Comparing model performance between the hydrodynamic models SOBEK and TYGRON

Case study: Overijsselse Vecht

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Cover Image	Combination between the TYGRON logo and the Overijsselse Vecht at Hardenberg.

Preface

About six months ago I started my thesis at the Regional Water Authority (R.W.A.) Vechtstromen in Almelo as the final part of my study Civil Engineering and Management at the University of Twente. My thesis topic concerned a comparison between the hydrodynamic modelling packages TYGRON and SOBEK for the case study of the Overijsselse Vecht.

I am grateful for the opportunity to work together in a multi-disciplined research project. In this project, R.W.A. Vechtstromen acted as a client and data manager, whereas Aveco de Bondt helped during the initial model setup in TYGRON. However, the Corona crisis prevented that I could be physically present at both places from April, which made the one-on-one contact a bit harder. It was a unique experience to work and graduate under such circumstances. I learned a great deal about hydraulic modelling, and it was a challenge to identify the source of the problems present in the TYGRON model. This study taught me to be critical about making statements from the model results because it never seems to have one specific origin.

Without the support of my supervisors Jeroen (R.W.A. Vechtstromen), Denie (University of Twente) and Matthijs (University of Twente) I would never have completed my thesis. I really want to give them my gratitude for presenting this opportunity to me, answering my questions, and giving advice during the process. In addition, I would like to thank Thijs (Aveco de Bondt) and Jesse (Aveco de Bondt) for their help with setting up the model in TYGRON. Also, I would like to thank the software engineers of TYGRON who helped to define several bugs. Finally, I would like to thank my girlfriend Benthe and my family for listening in times of modelling struggles during the entire process.

With this thesis, I am ending my time as a student and starting my time in the professional field of water management.

Raymond van Renswoude
Velp, August 2020

Summary

Since May 2018, TYGRON presents a 2D hydrodynamic model in their geo-design platform. TYGRON proves to be valuable in modelling overland flow in urban and rural areas. However, the model performance of TYGRON in an applied river case is not fully tested. To study the model performance of TYGRON in a river study, a comparison is made with the reference case of the Overijsselse Vecht in the 1D (main channel)/2D (floodplains) SOBEK model of Regional Water Authority (R.W.A.) Vechtstromen between the German border-weir Hardenberg.

The goal of this thesis is to analyse the extent to which TYGRON can be used for a river study and which practical/hydrodynamic problems are encountered. This is done by comparing the following 5 aspects of model performance: the accurate simulation of 1) flood water levels, 2) inundation and 3) flow velocities, 4) realistic model sensitivity to the calibrated parameters and 5) how to implement a measure.

1) To study the performance of TYGRON to accurately simulate water levels, TYGRON is calibrated by changing the hydraulic roughness of the main channel and the floodplains for the 1/4Q (average winter scenario) and T10 (flood frequency of 1/10 years) discharge scenario, respectively. Reaching the design water level in the 1/4Q scenario was not possible since the difference between the simulated water level and the design water level was 1.67 m at the main channel roughness of 0.025 $m^{1/3}/s$ (lowest roughness value for a river described by the table of Chow, (1959)). Calibration of the T10 scenario in TYGRON results in a smaller difference between the simulated water level (10.66 m) and the design water level (10.36 m) compared to the SOBEK model (9.92 m).

   The malfunctioning of weirs in a wide river section is one of the reasons why the 1/4Q scenario was not possible to calibrate on hydraulic roughness. Weirs connect with one grid cell centre point causing the flow to be simulated past the weirs instead of over the weirs when the river is wider than the connected grid cell. Another reason can be allocated to the larger simulated water levels in TYGRON, namely the high influence of numerical viscosity in a square grid cell. A square grid may increase the influence of numerical viscosity in a meandering river profile (i.e. the course of Overijsselse Vecht) and hence result in large simulated water levels. Furthermore, it is not possible to obtain the actual simulated water levels as a result output in TYGRON. In TYGRON water levels are defined by the sum of the simulated water depth and bed level. To retrieve water levels from the grid overlay the measuring tool must be used. However, the simulated water depths are simulated based on reconstructed bathymetry. This results in irregular water levels in the length profile since the original bathymetry data is exported with the measuring tool.

2) Five inundation images in the floodplains of De Haandrik and Hardenberg of the 2018 flood event are used to validate the performance to simulate inundation. Although the discharge event of 2018 is overestimated in TYGRON, another clear difference can be seen from the SOBEK simulation. In SOBEK it is difficult to relate the inundation from the images to the simulated inundation on a specific location because of the large 25x25 m grid results in a lower bathymetry accuracy and hence a rough inundation prediction. The 2018 event in TYGRON is overestimated, locally TYGRON simulates the inundation according to the flood images.

3) The performance of the flow velocities is qualitatively analysed in the river bend and floodplains at Hardenberg. In literature, it is described that high flow velocities occur in the outer bend of the main channel and gradually decrease towards the inner bend (e.g. Luchi et al., 2011; Sukhodolov, 2012). Due to the missing 2D flow components in the main channel, SOBEK is not fit to correctly predict the expected flow velocity pattern in the main channel of the Overijsselse Vecht. Furthermore, the low resolution of the used grid in SOBEK (25x25 m) results in an over-discretization of the bathymetry and hence the flow velocities in the floodplains are generalised. The TYGRON model computes unexpected high flow velocities at both sides of the main channel. The steep slope near

the banks of the main channel causes a wrong estimation of the flow velocity between two adjacent cells resulting in an overshoot. The overshoot is inherent to the used algorithm in the 2D scheme which is currently under development at TYGRON (TYGRON, 2019).

4) A sensitivity analysis is executed on the calibrated parameters (i.e. weir dimensions, hydraulic roughness and grid cell size). Analysing the flow over the weir indicates that the weirs in TYGRON are not correctly implemented. The sensitivity analysis on the weir's dimensions shows that at De Haandrik the discharge over the weir is highly influenced by changing the dimensions in the 1/4Q scenario.

   Three floodplain roughness scenarios were analysed in the T1 and T10 discharge scenario in TYGRON and SOBEK. Before this analysis can be executed the Chézy coefficients from SOBEK are converted to Manning values to implement them in TYGRON (TYGRON can only consider Manning roughness values). This analysis showed that the SOBEK model is not sensitive by changing the Chézy coefficient with 20%, the water levels are only slightly increased in the T10 scenario. However, for TYGRON, in contrast to SOBEK, changes in the hydraulic roughness of the floodplains had a major influence on the simulated water levels.

   Three different grid cell sizes (1x1, 2x2 and 5x5 m) were analysed in TYGRON for the 1/4Q and T10 discharge scenarios. The results show that in the 1/4Q scenario the water level slope is more similar to the water level slope simulated by SOBEK when using a 1x1 m than a 2x2 m grid cell size. In the T10 discharge scenario, the 1x1 m grid shows comparable simulated water levels to the 2x2 m grid. However, the computation time in TYGRON is significantly increased from 1 hour to 4-6 hours when using a 1x1 m compared to a 2x2 m grid. Simulation with a 5x5 m grid shows a distorted result and as some of the inlets (functioning as upstream boundary condition) were turned off by overlapping connection points.

5) To analyse how easily a measure can be implemented in TYGRON and predict the hydraulic effects, a side-channel is implemented in the case of the Overijsselse Vecht. TYGRON can change the used elevation model by lowering/raising the absolute or relative height values and therefore, only separated elements in the height can be changed. This makes it difficult to adjust a side-channel since corrections to the elevation model cannot be undone. On the other hand, there is an option in TYGRON to exchange geodata such as height elements (GeoTIFF) and object elements (GeoJSON). This makes it possible to design a certain measurement in another software program (e.g. GIS or AutoCAD) and implement the design in TYGRON to analyse the hydraulic effects.

Based on this study, it can be concluded that, at the moment, TYGRON is not suitable for a river study like the river Overijsselse Vecht, although extreme discharge conditions can be predicted with more accuracy compared to average and low discharge scenarios where the influence of river weirs is significant. The following possible reasons can be mentioned why TYGRON is not yet suitable for a river study: 1) the absence of water levels as result output, 2) incorrectly simulation of weir dependent river sections, 3) the non-optimal functioning of boundary conditions and 4) the influence of numerical viscosity by the square grid shape. In the update of 9 May 2020 of the current TYGRON model, structures can be implemented over an area instead of one grid cell centre point, which may improve the simulation of flow in river scenarios where the influence of weirs is significant. In case TYGRON wants to expand the application of their water module in river studies, it is recommended to include water levels as result output. Furthermore, grid cell sizes lower than 1x1 m probably improve the flow distribution over the grid cells in the downstream direction and hence decrease the influence of numerical viscosity and friction in a square grid cell. However, additional problems in hydrodynamic modelling may occur when simulating in such small grid cell sizes (e.g. overshoot in the simulated flow velocities). It is recommended to analyse if flow distribution indeed improves in a square high-resolution grid and which hydraulic problems may occur at simulating in such high-resolution.

Table of contents

List of Figures

List of Tables

1. Introduction

In this chapter, an introduction is given of the presented thesis. At first, the context of this thesis is described. Secondly, a more in-depth description is given of the theory behind grid related properties and uncertainties in hydrodynamic modelling. Based on the underlying context and theory, the objective of this thesis is described resulting in five research questions. Thereafter, the thesis outline is presented.

1.1. Context

Worldwide there is an increasing demand to simulate flow variables (e.g. water levels and flow velocity profiles) of a river system. Climate change increases risks on human societies and ecosystems because of weather conditions becoming more extreme (i.e. high rainfall intensity and long periods of drought) (Bates et al., 2008; Bosshard et al., 2014). Furthermore, the Dutch government is required by law to protect the country against high water from floods and at the same time provide a clean and sustainable water system (Waterwet, 2009). River managers are therefore required to design and evaluate measures for flood water safety, which ask for a deterministic approach (Warmink et al., 2011). To support Regional Water Authorities (R.W.A.), consultancies, research institutes and universities in river studies, flow variables (e.g. water levels, inundation, and flow velocity) are solved numerically by hydrodynamic models.

Hydrodynamic models simplify the three-dimensional flow processes in natural channels by simulating flow in which the Shallow Water Equations are solved in either 1D, 2D, or 3D (Liu et al., 2019). Hydrodynamic models are mainly used to predict flood situations, to simulate the effects of a measure, interpolate water levels between known points and help river managers to substantiate their choices (Warmink et al., 2011). The choice for a model depends on the type of model, the complexity of the scenario and the goal of the assignment. 1D models describe flow interaction in the streamwise direction while 2D models describe depth average flow interaction. In semi two-dimensional models (1D/2D) the main channel is schematized in 1D while the floodplains are schematized in 2D, (Figure 1). Some examples of hydrodynamic modelling packages are MIKEFLOOD-1D/2D, SOBEK-1D/2D, TUFLOW-1D/2D, DELFT3D and new on the market TYGRON-2D. This thesis focuses on the comparison between the hydrodynamic modelling packages SOBEK (commonly used in the Netherlands) and TYGRON.

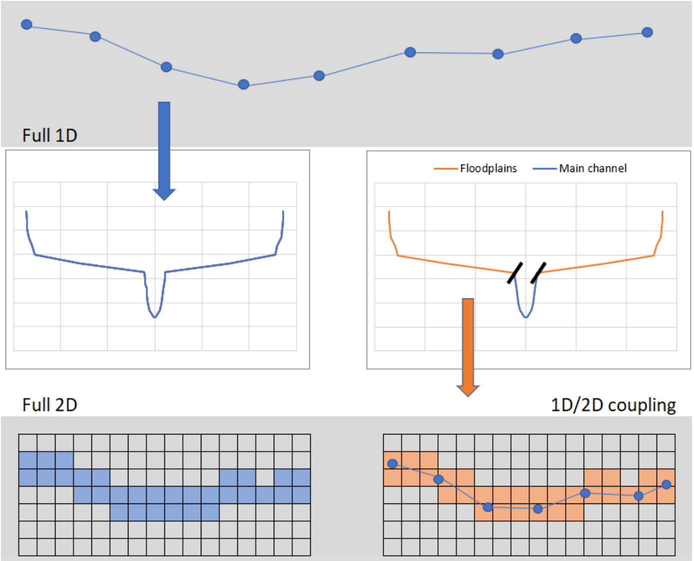


Figure 1: Conceptualization of 1D, 2D and 1D/2D hydrodynamic model. The bathymetry of a full 1D model is described by cross-sections (nodes) and interpolated over the length between the neighbouring cross-sections (upper figure). The bathymetry of a full 2D model is defined by a rasterized elevation model (lower left figure). In 1D/2D models, a connection is made between the main channel (described by the interpolation between cross-sections) and floodplains (described by a rasterized elevation model).

Since May 2019, TYGRON presents a new water module in their Geo-design platform. TYGRON uses an external computer and incorporates a square grid which makes it possible to reduce computing time in 2D from hours to minutes (TYGRON, 2019). Originally TYGRON is set up to solve the behaviour of overland flow in urban and rural areas. R.W.A. Vechtstromen is currently developing a 1D/2D model of the river "Overijsselse Vecht" between De Haandrik and Hardenberg in SOBEK. Nevertheless, R.W.A. Vechtstromen is interested in TYGRON, due to its ability to simulate water levels and flow velocities fast and because visual results such as flooding are presented attractively to stakeholders. However, TYGRON's water module is quite new and not yet validated on an applied river case.

R.W.A. Vechtstromen provides a reference model of the Overijsselse Vecht between De Haandrik and Hardenberg in SOBEK and requests to identify the mayor differences between TYGRON and SOBEK in a river study. To compare the model performance between the two hydrodynamic models, the TYGRON model is setup based on the reference model of the Overijsselse Vecht from R.W.A. Vechtstromen.

1.2. State of the art

This section describes a more in-depth context behind the presented study, which includes grid related properties (1.2.1.), uncertainty in the hydrodynamic modelling (1.2.2.), using a sensitivity analysis (1.2.3.) and the design principles for implementing a side-channel (1.2.4.).

1.2.1. Grid related properties

The performance of the simulated water levels in a 2D hydrodynamic models are generally dependent on the used resolution (bathymetry accuracy and numerical friction) and the used grid shape (numerical viscosity) (Bomers et al., 2019; Caviedes-Voullième et al., 2012; Schubert et al., 2008).

- Bathymetry accuracy as a result of the grid resolution (e.g. Bomers et al., 2019). Bathymetry accuracy can be increased by using a smaller grid cell size. The resolution determines how well the bathymetry from the Digital Elevation Model (DEM) is captured in the governing flow equations of the hydrodynamic model. A low resolution may result in an over/underestimation of the translated bathymetry from the DEM and hence the simulated water levels.
- Numerical friction as a result of the grid resolution (Caviedes-Voullième et al., 2012; Schubert et al., 2008). Increasing grid cell sizes increase the generated friction by the grid cell itself and hence increase the simulated water levels. Increasing the grid cell size has the same effect on the water levels as increasing the hydraulic friction (i.e. dampening of the discharge wave and delay in peak flow).
- Numerical viscosity as a result of the grid shape (Bomers et al., 2019; Caviedes-Voullième et al., 2012). The distribution of flow exchanged between neighbouring grid cells may increase water levels when the grids cells do not follow the course of the river. This is referred to as the influence of the numerical viscosity by the grid shape. Grid shapes that follow the course of the river (e.g. grid with perpendicular edges parallel to the course of the river) have a lower numerical viscosity than grid shapes that do not follow the course of the river (e.g. square or triangular grids). A large influence of numerical viscosity also has the same effect on the simulated water levels as increasing the hydraulic friction.

1.2.2. Uncertainty in calibration

Accurate hydrodynamic models can predict the effects of drought during low water conditions and floods during high water conditions. Insufficiently accurate predictions may lead to the wrong decisions which can lead to major damages and casualties during flood events (Apel et al., 2006; Bates et al., 2008). Multiple studies have investigated uncertainty sources of hydrodynamic models and agree that the upstream discharge and main channel roughness are the main aspects that lead to flood water level uncertainty (Pappenberger et al., 2008; Warmink et al., 2011). Typically, flood levels are assessed based on extreme flow conditions. Extreme flow conditions can be predicted by recorded water levels and discharges during flood events. However, extreme flood events are rare and uncommonly measured. In a situation of data scarcity, extreme flood events are probably never measured, which means that the values of extrapolated discharges and water levels are derived with large uncertainty. Considering uncertainty in decision-making processes in river studies is important because in case of high uncertainty the risks of making the wrong decision are increased (Xu & Mynett, 2006). Therefore, it is necessary to describe this uncertainty by a proper calibration and validation process of the used hydrodynamic model.

In literature, the most common method of calibrating hydrodynamic models is changing the value of the hydraulic main channel roughness until the best fit is obtained between the observed and simulated water levels (Kidson et al., 2002; Liu et al., 2019; Matgen et al., 2004). Calibration should be executed with caution since the parameter will be calibrated against distributed flow data, which lead to a high degree of equifinality in model realizations (Fabio et al., 2010). Equifinality is the principle that it is possible to reach the same end state by different means and could lead to an increased variance in the roughness scale where many parameter sets perform equally well. In river models, this is dependent on the model region and boundary conditions (Pappenberger et al., 2005). The unwanted effect of equifinality results in over/underestimation of the calculated flow parameters from the hydrodynamic model outside the calibration domain. The uncertainty in the calibration process and from equifinality needs to be considered by predicting the flood water levels in this study.

1.2.3. Sensitivity analysis

Typically, a sensitivity analysis is applied where the quantities in the system being analysed are not known exactly (e.g. hydraulic roughness and river discharge) (Hall et al., 2009). The roughness parameter in a hydrodynamic model describes the conceptualization of vegetation in the model structure and how this interacts with the flow variables (Werner, 2004). Therefore, after calibration, the simulated water levels can be tested on sensitivity by adjusting the hydraulic roughness of the floodplains. Furthermore, computation time is mainly related to the dimensionality of the hydrodynamic model and the defined resolution (Horritt & Bates, 2002; Jowett & Duncan, 2012). This relation can show how the selection of a hydrodynamic model is influenced by the effect of different resolutions on the performance to simulate water levels. Other dependent model parameters are the weir parameters (Pappenberger et al., 2006). The weir parameters consist of the hydrodynamic roughness, height, and width of the structure. Changing height and width have the most effect on the flow variables around the weir and cause significant backwater effects (Pappenberger et al., 2006). These backwater effects can be reproduced by adjusting the hydrodynamic roughness around the weir with unrealistic high values. This can lead to uncertainty in the calibration process since higher roughness values are needed to reduce the error between the simulated and observed water levels at weirs. A sensitivity analysis provides information on how both models react to changes in uncertain model parameters and at the same time, the results of both hydrodynamic models can be compared.

1.2.4. Design principles side-channel

Analysing the hydraulic effects of a measure is one of the main purposes to use a hydrodynamic model (e.g. analysing the backwater effects of a side-channel). Rijkswaterstaat developed a technical report for the designing of rivers, including the design principles of side-channels (Ministerie van Verkeer en Waterstaat, 2007). The design principles of side-channels are based on a monitoring study of Jans et al., (2004), which results in three core aspects 1) ensure high water safety, 2) maintain shipping and 3) improve nature. The design principles indicate whether the effects of the side-channel comply with the hydraulic requirements. Model performance is dependent on the user-interface (e.g. how the hydrodynamic effects are presented and how easily the initial model can be changed). By implementing a side-channel, it can be analysed if the eventual effects of the measure comply with the hydraulic requirements and what the user-interface is of TYGRON. In this study the design principles of

Rijkswaterstaat for designing a side-channel are used to analyse the designing properties between TYGRON and SOBEK.

1.3. Research objective

Typically, 2D models are used in river sections to correct 1D models in floodplain flow simulation. R.W.A. Vechtstromen is interested in the additional value of TYGRON compared to their current SOBEK 1D/2D model of the Overijsselse Vecht. 1D/2D models such as SOBEK are proven to be effective in predicting flood scenarios of long river sections in which also floodplain flow needs to be captured. 1D/2D models are time-consuming in setting up the initial model and accurate floodplain flow is dependent on the used resolution (Lin et al., 2006). TYGRON may give additional value because it can quickly set up and simulate different flood scenarios. However, it is unknown how TYGRON performs in a river study where an accurate prediction of flood scenarios is required.

The goal of this thesis is to analyse to what extent TYGRON can be used for a river study by comparing the differences in model performance with SOBEK. In this case, a river study is defined to include the following aspects of model performance:

- An accurate simulation of water levels.
- An accurate simulation of inundation.
- An accurate simulation of flow velocities.
- Realistic model sensitivity to the calibrated parameters (hydraulic roughness, weir dimensions and resolution).
- Implementing a measure in a case study.

Comparing model performance in this sense of river studies will lead to the qualities in which TYGRON is better as a 2D hydrodynamic model instrument over the 1D/2D approach of SOBEK, what practical/hydrodynamic problems are still included in the software program and how to improve the TYGRON model (Figure 2).

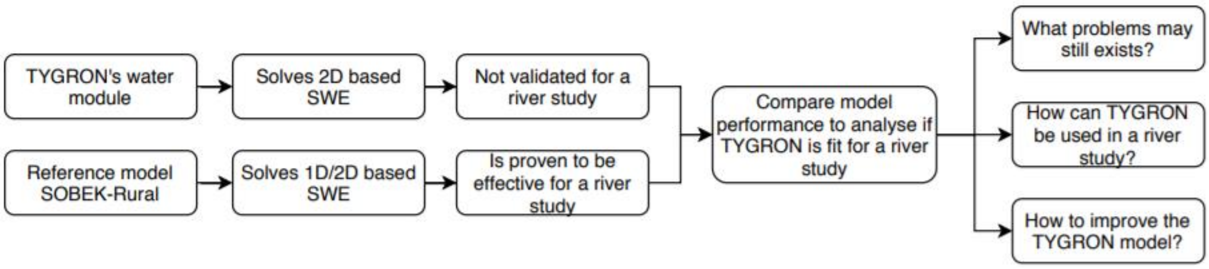


Figure 2: The research gap is filled by analysing if TYGRON can be used for a river study. To achieve this, a comparison in model performance is made with the reference case of the Overijsselse Vecht in SOBEK. The questions following from the comparison are answered by the discussion, conclusion and recommendations, respectively.

