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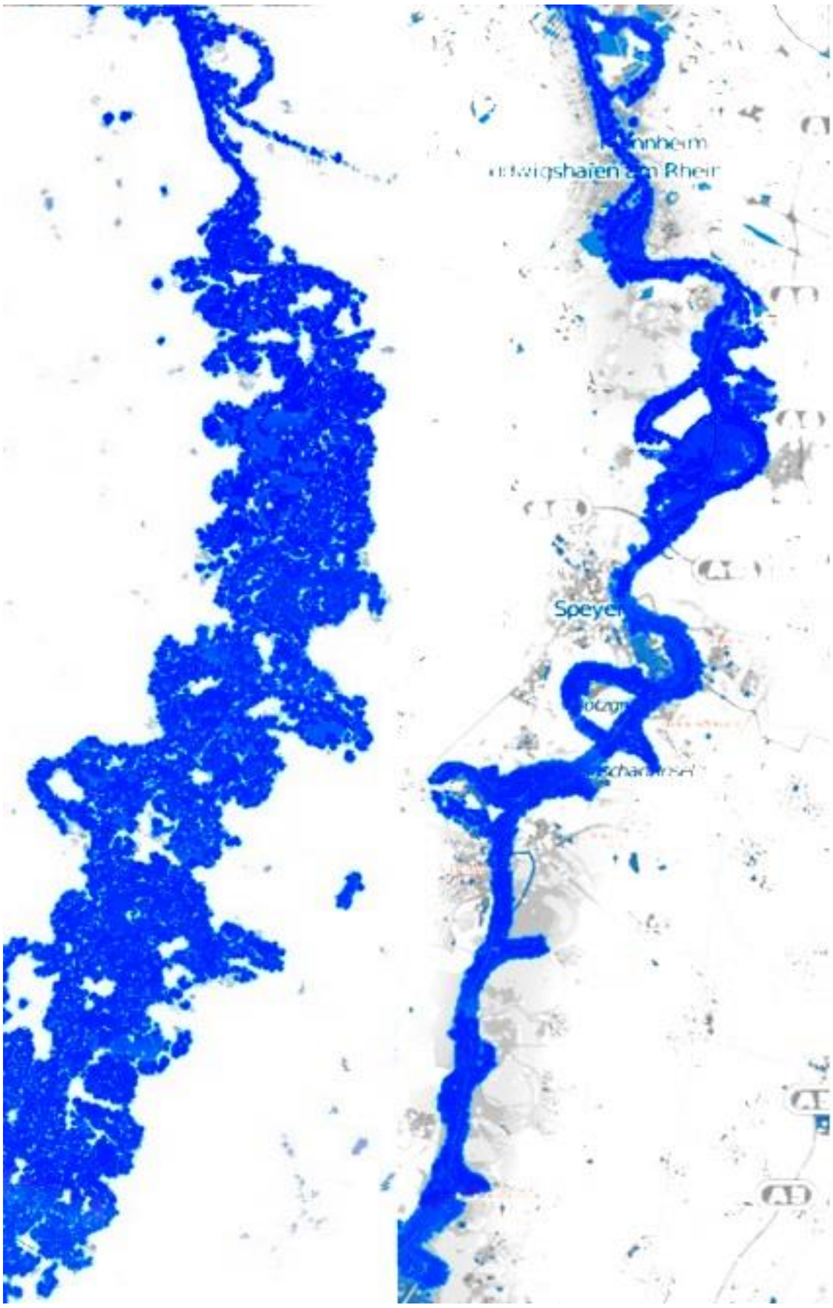
Evaluating and improving a two-dimensional hydraulic model of the Oberrhein

Bachelor Thesis Deltares



Bachelor Thesis, Michiel van den Berg

Deltares

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EVALUATING AND IMPROVING A TWO-DIMENSIONAL HYDRAULIC MODEL OF THE OBERRHEIN

Bachelor thesis for the Bachelor's programme Civil Engineering at the Faculty of Engineering Technology of the University of Twente, in collaboration with an internship at Deltares

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First, I must congratulate Eva Hoekstra for developing such a great model in a very limited time span. The main issues the model did appear to have were not caused by errors on her part but mostly faulty software was the culprit. Only when closely examining the model and eliminating all other possible causes the software issue came to light. Furthermore, because no clear warnings were given in the program that something was not working properly Eva could not have known that there was an issue with the model. Also I would like to thank Rita Lammersen from Rijkswaterstaat for giving me permission to use the discharge data from various gauging stations along the Rhine.

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ABSTRACT

This paper improves and evaluates a two-dimensional model of the Oberrhein. The reason why the output data of the previous developed model (PD-model) of the Oberrhein seemed to overestimate the inundation extent was mainly a software issue. Some bugs in the GUI (graphic user interface) of the D-HYDRO software package caused the primary flood defences to be excluded from the calculation. Because of the exclusion of the weirs, the water in the model was only confined by the elevation of the landscape. Using an alternate module of the D-HYDRO package called DIMR, this problem was resolved. This study also found that adding a warm-up period to the PD-model resulted in a smoother transition to a high discharge event.

By validating the model, the correctness and reliability of the improved model was assessed. The improved model simulated discharge accurately. The model had a RMSE value of 34.2 m^3/s, this is less than half the standard deviation of the observed data and thus was deemed acceptable. The NSE had a value of 0.85, this value lies between 0 and 1 and therefore was deemed acceptable. Also the improved model simulated the inundation extent better, the FAR and CSI tests both improved although the PD-model did score better on the POD test. This suggested that instead of a overestimation now an slight under estimation of the inundation extent occurred at some locations throughout the model.

A sensitivity analysis revealed that the simulated discharge of the model was not very responsive in respect to changes to parameters like the surface roughness and eddy viscosity. Therefore the model was very robust in respect to these parameters

To examine which modelling technique was most appropriate in the area of interest a literature review was conducted. The revelations found were backed up with experiments using the improved model. Using the review and the experiments it was established that two-dimensional computations are vital to simulate the Oberrhein regardless of using average or high discharge.

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1 INTRODUCTION

1.1 THESIS OUTLINE

The subject that I have examined in my Bachelor thesis was the simulation the Oberrhein river using hydraulic models. The first chapter consists of an introduction of the subject. The introduction consists of the context and description of the problem and some background information (Section 1.2). The used software and data are described in the following section (Section 1.3). Next the study area is examined (section 1.4).

Chapter 2 gives a brief theoretical background concerning the used hydraulic models and modelling in different dimensions. The main research questions that needed to be answered are formulated in Chapter 3 as well as the sub-questions. The methods used to answer these questions are introduced and explained in Chapter 4. Chapter 5 examines the results of the experiments described in chapter 4. Chapter 6 discusses the findings of the model as well as the limitations of the study. Chapter 7 consist of the conclusion of the study and finally a recommendation in chapter 8.

Introduction

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1.2 BACKGROUND INFORMATION AND PROBLEM DEFINITION

The Rhine is the major river of the Netherlands. The Rhine stands out as one of the longest and most prominent rivers in Europe since the Roman era (Mutton, 2016). Since this era many European cities (Rotterdam, Andernach, Cologne, etc) have established themselves near the Rhine. These cities have evolved from small trading posts or villages into large cities with a considerable resident community. Although the Rhine brings a broad range of advantages for these cities, a large river like the Rhine also harbours dangers. Peak discharge may cause the Rhine to overflow which, if not managed correctly, can lead to catastrophic flooding, the loss of lives and costly damages. The flooding event on 31 January 1995 for example killed at least 4 people in the Netherlands, some 250,000 had to be evacuated and large tracts of cities were submerged (Rhine-effects, 2018). Therefore, it is crucial to accurately predict the nature of a peak discharge event, to assess the risk and decide whether precautions can or have to be made. Especially in an era of climate change with its increasingly volatile and unpredictable weather conditions, predicting the impact of the discharge of the Rhine is vital.

In Europe, water management is moving from flood defence to a risk management approach (te Linde, Bubeck, Dekkers, de Moel, & Aerts, 2011). It is expected that climate change and socio-economic development will lead to an increase in flood risk in the Rhine basin (Bouwer, 2010; te Linde et al., 2011). Many studies were recently conducted to assess this increasing flood risk. Studies that examined the Rhine itself like the spatiotemporal patterns of the flows on the floodplains at extreme discharge events (Hoekstra, 2018) and the inner dike flow patterns at extreme discharge events (Kriebel, 2016). And various studies that tackle the risk methodology to assess current and future flood risks (Bubeck, Linde, & Aerts, 2013; te Linde et al., 2011).

Currently there are a lot of different means to predict and assess the flow of the Rhine. A whole range of models can be used to simulate the discharge of the river. Like the widely used SOBEK and Delft 3D Flexible Mesh models. SOBEK has been used previously to simulate the Rhine (M. Hegnauer, Beersma, van den Boogaard, Buishand, & Passchier, 2014), in this case the section Oberrhein, in a one-dimensional hydraulic model (Van den Boogaard, Hegnauer, & Beersma, 2014).

One-dimensional hydraulic models (1D models) are made up of a series of cross sections describing the topography of the river and its floodplain (Betsholtz & Nordlöf, 2017). Water levels are calculated by using the one-dimensional form of the governing equations. 1D models however fail to capture channel-floodplain dynamics (Betsholtz & Nordlöf, 2017).

An alternative for a 1D model is a two-dimensional hydraulic model (2D model). A 2D model also consists of a series of cross sections describing the topography of the river and floodplain. But it also takes into account the bathymetry of a river (Betsholtz & Nordlöf, 2017). A 2D model simulates a water system in two dimensions using a grid for explicit floodplain flow.

The SOBEK model is part the Generator of Rainfall and Discharge Extremes for the Rhine and Meuse basins (GRADE) (Van den Boogaard et al., 2014). Because 1D models mainly perform adequately when flow is restricted between channel banks (Betsholtz & Nordlöf, 2017) these models do not simulate floodplain flow accurately, consequently this may result in the output data being faulty or inaccurate.

Recently a 2D model was developed (Hoekstra, 2018) to study flow patterns within the inner dike area of the Oberrhein. This model was not yet without errors however and had some imperfections. Mainly the inundation extent of the model was not simulated accurately yet. At low discharges there already occurs flooding which, according to ICPR Rhine Atlas, should not be possible. In my Bachelor thesis I have examined these flaws and proposed some improvements that can be made to the model. Furthermore, I will determine if modelling in two dimensions has significant advantages to the previously used one-dimensional modelling approach.

The aim of the study is to assess whether the previously developed 2D model (PD-model) of the Oberrhein can be improved so inundation extent can be simulated more accurately. Another aim of the study is to determine whether the two-dimensional modelling approach currently used in the PD-model was the most suitable modelling technique or that other techniques like a one-dimensional approach would be more appropriate.

1.3 SOFTWARE AND DATA

The software this thesis mainly focusses on is the D-HYDRO Suite 2016.2 version 1.3.4.38227 package and the D-HYDRO Suite 2018.2 version 1.4.5.3975 package. Among other modules it contains the D-Flow Flexible Mesh (D-Flow FM) module. This study however mainly focusses on the simulation of a river, hence tidal motions and salinity and many additional features were not mentioned in this paper. The software is still in development. Therefore, in addition to the research topic itself a recommendation for future development is also given.

The data and material used in this study was naturally the 2D model that was developed (Hoekstra, 2018) . Along with the PD-model came the baseline database that described the topographical and geographical input of the model. The discharge data at various time intervals and locations along the Oberrhein was provided by Rijkswaterstaat. The majority of the data concerning the inundation extent at certain discharges was taken from the ICPR Rhine Atlas.

1.4 STUDY AREA

This study examines a 2D model of the Rhine. The area of interest of this study was the Oberrhein and its floodplains. More specifically the section of the Rhine between Maxau and Bingen am Rhein was simulated in the PD-model.

A large part of the Oberrhein located in the area of interest flows through a wide valley (Hoekstra, 2018). This valley is located near Maxau and is on average around 40 kilometres in width, this results in a large segment of the floodplain being very flat. After Mainz the valley becomes more confined between land boundaries. When unconfined by raised land, there is a lot of potential for flooding, consequently at high discharges a considerable portion of the floodplain can overflow and become inundated. Because of human interference the Oberrhein does not display its natural braided course. The river leads a straight path with only some meandering characteristics (Hoekstra, 2018).

