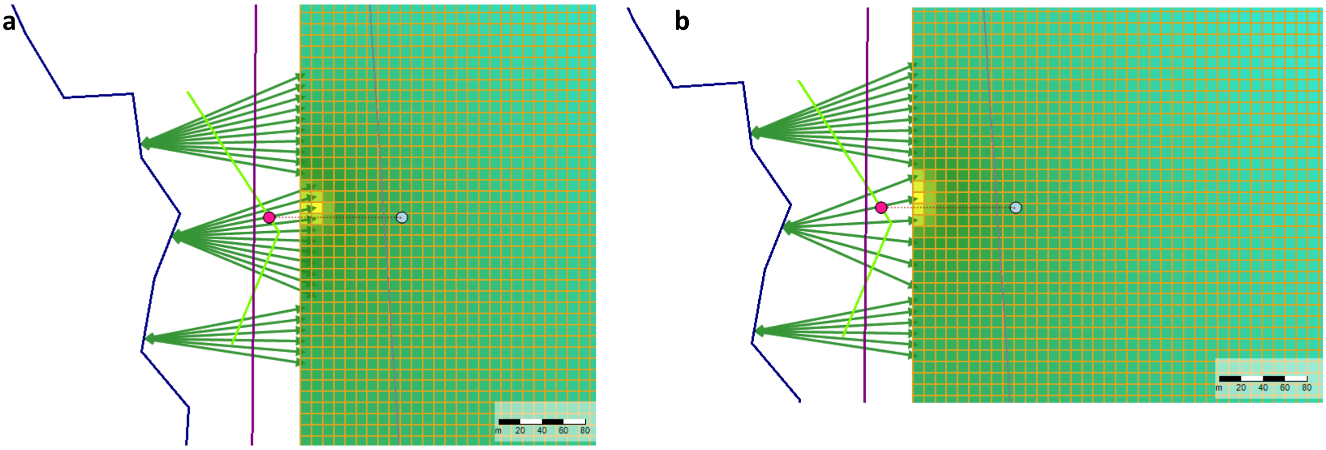

Figure D. 3: Adjusted 1D2D links with a) links to second cell from edge and b) alternately linked.

Comparing the breach outflow of the 5m, 10m, and 40m show a difference in flow velocity and breach outflow (Figure D.3 and Figure D.4) A model with a finer grid has lower breach outflow and is caused by a lower flow velocity (Figure D.4). Models with a finer grid resolution have higher water levels in the grid cells that are linked to the 1D model because water accumulates in the grid cells that are directly linked to the 1D model (Figure D.1). One hour after the dike breach, the 5m model has a water level of 3.91 m+ NAP in the grid cells directly linked to the 1D model and is significantly higher than the neighbor cells (Figure D.1c). In the 10m and 40m models, the water levels in these grid cells are 3.82 m+ NAP and 3.64 m+ NAP respectively (Figure D.1a, Figure D.1b). In the 40m model, the difference in water level between this cell and neighbor cells is smaller than in the 5m and 10m models.

In models with a fine grid, more water accumulates in the grid cells directly linked to the 1D model and the difference in water level upstream and downstream of the dike breach is smaller. As a result, the flow velocity is lower in models with a fine grid and the breach outflow is lower (Figure D.3 and Figure D.4).

By adjusting the 1D2D links to the second cell from the edge or by linking them alternately, water can flow more easily to surrounding cells, which reduces the water level in the links cells (Figure D.2a and Figure D.2b). Due to a lower downstream water level, the breach outflow in the 10m models with adjusted 1D2D links is higher than in the 10m model without adjustments to the 1D2D links. However, the breach outflow of the 10m models with adjustments to the 1D2D links is still lower than the model with grid cells of 40m (Figure D.4).

To conclude, adjusting 1D2D links affects breach outflow. Adjusting the 1D2D links can increase the breach outflow of models with a fine grid can, but breach outflow is still lower than the breach outflow of a model with a coarse grid.

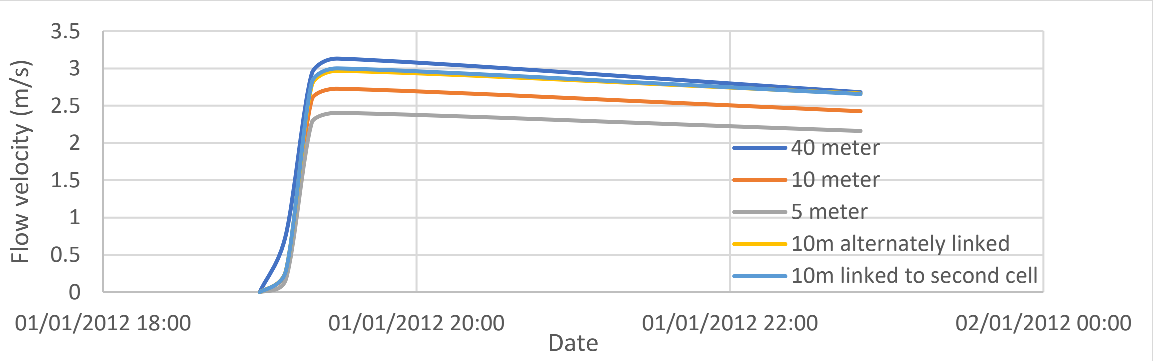

Figure D. 4: Flow velocity through dike breach

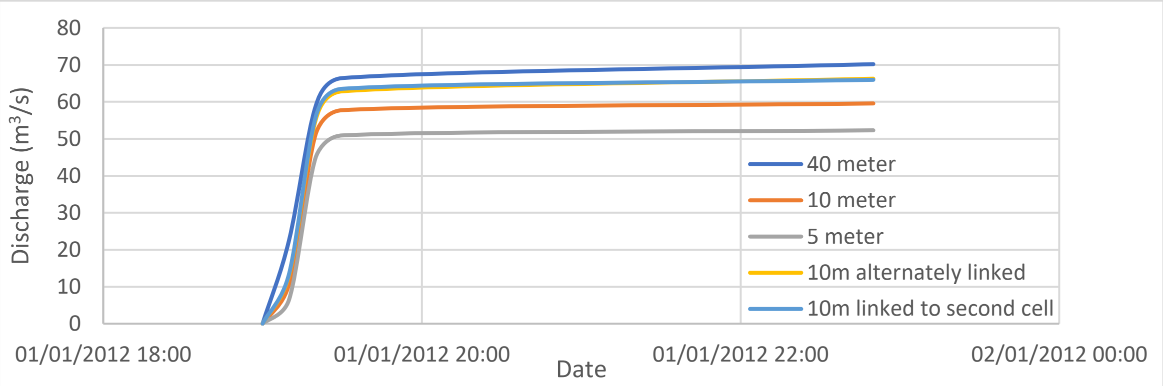

Figure D. 5:Discharge through dike breach

Figure 25: Difference in water depth between 20m model with roads as fixed weirs and reference modelFigure D. 6:Discharge through dike breach