To achieve the goal of this thesis, the following research question will be answered:

"To what extent can TYGRON be used as a hydrodynamic model in river studies based on a comparison in model performance with the reference case of the Overijsselse Vecht in SOBEK?

The following sub-questions can be formulated to answer the research question:

RQ1: What is the performance of TYGRON to accurately simulate water levels, when TYGRON is setup based on the reference case of the Overijsselse Vecht in SOBEK?

a. To what extent can the design water levels from SOBEK be reached in the discharge scenarios 1/4Q (average winter scenario) and T10 (flood that occurs 1/10 years) by calibrating TYGRON on the hydraulic roughness of the main channel and floodplains?

b. What is the influence of river weirs on the calibration process and simulation of maximum water levels in the 1/4Q and T10 discharge scenario in TYGRON?

c. What are the differences in maximum simulated water levels in the discharge scenarios 1/100Q (average summer scenario), T1 (yearly scenario) and T200 (flood that occurs 1/200 years) in TYGRON?

d. What are the differences in the discharge wave propagation in TYGRON and SOBEK?

RQ2: What is the performance of TYGRON and SOBEK to accurately simulate inundation, based on data from the historical flood event in 2018, in the Overijsselse Vecht?

RQ3: What is the performance of TYGRON and SOBEK to simulate depth-averaged flow velocity profiles in the main channel and floodplains?

RQ4: To what extent are the maximum simulated water levels from TYGRON and SOBEK sensitive to changes of the calibrated parameters (i.e. floodplain roughness and weir dimensions and resolution)?

RQ5: How easy is it to implement a side-channel in TYGRON based on the design principles of Rijkswaterstaat?

1.4. Research outline

The outline of this thesis is described in this section.

At first, background information about R.W.A. Vechtstromen and the study area is described followed by a description of the reference case of the Overijsselse Vecht and the data used in SOBEK (Chapter 2). Secondly, the TYGRON model is set up and the used data are described (Chapter 3).

For each research question, the method is described as first, the results are presented as second and a small conclusion is given at the end (Chapters 4-8) (Figure 3). Finally, the discussion, conclusion and recommendations are given in (Chapters 9-11), respectively.

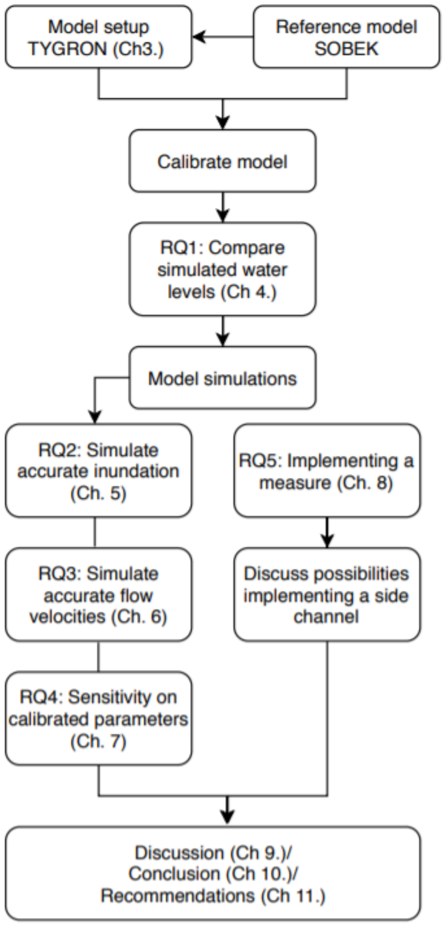


Figure 3: Flowchart linking the research questions to the structure of this thesis.

2. Background information, study area and reference model

2.1. R.W.A. Vechtstromen and the Vecht

After the Country and Provinces, Regional Water Authorities (R.W.A.) and municipalities form the third-largest governance in the Netherlands. R.W.A. Vechtstromen is responsible for the water management in Twente, North-east Overijssel and South-east Drenthe, which covers the upstream part of the Overijsselse Vecht in the Netherlands. The Overijsselse Vecht is a rainwater river originating from multiple sources around Münsterland (Germany) and flows through the Dutch province of Overijssel, connects with the river Zwarte Water above Zwolle and eventually ends in the lake Zwarte Meer. Figure 4 illustrates the trajectory of the Vecht, where the domain of the Regional Water Authority (R.W.A.) Vechtstromen is indicated with the red boundary line.

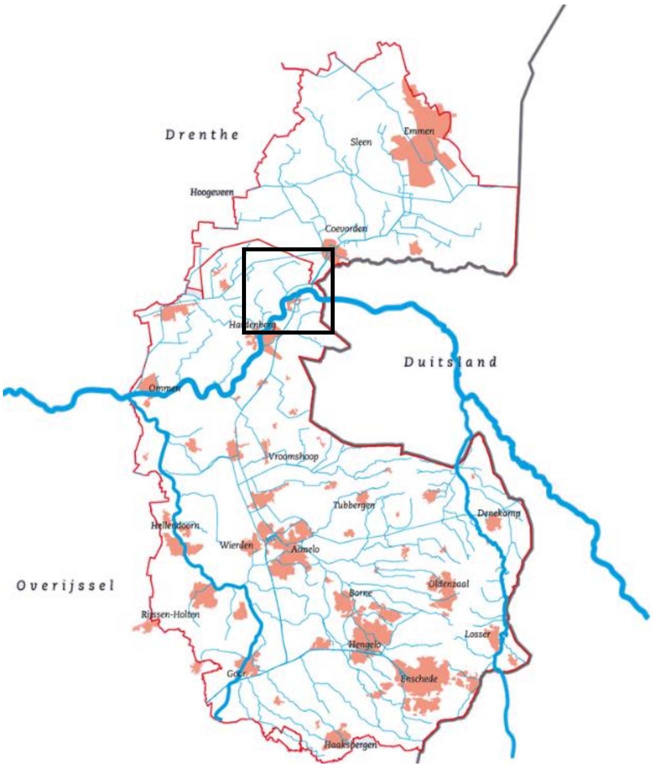


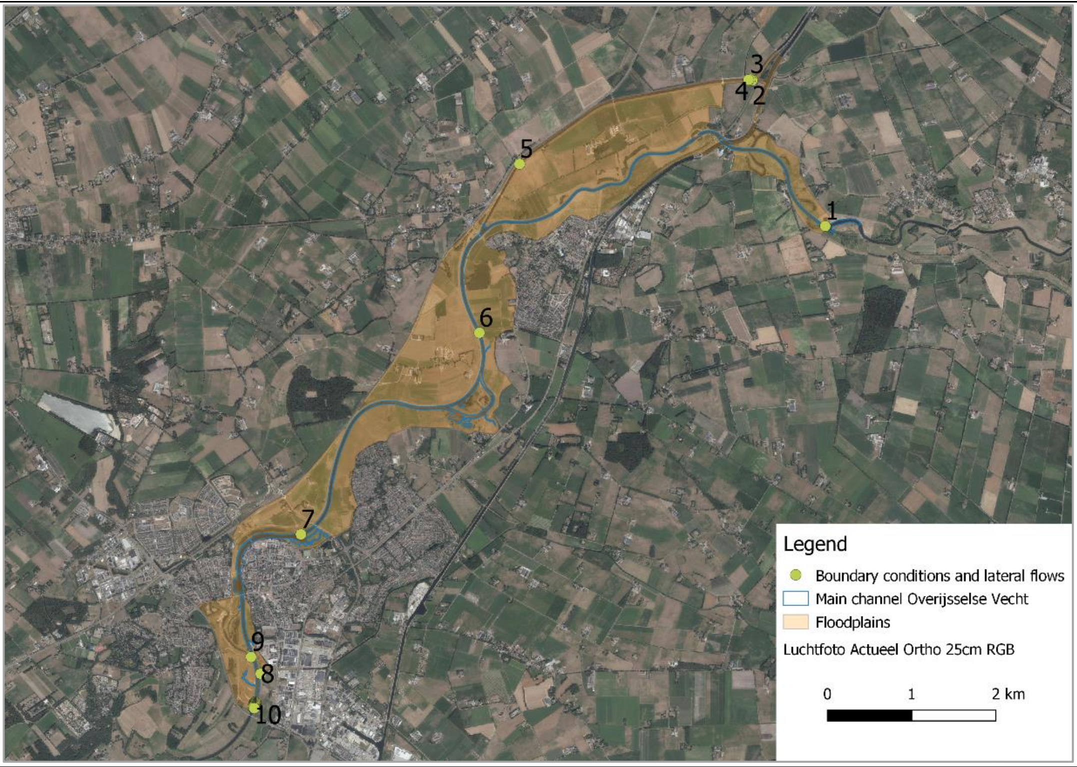
Figure 4: River section of the Overijsselse Vecht and management area of R.W.A. Vechtstromen. The blue line in the black square represents the Overijsselse Vecht between De Haandrik and Hardenberg.

Plans of the Overijsselse Vecht are designed based on multiple policies like the "Grensoverschrijdende Vechtvisie" and "Ruimte voor de Vecht", both dating from 2009. Meanwhile, multiple river rehabilitation projects are executed where attention has been set on area development. These projects have a coupled general goal and therefore an overarching strategy has been developed. This strategy describes the development of the Vecht into a half-natural lowland river towards the year 2050 and gives impulse to spatial quality and flood protection (Alterra; HKV; KWR, 2009). For the transition towards a half-natural lowland river, the Overijsselse Vecht needs space for meandering, broadening the river bed, creating side-channels, maintaining flood protection and preserve a half-natural weir control (Arcadis & HKV, 2009).

To properly fulfil the duties and associated responsibilities of the transition to a half-natural lowland river, R.W.A. Vechtstromen uses a set of model instruments (e.g. Sobek River, Sobek Rural, Waqua and Fews Vecht) (R.W.A. Velt en Vecht, 2012). R.W.A. Vechtstromen developed a new model between De Haandrik and Hardenberg for the Overijsselse Vecht in SOBEK which will be used to simulate scenarios within the project "Vechtrijk Gramsbergen" (R.W.A. Vechtstromen, 2015).

2.2. Study area

The black square in Figure 4 presents the study area of this research and this area is enlarged in Figure 5. The 1D/2D part of the SOBEK model of R.W.A. Vechtstromen consists of the main channel and the floodplains between the German border and ends just after weir Hardenberg. Within this trajectory, eight channels connect with the Vecht and provide extra water to the system. Furthermore, the project area includes two fish migration constructions (Molengoot and De Haandrik), a canoe track (Molengoot) and a side-channel (Loonzensche linie). The location of the lateral flows and the upper and lower boundary conditions are illustrated in Figure 5 and a schematization of the flow network is presented in Figure 6.



1. Upstream boundary
2. Pumping station Germany
3. Weir Drentse stuw
4. Pumping station De Kleine Vecht
5. Pumping station Noord Meene
6. Pumping station Willem Snel
7. Pumping station Baalder
8. Weir Vrouwenhoek
9. Pumping station Molengoot
10. Downstream boundary

Figure 5: Study area of the Overijsselse Vecht between the German border and Vechtpark Hardenberg. The blue line indicates the main channel of the river Vecht, the orange shape indicates the floodplains and the yellow points the side-channels and boundary conditions that regulate water in the Vecht model.

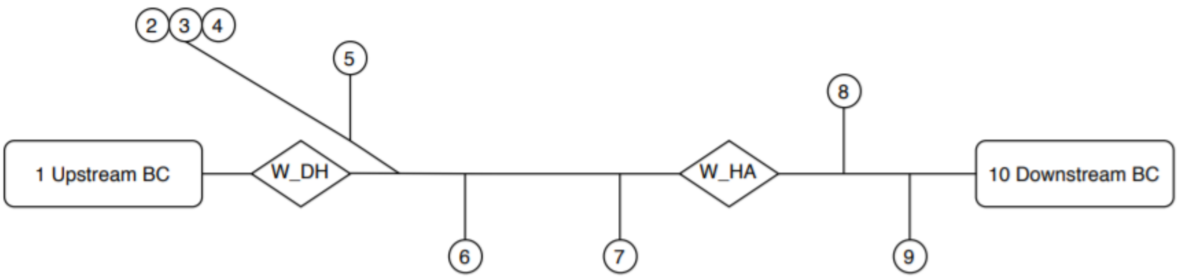


Figure 6: Schematization of the network of the Overijsselse Vecht, including the connections and weirs. In this Figure, W_DH stands for weir De Haandrik and W_HA stands for weir Hardenberg.

The bed profile dimensions of the Vecht are described in the water system analysis of the Overijsselse Vecht and are based on peak discharges (R.W.A. Vechtstromen, 2017). The width of the main channel is approximately 20 m and increases in the downstream direction. From weir De Haandrik to weir Mariënberg the height difference is 1.7 m (3.1 m+NAP to 1.4 m+NAP). Globally, the slope of the Overijsselse Vecht between De Haandrik and Vilsteren is 18 cm/km. Compared to the river Rijn (1-11 cm/km) and IJssel (4-13 cm/km) the slope of the Overijsselse Vecht is larger (R.W.A. Vechtstromen, 2017).

2.3. Sobek reference model

SOBEK Rural provides water managers with a tool for modelling irrigation systems, drainage systems and natural streams. The software calculates the rainfall run-off process of urban areas, considering land use, groundwater flow and interaction of water levels in open water surfaces (Deltares, 2019). The graphic display of SOBEK maps an area of interest over a GIS or aerial photo and can visualize an animation of the flow direction as well as graphs of the water level at a predefined point and time. By using a 1D/2D approach, the equations of continuity and momentum are solved in 1D and 2D for the main channel and river-floodplain based on Cunge et al., (1980). Below are the 1D equations presented for continuity (1) and momentum (2).

$$\frac{\partial A_T}{\partial t} + \frac{\partial Q}{\partial x} = q_{lat} \tag{1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A_F}\right) + gA_F\frac{\partial \zeta}{\partial x} + \frac{gQ|Q|}{C^2RA_F} - w_f\frac{\tau_{wind}}{\rho_w} + gA_f\frac{\xi Q|Q|}{L_x} = 0 \tag{2}$$

For the solving flow components in 2D, the following equations are solved for continuity (3) and momentum (4 and 5).

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0 \tag{3}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial \zeta}{\partial x} + g\frac{u|\vec{u}|}{C^2h} + au|u| = 0 \tag{4}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial \zeta}{\partial y} + g\frac{v|\vec{v}|}{C^2h} + av|v| = 0 \tag{5}$$

In this scheme, A_T is the total area (flow area and storage area) in m^2, Q the discharge in m^3/s, q_{lat} the lateral discharge per unit length in m^2/s, A_F the flow area in m^2, C the Chézy value in m$^{1/2}$/s, ζ the water level in m, L_x the length of the branch segment (extra resistance node) in m, R the hydraulic radius in m, w_f the water surface width in m, τ_{wind} the wind shear stress in N/m^2, ξ extra resistance coefficient in s^2/m^5, u, v are the flow velocities in m/s in x, y-direction respectively, $\overrightarrow{|u, v|}$, are the velocity magnitudes in m/s in x- and y-direction, respectively and a the wall friction coefficient in 1/m.

The R.W.A. Vechtstromen reference model of the Vecht is a Sobek Rural 215 1D/2D model. In the following sections, the data used to provide the model input is described.

2.3.1. Data

The data presented in Table 4 are used to schematize the 1D and 2D components of the Vecht system between the German border and just after weir Hardenberg.

Table 1: The used data sources that function as input to schematize the hydrodynamic model of SOBEK, based on the technical report "Uitgangspuntennotitie oppervlaktewater modellering voor project Vechtrijk Gramsbergen en project Baalder" (R.W.A. Vechtstromen, 2019).

Data Reference case:	**SOBEK-1D model (2.3.2.)**	**Measured bed level main channel Vecht (2.3.3.)**	**AHN2 (2.3.4.)**	**Ecotope map (2.3.5.)**	**Water level and discharge measurements Vecht (2.3.6.)**
Used for:	The base model of the Vecht between the German border and Ommen. Version 2.15	Measured Vecht profile between the German border till weir Hardenberg. Used to determine 1D cross-sections in the main channel.	Elevation model between the German border till Hardenberg. Used as a surface map for 2D components of the floodplains and hinterland.	Ecotype map that describes which roughness value is related to a specific ecotope and location. Used for the description of the roughness of the floodplains.	Measured downstream discharges and water levels at weirs, De Haandruk, Hardenberg, Mariënberg, Junne and bridge Ommen. Used to determine boundary conditions and for calibration.
Input files:	Vcht.lit	ZomerbedRaster1.tif and ZomerWinterbedRaster20201.tif	SOBEKHOOGTEGeheel.ASC	SOBEKRUWHEIDGeheel.ASC	Opperwatermodellering Vecht (R.W.A. Vechtstromen, 2015) and Ruimte voor de Overijsselse Vecht (Arcadis & HKV, 2009).

2.3.2. SOBEK-1D

The SOBEK-1D model is the underlying model where the 2D part is connected to. For the trajectory between the German border and just after weir Hardenberg, a 2D connection is made between the main channel and the floodplains. Between weir Hardenberg-Ommen the main channel and floodplains are simulated in 1D.

2.3.3. Measured bed level main channel

The profile of the Overijsselse Vecht is measured with a radar boat between the German border till weir Hardenberg. The measured points are converted to a grid cell size of 1m. The measurements stop just before and just after weir De Haandrik since this area cannot be reached by the radar boat. The cross-sections of the 1D main channel in SOBEK are based on the profile measurement. The measured profile is translated to symmetrical cross-sections in a YZ-profile in SOBEK (Appendix A1). The bed levels are defined for multiple cross-sections in the trajectory (approximately every 100m). The SOBEK model interpolates the bed level between two adjacent cross-sections connected by a line segment, this results in a bed level for the main channel over the entire trajectory.

2.3.4. AHN2 - 2D connection

The AHN2 0.5 m surface elevation model is used for the 2D connection of the floodplains with the 1D main channel. The AHN2 0.5 m is merged to one file named AHN05. The AHN2 map consists of detailed surface data with on average eight surface measurements per square meter which are measured by airborne laser altimetry. The grid cell size used for the 2D grid is a square grid of 25x25 m.

A connection is made between the main channel in 1D and floodplains in 2D. The option "lowest level of embankments" is chosen for the vertical connection between the 1D main channel and 2D floodplains, (Figure 7). In the option lowest level of the embankment, water enters the 2D grid when the lowest level in the 1D profile is overtopped (Deltares, 2019).

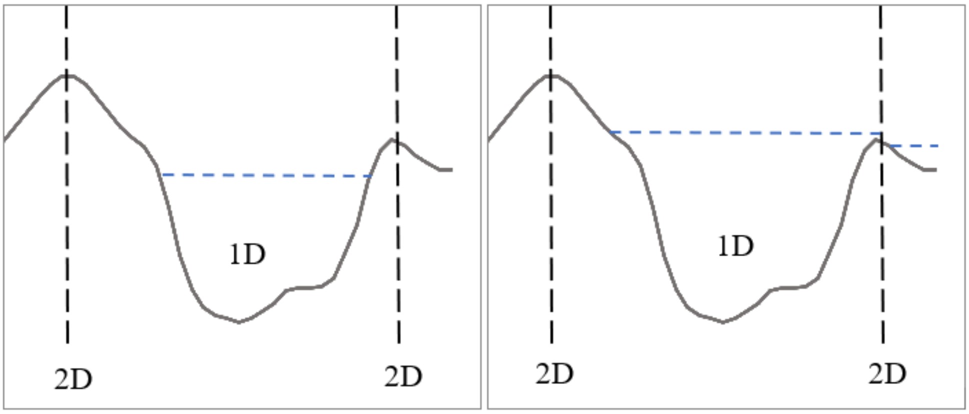


Figure 7: Connection 1D grid with the 2D grid at "the lowest level of embankment". When the water level is lower than the banks, there is no interaction between the 1D and 2D grid (left figure). When the water level is higher than the one of the banks, the 1D grid exchange information with adjacent 2D cells of the coupling zone at the overflowing side (right figure).

2.3.5. Ecotope map - roughness

The ecotope map is a shapefile that describes which ecotope is located where and is based on aerial photographs (Luchtfoto2018). The ecotopes are coupled with roughness values. The roughness values of the ecotope map are based on the report "stromingsweerstand vegetatie in uiterwaarden" from Rijkswaterstaat (van Velzen et al., 2002). The technical report describes that roughness of the vegetation is dependent on the water depth. The Vecht is calibrated with a representative water depth of 1.5 m. Table 2 presents the roughness values (Chézy) coupled with the ecotope type in SOBEK corresponding to a representative water level of 1.5 m.

Table 2: Roughness per ecotope for the Vecht with a representative water depth of 1.5 meters (van Velzen et al., 2002).

Ecotope:	**Roughness (Chézy) per ecotope at 1.5 m water depth [$m^{1/2}/s$]**
Water	37.43
Agricultural land	35.18
Production grassland	32.38
Natural grassland	28.6
Reeds	9.1
Thicket	7.08
Forest	16.44
Paved	26.59

2.3.6. Boundary conditions

The upstream boundary condition for T1 (discharge that occurs once a year), T10 (once in ten years) and T200 (once in two hundred years) is a Q-t relation which represents a discharge wave. The discharge wave is adopted from earlier studies of the Overijsselse Vecht (Appendix A2) (Arcadis & HKV, 2009). For the 1/4Q scenario (average winter scenario) a constant discharge is used for the upstream boundary condition as well as for the lateral flows m^3/s (Table 3). Furthermore, the discharge measurements contain an uncertainty of approximately 40% (without applying too much statistics) (R.W.A. Vechtstromen, 2015).