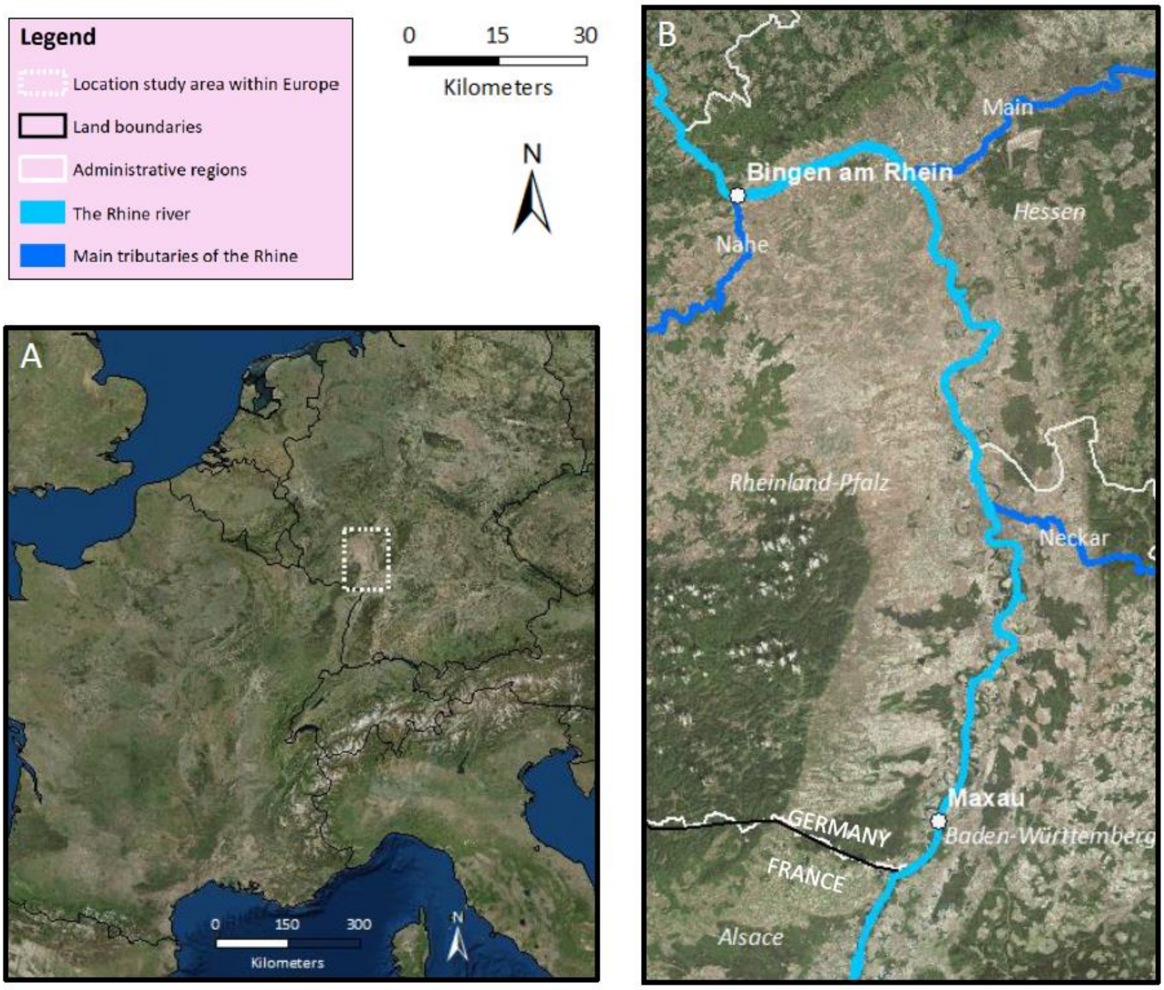

Figure 1.1 (A) Location of the river section used for this study within Europe and (B) More detailed image of the study area (Hoekstra, 2018)

2 THEORETICAL BACKGROUND

2.1 THEORY BEHIND THE A HYDRAULIC MODEL

The model that was used in this study was a Delft3D flexible Mesh model. Like the name suggests Delft 3D flexible mesh has a computational grid that can be freely arranged. Different types of grids can be combined to make a mesh that portrays a specific water system in the best possible way. This makes Delft 3D flexible mesh a very useful tool for modelling waterbodies with a lot of different shapes (like a river). Furthermore Delft3D flexible mesh has a lot of extra features that can be useful when modelling the Rhine (Deltares, 2016) like, forcing, wind and other factors have influence on the simulated river flow.

Delft 3D Flexible Mesh is a hydraulic model that can be used in 1D, 2D,1D-2D and even 3D simulations. The program allows for different shapes and sizes within the grid (Toombes & Chanson, 2011). A flexible mesh is an unstructured grid in addition to a normal structured grid. A structured grid contains the same types of elements within the grid with regular connectivity. Whereas a unstructured grid has elements of mixed type with irregular connectivity. (Mavriplis, 1997).

Flexibility of a grid is important because otherwise it can be hard to incorporate and connect irregular shapes of entities in the model, rivers and floodplains for example. The use of a flexible grid instead of a regular grid can also have a positive effect on performance of a model. The reason for this is that the cell sizes can differ. A fine resolution of the grid in an area of interest for example but a coarser resolution in a less important region. This reduces computation time significantly.

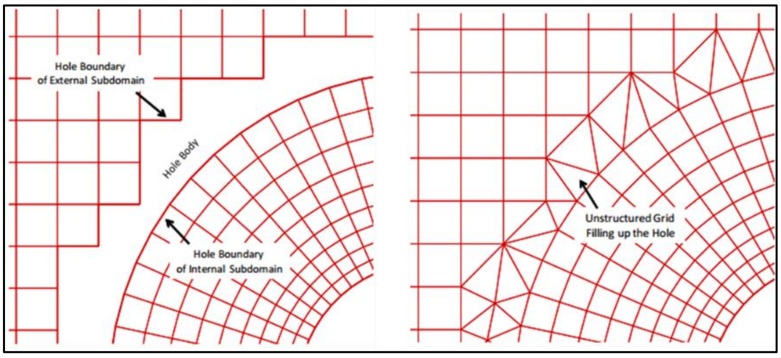

Figure 2.1 Difference using only a structured grid and using a combination of a structured grid and a unstructured grid.

Delft 3D flexible mesh gives users the choice of 3 different types of grids: a uniform rectangular grid, a curvilinear grid and an unstructured grid. A combination of the 3 types also is possible, which is called a flexible mesh (Deltares, 2016a).

The power behind the Delft3D Flexible Mesh software is the D-Flow FM engine. D-Flow Flexible Mesh (D-Flow FM) is a state-of-the-art software engine for hydrodynamical simulations on unstructured grids. A computational cell in a D-Flow Flexible Mesh grid or network consists of corner nodes and edges connecting the corner nodes (1 and 2 in figure 2.2). A cell in a network in D-Flow FM should have at least three corner nodes and may contain up to six corner nodes. The following topological conventions are used (Deltares, 2016):

1. netnodes: corners of a cell;
2. netlinks: edges of a cell, connecting netnodes;
3. flownodes: the cell circumcentre, in case of triangles the exact intersection of the three perpendicular bisectors and hence also the centre of the circumscribing circle;
4. flowlinks: a line segment connecting two flownodes.

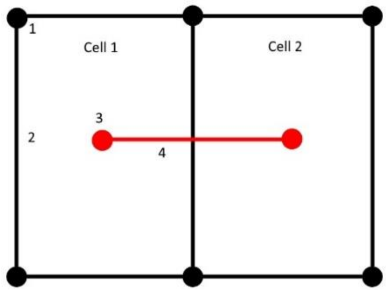

Figure 2.2 Representation of a grid

A hydraulic model is a mathematical model of a water system. Its purpose is to solve the Saint Venant equations or simpler forms of the Venant equations, the local inertia equations for example. The Venant equations describe the flow below a pressure surface in water (Dawson & Mirabito, 2008), in conservative form the Saint Venant equations are also commonly known as the shallow water equations and are derived from the Navier–Stokes equations. The Navier–Stokes equations describe equations of conservation of mass and conservation of momentum (Dawson & Mirabito, 2008). The software used in this study is the hydrodynamic modelling software Delft3d Flexible Mesh, a module that is part of the D-HYDRO package developed by Deltares. The software solves the two-dimensional depth-averaged continuity equation for incompressible fluids (Kriebel, 2016):

$$\frac{\delta h}{\delta t} + \frac{\delta U h}{\delta x} + \frac{\delta V h}{\delta Y} = Q \tag{1}$$

$$Q = \int_0^h (q_{in} - q_{out}) dz + P - E \tag{2}$$

In which:

h = water depth [m];

U and V = depth-averaged velocity components [m·s-1];

Q = contributions per unit area due to discharge/withdrawal of water, precipitation and evaporation [m·s-1];

q_{in} and q_{out} = local sources/local sinks of water per unit of volume [1·s-1];

P and E = non-local source/non-local sink terms due to precipitation/evaporation [m·s-1].

(Deltares, 2016; Kriebel, 2016)

Besides the depth-averaged continuity equation the software also solves depth-averaged two-dimensional momentum equation. The software solves the following equation in both the x- and y-direction:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{dz}-fv=-\frac{1}{\rho_0}\frac{\partial P}{\partial x}+F_x+\frac{\partial}{\partial z}\left(\gamma_v\frac{\partial u}{\partial z}\right)+M_x \tag{3}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{dz}-fv=-\frac{1}{\rho_0}\frac{\partial P}{\partial y}+F_y+\frac{\partial}{\partial z}\left(\gamma_v\frac{\partial u}{\partial z}\right)+M_y \tag{4}$$

In which:

u and v = depth-averaged velocity in the x- and y-direction respectively [m·s-1];

w = vertical velocity [m·s-1];

z = water depth [m];

f = Coriolis parameter [s-1];

$\rho 0$ = reference density of water [kg·m-3];

P = pressure [kg·m-1·s-2];

Fx and Fy = forces per unit of mass in the x- and y-direction respectively that represent the unbalance of horizontal Reynolds stresses [m/s2];

Mx and My = represent the contributions due to external sources or sinks of momentum such as external forces by hydraulic structures and discharge or withdrawal of water [m·s-2];

ΥV = vertical eddy viscosity coefficient [m2·s-1].

(Deltares, 2016; Kriebel, 2016)

The Delft 3D flexible mesh software solves the equations both in the longitudinal and transversal direction. Therefore, it can solve both 1D,2D and 1D-2D models. The difference can be found in how many dimensions are considered. The more dimensions used, the more accurate model will be. But accuracy comes with complexity, especially in systems with large undivided flows 1D models are not up to the challenge.

2.2 MODELLING IN ONE AND TWO DIMENSIONS

When simulating a river system, one has a lot of different alternatives to tackle the way the river and its floodplains are modelled. There are different options: modelling in one dimension, in two dimensions and variants that incorporate both techniques.

The added value of the addition of two-dimensional computations in the area of interest is examined in this section. First a literature review was conducted to determine what, according previous research papers, would be the most sensible choice regarding the modelling technique in the area of interest. These findings were then applied to the model that was examined to see if the two-dimensional calculations are indeed appropriate in the simulated area.

2.2.1 ONE-DIMENSIONAL MODELLING

As mentioned in the introduction 1D models consist of a series of cross sections describing the topography of the river and its floodplain (Betsholtz & Nordlöf, 2017). Water levels are calculated by using the one-dimensional form of the governing equations. 1D models perform accurately when flow is restricted between channel banks, 1D models fail however to capture channel-floodplain dynamics (Betsholtz & Nordlöf, 2017). Especially rivers with large flat floodplains require a two-dimensional approach to accurately simulate the flow on these plains (Morales-Hernández, Petaccia, Brufau, & García-Navarro, 2016). The main reason for this is the fact that when simulating a floodplain flow the model needs to account for many individual 2D flow paths that will arise (Horritt & Bates, 2002).

2.2.2 TWO-DIMENSIONAL MODELLING

2D models consist of a two-dimensional computational grid representing the underlying topography by connected elements (Betsholtz & Nordlöf, 2017). The minimum element size in a 2D model is defined by the width of the stream channel (Moore, 2011). Water levels are calculated by using the two-dimensional form of the governing equations. A 2D model requires a detailed representation of the river bathymetry, (Betsholtz & Nordlöf, 2017), this data is fortunately increasingly more available due to the development of Light Detection And Ranging (LI-DAR) techniques for land surveying (Betsholtz & Nordlöf, 2017). This development is favouring the development of 2D hydraulic models and will only increase with time. Furthermore, 2D models often need a lot of simplification. These simplifications are only valid for certain flow conditions, meaning that the understanding of their respective use and limitations is necessary if they are to be employed (Betsholtz & Nordlöf, 2017).

2.2.3 COMPARING THE DIFFERENT MODEL TECHNIQUES

One major advantage of this simpler method of calculating flow in a system is relatively small required computer time and power needed to complete the calculation. A previous study of a hydraulic model showed that a 2D model needed up to 5 hours to complete a single simulation whereas a 1D model only needed 2 minutes (Kriebel, 2016). A shorter computation time would also make some sensitivity analysis methods such as the Monte Carlo technique possible considering this technique needs many simulations to provide accurate results (Mark Hegnauer, Kwadijk, & Klijn, 2015). Furthermore 1D modelling has been standard practice for decades, many techniques that have been developed like techniques for representation of hydraulic structures are based on empirical relationships derived for 1D applications (Betsholtz & Nordlöf, 2017).

1D models only use cross-sections, therefore 1D models only require topographical data to be collected at these cross sections, which is a major advantage when access to topographic data is limited (Betsholtz & Nordlöf, 2017). Rivers where the bathymetry isn't accurate or accessible at all can still be simulated, consequently the use of cross-sections results in the river geometry being a lot smoother in comparison to 2D models. The reason for this is that cross sections are interpolated to construct the geometry (Gharbi, Soualmia, Dartus, & Masbernat, 2016) therefore, a lot of 1D models will generate slight deviations and errors in water levels and the timing of flood waves in contrast to 2D models. This fact was also illustrated in many other studies (Gharbi et al., 2016; Kriebel, 2016).

2D models are excellent for calculating explicit floodplain flow, something 1D models only achieve with great difficulty or not at all. Therefore, when simulating floodplain flow 2D computations are virtually always necessary. The disadvantage of a 2D model however is a greatly reduced computational efficiency compared to a 1D model (Lin, Wicks, Falconer, & Adams, 2006; Moore, 2011). Unlike a 1D model, a 2D model simulates water systems in two dimensions using a grid for explicit floodplain flow. To achieve adequate accuracy many computational cells are necessary which in turn requires a lot of computer power.

3 RESEARCH QUESTIONS

Taking the aim of the study into account, the main research question is composed: How can the previous developed 2D model of the Oberrhein river and its floodplains be improved and what is the added value of this modelling approach compared to the 1D approach ?

This primary question is answered by proposing the following sub questions:

a. Why does the PD-model not accurately simulate the inundation extent?

b. What improvements can be made to the PD-model to more accurately predict inundation extent?

c. What is the added value of modelling in two dimensions instead of the previously used one dimension?

d. How will output data like discharge and inundation extent respond to adjustments of different parameters?

4 METHODOLOGY

4.1 EXAMINING THE PD-MODEL

Using the ICPR Rhine Atlas one can determine the highest possible flooding extent at a certain discharge. The ICPR Rhine Atlas is a tool that was used to examine the flooding extent at different possible scenarios at different locations (ICPR, 2015). When comparing the flooding extent of the PD-model and the ICP Rhine Atlas at this discharge one peculiarity stood out. Especially between Mainz and Maxau the original model greatly overestimated the extent of the flooding, figure 4.1 illustrates this overestimation. The PD-model predicts flooding at discharges below 5,000 m^3/s were flooding should not be possible on this scale (ICPR, 2015). In the following chapter the reason for these irregularities will be examined. Once established why the PD-model overestimated the inundation extent, possible ways to rectify this problem will be examined.

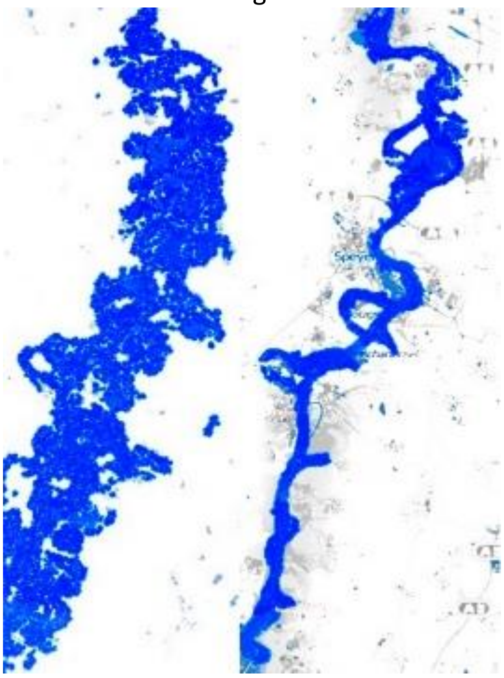

Figure 4.1 Inundation extent, PD-model (left) and Rhine Atlas (right). Discharge 5300 m^3/s at Maxau

The PD-model employed a dry start, at the commence of a simulation, there was no water present in the system, in reality this is of course never the case. To examine what the effect of the use of a dry-start was compared to a model that was saturated at the commence of a simulation a warm-up period is introduced to the PD-model. In this case the improved model was forced with average discharge. This resulted in the improved model being saturated at the beginning of the simulated events. This does require more simulation time and there for computing power. A more efficient alternative is the use of data from earlier simulations to create a restart file. This restart file had the effect that the model acts as if there is already water present at the start of the simulation. The impact of using a restart file instead of a dry start was also examined.

4.1.1 RESEARCH LOCATIONS

To be able to examine why the overestimation of the inundation extent occurred in the PD-model, a few locations were selected that were suitable for experimenting. These areas were selected because they clearly showed an irregularity in comparison of what should occur according to the ICPR Rhine Atlas. The selected locations were the area near Speyer and the area near Nackenheim. As shown in figure 4.2 the inundation extent was highly overestimated in the PD-model in comparison with the flooding that should have occurred according to the ICPR Rhine Atlas. Also, the fact that the primary flooding defence was visible both in the PD-model and in the ICPR Rhine Atlas makes these locations ideal for experimenting.

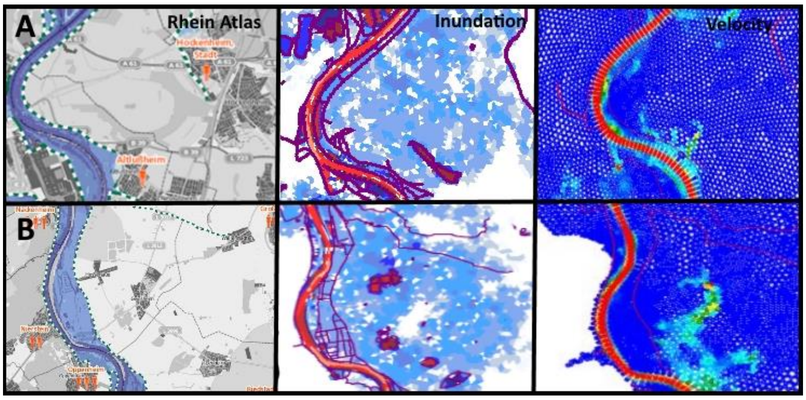

Figure 4.2 From left to right: Rhein Atlas, simulated inundation and simulated velocity at the locations Speyer (A) and Nackenheim (B) with a simulated discharge of 5300 m^3/s at Maxau

Utilising the velocities of the water in the simulation one can also easily trace were primary flood defences were initially breached. One peculiar feature of the simulation was that at some locations the water behaves like it passed straight through the primary defences with seemingly no resistance at all. This peculiarity is illustrated using the flow patterns visible in the velocity map in figure 4.2. The locations where water first entered the outer dike region near Speyer and Nackenheim in the PD-model were uncovered. These areas were examined closely to ascertain why the primary flood defence was breached.

4.1.2 DETERMINING THE CAUSE OF THE IRREGULARITIES

A hypothetico-deductive method was employed to find possible causes of the irregularities within the output data of the PD-model.

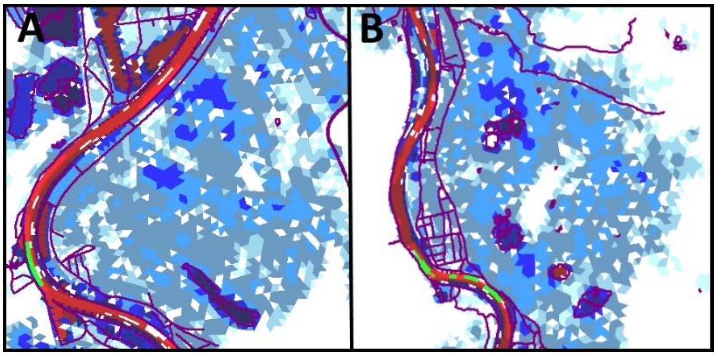

Figure 4.3 Locations with reviewed connections . Speyer (A) and Nackenheim (B) with a simulated Discharge of 5300 m^3/s at Maxau

The problem was the fact that the PD-model simulated flooding at discharges where this should not be possible. The first conjecture for why this occurred is that water passed through the elements, this implies that the elements were not well connected. To verify this hypothesis all connections between elements at the chosen locations were reviewed after which the model was rerun.

After reviewing the connections between elements and ensuring the water cannot pass through the connections another simulation was done. The result of this simulation is visible in figure 4.3. The model output did not exhibit a difference in inundation extent in comparison with the previous simulation. Thus, the first hypothesis was rejected.

The next conjecture was that the crest heights of the primary dikes were incorrect. To test this hypothesis the dikes in the model were raised at the control locations. At the location near Speyer and Nackenheim the primary flooding defences were raised with an additional 300 meters, in reality this would not a practical proposition. After running the updated model with the higher primary flood defences there still appeared to be a significant inundation extent, this is illustrated in figure 4.4. Therefore, this hypothesis was rejected as well.

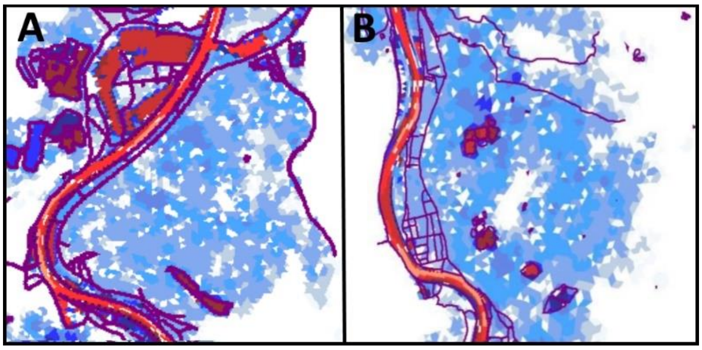

Figure 4.4 Locations with raised dikes . Speyer (A) and Nackenheim (B) with a simulated Discharge of 5300 m^3/s at Maxau

It seemed that the water was passing through the flooding defences regardless of its connectivity or the height of the dikes. A possible reason for why this occurred is that the model excluded the added primary flood defences (fixed weirs) in the calculation. Therefore, the next conjecture for why water was passing through the dikes is that there might be an error in the model software itself that resulted in the primary flooding defences being disregarded in the calculation. To assess if the model incorporated the dikes, a simulation was conducted were all primary flooding defences where purposely removed from the PD-model. The inundation extent was identical to the extent of the previous simulations, this is visible in figure 4.5. Thus, the hypothesis was accepted, the primary flooding defences were likely not being incorporated in the calculation. This also explained why earlier experiments did not seem to have any effect on the simulation, for they only varied weir characteristics which were excluded from the calculation. Hence no changes in the output data were detected.

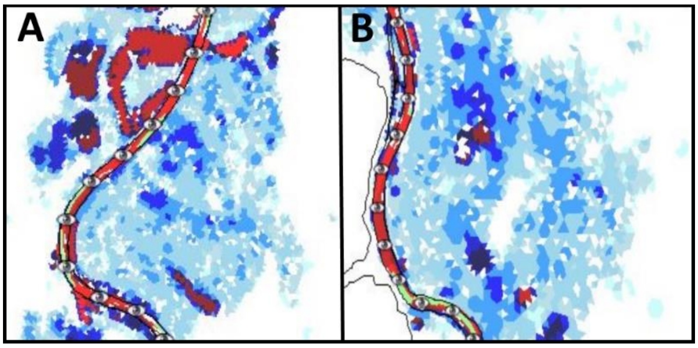

Figure 4.5 Locations with removed dikes. Speyer (A) and Nackenheim (B) with a simulated Discharge of 5300 m^3/s at Maxau

4.2 IMPROVING THE MODEL

4.2.1 INCLUDING WEIRS IN THE CALCULATION

A close inspection of all model variables was conducted. This revealed that the weir scheme of the PD-model was not active, however even with the weir scheme active the weirs were ignored. A quick survey of fixed weir files revealed that the files missed two columns of data. The missing data was added by using averages and default settings, the model still experienced difficulties while simulating the dikes however. It was established that the software had some bugs that prevented the weirs from working correctly. Therefore, another program, DIMR, was suggested that did function correctly. DIMR is a component of the D-Hydro software but it avoids the Graphical User Interface (GUI). By using DIMR the model was converted and simulated without any further problems. The improved model now seemed to perform much better, at average discharges the system performed as expected. As illustrated in figure 4.6 the simulated inundation extent matched better with the expected inundation extent. There even seemed a slight under estimation at average discharge. This was a big difference with the PD-model were average discharge resulted in wide spread inundation of the floodplain. One plausible reason for the underestimation was the fact that the PD-model started empty. In the next paragraph the impact of this so called “dry-start” is discussed. Another finding was that at high discharges there was a significant inundation extent visible, but this can be expected when a very high discharge event is being examined. The main issue, a significant inundation extent at impossibly low discharges, seemed to be partly resolved by including the weirs in the calculation. However, there still seemed to be some irregularities, even at low discharges random patches of water occurred at locations throughout the improved model. A few of these patches are visible in figure 4.6B and in figure 4.9 These patches did not seem to be connected with the river but appeared very early on in the simulation and expanded over time. Furthermore, some primary flood defences still tended to overflow at discharges that were lower than the discharge that the dikes were designed for.

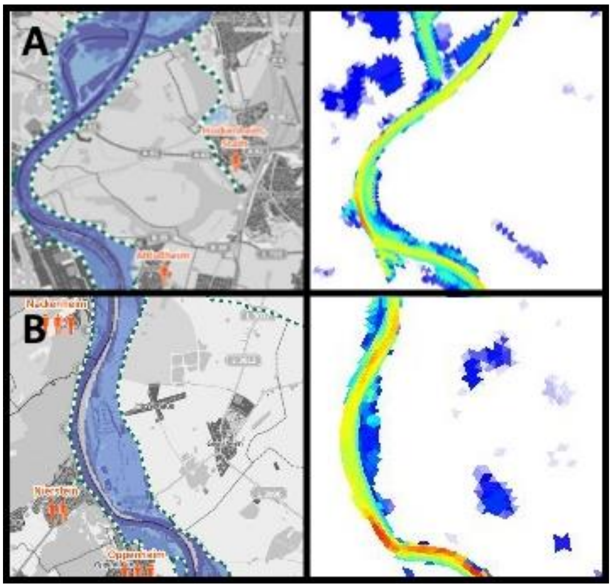

Figure 4.6 Inundation at locations. Speyer (A) and Nackenheim (B), reality (left) and simulated (right) with a simulated Discharge of 5300 m³/s at Maxau

4.2.1 ADDING WATER AT THE START OF A SIMULATION

The inspection of the PD-model revealed that the PD-model started empty, no water was present in the system at the start of a simulation. To resolve this problem a warm-up period can be implemented or a restart file can be used (Brunner, 2014). A warm-up period means adding a period at the start of the calculation with average discharge, this period should be long enough so that the model is able to completely saturated with water and converges to a steady state where differences in the model states per time step are sufficiently small. Another option is to create a restart file with average discharge and then using it to saturate the model at the start of the simulation. This option does not require an added computing period to the simulation and thus needs less computing power. Both options were implemented in the PD-model and compared to each other and to the output data of a model that started empty.