The downstream boundary condition is a Q-h relation (Figure 8). The design water level is determined by the historical measurement data between 1997-1998 and extrapolated by model-based simulations with increasing constant discharge. The reason for the combination of the measurement data and the model results is because the discharge and water level measurements are two separated data sets. This means that the design discharge with a certain return period does not directly correspond with the design water level with the same return period. The Q-h relation is based on the historical measurements of a high-water event in 1997-1998 at Vilsteren. Discharges larger than 550 m^3/s are extrapolated because no data is available at such extreme events. The water levels between De Haandrik and Hardenberg are less influenced by the downstream boundary condition since it is located at Vilsteren.

Table 3: The lateral constant discharges of the 1/4Q discharge scenario.

Location input flow to the Vecht system	**Discharge lateral flow m^3/s**
1. Upstream boundary	23
2. Pumping station Germany	0.94
3. Weir Drentse stuw	4.9
4. Pumping station De Kleine Vecht	0.51
5. Pumping station Noord Meene	0.57
6. Pumping station Willem Snel	0.32
7. Pumping station Baalder	0.14
8. Weir Vrouwenhoek	0.88
9. Pumping station Molengoot	0.38

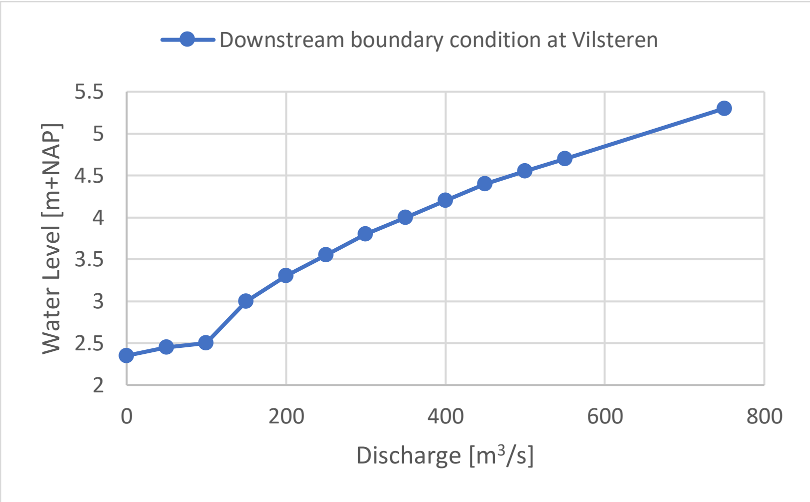


Figure 8: Downstream boundary condition (Q-h) of the SOBEK model at Vilsteren.

Table 4: Discharges with corresponding return period based on measurements in the Overijsselse Vecht.

Return period [times/years]	**Discharge [m^3/s]**		
	Emlichheim	**De Haandrik**	**Hardenberg**
1/200	247	249	315
1/10	199	200	248
1	115	116	150
Q1/4	23	23	30
Q1/100	0.5	0.5	0.6

3. Model setup TYGRON

The Geo-design platform of TYGRON is a multifunctional software package, suitable for solving geotechnical issues with interdependent themes like energy, water, mobility, and air quality and can visualize these variables (TYGRON, 2019). The TYGRON platform is an integrated software package and acts as a central hub where geodata can be collected and processed. Some of the advantages of TYGRON are that the software is continuously maintained where features can be extended, functions are available for all users in the project and interoperability is preserved. TYGRON's water module simulates 2D water flow across a predefined surface. This surface represents the area of interest determined by the user. After determining the project area, geodata is collected from multiple sources (e.g. Kadaster, Basic Registration Underground, Actual Surface Elevation Netherland). Geodata consists of either vector data (points, lines, and polygons) or raster data (data in grid cells).

To initialize a flood event in TYGRON, the Flooding overlay is presented. The Flooding overlay connects with the water module, which calculates and visualizes the movement of water over land. When simulating a flood event, the results are presented in multiple timesteps for the selected result type (e.g. inundation, flow velocity). For calculation of the water depths, the water module of TYGRON discretizes x and y cells depending on a configurated grid cell size and initialize water in the model. Each grid cell has a unique bed level ζ, water depth h and accompanying roughness coefficient n (Gauckler-Manning) and calculates for each neighbouring grid cell the new water depth based on the initial condition. Water levels in TYGRON are described by the sum of the water depth and the bed level and can be exported with the measuring tool.

The behaviour of the flow in TYGRON is schematized by a second-order semi-discrete central-upwind scheme based on (Kurganov & Petrova, 2007). The following equations are used to simulate flow in TYGRON:

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0 \tag{6}$$

$$\frac{\partial (hu)}{\partial t} + \frac{\partial}{\partial x}\left(hu^2 + \frac{1}{2}gh^2\right) + \frac{\partial (huv)}{\partial y} = -gh\frac{\partial \zeta}{\partial x} - ghn^2u\sqrt{u^2+v^2}h^{-\frac{4}{3}} \tag{7}$$

$$\frac{\partial (hv)}{\partial t} + \frac{\partial}{\partial y}\left(hv^2 + \frac{1}{2}gh^2\right) + \frac{\partial (huv)}{\partial x} = -gh\frac{\partial \zeta}{\partial y} - ghn^2u\sqrt{u^2+v^2}h^{-\frac{4}{3}} \tag{8}$$

In equation 6-8, h is the water depth in m, u, v a is the flow velocities in m/s in x, y-direction respectively, ζ the bed level in m, g the gravitational constant in m/s^2 and n the Gauckler-Manning roughness coefficient in s/m$^{1/3}$.

The hydrodynamic model of TYGRON is setup based on the SOBEK reference case described in section 2.3. and contains the same study area. Chapter 3 is divided into 5 steps:

- Determining the boundaries of the study area (3.1.).
- Selection of data sources (3.2.).
- Apply data to model input (3.3).
- Selecting the grid cell size (3.4.).
- Check before calibration (3.5.).

3.1. Boundaries case

R.W.A. Vechtstromen provides a 1D/2D model of the Overijsselse Vecht in SOBEK Rural. The 2D connection is located from the German border until just after weir Hardenberg. To compare model performance, the TYGRON model is set up based on the reference case of the R.W.A. Vechtstromen.

Therefore, the TYGRON model is also bound between De Haandrik and Hardenberg. The model area of TYGRON is 10,250x10,250 m, (Figure 9). This area is relatively small for a river study. The downstream boundary condition needs to be placed downstream at weir Hardenberg, which results in that the upstream water levels are highly influenced by the upstream regime. However, when a large study area is selected, the hydraulic effects can be more difficult to interpret. The reason for this is that the flow variables could be influenced by more than one parameter in the model regime. Furthermore, computation time takes longer at large project areas. By selecting a relatively small study area the effects of changes can be analysed one-on-one in a usable model regime in terms of computation time and resolution. Another reason for using the area between De Haandrik and Hardenberg is because the maximum model area in TYGRON is 30,000x30,000 m in which the whole trace of the Overijsselse Vecht cannot be created.

Figure 9: The project boundaries (blue square) between the German border (purple line) and Hardenberg in TYGRON. The total area is 10,250x10,250 m.

3.2. Selection of data

Table 5 presents the used data for the TYGRON model and are described in the following sections.

Table 5: Used data sources to feed the TYGRON model.

Data sources:	**Sources connected to the TYGRON platform (3.2.1.)**	**Measured surface Vecht (GeoTIFF) (3.2.2.)**	**Weir files of R.W.A. Vechtstromen (GeoJSON) (3.2.3.)**	**Design-water levels and discharges Vecht: Report Vechtstromen and HKV study. (3.2.4.)**
Needed for:	To create a 3D map environment (visualization) consisting of open data sources	Surface elevation of the main channel of the Overijsselse Vecht.	Used to include relevant hydrodynamic constructions in the model which regulate the flow of water through the Vecht system.	To create boundary conditions of the TYGRON model of the Vecht and to calibrate/validate the simulation of water levels.
Files:	See Appendix B1.	Bodemvecht_1.tif and Bodemvecht_2.tif	Stuwen_VNoord.shp	Opperwatermodellering Vecht (R.W.A. Vechtstromen, 2015) and Ruimte voor de Overijsselse Vecht (Arcadis & HKV, 2009).

3.2.1. Sources connected to the TYGRON model

TYGRON uses geographical data which have a local component for the creation of the 3D model world. This data consists for example of base registers, open street maps and land use maps. Appendix B1 presents a list of relevant sources connected to the platform.

3.2.2. Measured profile Vecht

To model the bathymetry of the Overijsselse Vecht in TYGRON a GeoTIFF-file is used (Bodemvecht_1.tif and Bodemvecht_2.tif). The GeoTIFF file overwrites the model defined bathymetry by measured geographical raster data placed on coordinates. The bathymetry of SOBEK and TYGRON are based on the same measured profile of the main channel. The surface level of the floodplains is based on the AHN2 (Sections 2.3.3. and 2.3.4.).

3.2.3. Construction files

A GeoJSON-file will be imported to initialize a weir in the TYGRON model. This file contains information about the structure's dimensions, location, and roughness. R.W.A. Vechtstromen provides a shapefile from their Geo-Information Database (Geoweb) of the weirs in their management (Stuwen_VNoord). The shapefile is converted to a GeoJSON-file and inserted to the TYGRON platform.

3.2.4. Boundary conditions

The same discharge and water level measurements that are used in the reference model are also used in the TYRGON model (Section 2.3.6).

3.3. Apply data to model input

3.3.1. Surface elevation Vecht profile

The bed level of the Overijsselse Vecht is measured with a radar boat between the German border until weir Hardenberg (Section 2.3.2.). Areas that are not measured need to be manually added in TYGRON. This is done by creating a raster in QGIS with a height attribute and importing the raster in TYGRON as GeoTIFF (Appendix B2).

3.3.2. Roughness

In TYGRON the hydraulic roughness is coupled to the terrain type which is expressed by the Gauckler-Manning coefficient n. The default Manning values are derived from the online accessible database WikiEngineer (TYGRON, 2019). If the value of the hydraulic roughness is changed to, for example, a water terrain, the hydraulic roughness is changed for all terrains defined as water. A new terrain needs to be initialized for the main channel of the Vecht, which overwrites the model defined terrain with Manning roughness values. To make a distinction between the main channel of the Vecht and all other water terrains in the model, a new terrain type "Main channel" is made.

3.3.3. Structures in TYGRON

There are three types of structures relevant to adjust in the TYGRON model, namely weirs, inlets, and bridges. The weirs and inlets are structure types that can be inserted as a GeoJSON file and need to have specific attributes to interact with the simulated water. The perception of a bridge in TYGRON is based on a function which describes the purpose and properties of a type of structure. The term function is, in this case, jargon from urban planning when dealing with zoning plans and not a mathematical formula. For a further explanation to structures included in the TYGRON model see Appendix B3.

3.3.4. Boundary conditions

The boundary conditions in the reference model of SOBEK are adopted for the TYGRON model. To define the boundary conditions in TYGRON, the point-based construction inlet is used (Appendix B3).

The upper boundary condition in SOBEK consists of a constant discharge for the 1/4Q discharge scenario and a Q-t relation of 744-timesteps of an hour for the T1, T10 and T200 discharge scenarios. The 1/4Q discharge scenario is defined by an inlet with a constant discharge by giving the attribute INLET_Q a value of 23 m^3/s. To adopt the same boundary condition for the larger discharge scenarios, (T1, T10, T200) the data input set of the discharge wave is adjusted. In TYGRON the number of input values that can be included in an inlet is restricted to 100 (this results in 50 values of time + 50 values of discharge = 100 input values). Therefore, the discharge wave in SOBEK is transformed and reduced to 50-timesteps with a corresponding discharge, (Figure 10). This method is applied for each discharge wave from the SOBEK model. For the smaller lateral flows (numbers 2,4,5,6,7 in Figure 5) the discharge wave has a square shape which can directly be copied from the SOBEK case.

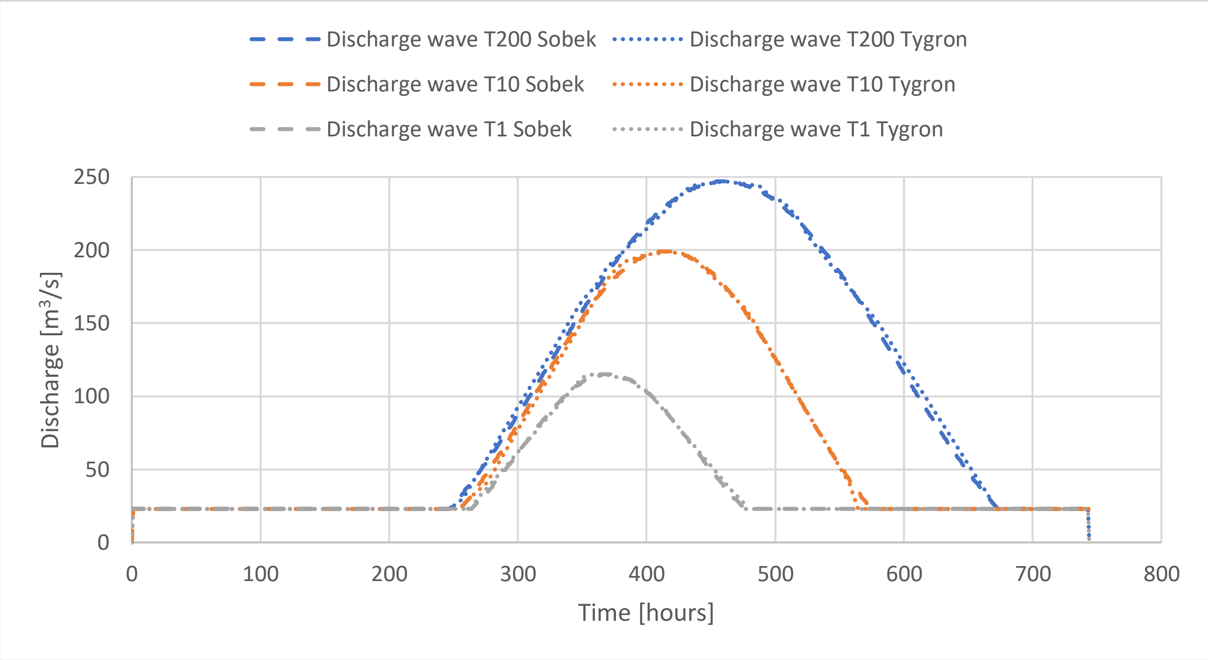


Figure 10: The discharge waves of the T1, T10 and T200 discharge scenarios from SOBEK (dashed lines) and the adjusted discharge waves with larger timesteps in TYGRON (point lines).

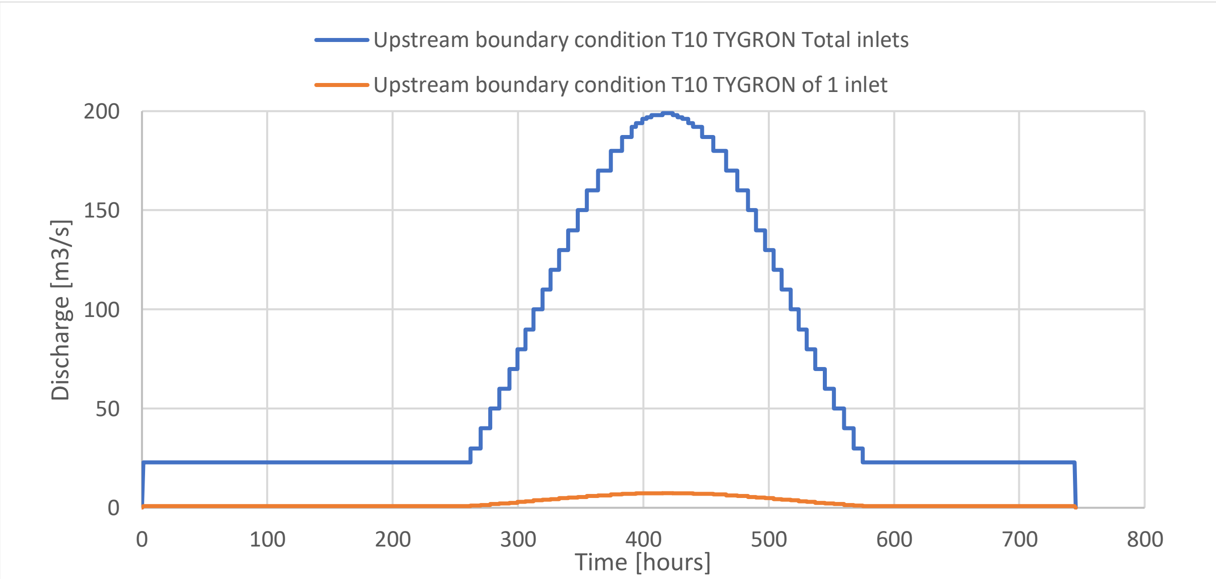
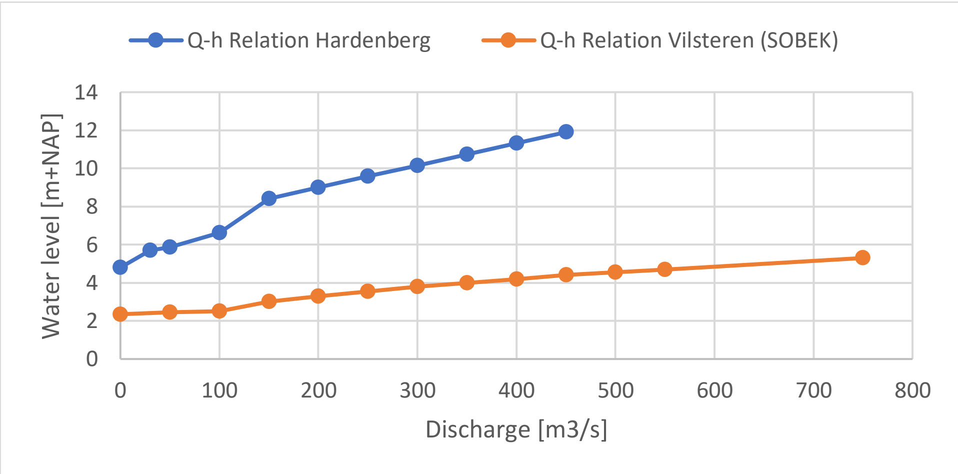


Figure 11: The input data in TYGRON causes a jump per defined discharge/time-step resulting in a non-linear discharge wave. When the total wave is divided over 28 inlets in the length and width of the location of the upstream boundary condition, the discharge wave is equally spread causing that the wave in SOBEK is reached.

To reproduce the discharge wave in SOBEK, 28 inlet structures are used as the upper boundary condition. The discharge and time values are equally divided over the length and width of the 28 inlets, (Figure 11 and 13b). Next to the inlet structures, a dam is created upstream from the upper boundary condition (Figure 13b). This dam prevents water flowing in the upstream direction and leaking out of the model domain.

The Q-h relation in TYGRON is based on the design water levels and discharges downstream at weir Hardenberg. Discharges larger than 150 m^3/s have never been measured at Hardenberg and have therefore been extrapolated (Figure 12). The lower boundary condition in SOBEK is a Q-h relation. In TYGRON it is not possible to create a Q-h relation with one condition because an inlet can only import water levels (Upper/Lower threshold) and discharges (Inlet Q). A Q-h relation can be approached by creating multiple outlets (inlet with a negative discharge). Per outlet, a water level (upper threshold) and a negative discharge (Inlet Q) is defined. When the defined water level is reached, the outlet will pump water with a defined amount of water out of the model. In total 33 outlets are defined and function as a Q-h relation (Figure 13a). In Figure 13a each row represents a water level with a discharge. To minimize the amount of water flowing past the boundary condition, three outlets are placed over the width of the channel. The middle outlet contributes to 60% of the discharge, while the left and right outlets both contributes to 20%. The outlets are placed in descending order by the value of water level.



Discharge [m^3/s]	Water level [m+NAP]
0	4.8
30	5.69
50	5.859
100	6.632
150	8.42
200	9
250	9.58
300	10.16
350	10.74
400	11.32
450	11.9

Figure 12: The Q-h Relation at Hardenberg is defined by 33 inlets, which “pump” water out of the system at a defined discharge and water level. The water level relation is based on the discharge measurements at De Haandrik and model results by increasing constant discharge in the upper boundary condition.

Figure 13: 33 inlets are used to define the lower boundary condition (left figure). Each row represents a water level (in descending order from north to south) over which the corresponding discharge is defined over 3 inlets in width. The middle inlet contributes to 60% and outer inlets contribute to 20% of the related discharge. The right figure presents the 28 inlets used as an upper boundary condition where the discharge is equally distributed over the length and width of the channel. The greyscale in the right figure presents the dam as a rasterized area where the height is increased to 20 m.

3.4. Used grid cell size

A grid cell size of 2x2 m is used to comply with a sufficient bathymetry accuracy and computation time see (Appendix B4). A grid cell size of 2x2 m results in a computation time between 0:45 – 2 hours.

3.5. Check before calibration

The TYGRON model is checked if the 1/4Q and T10 discharge scenarios simulate as expected. It is expected that in the 1/4Q scenario water will only flow in the main channel and the floodplains flow with the main channel in the T10 scenario.

During the simulation of the 1/4Q event, the water flowed over the main channel to the floodplains. This results in an unexpected simulation of the 1/4Q scenario. Additional calibration of the weir height is required to increase the amount of flow over the weirs and decrease the water levels upstream from weir De Haandrik. Weirs in TYGRON are connected to two grid cell centre points, one for the entry and one for the exit of flow over the weir. This results in simulated flow, which partly flows over the weir and partly flows past the weir in the 1/4Q scenario (in which water only should flow over the weirs). See Appendix B5 for a more detailed description.