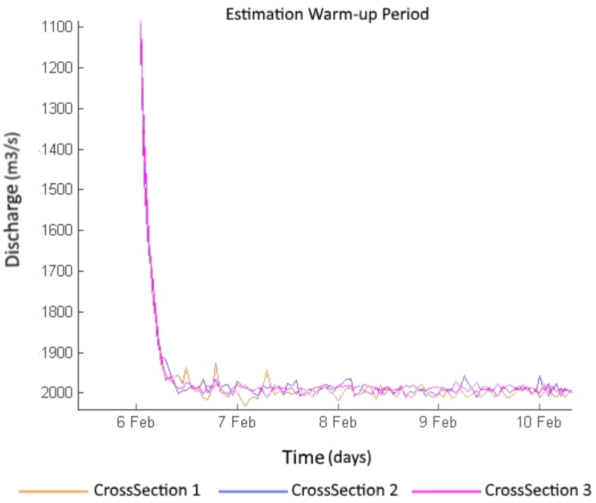

Figure 4.7 Determination of the warm-up period using the observation cross-sections in the model

First the model was saturated using a warm-up period. A simulation with average discharge was used to examine the time needed for the model to stabilise. The simulation with average discharge stabilised after 4 simulated days, after this period the model seemed saturated and stable like illustrated in figure 4.7. This 4-day period should therefore always be added a simulation were a saturated start is desired.

The restart file initially took more preparation but did not need to be simulated every run which reduced computing time. First the main upper boundary condition was set to the average discharge of 2,000 m^3/s. Next also the sources Neckar and Main were added to the model with their respective average discharge. The model was executed with the setting for the creation of restart file active. The created restart file was then exported and incorporated in the model so future simulations used the restart file to saturate the model.

4.2 VALIDATION

In this section the plausibility of the PD-model and the improved version were examined. The simulated discharge and inundation extent were validated using various techniques. This gives an indication on how the models performed.

4.2.1 DISCHARGE

The most common method for validating the discharge would be using the approach of real system measurements. This method compares the simulated discharge of a model with a real system (Zimmerman, 2000). To be able to do this historic data was necessary. For many of the simulated scenarios in this study the data was not available because they only represent possible extreme high flow events which have not been recorded yet. However, discharge can be validated if observed data is used as forcing. A month of discharge data from the gauging station near Maxau was used to generate the input data for the improved model starting at 9th of April 1999 to the 9th of May 1999 . Then downstream gauging stations were used to compare the simulated output of the improved model with historic measured discharge during the same interval. The gauging station near Speyer (observation point 396 in the model) for example was suitable because no tributaries are interfering with the main river flows. The addition of tributaries would complicate an accurate validation, this is caused by the introduction of more sources and thus more unknown variables.

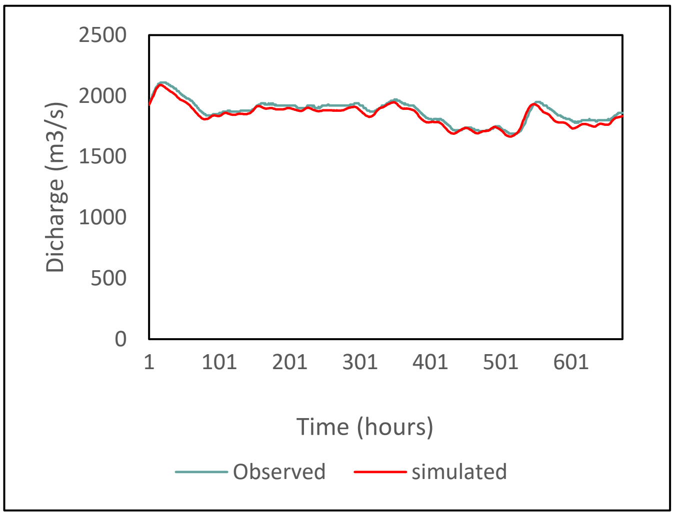

Figure 4.8 Observed discharge versus simulated discharge at Speyer

A few tests were selected to validate simulated discharge. Assessing how closely the simulated discharge of the improved model fitted the observed discharge was done by using the root mean square error test (RMSE) (Bennett et al., 2013). In addition to this a Nash-Sutcliffe model efficiency (NSE) test was computed, this test is one of the most widely used tests in hydrology to assess predictive power of hydrological models (Croke, 2009). The NSE is a normalised statistic that determines the relative significance of the residual variance compared to the measured data variance (D. N. Moriasi et al., 2007). It indicated how closely the plot of observed discharge versus simulated discharge fits the identity line (D. N. Moriasi et al., 2007).

4.2.2 INUNDATION EXTENT

Besides discharge also the inundation extent was examined. This gave an indication how well the inundation was simulated in both models. The event that was examined was a discharge event that should only occur 1/100 years. At Maxau this is a discharge of 5,300 m^3/s (ICPR, 2010). To compare both models a probability of detection (POD), false-alarm ratio (FAR) and critical success index (CSI) test were performed.

$$POD = \frac{hits}{hits + misses} \tag{5}$$

$$FAR = \frac{false\ alarms}{hits + false\ alarms} \tag{6}$$

$$CSI = \frac{hits}{hits + misses + false\ alarms} \tag{7}$$

These tests measure the correspondence between the estimated and observed events (Bhatt, Rao, Diwakar, & Dadhwal, 2017). The POD indicates what fraction of the observed inundation extent matches with that of the simulated extent (Bhatt et al., 2017). The POD measures hits, but disregards false alarms. The FAR indicates what portion of the simulated inundation extent did not occur. The CSI takes into account hits but also false alarms and missed events. It indicates how closely the simulated events correspond to the observed events (Bhatt et al., 2017).

4.3 SENSITIVITY ANALYSIS IN RESPECT TO DISCHARGE

This section shows how the improved model responded to adjustments of different parameters. The surface roughness of the channel or floodplain, eddy viscosity, and mesh resolution (Moore, 2011) can be examined for example. Furthermore, the robustness of the model was examined. Robustness is a characteristic of a model describing its ability to effectively perform while its parameters or assumptions are altered. A robust model can perform without failure and under a variety of conditions (Gulden, Rosero, Yang, Wagener, & Niu, 2008).

There are a variety of elements in the model that can be adjusted. One might choose to vary any or all of the following (Pannell, 1997):

- the contribution of an activity to the objective;
- the objective (e.g. simulating discharge or inundation extent);
- a constraint limit (e.g. the maximum availability of a resource);
- the number of constraints (e.g. add or remove a constraint);
- the number of activities (e.g. add or remove an activity);
- technical parameters (e.g. surface roughness or viscosity).

This study mainly focussed on parameters that were easily adjusted and were suitable for the calibration of the improved model. Commonly, the approach is to vary the value of the numerical parameters through several levels. In the other cases a model often requires structural changes and this increases uncertainty (Pannell, 1997). Numerical parameters like the technical parameters are best suited for this purpose so these were mainly used.

There are different techniques to conduct a sensitivity analysis. The most straight forward one is the one-at-a-time (OAT) technique. Like the name suggests, it analysis the impact of each parameter separately. The second frequently used approach is the Monte Carlo technique (RiskAmp, 2012). Instead of just one simulation, this technique runs the model many times varying the initial conditions. This gives a distribution of all possible outcomes of the simulation. The technique would however require a lot of computing time and power to execute and was therefore not suitable for this study.

The technical parameters like uniform friction coefficient and eddy viscosity can easily be differed. These parameters are commonly used for calibration (Moore, 2011), therefore the sensitivity of these parameters was examined. The value of each separate parameter was changed with a percentage that ranges from a 75% increase to a 75% decrease of the value, these were the upper and lower boundaries. Starting at the lower boundary the value was increased with 25% repeatedly until the upper boundary of the interval was reached. These boundaries were chosen because a small survey concluded that the parameters were not very responsive so relatively large variations were necessary to measure the responsiveness. The reason why the interval used an increase of 25% was because a smaller interval would need more simulations and this would require more computing time whereas a larger interval would decrease the accuracy of the analysis.

Two scenarios of each varied parameter were simulated. One scenario was steady state with an upper boundary condition that was set to 2,000 m^3/s , the average discharge of the Oberrhein (Sprokkereef, Spreafico, & Belz, 2010). The purpose of the second scenario was to examine what effect each parameter had on the propagation of a discharge wave. This scenario was not a steady state scenario, instead it used a discharge wave that resembled a sinusoid with an amplitude of 500 m^3/s, a vertical shift of 2,000 m^3/s (again the average discharge) and a period of 150 hours. This discharge wave was used so changes in the propagation of the discharge wave when varying the parameters were clearly visible.

The initial values of the examined parameters were equal for both scenarios and are displayed in table 4.1.

PARAMETER	INITIAL VALUE IN MODEL
UNIFORM FRICTION COEFFICIENT	0.023
UNIFORM FRICTION TYPE	Manning
UNIFORM HORIZONTAL EDDY VISCOSITY	1
UNIFORM HORIZONTAL EDDY DIFFUSIVITY	1

Table 4.1 Initial values of different parameters in the model

4.4 APPROPRIATE MODELLING TECHNIQUE IN THE AREA OF INTEREST

4.4.1 APPROPRIATE MODELLING TECHNIQUE ACCORDING TO LITERATURE

For the river itself a 1D approach can be sufficient. Like mentioned earlier due to human interference the river has a straightforward and well-defined channel. At regular discharges, discharges below 2,000 m^3/s (Sprokkereef et al., 2010), floodplain flows only occurred occasionally. However due to climate change high discharge events are likely occur more often. Moreover, the model that has been examined in this study also mainly focused on high discharge events with significant inundation extents. At high discharges floodplain flow did occur often. 1D models do not succeed in capturing channel-floodplain dynamics (Betsholtz & Nordlöf, 2017). Looking at the advantages and disadvantages of each technique in chapter 2.2 , one must conclude that 1D models are not sufficiently accurate or future proof when modelling the Oberrhein. Therefore, 2D computations were be considered. However there still is a problem with unacceptable large computation times that accompany this technique.

To counter this problem there is a third option available. A 1D model coupled with a 2D model. A coupled 1D-2D model is a model where river flow is simulated in one dimension and floodplain flow in two dimensions. The geometry of the 1D-2D model uses a 1D model as a base (Betsholtz & Nordlöf, 2017). The SOBEK 1D model can fulfil this purpose for example. Flooded regions like retention areas are then modelled in 2D. Coupled 1D-2D models do however retain a part the characteristic of a 1D model that allows lower computing times in the next section the found revelations were put to the test to examine whether they were valid in practice.

5 RESULTS

In this chapter the results of various experiments and tests are examined. First a simulation of the improved model that included the weirs and a warm-up period was inspected. Next a validation of the improved model was performed to determine the performance of the model. Furthermore a sensitivity analysis was conducted to examine how the simulated discharge responded to adjustments of different parameters. Last, different modelling techniques like modelling in one dimension or in two dimensions were reviewed.

5.1 MODEL RESULTS

In this section the results of the improved model were examined. First the improved model using a warm-up period or restart file was compared to a model that was not saturated at the commence of a simulation. Then the spatiotemporal patterns that the model displayed were described and compared to the patterns visible in the PD-model. Last the flow velocities in the model were examined and again compared to the velocities the PD-model simulated.

5.1.1 ADDING A WARM-UP PERIOD

The output of the simulation using a warm-up period and the simulation using a restart file was identical. This is not surprising because both saturation methods used the same average discharge. However using a restart file did reduce the computation time in comparison to using a warm up period because four less days needed to be simulated. When the model started saturated it did have a significant impact on the simulation. Especially in the first part of the simulation using a warm-up period or restart file gave a big difference in comparison with a dry start. The dry start simulation spiked at the beginning of the calculation while a model with a warm-up period or restart file incorporated exhibited a curve starting at average discharge, illustrated in figure 5.1.

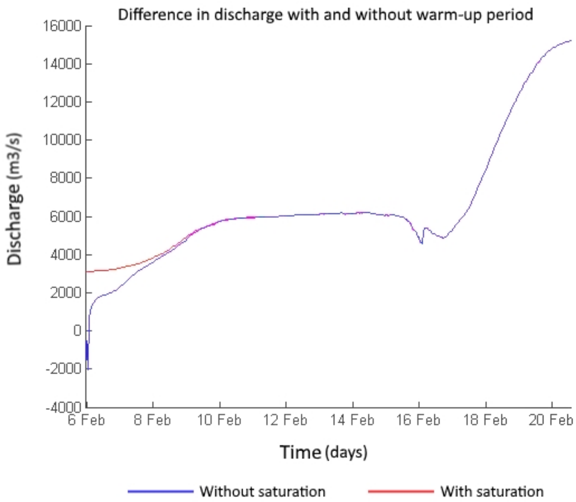

Figure 5.1 Discharge near Bingen am Rhein

5.1.2 SPATIOTEMPORAL PATTERNS AT HIGH DISCHARGE

To assess how the improved model performed at high discharges a simulation of a month was done starting the sixth of February and ending the sixth of March 2019. A high discharge event at this time interval generated by GRADE was used for forcing in this simulation, at these high discharges the primary flood defences seemed to overflow. Therefore, the spatiotemporal patterns of the flooding event were very similar to those Eva Hoekstra found in the PD-model (See appendix A). The flooding expanded in the transverse direction. Furthermore, waterflows parallel to the river channel were visible once the primary flood defences breached. A flow parallel to the main channel expanded southwards. This flow was followed by another flow towards the north (figure 5.2). Once the discharge reached a certain value flooding occurred along almost the entire stretch of the river. This again resembled the findings of Eva Hoekstra, there were however differences. First, adding the warm-up period resulted in the improved model already being saturated at the start of the simulated events, consequently more water is visible on the 14th of February. The random patches of water also seemed to have become larger and a few have been added. In the improved simulation the Rhine bursts its banks in the same manner as it did in the PD-model. However, it took more simulation time in the improved model to reach the inundation extent that the PD-model displayed. It seemed that the spatiotemporal pattern was delayed. The improved simulation displayed flooding closer to the discharge peak than the PD-model. This model displayed these patterns at an earlier time interval. The inundation extent of the improved model did catch up, the patterns on February 20 and February 22 were almost equal to the patterns of the PD-model.

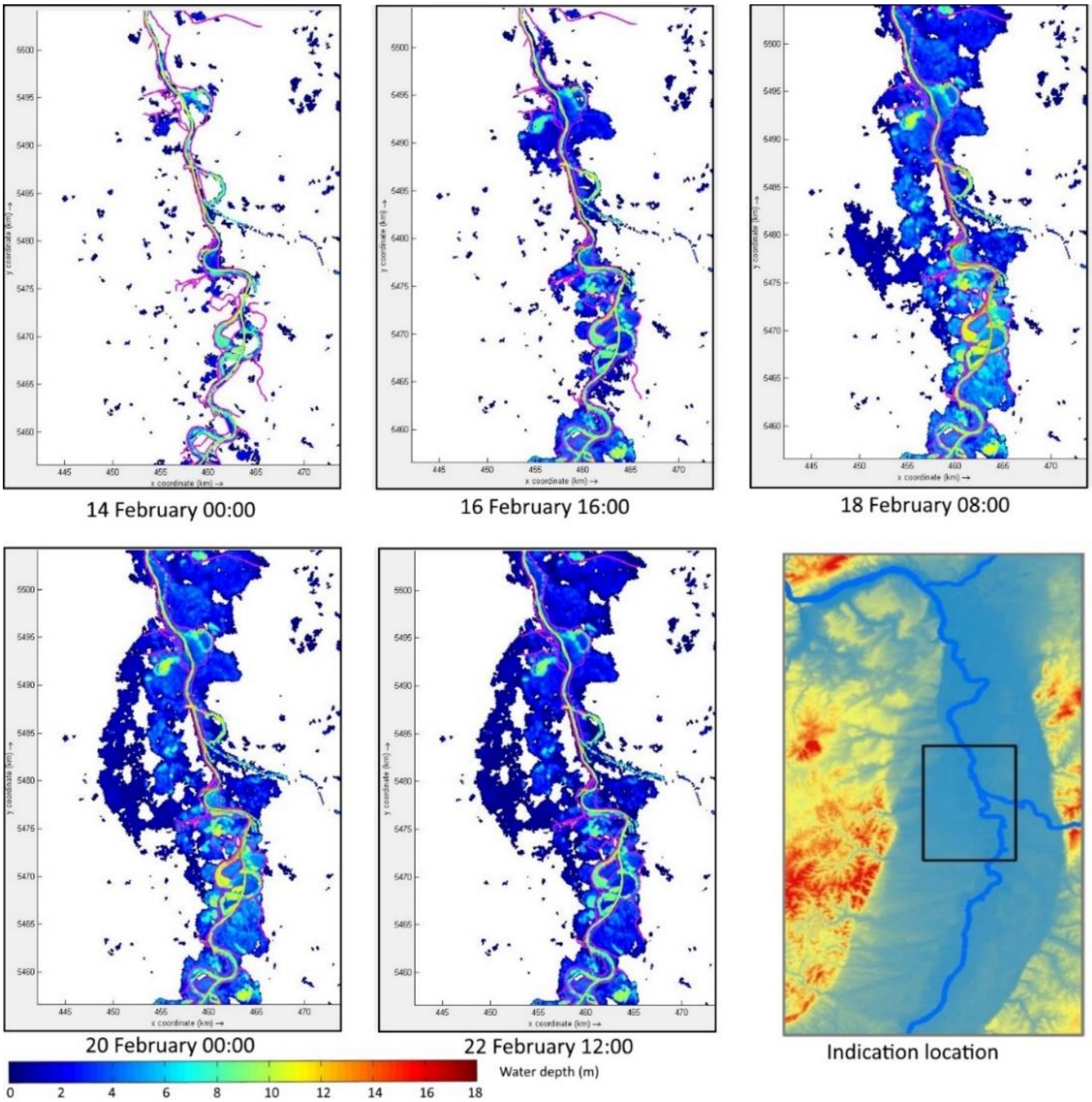

Figure 5.2 Illustration of the progression of the inundation of the floodplain near Ludwigshafen am Rhein.

5.1.3 FLOW VELOCITY AT HIGH DISCHARGE

Figure 5.3 illustrates the presence of major floodplain flows in the improved model at high discharges. The nature of these flows was inspected in more detail using velocity maps. Velocity maps were very suitable to be used to increase the understanding of spatial flow distributions and temporal flow variations in the area of interest. One can investigate how the water behaves in the improved model once it had breached the primary flood defences and flowed unconfined over the floodplains. Overall the magnitude of the velocity seemed to have diminished in comparison to the velocity magnitude Eva Hoekstra found (appendix B). The pattern of the velocity magnitude was however similar. Relatively high velocities occurred near the river channel with speeds up to 3.0 m/s. Further away from the river channel lower velocities dominated, often with speeds lower than 0.5 m/s. A more detailed map of the velocity magnitude was given in appendix C.

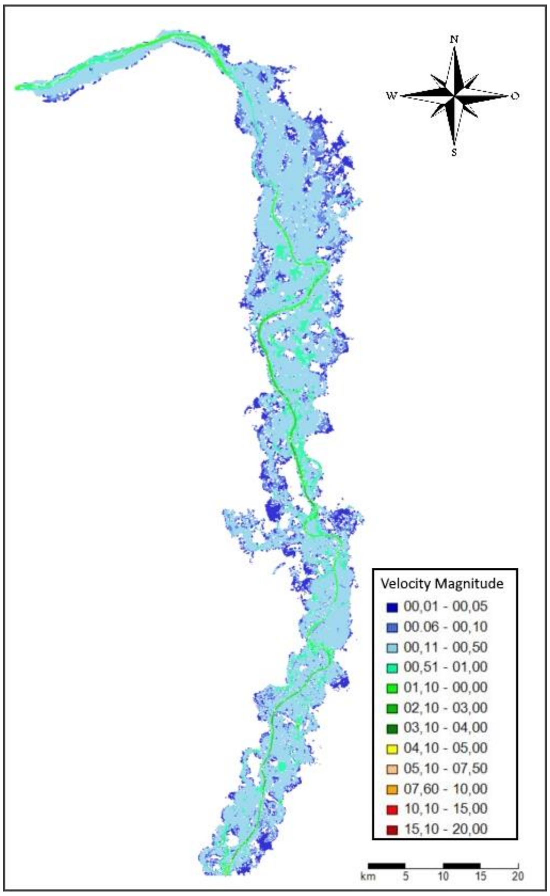

Figure 5.3 Velocity magnitude map of the Rhine

It is evidently visible that in both figures 5.4 and 5.5 that the flow path of the water on the floodplains traced the depressions and curvatures present in the landscape. The landscape is therefore the main factor that drove the flow direction. However, the majority of the floodplain flows ultimately travelled in the downstream direction parallel to the main channel. A flow pattern that often occurred was that at certain locations in the system water left inner dike area. Once no longer constricted by the dikes the water flows travelled over land and joined the main channel again at more downstream locations.

When confided between two elevated land boundaries water circumvented these landscape features. The velocities between these features were also higher because the water had to squeeze between the elevated boundaries. In both figures this phenomenon is clearly visible. Another observation that has been made was the manner the flows interacted with the present dikes. The discharges that are simulated were very high but the dikes still partly acted like a boundary. The primary flood defences were not able to contain the water, nevertheless the water had some hinderance when interacting with the dikes. For example, some flows changed direction when approaching the dikes and if the flows crossed over the dikes the velocity often seemed to decrease.

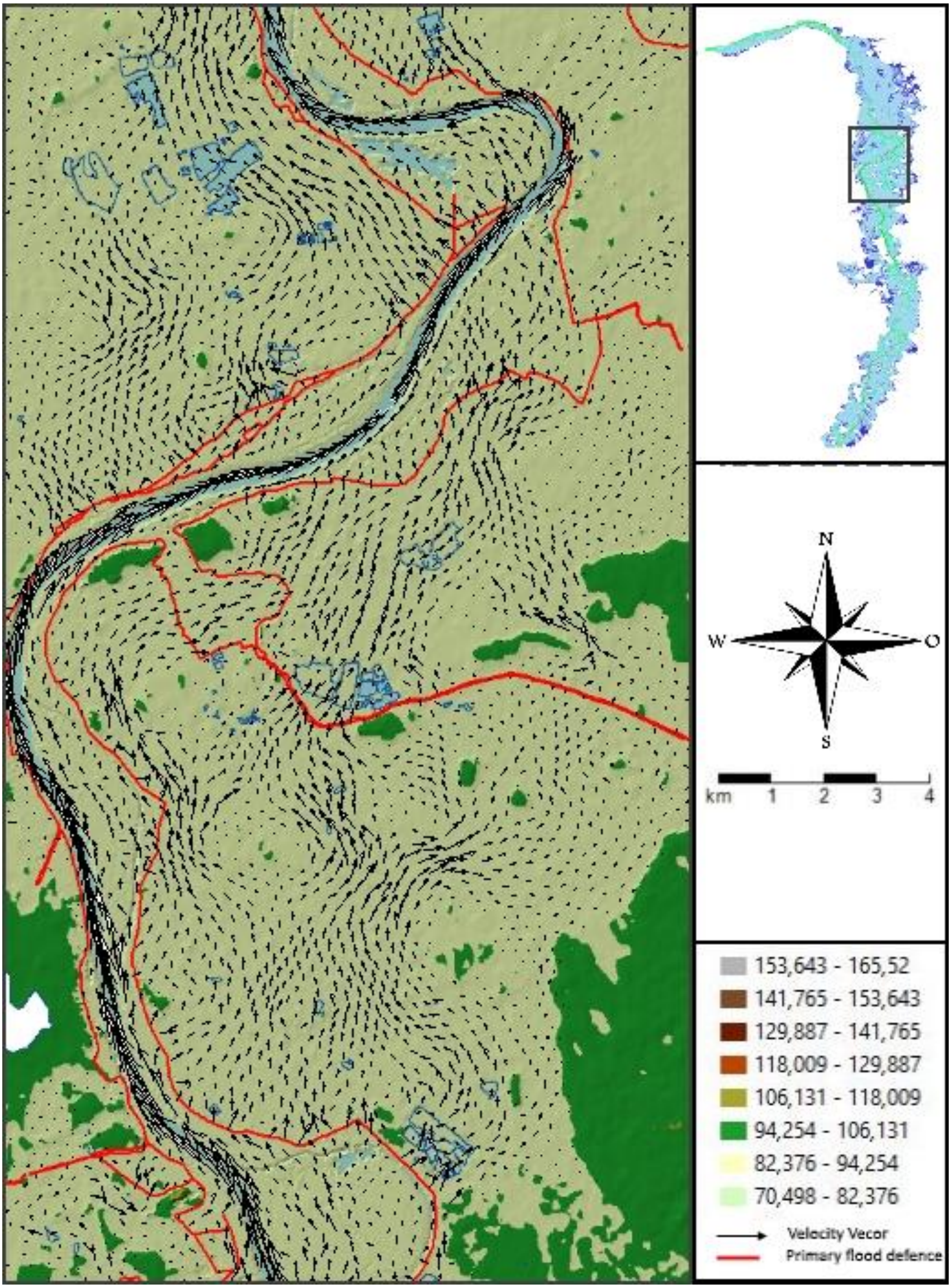

Figure 5.4 Flow patterns of the Rhine at the 18th of February, a day after the peak discharge at Maxau. The region is indicated by the box in the velocity magnitude map in the upper right corner.