4. RQ1: Comparing the simulated water levels

In this chapter, the simulated water levels in TYGRON are analysed and compared with SOBEK. The calibration and validation methods are described as first and next, the results are presented per sub-question.

4.1. Method RQ1

TYGRON is calibrated for two scenarios: 1) a simulation of flow only in the main channel (1/4Q scenario) and 2) a simulation of flow in the main channel and the floodplains (T10 scenario).

The TYGRON model needs to be calibrated on the weir height for the 1/4Q scenario (Appendix B5). After the 1/4Q scenario is calibrated on the weir height, the model will be calibrated on the hydraulic roughness. The 1/4Q scenario is calibrated on the hydraulic main channel roughness while the T10 scenario is calibrated by the hydraulic roughness of the floodplains.

4.1.1. Calibration threshold weir

As stated in Section 3.5, water levels are influenced by the way weirs interact with the 2D computation scheme. Due to the constant weir height in TYGRON, the weir threshold cannot be controlled in the 1/4Q scenario. To obtain a balance between the representative water levels upstream/downstream of the weir and an appropriate weir height, the height is changed between its maximum and minimum values (Appendix B3). The 1/4Q scenario is simulated with a hydraulic main channel roughness of 0.025 s/m$^{1/3}$ when the weir heights are changed.

The 1/4Q scenario is calibrated on the weir height when 1) there is no inundation in the floodplains and 2) the difference between the upstream water level and the upstream weir threshold is minimal at weirs De Haandrik and Hardenberg. In the T10 scenario, a maximum of 200 m^3/s will flow through the system. In this situation, the weirs need to be on its minimum value to convey a large amount of water quickly through the river system of the Overijsselse Vecht. Therefore, the minimum weir height value is used for the T10 and more extreme discharge scenarios.

4.1.2. Calibration roughness

In the 1/4Q scenario water only flows through the main channel and in the T10 scenario water will also flow in the floodplains. The SOBEK model is already calibrated and the value of the calibrated main channel roughness corresponds to a Chézy value of 25 m$^{1/2}$/s for the 1/4Q scenario and 35 m$^{1/2}$/s for the T10 scenario. The Chézy values of SOBEK are converted to Manning values to compare the results with the calibrated values in TYGRON, (Table 6). The Chézy roughness values are converted based on the symmetrical cross-section at De Haandrik (Appendix A1).

Table 6: Design water levels and calibrated main channel roughness values of the 1/4Q and T10 discharge scenario

Measurement location:	**De Haandrik**	**Calibrated Chézy value Sobek [m$^{1/2}$/s]**	**Manning value Sobek [s/m$^{1/3}$]**
Design water level 1/4Q [m]:	7.47	25	0.036
Design water level T10 [m]:	10.36	35	0.026

First, the main channel roughness is calibrated in the 1/4Q scenario. The hydraulic roughness (Manning) of the main channel should be in a valid range between 0.025-0.050 s/m$^{1/3}$ which represents roughness values of a clean straight stream to winding streams with some pools and shoals (Chow, 1959). Secondly, the floodplains are calibrated in the T10 scenario. The same value used for the calibrated main channel roughness in the 1/4Q scenario is used for the main channel in the T10 scenario. The hydraulic roughness of the floodplains is dependent on the land-use or ecotope and can vary between 0.030-0.150 s/m$^{1/3}$ (Chow, 1959). The values of the hydraulic roughness in the floodplains and main channel are presented in Appendix C1. The roughness is changed with 0.005 s/m$^{1/3}$ till a minimum error is found between the design water levels and the simulated water levels downstream at the weir De Haandrik. Since weirs are not working properly in TYGRON (Section 3.5.), the 1/4Q and T10 scenario are also simulated in a situation without weirs. This is done to analyse the simulated water levels as result of the governing flow equations and parameter sets without the influence of the weirs.

4.1.3. Performance calibration TYGRON

To test the performance of the calibrated TYGRON model at average conditions and extreme floods, the calibrated weir height and main channel roughness values for 1/4Q scenario are used to simulate the 1/100Q scenario (average summer condition) and the calibrated main channel and floodplain roughness for the T10 is used to simulate the T1 (average flood), and T200 (extreme flood) scenarios. The difference will be analysed between the simulated maximum water levels and the design water levels downstream at weir De Haandrik and the water levels over the whole trajectory in all scenarios. The results give insight where the calibrated main channel roughness in 1/4Q or T10 is a better/worse approximation of average/extreme flood conditions and if this is influenced by variations of the main channel roughness and the weir threshold value.

4.1.4. Propagation of the discharge wave

To analyse the diffusive and advective effects on the discharge wave, the propagation of the discharge wave is analysed between De Haandrik and Hardenberg in the T10 scenario. The propagation of the discharge wave is compared to the SOBEK case to analyse whether the discharge wave behaves differently in TYGRON due to the hydraulic roughness, boundary conditions or grid properties.

4.2. Results RQ1

4.2.1. Calibration weir height

First, the weir height of weir De Haandrik is changed to a value where there is no inundation of the floodplains. This results in a weir height of 8.50 m for weir De Haandrik.

Secondly, the weir height of weir Hardenberg is changed. Using the maximum weir height in the 1/4Q scenario (7.10 m) results in a maximum simulated water level of 9.18 m at weir De Haandrik and 7.32 m upstream at weir Hardenberg. The downstream simulated water level of weir Hardenberg is 5.69 m because of the influence of the downstream boundary condition.

By decreasing the weir height to 6.00 m, the maximum simulated water level upstream at weir De Haandrik is 9.10 m and upstream at weir Hardenberg 6.80 m. Combining the 8.50 m weir height at weir De Haandrik with the 6.00 m weir height at Hardenberg results in a preservation of the upstream weir threshold at De Haandrik and Hardenberg.

4.2.2. Calibration hydraulic roughness

1/4Q discharge scenario

Six simulations were executed with hydraulic roughness values between 0.025-0.050 s/m$^{1/3}$ with steps of 0.005 s/m$^{1/3}$ difference. Table 7 presents the hydraulic roughness and the corresponding water levels just downstream of weir De Haandrik.

A minimum difference between the simulated water levels and the design water level is not reached with a Manning value of 0.025 s/m$^{1/3}$. The difference between the simulated water level and the design water level is 1.67 m. The difference decreases with lower roughness values, but values lower than 0.025 s/m$^{1/3}$ are out of the range of valid roughness values described by Chow, (1959). Therefore, the calibrated main channel roughness is set to a Manning value of 0.025 s/m$^{1/3}$ based on the simulation of the 1/4Q discharge scenario. Compared to the calibrated hydraulic main channel roughness in SOBEK (0.036 s/m$^{1/3}$), the calibrated roughness in TYGRON is much smoother. Calibration on hydraulic roughness is not sufficient for the 1/4Q scenario. This is because of the large difference (1.67 m) presented between the simulated water level and design water level at weir De Haandrik at the main channel roughness of 0.025 s/m$^{1/3}$ and it is expected that lower roughness values still result in a significant difference.

Table 7: The results of the simulated maximum water levels downstream at weir De Haandrik and the difference with the design water levels at De Haandrik are presented. The lowest error is obtained beyond the lowest boundary of the calibrated reach; therefore, the main channel is calibrated with a hydraulic roughness value of 0.025 $s/m^{1/3}$.

	Downstream weir De Haandrik	
Design water level [m+NAP]	7.47	
	Simulated water level [m+NAP]	The difference [m]
Manning 0.025	**9.14**	**+1.67**
Manning 0.030	9.18	+1.71
Manning 0.035	9.21	+1.74
Manning 0.040	9.24	+1.77
Manning 0.045	9.26	+1.79
Manning 0.050	9.28	+1.81

Figure 14 presents the maximum simulated water levels in length profile of the Vecht between the German border until just after weir Hardenberg in SOBEK and TYGRON for the 1/4Q scenario. In Figure 14, the maximum simulated water levels in SOBEK are saved at calculation points with a mutual distance of approximately 100 m. In TYGRON the maximum simulated water levels are extracted from measurement points with a mutual distance of approximately 200 m.

A clear difference in water level slope profile was found between the SOBEK and TYGRON simulations. The water level slope in SOBEK is less steep than the simulation in TYGRON. On average, the TYGRON simulation results in larger maximum simulated water levels compared to SOBEK. The SOBEK profile shows a hydraulic jump at weirs De Haandrik and Hardenberg while in TYGRON this only occurs at weir Hardenberg.

In TYGRON flow is unexpectedly simulated along the weirs, resulting in the higher water levels at weir De Haandrik (Appendix 5). However, the hydraulic jump should be presented at weir De Haandrik as a result of the obstruction caused by the weir and the minor slope in the weir section. At Hardenberg, the elevated area of the weir causes that the upstream water levels are maintained while the downstream water levels are maintained by the downstream boundary condition. Compared to the simulation without weirs, the water level slope is the same over the length profile. Notably, the simulation without weirs still results in large water levels at De Haandrik. The large water levels can therefore not be linked to the malfunctioning of the weirs in TYGRON.

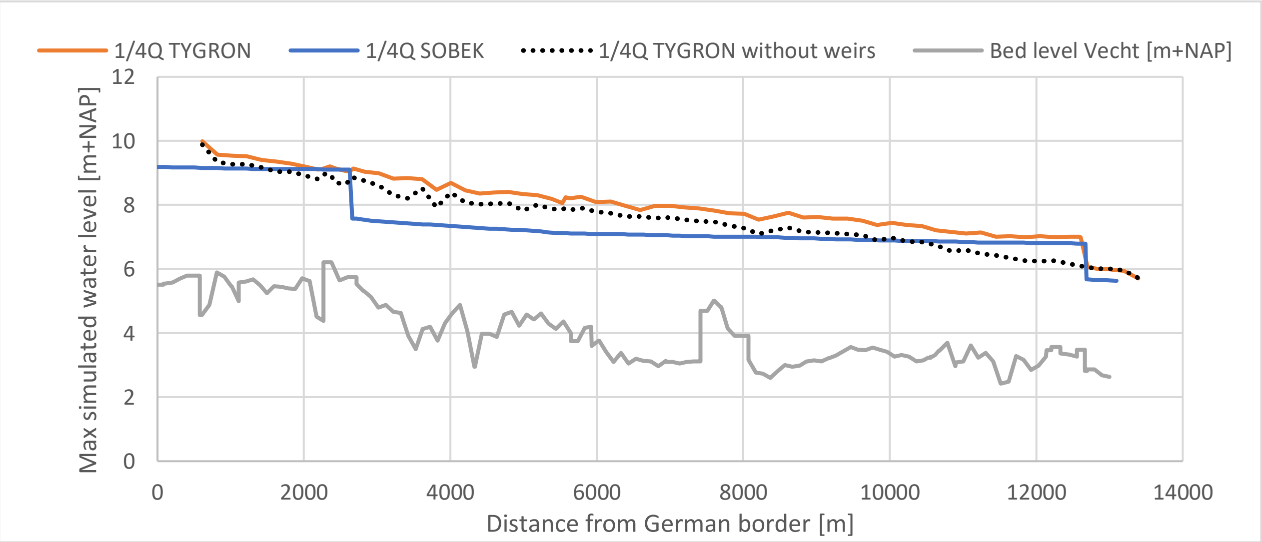


Figure 14: The length profile of the maximum simulated water levels in the 1/4Q scenario (average winter scenario).

T10 discharge scenario

Five simulations were executed with different floodplain scenarios ranging from minimum to maximum valid hydraulic roughness values per ecotope/land-use for the T10 discharge scenario described by Chow, (1959) (Table 8). The results are presented in Table 9. The minimal difference between the simulated water levels and design water levels are, just in the 1/4Q scenario, lower than the lowest value for the hydraulic roughness defined by Chow, (1959). Therefore, the calibrated value of the hydraulic floodplain roughness is set to the minimum value (Scenario 1).

The difference between the simulated water levels and the design water level is 0.30 m downstream at weir De Haandrik. The calibrated roughness values of the floodplains are in line with the SOBEK reference case. The difference between the cultivated area and grassland roughness values is 0.003 $s/m^{1/3}$. SOBEK is calibrated with larger values for the grassland roughness (0.033 $s/m^{1/3}$) and TYGRON is calibrated with larger values for the cultivated areas (0.030 $s/m^{1/3}$). The largest difference between the roughness values in the SOBEK reference case is the roughness value for ecotope dense bushes with trees (0.058 $s/m^{1/3}$). In TYGRON this value is 0.012 $s/m^{1/3}$ larger compared to SOBEK. However, the effects on the maximum simulated water levels are only locally affected by this ecotope because the occurrence is minimal and not widely spread in the hydrodynamic model. It is expected that roughness values far out of the reach of Chow, (1959) are needed to calibrate the TYGRON case for the T10 scenario.

Table 8: Hydraulic roughness values (Manning in $s/m^{1/3}$) for the different ecotopes in TYGRON per floodplain scenario.

Ecotope roughness /Floodplain scenario	**Scenario 1 (Minimum)**	**Scenario 2**	**Scenario 3 (Average)**	**Scenario 4**	**Scenario 5 (Maximum)**
1. Grassland/Openland	0.030	0.033	0.035	0.043	0.050
2. Cultivated areas	0.030	0.035	0.040	0.045	0.050
3. Dense bushes with trees	0.070	0.085	0.100	0.125	0.150

Table 9: The results of the maximum simulated water levels directly downstream from weir De Haandrik. The minimal difference between the maximum simulated water levels and the design water level at the lowest reach is 30 centimetres.

Ecotope roughness /Floodplain scenario	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Design water level [m +NAP]**
Simulated water level De Haandrik [m+NAP]	**10.66**	11.08	11.11	11.26	11.39	10.36
Difference [m]	**+0.30**	+0.72	+0.75	+0.90	+1.03	

Figure 15 presents the maximum simulated water levels in length profile of the Overijsselse Vecht between the German border until just after weir Hardenberg in the T10 scenario for SOBEK and TYGRON. In Figure 15 it is visible that the water level slope is the same in both hydrodynamic models. The SOBEK simulation results in an underestimation of the design water level (-0.44 m), directly downstream at De Haandrik. The TYGRON simulation results in an overestimation of the design water level (+0.30 m). On average the maximum simulated water levels are larger in TYGRON compared to SOBEK.

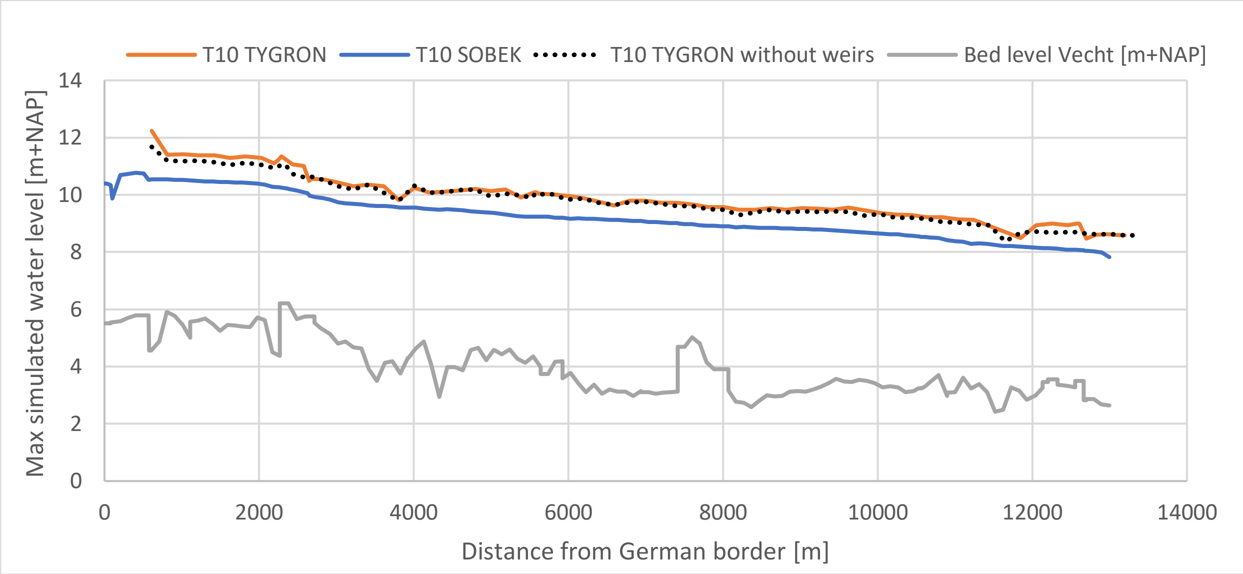


Figure 15: The length profile of the maximum simulated water levels in the T10scenario (1/10 years).

4.2.3. Performance calibration TYGRON

The performance of the calibrated main channel and floodplains is analysed by simulating the calibrated values in the 1/100Q, T1 and T200 scenarios. The results are presented in Figure 16.

All scenarios have the same water level slope in the length profile. At the 1/100Q scenario, the simulated water levels after weir Hardenberg are larger compared to the water levels in between the weirs. The downstream boundary condition causes that the water levels are maintained and therefore increased after weir Hardenberg, while weir De Haandrik and Hardenberg partly prevent water flowing in between the weir section. The performance of the simulated water levels in the 1/100Q scenario can be increased after the recalibration of the weir height and hydraulic roughness.

Overall, the simulated water levels show a large local variance in the length profile. The local variance of the simulated water levels is related to complex geographic reaches (e.g. steep bends, incoming lateral flows, and floodplains) of the Overijsselse Vecht. In Appendix C2 are the locations presented, which show a local difference of > 0.10 m in the length profile of the 1/4Q and T10 scenario.

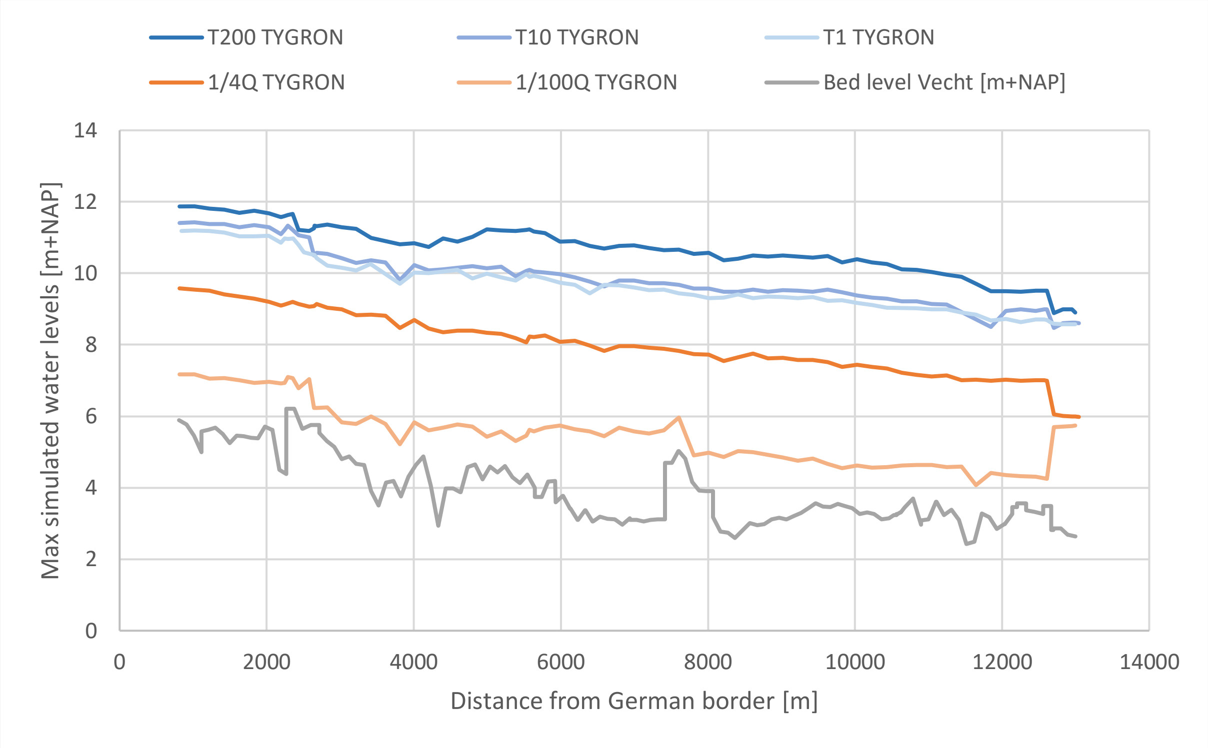


Figure 16: The maximum simulated water levels in the T200 (1/200 years), T1 (yearly event) and 1/100Q (average summer condition) scenarios as result from the calibrated values used in the T10 and 1/4Q scenario.

4.2.4. Propagation discharge wave

The diffusive and advective effects of the discharge wave are analysed in the T10 discharge scenario. Figure 17 presents the propagation of the discharge wave between the upstream boundary condition until weir Hardenberg in TYGRON (left figure) and SOBEK (right figure). The height of the discharge wave increases with 0.6 m between the upstream regime until the middle regime of the river Vecht. The increasing discharge wave is the result of incoming lateral flows. Between 715 and 5,784 m, it is also visible that the wave increases in width because of diffusion. Further downstream the wave shows a different pattern which can be related to the influence of the downstream boundary condition. As described in Section 3.3.4., the downstream boundary condition is not a Q-h relation. The steep shape of the discharge wave at 11,445 m and 13,194 m is the result of the constant outflowing discharge at an imposed water level. Compared to the discharge wave in SOBEK, both waves decrease with the same rate over the length of the Vecht and reach their maximum value at the same time.