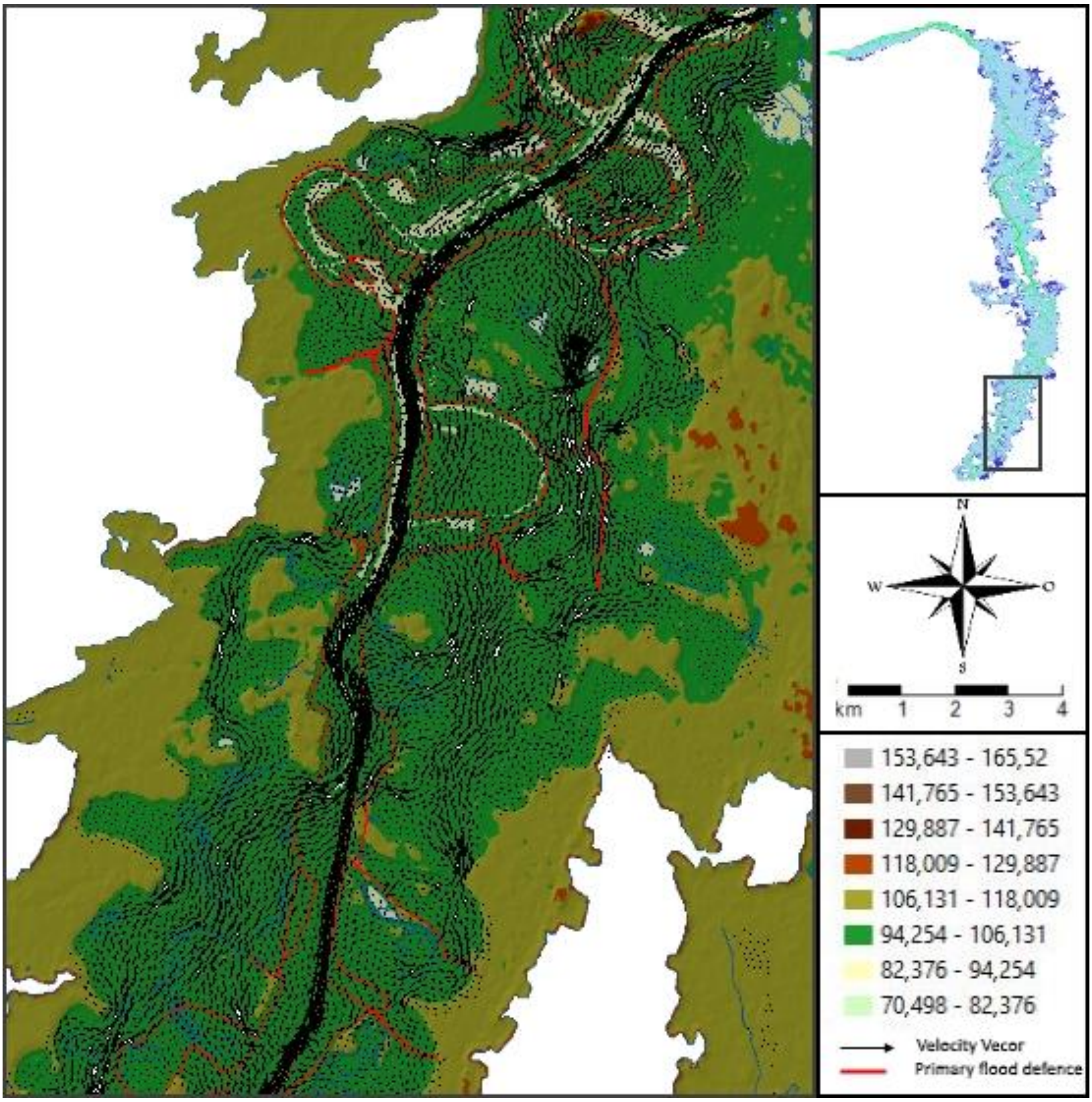

Figure 5.5 Flow patterns of the Rhine at the 18th of February, a day after the peak discharge at Maxau. The region is indicated by the box in the velocity magnitude map in the upper right corner.

5.2 VALIDATION

In this section the results of the validation of the discharge and the inundation extent were considered. The model performance in respect to discharge is examined using of various tests like the RME test and the NSE test. Next the inundation extent of the improved model and the inundation extent of the PD-model were examined to establish how the improved model performed compared to the PD-model.

5.2.1 DISCHARGE

To validate model output, an output-interval of one hour was selected because this is the same interval used by the observed data set. The RSME was calculated using the observed and simulated data (D. N. Moriasi et al., 2007). When the RSME value is 0 it indicates that the model is a perfect fit with the observed data. So, a low RSME indicates that a model has a good fit with the observed data. When the RMSE value is less than half the standard deviation of the measured data the RMSE may be considered being low (Singh, Knapp, Arnold, & Demissie, 2005). The standard deviation of the observed data set was 92.7 m^3/s, so half the standard deviation was 46.4 m^3/s. The calculation of the RMSE of the improved model has determined the value of the RMSE: 34.2 m^3/s.

For the Nash-Sutcliffe efficiency the value interval ranges from -∞ to 1. Values between 0 and 1 are generally viewed as acceptable levels of performance, whereas values that are lower than 0 indicate unacceptable performance (D. N. Moriasi et al., 2007). The result of the NSE test for the improved model was 0.85

Test	*Value*		*Performance*
RSME	34.2 m^3/s	< 46.4 m^3/s	Acceptable performance
NSE	0.85	> 0	Acceptable performance

Table 5.1 Results of the validation of the simulated discharge

5.2.2 INUNDATION EXTENT

MODEL WITHOUT MODIFICATIONS

When the value of the Probability of Detection (POD) approaches 1 it indicates that almost no detections were missed. The PD-model had a probability of detection value of 0.83.

Like the name suggests the False Alarm Ratio (FAR) describes the fraction of the hits that turn out to be incorrect. The false alarm ratio of this model at the chosen time interval had a value of 0.68. This suggest that nearly 70 percent of all hits were false. This large overestimation of the inundation extent is also clearly visible in the hit-miss-false map of the area with the simulated high discharge, this is illustrated in figure 4.13.

The critical success index (CSI) reviews the hit fraction of the total hits including the misses and false detections. The CSI indicates how the PD-model performed when all parts of the simulated flooding were taken into account. The PD-model has a CSI value of 0.3. The high amount of false detections was most likely responsible for this low value, in the equation of the CSI a high amount of false alarms increases the denominator so the CSI decreases.

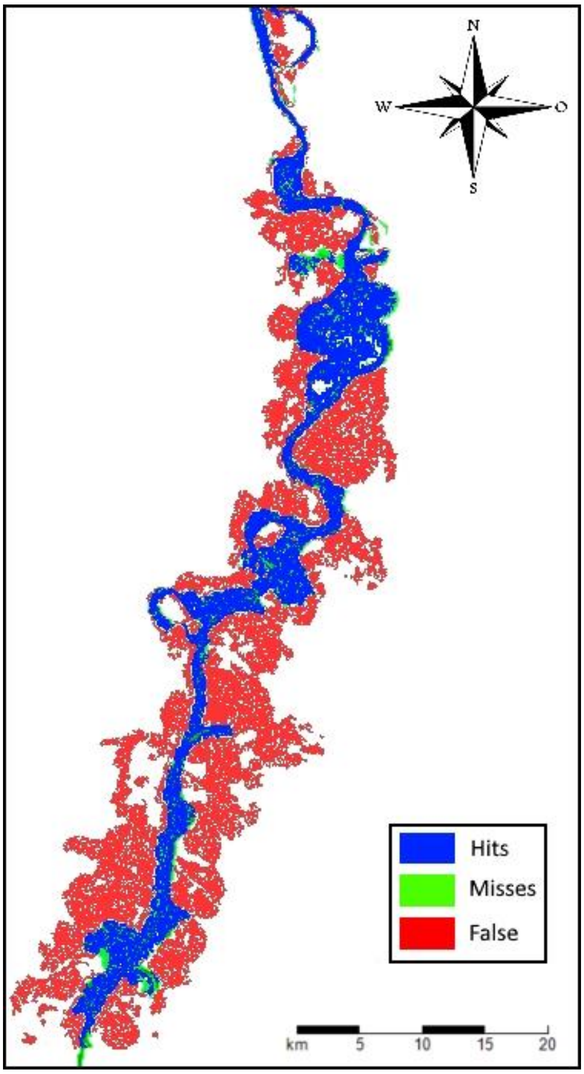

Figure 5.6 False-hit-miss-map of the model developed by Eva Hoekstra

MODEL WITH MODIFICATIONS

Another validation was conducted on the improved model. Again, the hits, misses and false hits are displayed in a Hit-Miss-False map in figure 4.14. Next the POD, FAR and CSI were calculated.

In the improved model one value stood out in comparison with the PD-model. The False alarm ratio had a value of 0.55. This value deceased which indicated less false detections appeared in the simulation. The value was still high, especially in the upstream region of the model because it still harboured a lot of falsely simulated flooding. The flooding in the downstream regions was reduced although there still appeared flooding that should not be possible according to the designed discharge of these areas. The reason for why these irregularities exist in the model can have many causes, for example that some weirs were not simulated correctly in the model.

The improved model simulated a lot less flooding near the meanders of the river, the water remained within the inner dike area, this is illustrated in figure 4.14. The probability of detection of the model was therefore lower than the PD-model. The improved model had a probability of detection value of 0.66.

The critical success index reviews the hit fraction of the total hits including the misses and false detections. The improved model had a CSI value of 0.36. This was a slight improvement relative to the PD-model but still low. The high amount of false detections and misses were most likely responsible for this low value because in the equation of the CSI a high amount of false alarms and misses increases the denominator so the CSI decreases.

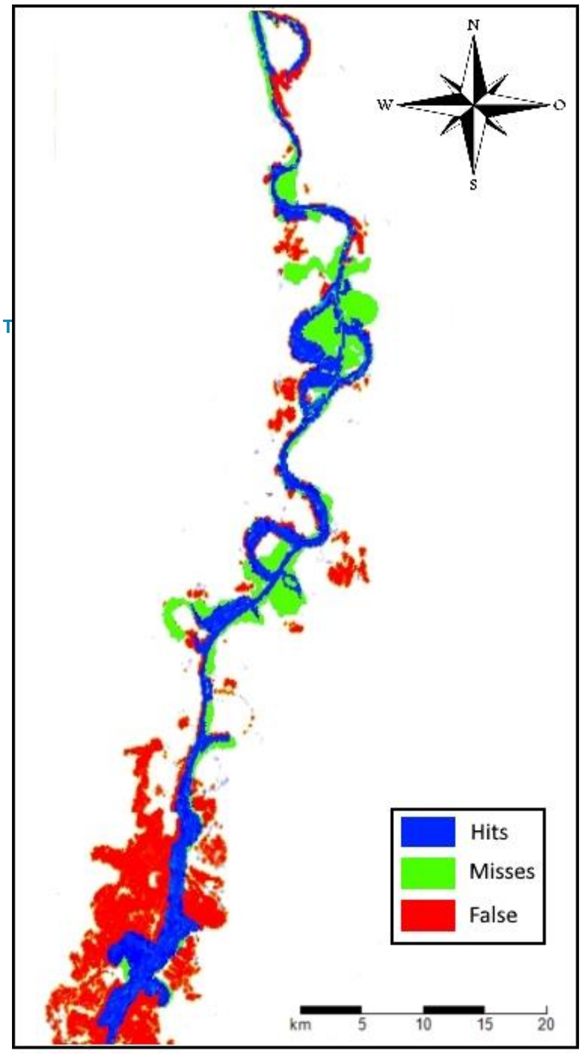

Figure 5.7 False-hit-miss-map of the improved model

Test	*PD-model*	*Improved model*
POD	0.83	0.66
FAR	0.68	0.55
CSI	0.30	0.36

Table 5.2 Results of the various tests on the simulated inundation extent of the PD-model and improved model

5.3 SENSITIVITY ANNALYSIS

In this section the sensitivity of the simulated discharge to adjustments of the surface roughness and the eddy viscosity was examined. This was examined using a steady state simulation with average discharge. The effect each parameter had on the propagation of a discharge was examined using a discharge wave.

5.3.1 SURFACE ROUGHNESS

The surface roughness was calculated using the Manning coefficient in the improved model. The Manning coefficient was determined using the formula:

$$V = \frac{1}{n} R_h^{\frac{2}{3}} S^{\frac{1}{2}}. \tag{8}$$

With:

V = cross-sectional average velocity [m/s];
n = Manning coefficient;
R_h = is the hydraulic radius [m];
S = channel bed slope when the water depth is constant.

The effect of adjusting the uniform friction coefficient (n) on the discharge was examined. After this the effect of different techniques of calculating the surface roughness like Manning and Chezy were reviewed. The uniform friction coefficient had very little impact on the total discharge as illustrated in figure 4.15. When using a 75% higher value for the uniform friction coefficient the discharge rose with less than 0,008 %. This was so small it is almost neglectable, the difference in discharge was only visible when greatly magnified. On a larger scale almost no impact was visible. All in all, changing the uniform friction coefficient wasn't very effective in the examined interval. To examine the effect the uniform friction coefficient had on the propagation the water in the model a flood wave was simulated. Again, no significant change was visible in the discharge wave. The propagation of the discharge wave appeared not to be affected by the change in the uniform friction coefficient value. Even when the uniform friction coefficient was increased or decreased with 75% no significant effect was detected.

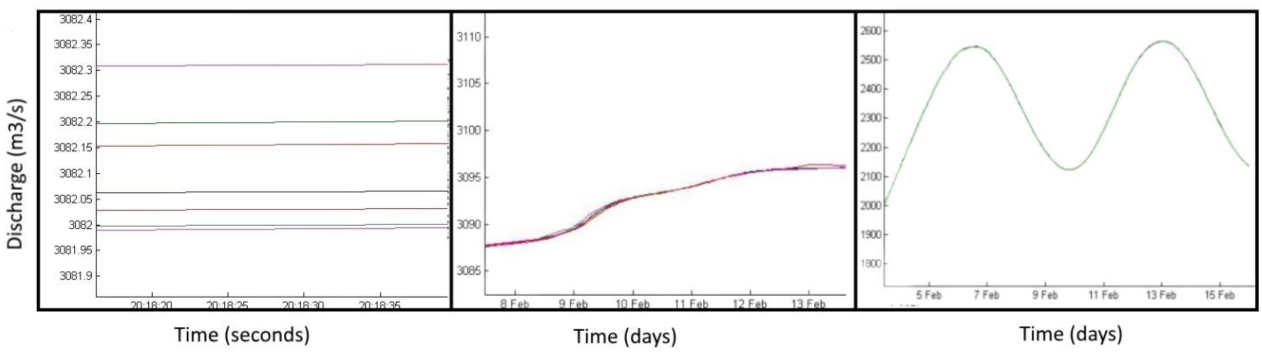

Figure 5.8 Results of the sensitivity analysis of the uniform friction coefficient

To examine what effect of the changing of technique for calculating the surface roughness was on the discharge, the improved model was simulated with four different scenarios. For one simulation the Manning coefficient was used, for the others Chezy, White-Colebrook and Z0.

Changing the technique for calculating the surface roughness did not have a large impact on the output discharge. The discharges that different techniques generated varied between 3,098 m^3/s and 3,100 m^3/s, this was not a significant change. In figure 4.16 the difference in discharge was only visible when greatly magnified. When simulating a discharge wave using different techniques again no large variations were visible. The peak of the discharge wave differed slightly with every technique, this is also shown in figure 4.16.

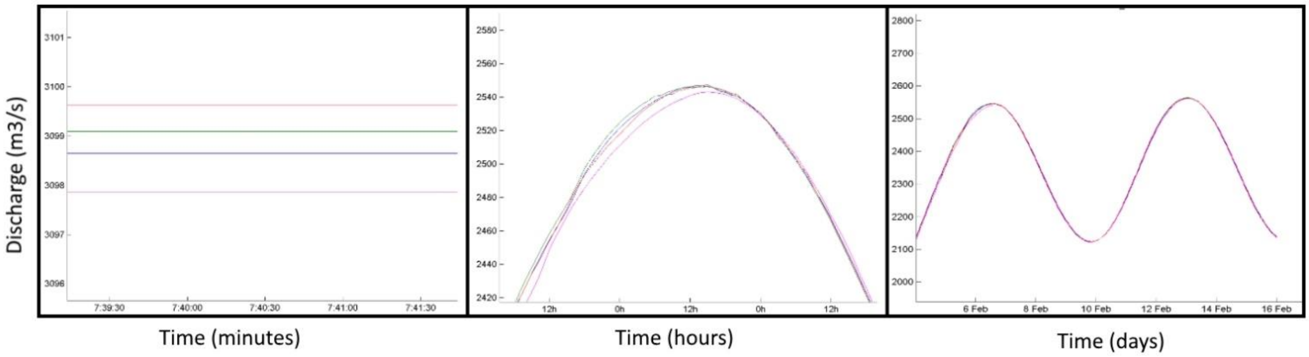

Figure 5.9 Results of the sensitivity analysis of different techniques for calculating the surface roughness. Green: Manning, Blue: Chezy, Pink: WC and Red: Z0

5.3.2 THE EDDY VISCOSITY

Changing the eddy viscosity did not have a big influence on the total discharge. The impact of the eddy viscosity is illustrated in figure 4.17, when increasing the value of the eddy viscosity with 75% the discharges raised with only 0.05%. On the propagation of a discharge wave the impact was slightly more considerable. The discharge wave reached its highest point earlier with a lower eddy viscosity and the peak discharge itself is also 0.4% higher at a 75% lower eddy viscosity. This was however still not a significant difference.

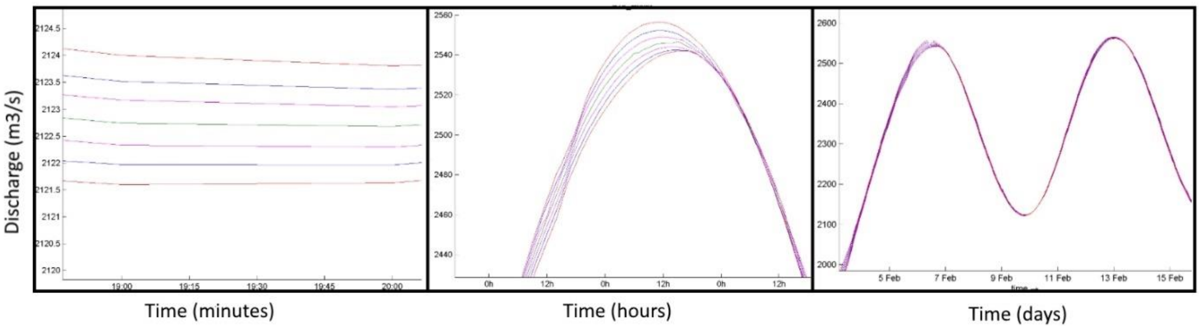

Figure 5.10 Results of the sensitivity analysis of the eddy viscosity

5.4 REVIEW OF MODELLING TECHNIQUES USING SIMULATIONS

The revelations of the previous paragraph need to be tested. To see if the river remained within the river channel at low discharges a simulation that matched this scenario was done. Furthermore, examining a simulation at high discharges can confirm if floodplain flow occurred often.

5.4.1 A SIMULATION WITH AVERAGE DISCHARGE

The Oberrhein harbours regular discharges of around 2,000 m^3/s (Sprokkereef et al., 2010). A steady state simulation using this discharge a forcing revealed if the water remained within the river channel. This can confirm if one-dimensional calculations were sufficient. Figure 4.18 illustrates that at average discharge the simulated river flow was for the better part constricted to the inner dike area, large scale floodplain flow did not occur in the simulation. The river however, was not always contained by the channel but did flow freely within the inner dike area.

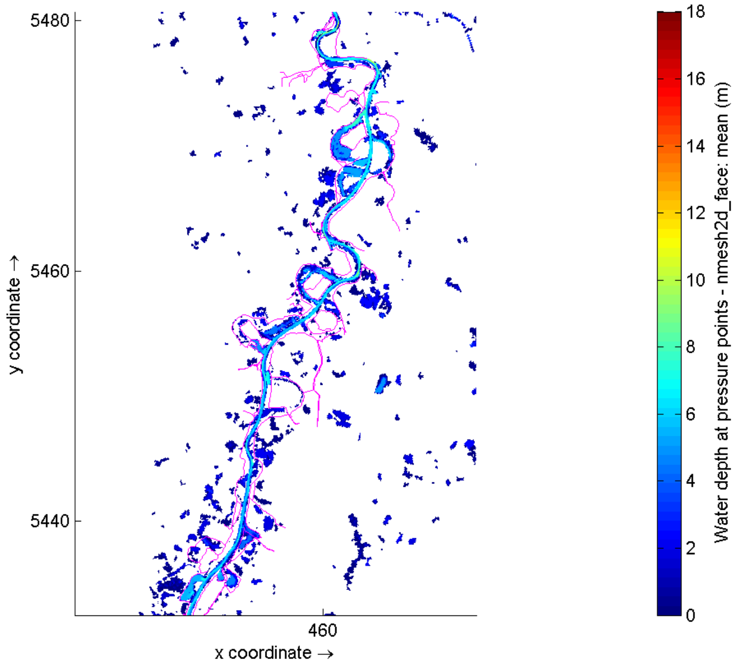

Figure 5.11 Simulating at average discharge

A high discharge event that only should occur 1/100 years was also simulated. this steady state simulation harboured discharges at Maxau of 5,300 m^3/s.

During this high discharge simulation the dikes did not manage to confine the water to the inner dike area. Especially in the upstream area's a large part of the floodplain became inundated. The inundation of the floodplain is illustrated in figure 4.19. The primary flood defence of did seem to handle the water better downstream, most of the flows remained within the inner dikes but were not channel bound.

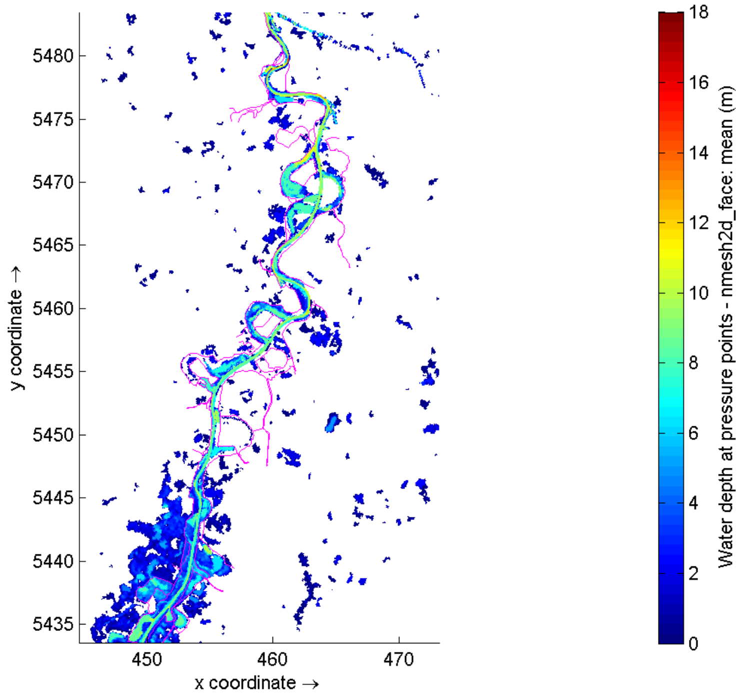

Figure 5.12 Simulating at High discharge

6 DISCUSSION

6.1 DISCUSSION OF THE FINDINGS

The study showed that one-dimension calculations were not suitable for the area of interest. This however does not suggest that one-dimension modelling is not suitable at all for simulating the Rhine. It only indicated that in the area of interest models using solely 1D calculations were not suitable for this the study. However one-dimensional models are highly suitable for simulations with no floodplain flow. Even in the area of interest one-dimensional models can be simulated at average discharge although not completely accurate, the 1D SOBEK model in the area demonstrates this.

When developing or evaluating 2D model or a model in general one must always be aware that some unexpected problems can arise. This was emphasized in this study, the main problem that occurred was not connected with the data or technique used while developing the model but was an unforeseen software issue.

Furthermore, the study found that adding a warm-up period to the model resulted in the transition to a high discharge wave being much smoother and gave more realistic results. Many more studies of hydraulic models have emphasized that adding a warm-up period to a hydraulic model will enhance its performance (Betsholtz & Nordlöf, 2017; Kriebel, 2016). However this is still a modellers choice and the effects of adding a warm-up period are only significant in the beginning of the simulation.

6.2 VALIDITY OF AVAILABLE THE DATA SOURCES

The validity of the available data is always an issue when developing a model of a real system, some inaccuracies that may have occurred are addressed.

First of all, topographical input data generally has large margin of inaccuracy. Topographical data like the DEM data used to develop a digital elevation map for a model can harbour a lot of errors (Kriebel, 2016). Furthermore, the data for the primary flood defences in the 2D model were not readily available so many of the dikes have been estimated using the designed discharge, the actual crest height of the dikes can differ however. These issues may not matter for the functioning of the model, it still can be a very accurate model, but one must always remember that the data used to develop a model may not be accurate.

While validating or calibrating a model accurate observed data of the area of interest is also vital. For this study it has to be noted that the data used for the inundation extent in the ICPR Rhine Atlas was not directly measured. The reason for this is simply because none of the extreme events that have been simulated in this study have happened in reality since monitoring the Oberrhein has started. The flooding illustrated in the ICPR Rhine Atlas was a result of various predictions of different institutes in Europe (ICPR, 2014) . For this study however, I used the inundation extents illustrated in the ICPR Rhine Atlas as if they were observed measurements in the validation. Another issue with the validation of the inundation extent was the fact that the validation used one time and discharge interval. The results can differ when using different discharges. However, the inundation extent data of other relevant discharges were not readily available. Also, more simulations would need more computation time which was not possible in the available time span.

6.3 LIMITATIONS OF THE RESEARCH

The sensitivity analysis did not describe the effect of each examined parameter on the inundation extent. Especially the surface roughness can have a very significant impact on floodplain flow. The most probable cause of the non-responsiveness of the surface roughness on the simulated discharge was the fact that the water during a scenario with average discharge was mostly confined within the inner area. Unconfined water which flows over the floodplains can behave differently when the surface roughness is differed. To measure the effect of the surface roughness and the other examined parameters on the inundation extent, a high discharge event that exhibits floodplain flow outside the inner dike area needs to be examined. Many simulations of this event have to be conducted while varying these parameters. Simulating all these variations would take a large amount of time because every simulation takes at least 8 hours or more to run. It was not possible to conduct this part of the sensitivity analysis in this study due to limits in the time available for the research. However, a small survey of the model while varying the surface roughness was done and it seemed the effect was again very small. For a more accurate conclusion a more detailed experiment must be conducted.