The main difference between the two waves is that the wave in TYGRON is wider and lower compared to SOBEK. This is possibly related to the following aspects: 1) a large influence of numerical viscosity in the square grid dampening the discharge wave, 2) the influence of how the upstream and downstream boundary conditions are created in TYGRON.

The discharge wave in SOBEK is translated into a fitted and compressed discharge wave in TYGRON (see section 3.3.4.). Due to the larger time steps used to create the discharge wave and the spreading of multiple points over the length and width at the location of the upstream boundary condition, the shape of the discharge wave is flattened in TYGRON. The square grid in TYGRON makes it more difficult to distribute flow in streamwise direction since the Overijsselse Vecht contains a meandering profile (Bomers et al., 2019; Caviedes-Voullième et al., 2012). A larger numerical viscosity has the same effect on the water levels as increasing the hydraulic friction (i.e. dampening of the discharge wave and delay in peak flow).

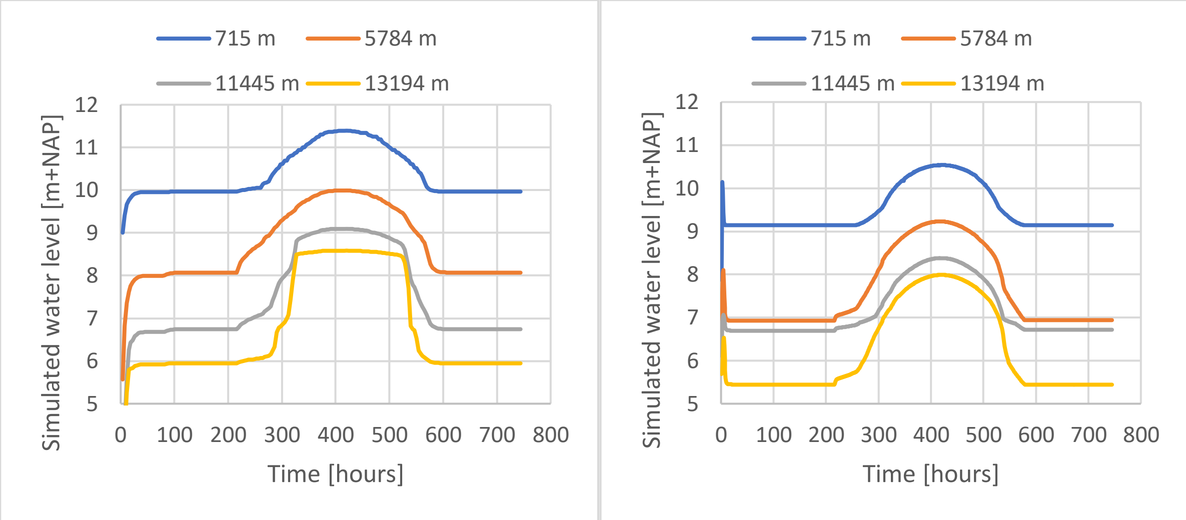


Figure 17: Propagation of the discharge wave in TYGRON (left figure) and SOBEK (right figure) derived at four measurement points at distance from the German border.

4.3. Conclusion RQ1

From this chapter, it can be concluded that TYGRON is capable to predict maximum water levels at large discharge scenarios (T1, T10 and T200) with a considerable degree of uncertainty. Based on the T10 scenario, the maximum simulated water level is overestimated by 0.30 m at weir De Haandrik. It is likely that the simulated water levels over the entire length profile are also overestimated. Furthermore, the smaller discharge scenarios (1/4Q and 1/100Q) results in unrealistic water levels in the length profile. During flow scenarios where the water levels are significantly influenced by river weirs, a hydraulic jump is expected in the length profile, which is not the case in the 1/4Q scenario in TYGRON.

4.4. Suitability calibrated model

The TYGRON model can simulate maximum water levels at extreme discharge scenarios. The maximum simulated water levels are probably overestimated since the downstream boundary condition is only “pumping” water out of the model over the main channel. In the T10 discharge scenario, water is also flowing in the floodplains resulting that water flows past the downstream boundary condition instead of being pumped away. Besides, the measured discharges consist of ±40% uncertainty (without applying too much statistics) (R.W.A. Vechtstromen, 2015). This uncertainty results in that the design water levels do not necessarily correspond to the discharge with the same return period and that the maximum simulated water levels are calibrated based on this uncertainty.

Compared to the T10 calibrated model in SOBEK, TYGRON results in a smaller difference between the design water level and the simulated water level at weir De Haandrik (0.06 m more accurate). Considering the aspects mentioned above, the simulated water levels modelled by TYGRON and SOBEK need to be interpreted with caution since the design water levels contain uncertainty and might differ from the actual water level in the Overijsselse Vecht at a given discharge.

For the remainder of this study, the 1/4Q, T1 and T10 discharge scenarios will be used to analyse the sensitivity of the calibrated parameters. The calibrated values used in the T10 discharge scenario are expected to predict a historical flood event and therefore validate the performance of the hydrodynamic model. Since TYGRON overestimates the T10 discharge scenario, the historical event is probably also overestimated. The calibrated 1/4Q scenario can be used to compare the effects on the simulated water levels and flow over the weirs when the dimensions are changed, despite that the simulated water levels between the weirs are incorrect. Making a comparison with the river weirs in SOBEK gives insight into the differences in the conception of weirs and how weirs can be improved in TYGRON.

5. RQ2: Validation flood event and inundation

In this chapter, an analysis is made whether TYGRON and SOBEK can provide a valid simulation based on a historical flood event in the Overijsselse Vecht. First, the method is described and next, the results are presented for two locations (De Haandrik and Hardenberg) where flood images are made of the Overijsselse Vecht. Thereafter, the results are discussed in the conclusion.

5.1. Method RQ2

Historical flood events in the Overijsselse Vecht are often photographed by citizens or by the R.W.A. Vechtstromen. The date of the photographs can be related to the measured discharges at weir De Haandrik to create the same input conditions as the recorded event. Based on the recorded inundation on the photographs and the water level measurement at the crossing Almelo-De Haandrik, the simulation of both hydrodynamic models can be validated.

The following photographs are used as a reference for the historical flood event of January-2018:

1. Inundation De Haandrik 9 at crossing Almelo-De Haandrik: January-2018a (Figure 21)
2. Inundation De Haandrik 9 at crossing Almelo-De Haandrik: January-2018b (Figure 22)
3. Inundation floodplains De Haandrik: January-2018 (Figure 23)
4. Video floodplains Hardenberg 4 January 2018: https://www.youtube.com/watch?v=o-uiEL98uP4 (Figure 26)
5. Video floodplains Hardenberg 6 January 2018: https://www.youtube.com/watch?v=U4UFWz-ZEJOQ (Figure 27)

The measured discharge corresponding to the period of the historical flood is presented in Figure 18. The discharge is measured between 01-01-2018/14-01-2018. To fit the shape of a discharge wave, the measurement is extended with the same measured discharge values from 7-January till 14-January and added for the period 14-December till 31-December. At the bridge at the crossing Almelo-De Haandrik, a water level measure point is located from Rijkswaterstaat (Dutch national government of infrastructure and water management). To analyse if the event of 2018 can be reproduced by both hydrodynamic models, the maximum simulated water level at the crossing Almelo-De Haandrik is compared with the measured water level. Furthermore, the recorded inundation at the photographs is compared with the simulated inundation in both hydrodynamic models.

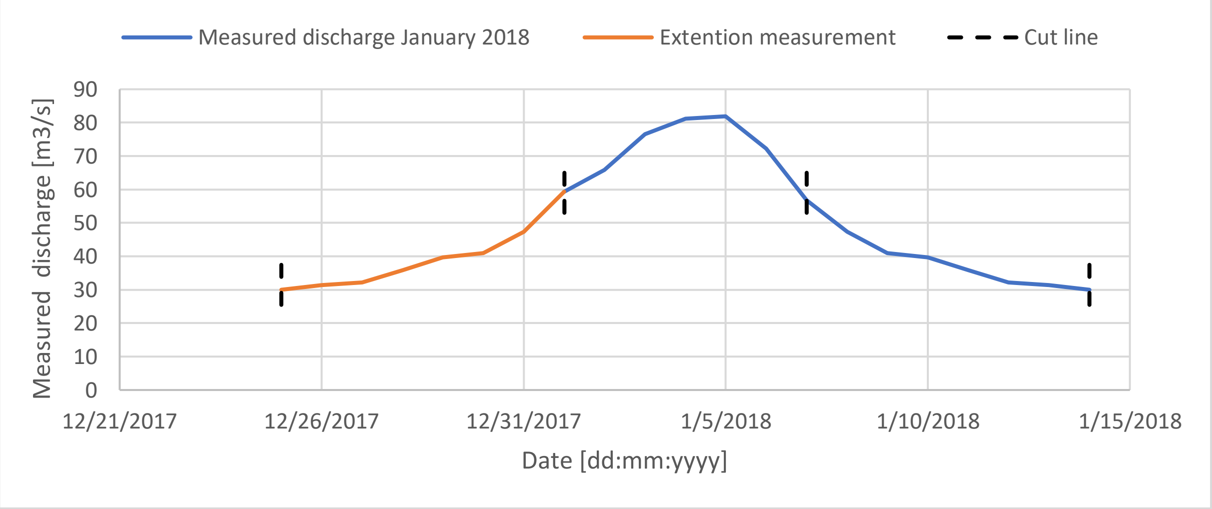


Figure 18: Discharge wave of the flood event 2018. The Blue line indicates the measured discharge from 01-01-2018 until 01-15-2018. After the peak, at 07-01-2018 the discharge wave is copied and pasted (Orange line) to fit the shape of the wave and fill the model with water before the peak flows into the model.

5.2. Results RQ2

Table 10 presents the maximum simulated water level and the measured water level at the crossing Almelo-De Haandrik and the floodplain in the north of Hardenberg. The measured water level is the same as the maximum simulated water level in SOBEK. The maximum simulated water level in TYGRON results in an overestimation of 0.54 m compared to the measurement at the crossing Almelo-De Haandrik. The maximum simulated water level at the floodplain in Hardenberg results in larger (0.61-0.71 m) water levels in TYGRON compared to SOBEK.

Table 10: Measured water level at crossing Almelo-De Haandrik and maximum simulated water level in TYGRON and SOBEK.

Measurement De Haandrik crossing Almelo-De Haandrik [m+NAP]	**Max simulated water level TYGRON [m+NAP]**	**Max simulated water level SOBEK [m+NAP]**
9.66	10.20	9.66
Max simulated water level at floodplain Hardenberg [m+NAP]	8.12-8.32	7.51-7.61

Furthermore, the simulated inundation and the recorded inundation at the photographs are compared. In Figures 21 & 22 it is visible that the residential building is surrounded by water and that the adjacent floodplains are inundated just over the toe of the dike. The simulated inundation in TYGRON complies with Figures 21 & 22. In TYGRON the inundation around the De Haandrik 9 is visible with higher quality compared to SOBEK. In SOBEK it is more difficult to indicate the inundation around De Haandrik 9 since the grid cell size in the floodplains is too large (25x25 m). Based on Figures 21 & 22, the area around De Haandrik 9 should be inundated. his is not the case in the simulated inundation in SOBEK (Figure 20). When looking at Figure 23, the floodplains on the south-side of the residential building are partly inundated which is in line with the simulated inundation in SOBEK. The simulated inundation in TYGRON results in a full inundation of the floodplains which relates to the overestimated simulation (Figure 19).

From video 1 and 2, 2 snapshots are made in Figures 26 & 27 and compared with the simulated inundation in TYGRON and SOBEK. Video 1 is made the day before the peak of the discharge wave and video 2 is made one day after the peak of the discharge wave. Based on Figures 26 & 27, the inundation is just over the toe of the dike in Figure 26 and the inundation reaches the toe of the dike in Figures 27. The TYGRON simulation results in an overestimated inundation at the dike which relates to the higher simulated water levels compared to the SOBEK case. The SOBEK simulation results in an underestimation of the inundation as the simulated inundation does not reach the toe of the dike which is presented in Figures 26 & 27.

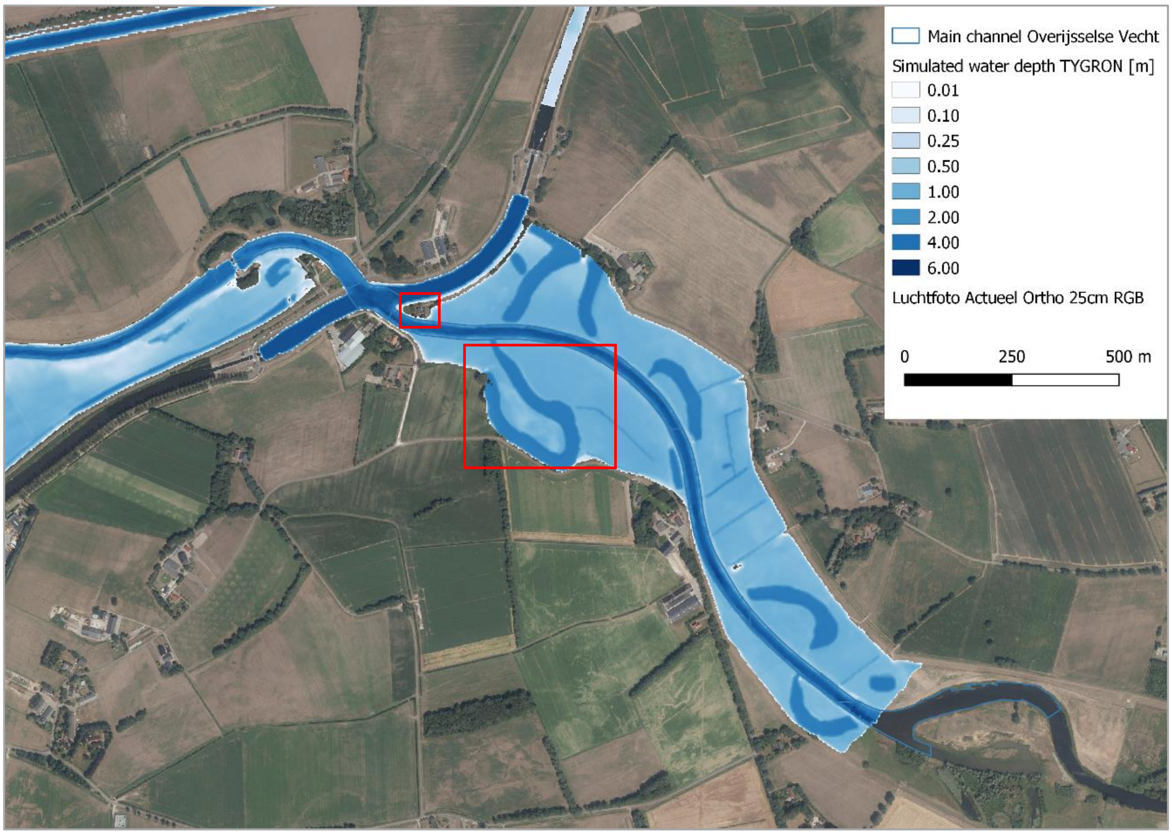


Figure 19: Inundation of the 2018 flood event in TYGRON at De Haandrik. The red rectangles indicate the location of the images. The upper rectangle indicates De Haandrik 9 and the lower rectangle indicates the floodplains.

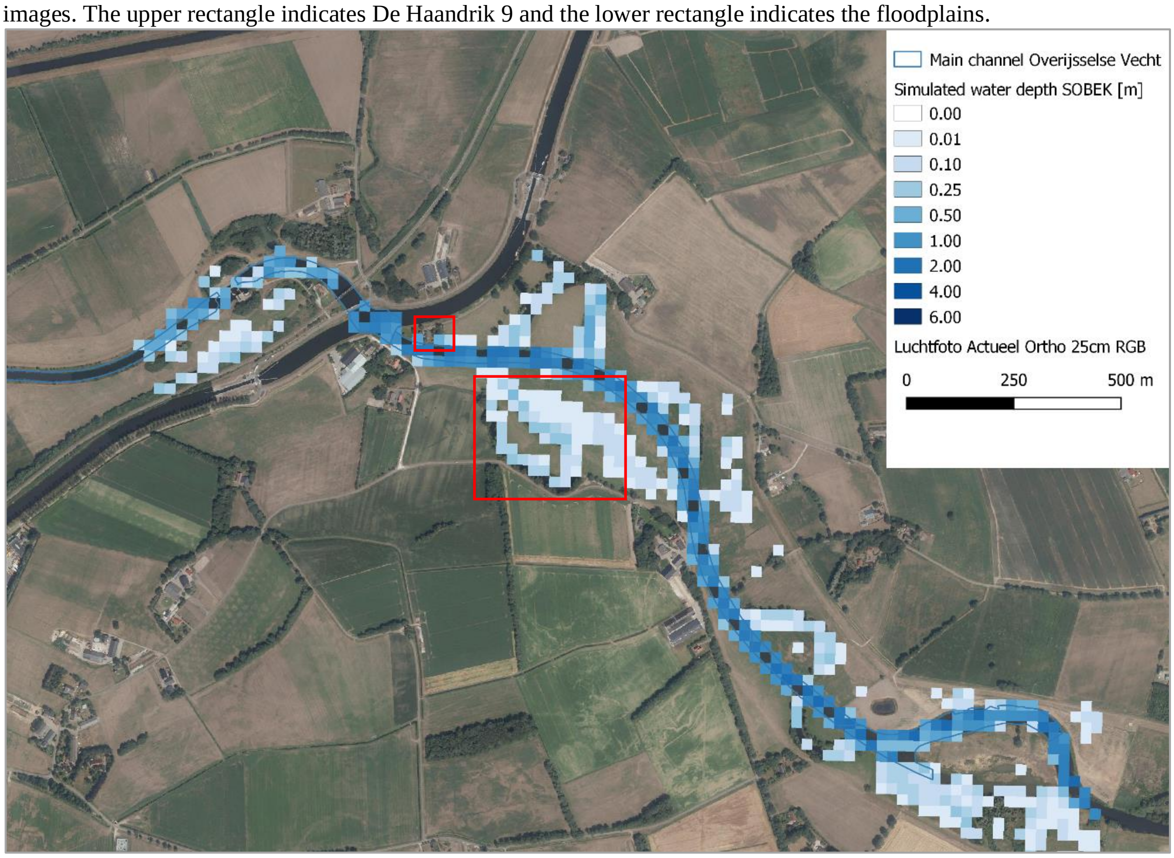


Figure 20: Inundation of the 2018 flood event in SOBEK at De Haandrik. The red rectangles indicate the location of the images. The upper rectangle indicates De Haandrik 9 and the lower rectangle indicates the floodplains.

Figure 21: Inundation De Haandrik 9 at crossing Almelo-De Haandrik: January-2018a

Figure 22: Inundation De Haandrik 9 at crossing Almelo-De Haandrik: January-2018b

Figure 23: Inundation floodplains De Haandrik: January-2018

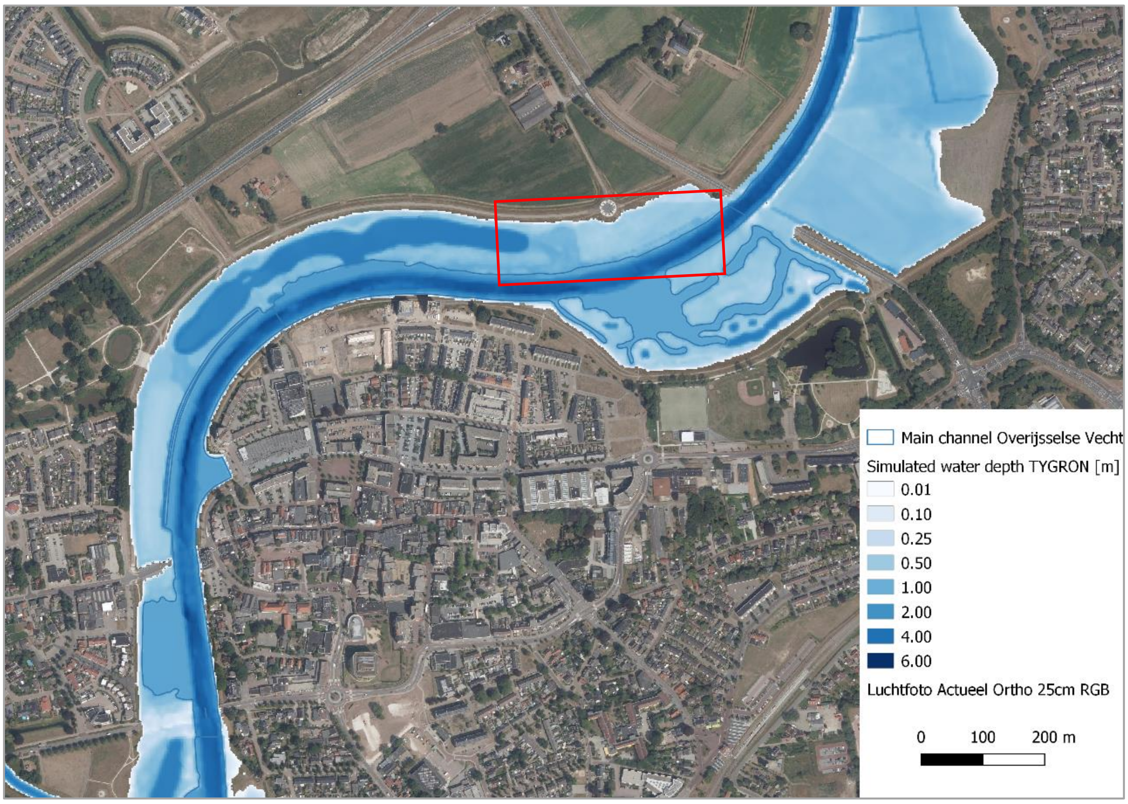


Figure 24: Inundation of the 2018 flood event in TYGRON at Hardenberg. The red rectangle indicates the location of the images.

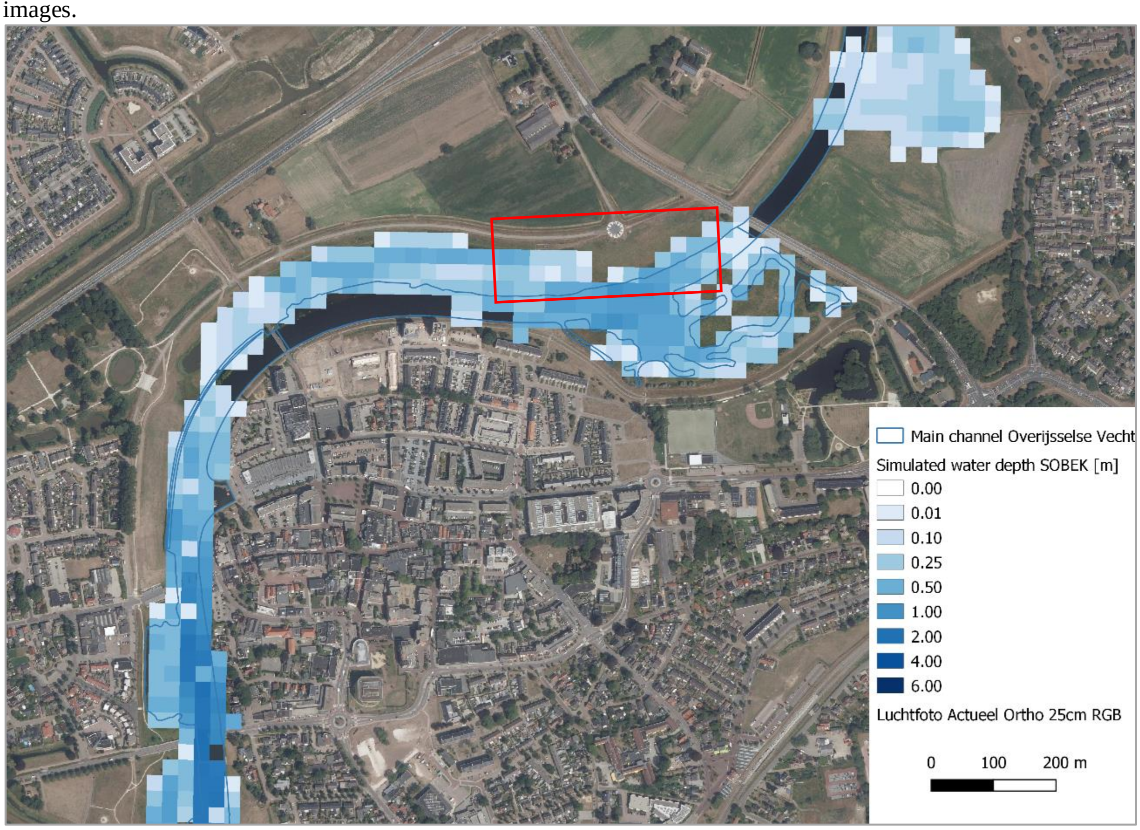


Figure 25: Inundation of the 2018 flood event in TYGRON at Hardenberg. The red rectangle indicates the location of the images.

Figure 26: Video floodplains Hardenberg 4 January 2018: https://www.youtube.com/watch?v=o-uiEL98uP4

Figure 27: Video floodplains Hardenberg 6 January 2018: https://www.youtube.com/watch?v=U4UFWz-ZEJOQ

5.3. Conclusion RQ2

From this analysis, it can be concluded that TYGRON overestimates the simulated inundation and that it is difficult to relate the simulated inundation to the recorded inundation with the SOBEK model. The simulated water level in the SOBEK model at the crossing Almelo-De Haandrik is the same as the measured water level. Therefore, it can be concluded that SOBEK is better suited to predict water levels at a selected point but only a rough indication of the inundation can be presented with the large (25x25 m) grid cell size. TYGRON can present the inundation attractively but the inundation is overestimated. Therefore, TYGRON can only be used to indicate the inundated flow path at large discharge scenarios.

6. RQ3: Comparing the simulated flow velocities

In this chapter, the simulated flow velocities from TYGRON and SOBEK are compared in the main channel and floodplains of Hardenberg. The method is described at first and the results as the second. Thereafter, the results are discussed in the conclusion part.

6.1. Method RQ3

A hydrodynamic model should correctly simulate flow velocities to e.g. predict morphological changes or vegetation development in floodplains (Sukhodolov, 2012). To analyse this, the simulated flow velocities at the maximum water levels are compared in the floodplains at Hardenberg in the T10 scenario. It is known that high flow velocities occur near the outer bend and gradually decrease towards the inner bend (e.g. Luchi et al., 2011; Sukhodolov, 2012). Since no velocity measurements are available in the Overijsselse Vecht, the flow velocity is qualitatively compared. In this comparison, the focus is set on where differences between the two simulations occur and why the flow velocities are different.

6.2. Results RQ3

Figure 28 presents the simulated flow velocity in TYGRON and Figure 29 in SOBEK, at the river bend in Hardenberg. The same order of velocity magnitudes are simulated (0.3-1.8 m/s). However, a clear difference can be observed in both simulations. TYGRON shows that the flow velocities in the meander bend are slightly increased from 0.3 to 0.9 m/s towards the outer bend in the main channel. This is in line with the expected flow pattern from literature (Luchi et al., 2011; Sukhodolov, 2012). However, in TYGRON the simulated flow velocity results in high flow velocities on both sides of the in the main channel. The results show that at the edge of the outer bend the flow velocities are between 1.5-1.8 m/s and at the edge of the inner bend 0.6-1.2 m/s while the flow velocities in the main channel are between 0.3-0.6 m/s.

The overshoot in flow velocities is inherent to the algorithm of the computational scheme in TYGRON (TYGRON, 2019). The overshoot becomes larger at steep edges when using a smaller grid cell size. In each time step, a velocity estimation is made between the cells which accelerate at steep edges.

The flow velocities simulated by SOBEK are simulated in 1D in the main channel and therefore the width and depth are averaged. Due to the missing horizontal components in the main channel, flow can only be distributed in the streamwise direction, which bottled up in the top of the bend. This results in large flow velocities (1.2 m/s) after the top of the bend and low flow velocities (0.6 m/s) in between the bends. The flow velocities in the floodplains are simulated in 2D and therefore depth-averaged. Another difference compared to the TYGRON simulations is the flow velocity values at the retention lake (in the northern part of the floodplains). The bathymetry accuracy in SOBEK is lower compared to TYGRON because the grid cell size is larger (25x25 m) compared to TYGRON (2x2 m). This results in more detailed flow velocities in the floodplains in TYGRON and more generalized flow velocities in SOBEK.

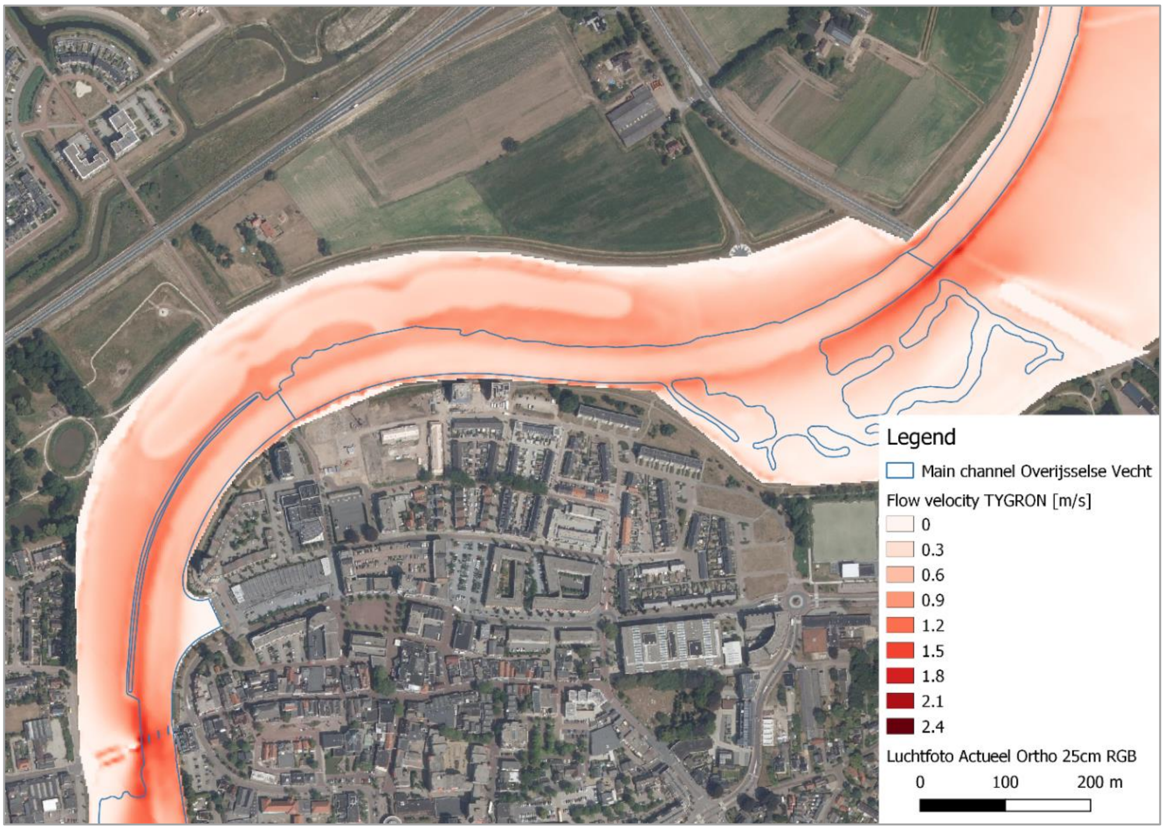


Figure 28: Simulated flow velocity at maximum water levels of the T10 event in the river bend at Hardenberg in TYGRON.

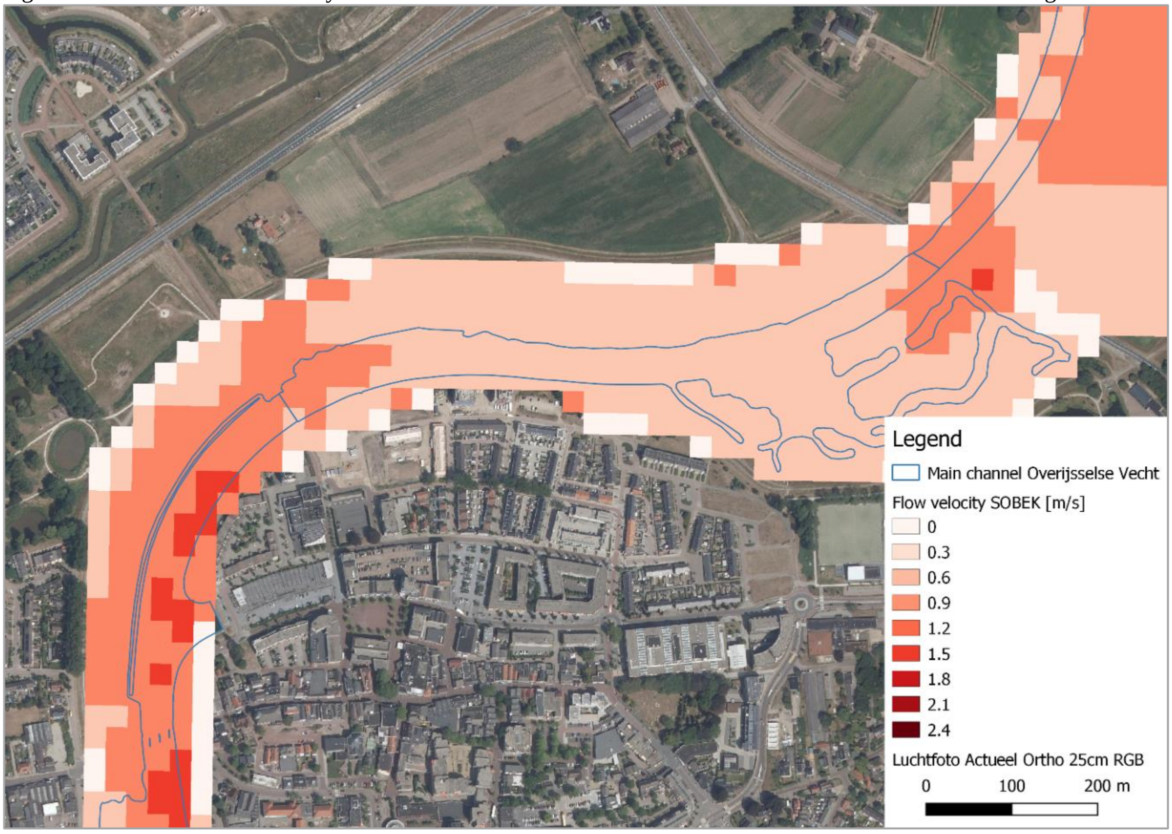


Figure 29: Simulated flow velocity at maximum water levels of the T10 event in the river bend at Hardenberg in SOBEK.

6.3. Conclusion RQ3

From this analysis, it can be concluded that TYGRON tends to predict larger flow velocities in the outer bend and lower flow velocities in the inner bend. However, at the edge of the main channel an overshoot is simulated which concludes that TYGRON cannot simulate the flow patterns as expected from the literature (e.g. Luchi et al., 2011; Sukhodolov, 2012). This is because small grid cell sizes together with the steep edges at the main channel result in an overshoot in the flow velocities in TYGRON. Nevertheless, in the main channel TYGRON simulates larger flow velocities in the outer bend. For SOBEK the flow velocities in the main channel are simulated in 1D in which horizontal flow is not captured.

The flow velocity simulations in SOBEK do not change at the location of the retention lake. Based on this can be concluded that TYGRON simulates flow velocities locally in more detail. The values of the flow velocities are comparable in both hydrodynamic models, but they cannot be validated since there are no velocity measurements available.

TYGRON is currently developing a second velocity prediction by implementing the fourth-order differential method of Runge & Kutta which may improve the transition of flow velocities at the steep edges of the main channel (TYGRON, 2019). However, it is not yet validated to what extent the new method will improve the velocity estimation in TYGRON.

7. RQ4: Sensitivity analysis

In this chapter an analysed is made of the difference in sensitivity of TYGRON and SOBEK to changes of the calibrated parameters (i.e. floodplain roughness, weir dimensions and resolution). The method is described first and next the results are presented per research question.

7.1. Method RQ4

Sensitivity analyses are mainly applied on uncertain quantities in the system (e.g. hydraulic roughness and upstream discharge) (Hall et al., 2009; Saleh et al., 2013; Xu & Mynett, 2006). In TYGRON the uncertainty of using the wrong weir height value is also included (Appendix B5). In terms of equifinality, uncertain variables and dependent model parameters could lead to the same end-state of the simulated water levels with different combinations of their values (e.g. modifications of the grid cell size, weir parameters and floodplain roughness) (Fabio et al., 2010; Papanicolaou et al., 2010; Pappenberger et al., 2005). In this analysis the influence of the following model parameters is analysed on the simulated water levels:

- Hydraulic floodplain roughness
- Weir dimensions
- Resolution (TYGRON only)

To find out if the sensitivity of the simulated water levels and flow velocities depend on the different discharge scenarios, the sensitivity analysis is executed for the mean winter discharge (1/4Q), yearly flood scenario (T=1) and extreme (T=10) discharge scenarios.

7.1.1. Hydraulic floodplain roughness

To compare how SOBEK and TYGRON respond to the same changes in the hydraulic roughness values, the roughness values in SOBEK (Chézy) need to be converted to roughness values in TYGRON (Manning) by using equation 9. The hydraulic radius used for this conversion is a cross-section of the floodplains and main channel just downstream from weir De Haandrik, (Appendix A1).

$$C = \frac{R^{\frac{1}{6}}}{n_m} \tag{9}$$

In equation 9, C is the Chézy coefficient in $m^{1/2}/s$, R the hydraulic radius m, and n_m the Manning coefficient in $s/m^{1/3}$. Table 11 presents the converted roughness coefficients for the main winter discharge (1/4Q) and the extreme flood condition (T10) on which the maximum water level is calibrated.

Table 11: Chézy values in SOBEK, which are converted to Manning values in TYGRON.

Calibrated main channel roughness	**Calibrated Chézy value Sobek in $m^{1/2}/s$**	**Converted Manning value TYGRON in $s/m^{1/3}$**
1/4Q	25	0.035
T10	35	0.027
Ecotope in the floodplain:	**Roughness (Chézy) per ecotype at 1.5-meter water depth in $m^{1/2}/s$**	**Converted Manning per ecotype at 1.5-meter water depth in $s/m^{1/3}$**
Water	37.43	0.025
Agricultural land	35.18	0.027
Production grassland	32.38	0.029
Natural grassland	28.6	0.033
Reeds	9.1	0.104
Thicket	7.08	0.133
Bushes with trees	16.22	0.058
Paved	26.59	0.036

The hydraulic roughness values of the floodplains are changed with 20% based on the calibrated roughness values in SOBEK (Chézy) and thereafter, converted to Manning values. The effect of adjustments in the floodplain roughness values is analysed and compared for the simulated water levels (in the entire trajectory De Haandrik-Hardenberg) and flow velocities (in the floodplains). The simulations are executed for the yearly discharge event (T1) and extreme discharge event (T10).

7.1.2. Weir dimensions

The different dimensionality in SOBEK (1D/2D) and TYGRON (2D) and conceptualization of the weir formula can cause simulated flow parameters to behave differently over weirs. The sensitivity analysis of the weir regime analyses the differences between a 1D/2D and a fully 2D simulation over weirs by describing the effect of the simulated water levels and discharges over the weir and how this is dependent to the weir dimensions. The weir height is changed by the maximum and minimum values and the width is changed accordingly to the same proportion (Table 12).

Table 12: Used weir dimensions (height and width) for the sensitivity analysis.

Scenario:	**De Haandrik**	**Hardenberg**
Maximum WEIR_HEIGTH m	9.10	7.11
Minimum WEIR_HEIGTH m	6.96	5.12
WEIR_WIDTH m	20.5	27
Increase WEIR_WIDTH m	23.23	31.32
Decrease WEIR_WIDTH m	17.77	22.68

The simulations are executed for the mean winter condition (1/4Q) and yearly discharge condition (T1) In the discharge conditions mentioned above, water is flowing entirely over the weir in the 1/4Q scenario and in the T1 scenario the weirs are completely drowned.

In addition, the initial settings of the weirs in SOBEK are different compared to TYGRON. In SOBEK the weirs consist of a Proportional-Integral-Derivative controller (i.e. PID controller). A PID controller applies a correction of the weir height based on the proportional, integral, and derivative terms. In other words, the water level upstream of the weir is maintained between the minimum and maximum values of the weir height. Therefore, in SOBEK the obliged weir threshold is changed instead of the weir height and width as the dimensions may not influence the simulated water level.

7.1.3. Resolution

In SOBEK it is not possible to adjust the grid cell size after the model setup. However, different grid cell sizes influence the resolution and thereby the accuracy of the simulated water levels (Benjankar et al., 2015; Bomers et al., 2019). Still, it is interesting to test which grid cell size is most effective in terms of calculation time and the accurate simulation of water levels in TYGRON. The sensitivity to the resolution will be tested using different grid cell sizes (1x1, 2x2, 5x5 m) based on low, average, and high discharge scenarios. Furthermore, a balance needs to be found between an accurate simulation of water levels and computation time. This will be analysed by comparing the length profile of the maximum simulated water levels for the grid cell sizes 1x1, 2x2 and 5x5 m.

Furthermore, for the SOBEK reference model, the difference in simulated water levels and computation time will be compared with the TYGRON model. The sensitivity analysis of the resolution describes how the selection of the appropriate model dimensionality influences the simulated water levels in terms of computation time and hydraulic friction. Finally, the simulated inundation in the floodplains is compared in SOBEK and TYGRON to analyse the reach of the inundation as results of different resolutions.

7.2. Results RQ4

7.2.1. Comparing floodplain friction

Figures 30 & 31 present the sensitivity of changes to the floodplain roughness on the maximum simulated water levels. The TYGRON model is more sensitive to changes of the floodplain roughness value and the differences between the simulated water levels increase with a larger simulated discharge.

In the T1 discharge scenario in TYGRON, the difference between the maximum simulated water levels is 0.15 m between De Haandrik and weir Hardenberg. This difference decreases in the downstream direction and shows no variation after weir Hardenberg. In SOBEK the simulated water levels only vary between the upstream boundary condition and weir De Haandrik, therefore the water levels are not influenced by the floodplain roughness. The large sensitivity in the simulated water levels is the result of the friction contributed by the floodplains. The simulated water levels in TYGRON are on average 1.3 m larger than SOBEK in the T1 scenario. Therefore, the simulated water levels are more influenced by the friction of the floodplains in TYGRON in this scenario.

This also complies with the results of the simulated water levels in the T10 discharge scenario. The sensitivity on the simulated water levels in TYGRON is 0.50 m in the upper regime of the T10 scenario and decreases to 0.25 m at weir Hardenberg. In SOBEK the difference between the maximum simulated water levels is 0.05 m between the upper regime and weir Hardenberg in the T10 scenario. Based on these results, the influence of the friction caused by the floodplains is decreasing in the downstream direction. The main reason for this decrease is caused by the fact that the Overijsselse Vecht has less space at Hardenberg and the floodplains are significantly smaller compared to the upper regime of the Vecht. A secondary effect can be related to the decreasing water levels in TYGRON. In TYGRON, the influence of the downstream boundary condition causes that the downstream water level is preserved. In SOBEK this is not the case since the downstream boundary condition is located at Vilsteren (±45 km downstream).