For the validation of the inundation extent, the extent at a certain discharge and time interval was used. It is possible that the results of the validation will be different with varying discharges. One could conduct more validations at different discharges to examine if the results change. This was not examined due to the time limit of this study.

7 CONCLUSION

7.1 WHY DOES THE PD-MODEL NOT ACCURATELY SIMULATE THE INUNDATION EXTENT?

The reason why the output data of the PD-model of the Oberrhein seemed to overestimate the inundation extent was mainly a software issue. Due to some bugs in the GUI (graphic user interface) of the D-hydro software package the primary flood defences were excluded from the calculation. Because to this exclusion the water in the PD-model was only confined by the elevation of the landscape.

7.2 WHAT IMPROVEMENTS CAN BE MADE TO THE 2D MODEL TO MORE ACCURATELY PREDICT INUNDATION EXTENT?

When simulating the river using the DIMR software of the D-HYDRO package the primary flood defences were included in the calculation, the issue of the primary weirs not being active was resolved. At very high discharges the floodplain flow that occurred was mainly governed by the slope and the landscape, this result was almost equal to a simulation without dikes. Thus the weirs do not have a large influence on simulation at very high discharges. At average discharges adding weirs to the simulation did have a large impact, water remains within the inner dike areas and no floodplain flow occurs. It can be concluded that at low to average discharges the flow is governed by weirs but once the discharge is sufficiently high so floodplain flow occurs throughout the model, the landscape is the driving factor of the waterflows

To ensure the improved model was saturated at start of a simulation, a restart file with average discharge was introduced in the model. When comparing a saturated model to a dry-start model it can be concluded that the saturated model exhibits a smooth transition to the high discharge wave instead of the rough transition simulated when a dry-start is employed. This seems far more natural and realistic than a spike appearing at the beginning of the simulation. Thus, a saturated model performs better at the commence of a simulation than a dry-start model.

By validating the improved model, the correctness and reliability of the model was assessed. The improved model had a RMSE value of 34.2 m^3/s, this is less than half the standard deviation of the observed. The NSE had a value of 0.85, this value lies between 0 and 1. Therefore, it can be concluded that the improved model simulated discharge accurately.

The improved model also simulated discharge better than the PD-model. The improved model especially scored better on the FAR test. Thus a lot less false flooding was simulated.

7.3 WHAT IS THE ADDED VALUE OF MODELLING IN TWO DIMENSIONS INSTEAD OF THE PREVIOUSLY USED ONE DIMENSION?

To examine which modelling technique was most appropriate in the area of interest a literature review was conducted. The revelations found were backed up with experiments using the improved model. The literature concluded that at high discharge events one-dimensional computations were not sufficient.

At low discharges the review suggested that one-dimensional computation were sufficient. The experiments showed however that, even at low to average discharges, two-dimensional computations were necessary to accurately simulate the river. Thus, two-dimensional computations are vital to simulate the Oberrhein regardless of the discharge.

7.4 HOW WILL OUTPUT DATA LIKE DISCHARGE AND INUNDATION EXTENT RESPOND TO ADJUSTMENTS OF DIFFERENT PARAMETERS?

The responsiveness of the simulated discharge to the numerical parameters of the model was assessed. Changing the uniform friction coefficient did not have a significant impact on the total discharge or the propagation of a discharge wave. The eddy viscosity was slightly more responsive but still the response of the simulated discharge to this technical parameter was very minor. On the whole the simulated discharge did not display much difference when changing the examined parameters. Thus, the simulated discharge of the improved model is robust in respect to changes to the surface roughness or eddy viscosity.

7 RECOMMENDATIONS

Considering the findings in this study some recommendations are made for future modelling approaches. The study also dealt with some errors and inconveniences within the hydraulic modelling software Delft Hydro Suite itself. Therefore, also some recommendations about future software developments are presented.

7.1 MODELLING STRATEGY

The main issue of the model was the fact that it excluded the weirs from the calculation. The problem was the software used when creating the model. If one were to investigate the 2D model of the Oberrhein further I would recommend being careful while using the GUI of the D-HYDRO software. One should always check the MDU file to verify if changes made in to the model in the GUI are actually implemented. Furthermore, it is not sensible to exclusively rely on the results that are generated by the GUI. I recommend to check the output data generated with the GUI with DIMR for example to reduce the chance any software issues are interfering with the model. Also when conducting several simulations DIMR is more suitable because it is able to run several simulations at a time and DIMR uses less time to run these simulations. Nevertheless the GUI of D-HYDRO does present the results of a simulation in a clear and structured way. Especially for novice users the GUI is far more comprehensible than the DIMR software.

With the weirs included the model performed better at average discharges, a lot less flooding occurred. It is however not perfected yet, there were still locations were the water passed the primary flood defences at discharges lower than the designed discharge of these areas. Also, the model is currently completely simulated in two dimensions. A coupled 1D-2D model can save a lot of computation time and is very suitable in this situation. To further improve the model, I would suggest reviewing the weirs and possibility to investigate additional line elements like railroads, local levees and highways that can additionally to the primary flooding defence be confining the water.

The dike heights were calculated using the designed discharge in a certain area. The actual crest height data was not readily available; therefore, the weirs will almost certainly have some errors. One can use an extensive literature review to gather the data or use a cruder estimation using Google street view. One could even go as far as visiting the dikes in the area of interest and measuring them personally, this would however most likely be a whole study on its own.

8 REFERENCES

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APPENDIX A FLOW PATTERN FOUND BY EVA HOEKSTRA

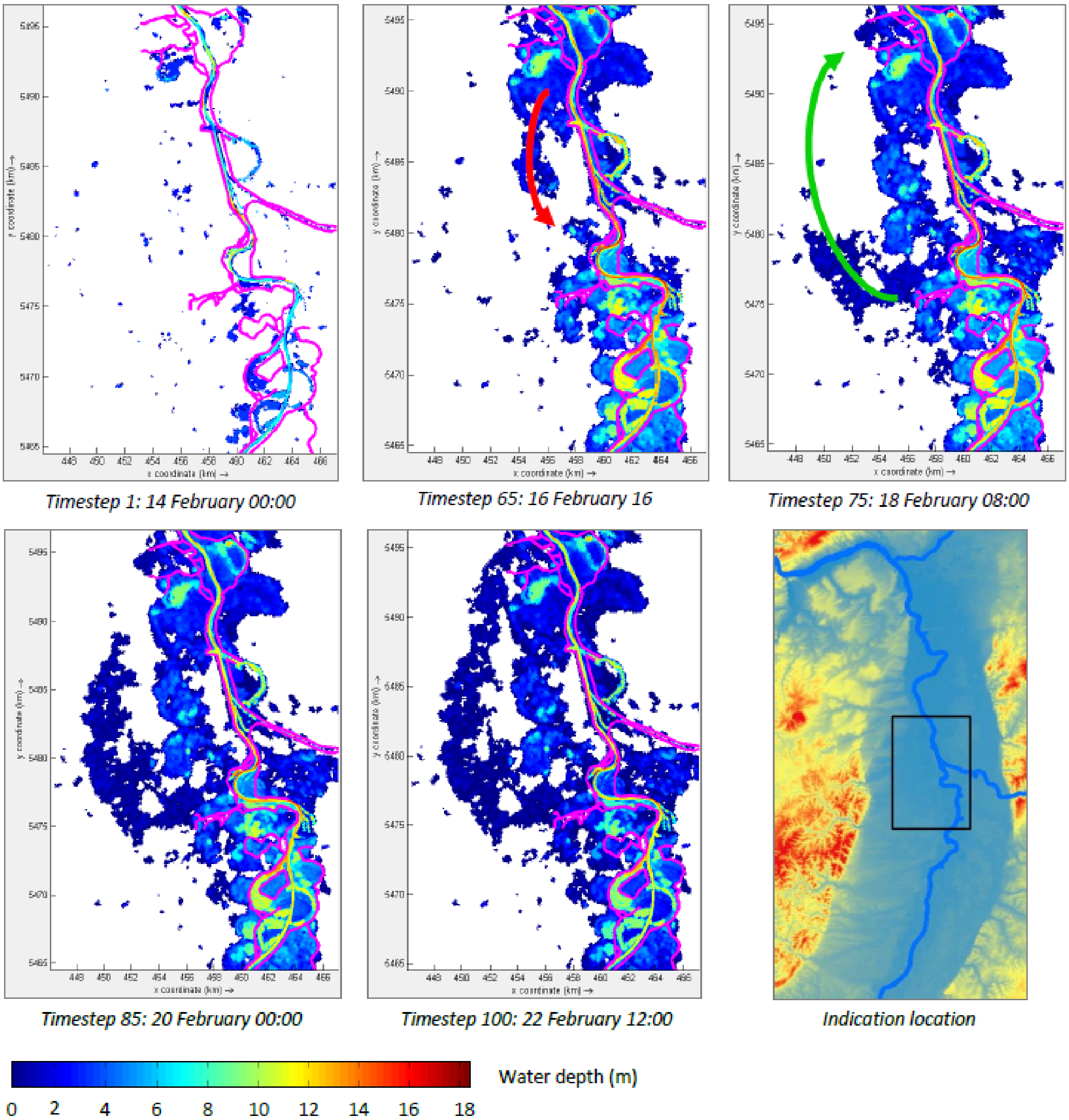
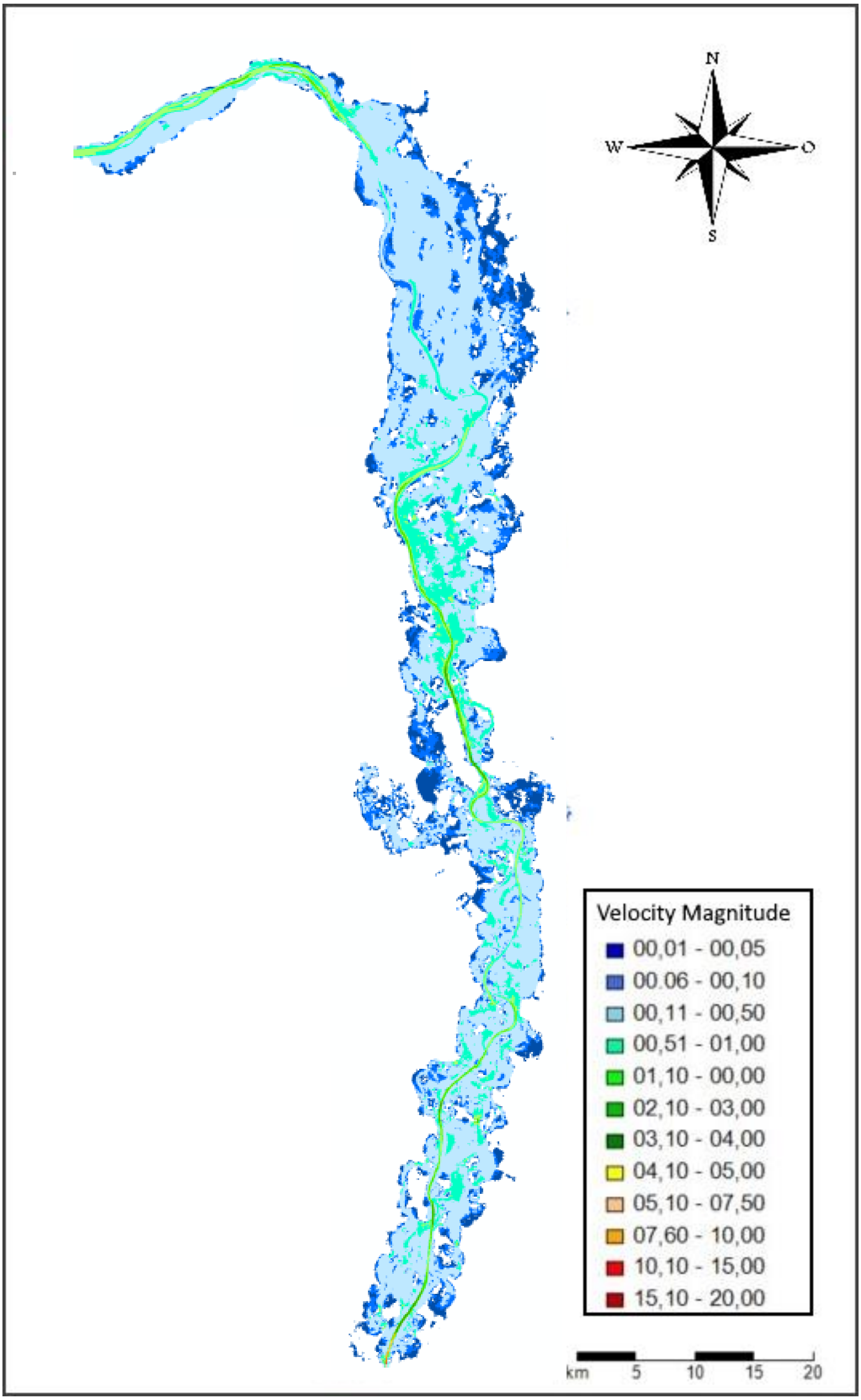


Figure 4.5: *Illustration of the expansion of the flood through the inner dike area near Ludwigshafen am Rhein. The red arrow indicates the flow of water southwards and the green arrow indicates the progression of the flood northwards at a later stage.*

APPENDIX B VELOCITY MAGNITUDE FOUND BY EVA HOEKSTRA



APPENDIX C VELOCITY MAGNITUDE OF THE IMPROVED MODEL