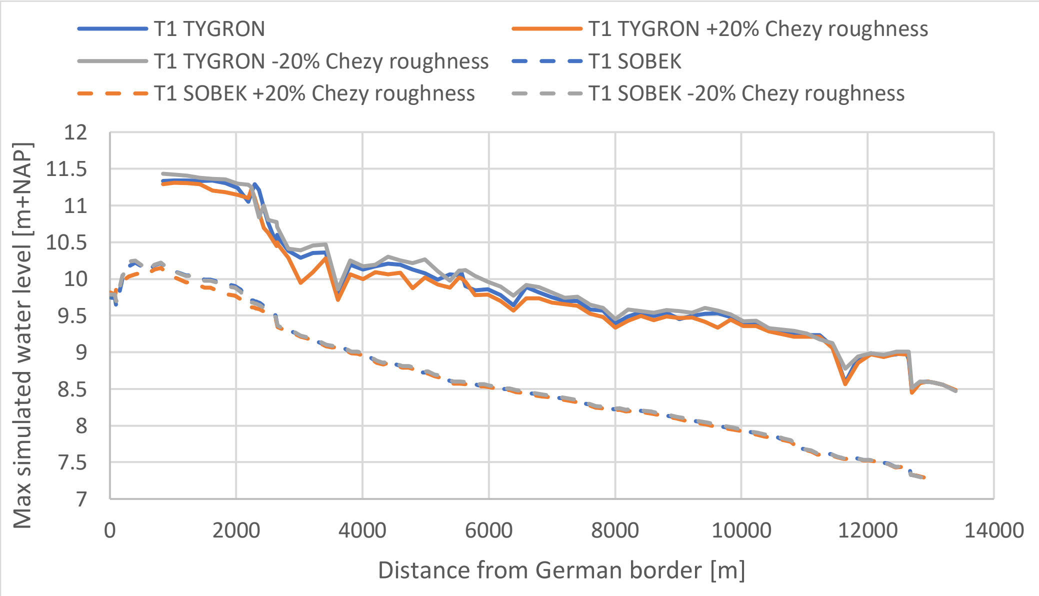


Figure 30: The sensitivity of the maximum simulated water levels when the Chézy roughness is changed with 20% in the T1 scenario.

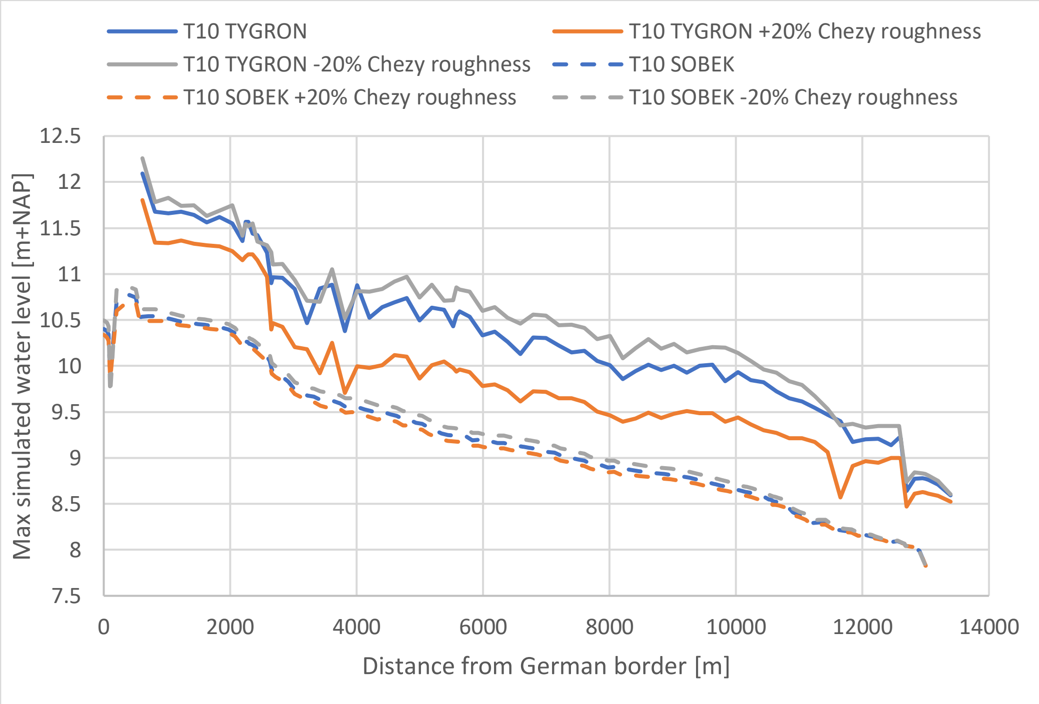


Figure 31: The sensitivity of the maximum simulated water levels when the Chézy roughness is changed with 20% in the T10 scenario.

7.2.2. Comparing weir dimensions

Figures 32 & 33 present the maximum simulated water levels and the sensitivity of the weir dimensions in the 1/4Q discharge scenario. The SOBEK simulations of the minimal and maximal weir threshold results in a cancelling of the simulation. The reason why the simulation is cancelled is that the PID controller in the weir tries to control the imposed threshold value by changing the weir height. This requires a very small timestep which eventually results in cancellation of the simulation. To indicate how the SOBEK model is sensitive to a change in the weir threshold, the threshold value of weir De Haandrik is set to 8 m.

Figure 33 presents that SOBEK is indeed not sensitive to changes of the weir width and that the weir threshold in the PID controller only influences the upstream water level accordingly to the threshold value. In the T1 discharge scenario, the upstream water levels from weir De Haandrik are also larger due to the larger weir threshold. The simulated water levels downstream from weir De Haandrik do not variate. The results of the TYGRON model to changes of the weir dimensions only shows a difference in the 1/4Q discharge scenario. In the T1 discharge scenario, the weirs are completely drowned and result in no difference in the length profile of the maximum simulated water levels. The difference in the maximum simulated water levels between the low/large weir height scenario is 0.34 m and 0.17 m between the low/large weir width scenario in 1/4Q.

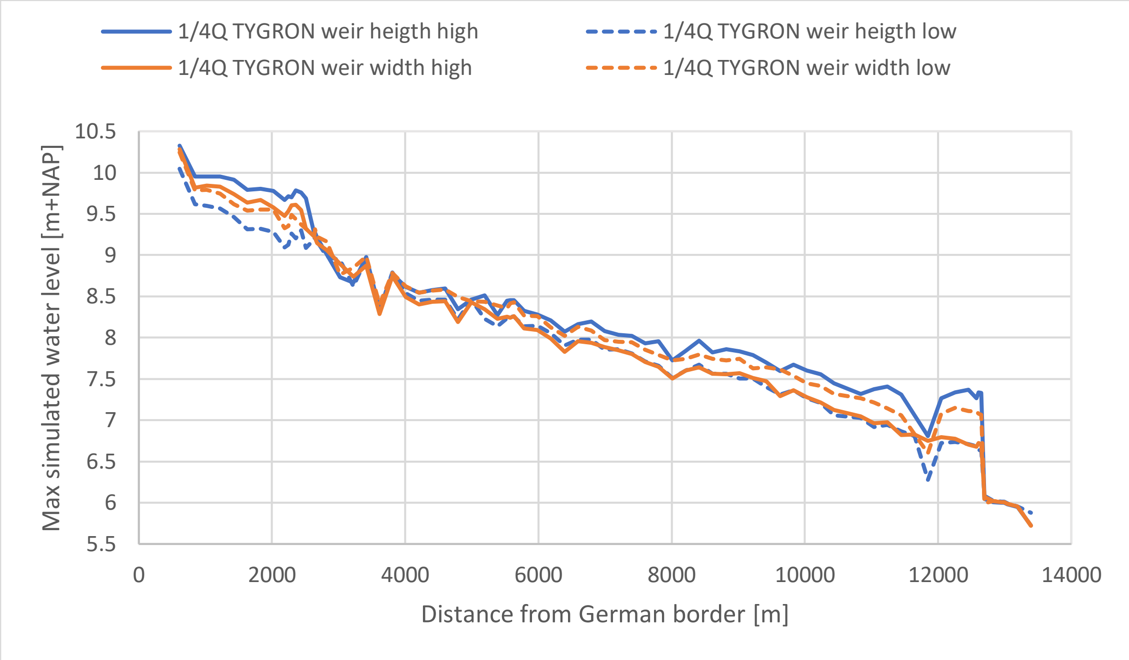


Figure 32: The sensitivity of the maximum simulated water levels at different simulations of the weir dimensions in TYGRON. The height of the weir is changed to its maximum and minimum value and the width changes according to the same ratio see (Table 12).

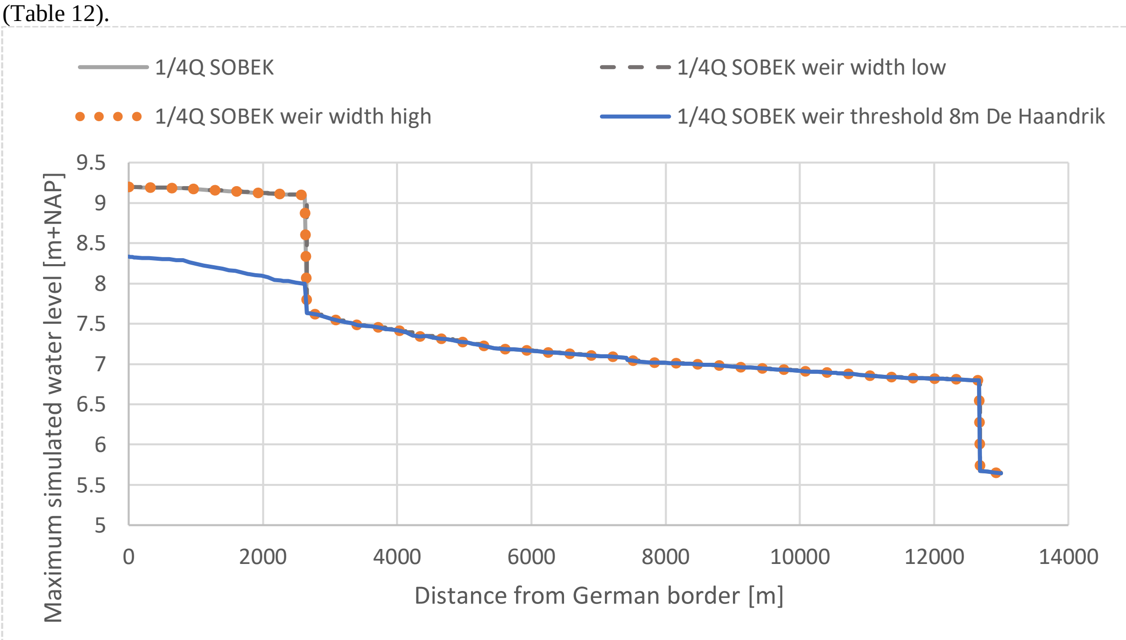


Figure 33: The sensitivity of the maximum simulated water levels at different simulations of the weir dimensions in SOBEK. The weir threshold value is changed to 8.0 m at weir De Haandrik and maintained by the PID-controller.

7.2.3. Flow over weirs

The discharge over the weirs De Haandrik and Hardenberg is compared at adjustments of the weir dimensions in the TYGRON and SOBEK case. Table 13 presents the recorded discharge over the weirs De Haandrik and Hardenberg in both hydrodynamic models. The discharge over weir De Haandrik is slightly influenced by changing the weir dimensions in the TYGRON case. More water will flow over weir De Haandrik when the height is decreased or when the width is increased. These results comply with the SOBEK case. Changing the width in SOBEK results in no difference in the discharge over the weir in the 1/4Q scenario and 4.6 m^3/s (at De Haandrik) and 2.7 m^3/s (at Hardenberg) in the T1 scenario. The T1 scenario in TYGRON results in 34 m^3/s discharge over weir De Haandrik for each weir dimension. The discharge over weir Hardenberg in TYGRON results in a large difference at an adjustment of the weir dimensions. At Hardenberg three weirs are implemented in the TYGRON model. In the case where the weir width is set to the maximum values (9.1 m at De Haandrik and 7.1 m at Hardenberg), this results in 4.84 m^3/s discharge over weir Hardenberg. Flow is partly simulated past the two weirs and over the two weirs resulting in a lower recorded discharge over weir Hardenberg.

Table 13: The discharge over the weirs in TYGRON and SOBEK per simulated scenario.

TYGRON	**Discharge over weir De Haandrik [m^3/s]**	**Discharge over weir Hardenberg [m^3/s]**	**SOBEK**	**Discharge over weir De Haandrik [m^3/s]**	**Discharge over weir Hardenberg [m^3/s]**
1/4Q weir height high	24.16	4.84	1/4Q weir height high	[-]*	[-]
1/4Q weir height low	25.84	29.82	1/4Q weir height low	[-]	[-]
1/4Q weir width high	24.85	15.45	1/4Q weir width high	23.08	26.47
1/4Q weir width low	26.34	28.49	1/4Q weir width low	23.08	26.47
T1 weir height high	33.57	43.37	T1 weir height high	104.33	89.38
T1 weir height low	34.71	84.74	T1 weir height low	104.16	97.86
T1 weir width high	33.55	39.54	T1 weir width high	105.68	88.30
T1 weir width low	34.19	84.06	T1 weir width low	101.08	85.57
*Simulations were cancelled by small time-steps due to the changed weir threshold height.					

7.2.4. Resolution

The 1/4Q and T10 scenarios are simulated for the grid cell sizes 1x1, 2x2 and 5x5 m, (Figures 34 & 45). The results show that larger grid cell sizes result in a larger variation in the simulated water levels in the length profile. However, if a scenario is simulated with a different resolution, recalibration is required.

A grid cell size of 1x1 m results in the smallest variation of the simulated water levels. However, the simulation takes 11 hours to complete in the 1/4Q scenario and 23 hours in the T10 scenario. The 1x1 m grid in the 1/4Q scenario results in a maximum simulated water level of 7.66 m upstream at weir Hardenberg. The weir height needs to be changed to a lower value to obtain the upstream weir level of 6.90 m. In addition, the water level slope in the 1x1 m grid shows the same pattern as in SOBEK (Figure 34) which was not the case in the 2x2 m grid. A smaller grid cell size may improve the discharge distribution in the streamwise direction of the main channel and hence result in a better estimation of the flow profile in TYGRON. Despite the irregularities in the length profile in the 2x2 m grid and the difference of the water level slope compared to SOBEK in the 1/4Q scenario, the computation time is within acceptable values (1 hour for the 1/4Q and 4 hours for the T10).

Simulation with a 5x5 m grid cell size shows a distorted result as the simulation results in larger water level differences in the length profile. Furthermore, the 5x5 m grid causes that the 3 inlets become inactive (which act as upstream boundary condition). The inlets connect with a centre point of a grid cell, which in the 5x5 m grid causes that 3 inlets have the same centre point and become inactive in the simulation. This can be avoided by replacing the inlets, but in that case, the initial upstream boundary is changed and hence unwanted. However, the 5x5 m grid simulates significantly faster compared to the other grids (Table 14).

Table 14: The dependency of grid cell size and computation time for the simulation of the 1/4Q and T10 scenarios compared to the SOBEK case.

Scenario:	**1/4Q**	**T10**
Computation time 1x1 m [hh:mm]	11:00	23:00
Computation time 2x2 m [hh:mm]	1:00	4:00
Computation time 5x5 m [hh:mm]	0:18	0:54
Computation time SOBEK [hh:mm]	0:02	1:15

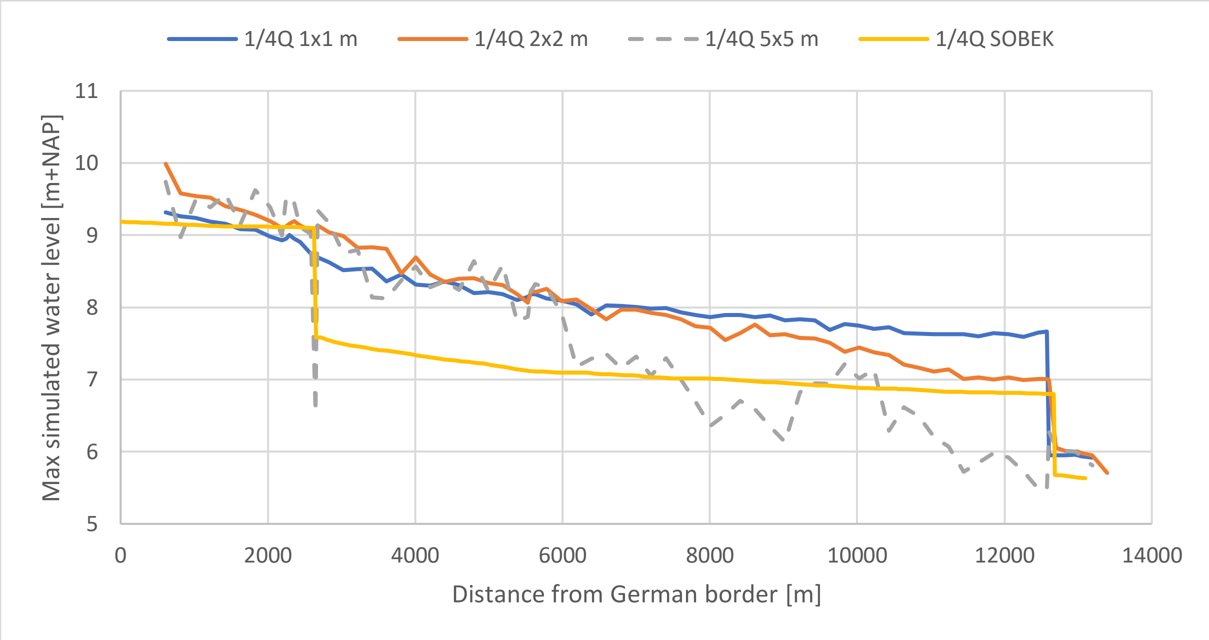


Figure 34: Length profile of the maximum simulated water levels at the grid cell sizes 1x1, 2x2 and 5x5 m in the 1/4Q discharge scenario.

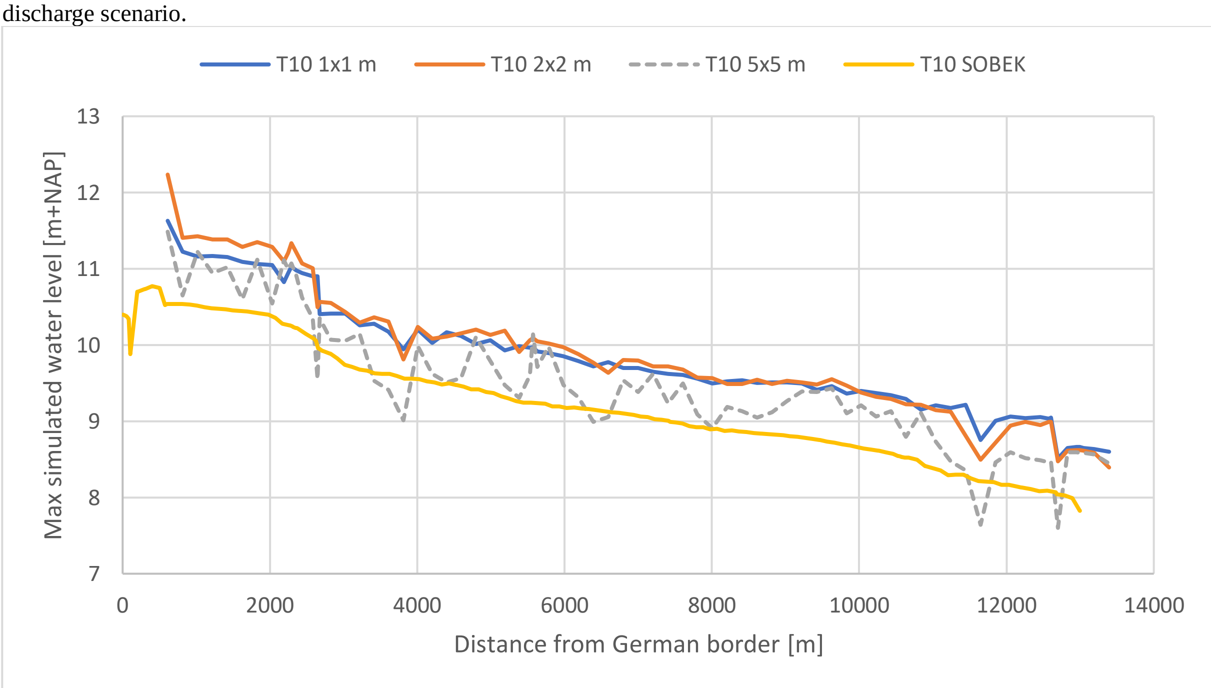


Figure 35: Length profile of the maximum simulated water levels at the grid cell sizes 1x1, 2x2 and 5x5 m in the T10 discharge scenario.

7.3. Conclusion RQ4

From this analysis, it can be concluded that TYGRON is more sensitive to changes of the floodplain roughness compared to SOBEK and that the sensitivity increases at more extreme discharge scenarios. The simulated water levels are overestimated in TYGRON resulting in a larger influence of the hydraulic friction in the floodplains. Furthermore, adjustments of the weir dimensions have a direct influence on the upstream water levels in TYGRON and therefore on the calibrated model results. Based on the maximum simulated water levels at different grid cell sizes, (1x1, 2x2 and 5x5 m) irregularities in the length profile still exist at a high resolution (1x1 m). The square grid causes that flow is discretized in x and y components which obstruct flow in the streamwise direction if the cell does not follow the course of the river (i.e. large influence of numerical viscosity). A 1x1 m grid results in a better approximation of the water levels in the case of the Overijsselse Vecht. However, computation time is significantly increased and uncertainty in the simulated water levels still exists. A larger grid cell size (5x5 m) results in larger water level differences in the length profile of the Overijsselse Vecht.

8. RQ5: Implementation side-channel

In this chapter, a side-channel is implemented in TYGRON to analyse whether TYGRON is fit for design purposes. The design principles of a side-channel are used from Rijkswaterstaat (Ministerie van Verkeer en Waterstaat, 2007; Wolters et al., 2001). The method is described as first, and the results are presented as second. Finally, the results are discussed by presenting a table which shows if the criterium of designing a side-channel can be achieved or not.

8.1. Method RQ5

Hydrodynamic models are used to predict the 3D behaviour of flow and simulate the effects of a measure, which helps river managers to substantiate their choices. Such a measure could be a new side-channel in a river. To analyse how easy and effective it is to implement and simulate a measure in TYGRON, a new side-channel is implemented in the case study of the Overijsselse Vecht. Currently, R.W.A. Vechtstromen is using SOBEK to get a first indication of the location of a side-channel in the floodplains of Gramsbergen. To get an indication of the possibilities to design a side-channel in TYGRON the following aspects are verified:

- What are the options to create a side-channel?
- How can the effects be interpreted of the measure?
- How can the new channel be adjusted?

Each aspect is analysed in TYGRON and compared to comparable features in SOBEK. The analysis focusses on the differences in detail level and usability for the creation of a new side-channel. Furthermore, Rijkswaterstaat developed a technical report for the design of rivers, including the design principles of side-channels (Ministerie van Verkeer en Waterstaat, 2007). The design principles of side-channels are based on a monitoring study of (Jans et al., 2004), which results in three core aspects 1) ensure high water safety, 2) maintain shipping and 3) improve nature. The design principles indicate whether the effects of the side-channel comply with the hydraulic requirements. The eventual effects need to be determined by a hydrodynamic and/or a morphologic model. In this thesis, it is analysed if the design principles of side-channels by Rijkswaterstaat can be created with TYGRON to comply with the hydraulic requirements.

8.2. Results RQ5

8.2.1. Creating a side-channel

In TYGRON a new channel can be created by 1) adjusting the elevation model in combination with a hydraulic inlet/outlet structure and 2) pre-develop the side-channel in another software program (e.g. GIS, AutoCAD) and insert the dimensions with coordinates of the new channel as GeoTIFF. Adjusting the elevation model in TYGRON can easily be executed by changing the elevation model. Table 15 presents the options to create a side-channel in the elevation model. There are two styling options, 1) selecting a shape and lowering/raising the height with absolute or relative values and 2) by lowering/raising/flattening the absolute height with live sculpting. The size can be adjusted to create the desired width of the side-channel. Furthermore, the slope between the new height and the existing height in the elevation model can be changed. Figure 36 presents the floodplains at Gramsbergen, with the area that needs to be changed in green. By changing the elevation model only separated elements of the height can be changed. The length of the channel cannot be created or indicated by the style option. TYGRON can create the location of the side-channel with a desired slope and width but the exact dimensions are not possible to reproduce in the model.

Therefore, with the TYGRON model, only an indication can be created of the location of the new channel with approximately the desired dimensions and simulate the measure accordantly. The second option in TYGRON is to create a side-channel in another software program. This option makes it possible to simulate and interpret the effects of different design stages in the hydrodynamic model by exchanging geodata (e.g. GeoJSON, GeoTIFF).

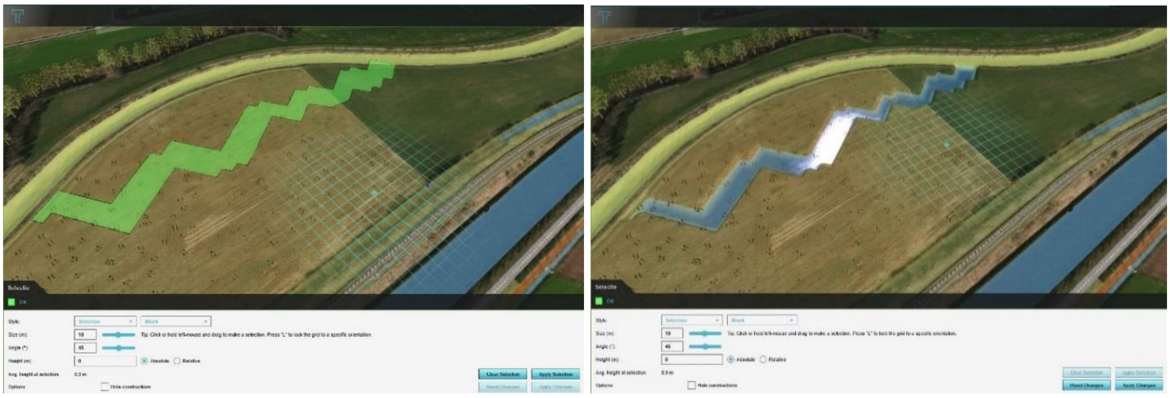


Figure 36: To implement a side-channel in TYGRON the elevation model is changed by lowering/raising the existing elevation. note: the white area is a reflection of the sun.

Table 15: Options to adjust the elevation model in TYGRON.

Style options:	**Selection (line, block, circle, polygon pick)**	**Live sculpting**
Height [m]:	Change to an absolute or relative height	Lower, raise or flatten the height with an absolute value
Size [m]:	1-20	
Angle [°]:	0-90	

To ensure water will flow into the side-channel at the desired water level, a hydraulic structure needs to be created in the model. The line-based weir structure in combination with a culvert can function as an inlet and outlet structure, respectively (Section 3.3.3.).

In SOBEK a 1D channel is described as a branch interconnecting with two nodes. These nodes may be boundary nodes or connection nodes. On top of the branch, the user can add other objects, such as weirs, pumping stations etc. Furthermore, the branch has no underlying mathematical equations, the length, boundary nodes and other objects attached to it determine the flow through the branch. To the length of the branch, a cross-section can be coupled with a cross-section node, which specifies the dimensions of the branch. Hereby, a new channel can easily be initialized and adjusted in the SOBEK model, if modelled in 1D. For an interaction with the 2D grid, SOBEK needs an interaction of the 1D main channel with the 2D surface based on the criteria that only one connection per grid cell is allowed (Deltares, 2019). These criteria determine the connection between 1D and 2D based on the coordinates of the 2D grid cell and the 1D connection node. This causes that it takes more effort to set up the initial 1D/2D model and modify the used case in SOBEK.

8.2.2. Interpreting the effects

The TYGRON model can interpret the desired hydraulic effects (e.g. flow direction, flow velocity and water depth) with a defined number of time frames using the measuring tool. Per time frame the hydraulic effects can easily be interpreted by the user. In TYGRON, measurements can be made by placing a measuring element in the 3D world. The element can be drawn freely as a cross-section between two points or as one individual point. Hereby, the user can interpret the effects of the side-channel locally. However, in river studies, it is important to analyse the hydraulic effects of a measure in a length profile. Creating water levels in length profile is only possible by creating multiple individual measured elements and exporting the data of each element. This method takes a lot of time and results in an inaccurate length profile. The measuring elements cannot be placed in the middle of the river and do not correspond to a length dimension of the river. Nevertheless, TYGRON can present the results with a high-quality time-lapse. The resolution of the simulation can be changed to get the desired bathymetry accuracy level. However, in a river case, a larger area needs to be simulated which leads to a larger computation time with significantly larger time frames (Section 3.4.). The larger computation time together with the larger time frames reduces the effectiveness to interpret the hydraulic effects.

SOBEK presents a 2D map connected to an elevation model. The effects of the measure (e.g. side-channel) can be presented in time-lapse and time history graphs at the selected location. The results in the map task are the most important when viewing and analysing results from a simulation. In the result maps, a length profile of the simulated water levels can be presented and used to interpret the effects of the measure over the length of the river.

8.2.3. Adjusting the channel

After the elevation model is changed in TYGRON it is only possible to change the model to a previous state by opening a saved version. In TYGRON, previous adjustments in the elevation model cannot be detected and cannot be changed to the original values. Changes in height are directly applied in the elevation model and the exact shape of the side-channel cannot be displayed in TYGRON. The user needs to know what the shape of the channel will look like before making any changes to the elevation model. It is possible to extract the elevation model (or part of it) to a GeoTIFF file, adjust the height in another software program (e.g. GIS) and insert it back to the TYGRON platform.

8.2.4. Designing based on principles RWS

The design principles of a side-channel are presented in Table 16. Per aspect, it is indicated if the identification/range of the criterium can be interpreted or adjusted in TYGRON. As described in section 8.2.1. it is possible to increase/decrease the height of the elevation model to create a side-channel. The hydrodynamic effects such as the flow velocity and water depth can be simulated and interpreted with high quality using the measuring tool. However, it is not possible to calculate the volume of the increased/decreased area, only an indication can be given of the excavated volume. The model is fit for simulating different discharge scenarios and gives an indication at which frequency the side-channel flows with the main channel. Nevertheless, the design principles state that a side-channel should comply with specific dimensions for vegetation development or shipping purposes which are difficult to create by the TYGRON model.

Table 16: Hydraulic design standards of a side-channel described by Rijkswaterstaat. For each standard is indicated whether the criterium is reached by the TYGRON and SOBEK model.

Function	**Face**	**Aspect**	**Criterium**	**Identification/range**	**Can the identification/range be interpreted or adjusted?**	
					TYGRON	**SOBEK**
High water safety	Construction	1. Lowering high water levels	Excavated volume and max water level	4-10 cm decrease per million m^3 (Wolters et al., 2001)	No	No
	Maintenance	2. Vegetation development	Bottom level in a channel	> 1 m water depth at average water level	Yes	Yes
			Bank slope in channel	1:5 or larger	Yes	Yes
		3. Maintenance winter dike	Distance winter dike till the channel	50-100 m	No	Yes
			Shore protection	Create extra width for erosion (Jans et al., 2004; Van Breen & Havinga, 2003)	No	Yes
Shipping	Maintenance	4. Maintenance groynes	Distance from groyne	Minimal 50 m	No	Yes
Nature	Construction	5. Dimensions	Water depth second slope	< 1 m water depth at average water level	Yes	Yes
			Bank slope second slope	1:10 or smaller	Yes	Yes
		6. Hydrodynamics	Flow velocity	0.05-0.3 m/s at average water level	Yes	Yes
	Maintenance	7. Durability	Frequency flow of side-channel	> 9 months/year	Yes	Yes

8.3. Conclusion RQ5

From this analysis can be concluded that TYGRON is suitable to implement different design measures by inserting geo-data (e.g. GeoTIFF and GeoJSON files) and analyse the hydraulic effects quickly. However, designing with the tools presented in the model itself only absolute and relative heights can be changed, which makes it difficult to create exact channel dimensions and change to a previous state after changes are made. Compared to SOBEK, TYGRON has the advantage to quickly implement different design scenarios and analyse the hydraulic effects, where SOBEK requires more actions to implement a new design scenario.

9. Discussion

In this study, an analysis is made how suitable TYGRON is for a river study. This is done by comparing the differences in model performance between TYGRON and the reference model in SOBEK. The differences in model performance between TYGRON and SOBEK are presented in the first column in Table 17. In the second column the discussion points are presented, which link the differences to a possible reason (each discussion point is also linked to a corresponding sub-section in this chapter). The third column presents a possible solution to the defined problem, which could lead to an improvement of the TYGRON model in a river case study. Furthermore, Table 17 is divided into the differences in the hydrodynamics and the practical differences between TYGRON and SOBEK.

Table 17: Differences in model performance between TYGRON with SOBEK based on the case of the Overijsselse Vecht.

Differences in hydrodynamics results	**Discussion points**	**Possible solution/improvement**
1. TYGRON can reach the design water level in the T10 scenario at weir De Haandrik, but only at an unrealistic low roughness value. 2. Expected hydraulic jump after weir De Haandrik is not present in the 1/4Q scenario in TYGRON.	- (9.1.1.) Weirs cannot connect over the full width of a wide main channel as they only connect with two grid cell's centre points in which flow can enter and exit (Appendix B5). - (9.1.2.) Numerical viscosity is large for grids that do not follow the trajectory of the main channel (Bomers et al., 2019; Caviedes-Voullième et al., 2012). - (9.1.2.) TYGRON uses a square grid over the whole project area.	- TYGRON developed a new update in which structures can interact over an area. - A grid shape that follows the course of the main channel may reduce the simulated water level as the influence of numerical viscosity will decrease (Bomers et al., 2019; Caviedes-Voullième et al., 2012). - Smaller grid cell sizes may distribute the flow better in streamwise direction (Figure 34). - Small grid cell sizes and low roughness values may correct large water levels from numerical viscosity as they both decrease the simulated water levels. (Bomers et al., 2019; Caviedes-Voullième et al., 2012)
3. TYGRON is more sensitive for floodplain roughness than SOBEK and the sensitivity increases with larger discharges. 4. In TYGRON hydraulic roughness is based on the Gauckler-Manning coefficient while in SOBEK different roughness relations can be used (e.g. Bos-Bijkerk, Chézy, Manning, Nikuradse Strickler and White-Colebrook.	- (9.1.5.) Chézy and Manning have fundamental differences in approaching roughness. - (9.1.5.) Momentum equations include roughness differently in TYGRON and SOBEK.	- Include other roughness relations in TYGRON (e.g. Bos-Bijkerk, Chézy, Nikuradse Strickler and White-Colebrook).
5. TYGRON can simulate floodplain flow in more detail because it used a 2x2 m grid cell size while SOBEK gives only a rough indication of the inundation of the 2018 flood event on its 25x25 m grid. 6. The water levels during the 2018 flood event are overestimated in TYGRON.	- (9.1.6.) Bathymetry accuracy is increased when using a high-resolution grid (Bomers et al., 2019). - (9.1.6.) TYGRON shows potential in predicting local flow patterns and inundation in floodplains. However, the water levels for the 2018 flood event are overestimated.	- Analyse and validate to what extent TYGRON can predict floodplain flow and inundation quantitatively.
7. TYGRON is completely 2D and can simulate spatial patterns in the depth-averaged flow velocities in the main channel and floodplains while SOBEK is 1D for the main channel and 2D for the floodplains 8. Although, in general, the flow velocities are of the same order, TYGRON simulates an overshoot in the flow velocities at the steep edges of the main channel.	- (9.1.6.) Bathymetry accuracy is increased when using a high-resolution grid (Bomers et al., 2019). - (9.1.6.) The used dimensionality in SOBEK (i.e. 1D/2D) does not give insight into the flow velocity pattern in the main channel. - (9.1.6.) A combination of small grid cell sizes and steep edges may result in high estimated flow velocities between the cells in TYGRON.	- TYGRON is currently under development to include a second velocity estimation based on Runge & Kuga (TYGRON, 2019). - A new problem in hydrodynamic modelling is rising when using small grid cell sizes. Additional research is necessary to identify the impact of small grid cell sizes on the model results in TYGRON

Practical differences	Discussion points	Possible solution/improvement
9. TYGRON does not have water levels as a result output but presents results such as water depths and flow velocities in a top view and with time-lapses, attractively. SOBEK can present the simulated water levels in length profile.	- (9.1.3.) The water level in TYGRON is defined by the sum of bed level + water depth, which is not the simulated water level. - (9.1.3.) Increasing grid cell sizes result in a larger difference between the selected bed level from the measuring tool and the reconstructed bed level on which the water depth is simulated.	- Include water level as result type may improve the overall applicability of TYGRON in a river study.
10. Boundary conditions from SOBEK are not directly reproducible in TYGRON.	- (9.2.2.) Structures in TYGRON connect with a centre point of one grid cell. - (9.2.2.) Q(-t) and Q-h relations cannot be created with one condition in TYGRON.	- A new update in TYGRON is available which let structures connect over an area instead of one grid cell. - Additional research: Compare how other 2D models include an upper and lower boundary condition and how does this differ from the method used in this study.
11. TYGRON can only create a 30x30 km project area. 12. The downstream boundary condition is located at weir Hardenberg in TYGRON (~15km downstream) and located at Vilsteren in SOBEK (~45km downstream).	- (9.1.4.) River studies larger than 30x30 km are not possible in TYGRON. - (9.1.4.) Upstream water levels may be highly influenced by the downstream water level in TYGRON.	- Increasing the project area in TYGRON so that it can be used in longer river sections.
13. Computation time in TYGRON is larger compared to SOBEK (Table 14).	- (9.2.2.) 1x1 m grid results in significantly large computation time. - (9.2.2.) 2x2 m grid results in comparable accuracy as 1x1 m and simulates much faster. - (9.2.2.) 5x5 m computes fast but creates an overlap in the grid cell connections of the inlets (upper boundary condition) which results in 3 inlets that are turned off and gives distorted results. - (9.1.2.) The influence of numerical viscosity by the square grid may be decreased in small grid cell sizes.	- Additional research: To what extend can the influence of numerical viscosity be compensated by calibration in high-resolution models? - For a quick analysis of the predicted flow pattern, a 5x5 m grid may be sufficient. - If more detail is required for the simulated flow pattern a 2x2m grid is recommended.
14. Different design stages can be implemented from other software packages and analysed in TYGRON while in SOBEK it is time-consuming to implement a new measure in 1D/2D. 15. In TYGRON it is not possible to create exact dimensions of a measure. 16. In SOBEK a new measure can be created according to more design standards.	- (9.2.2.) Despite that SOBEK can create dimensions in more detail it takes more effort to implement the adjustments within the 1D/2D connection.	- Use SOBEK for a long river study in which floodplain flow needs to be included. - TYGRON can, for example, be used to quickly analyse the effects of different design stages of a measure.
17. The model setup check resulted in unexpected inundation of the floodplains at De Haandrik in the 1/4Q scenario in TYGRON.	- (9.2.2.) Only one value can be defined for the weir height in TYGRON. - (9.2.2.) SOBEK maintains the upstream water level in weir dependent river systems by a PID-controller.	- Additional calibration of the weir height was needed in TYGRON to correct high water levels upstream from weir De Haandrik. - Implementing a PID-controller in the weirs, which applies a correction of the weir height based on proportional, integral, and derivative terms.

9.1. Reflection on the results

Concerning the comparison in model performance, TYGRON and SOBEK are two different hydrodynamic models (1D/2D vs 2D) and are used for different end purposes. Therefore, it is not possible to state if one model performs better than the other since their different origins. Typically, 2D models are used to give insight into the local flow pattern, flow velocities and morphological processes in the main channel and floodplains. 1D/2D models are generally used in longer river sections where the more complex flow components in the floodplains need to be included. TYGRON was originally not developed for predicting river flow scenarios. TYGRON originates from a serious gaming application with the performance to simulate 2D flow components in the Saint Venant regime, applicable for rainwater and overland flow in urban and rural areas. However, R.W.A. Vechtstromen is interested in how TYGRON could be used in a more general description of a river study. In this study, model performance in a river study is described in a broad sense by comparing TYGRON and SOBEK (see section 1.3.). As a result, the presented research is partly derived from the perspectives of R.W.A. Vechtstromen. Furthermore, a hydrodynamic model simplifies the real flow processes in rivers. It is unknown which model predicts flow processes better since both TYGRON and SOBEK cannot predict flow processes with 100% accuracy. To give insight which method may be better to use within a specific purpose of a river study, the model results are discussed based on the differences between TYGRON and SOBEK described in Table 17.

9.1.1. The influence of weirs

To calibrate the TYGRON model the hydraulic roughness (Manning) is varied within a valid range described by Chow (1959). The design water level directly after weir De Haandrik is approached as closely as possible within the calibrated range. Unrealistic low roughness for the main channel and floodplains are required to attain simulated water levels close to the design water levels. The horizontal flow component in 2D models causes that flow is simulated past the structures in a scenario where water should flow over a structure, in case the structure is not well implemented in the Digital Terrain Model (Lin et al., 2006; Marzocchi et al., 2014).

9.1.2. Influence of numerical friction/viscosity

Bomers et al., (2019) described in their study that the low-resolution grids result in large numerical friction and that numerical viscosity is predominant at grids that are not capable of following the course of the river channel. Numerical friction and viscosity also affect the simulated water levels in TYGRON. Smaller grid cell sizes in TYGRON result in lower numerical friction as the water levels are decreased with smaller grid cell sizes. Because of the influence of the numerical friction caused by the grid cell sizes, recalibration of the weir height and hydraulic roughness is necessary when using a new grid cell size.

The water levels in the 1/4Q scenario are probably influenced by the grid shape and grid cell size. The square grid in TYGRON does not follow the trajectory of the main channel, which results in a large influence of numerical viscosity and hence the proper distribution of flow in the streamwise direction. The influence of the numerical viscosity in the square grid can be compensated by the lower numerical friction in small grid cell sizes and low calibrated values outside the calibrated range of Chow, (1959). This results that the roughness values described by Chow, (1959) are not representative for TYGRON. Furthermore, it is expected that the flow distribution, over the grid cells, in streamwise direction may be improved when simulating the main channel in a high-resolution. However, a high-resolution grid may increase bathymetry accuracy and hence changes in the bathymetry are incorporated better, more accurate results are still dependent on the bathymetry in the input data. If the input bathymetry is originally measured over a larger grid than the used grid cell size of the hydrodynamic model, model results may not be improved by using a high-resolution grid.

9.1.3. No water level as output in TYGRON

It is not possible to obtain a length profile of the simulated water levels as a result type in TYGRON. To retrieve water levels from the grid overlay the measuring tool is used. The measuring tool in TYGRON can extract water depths and bed levels at a selected location in the 3D graphical world. In TYGRON water levels are defined by the sum of the grid cell averaged water depth and bed level. The water depths and bed levels can be extracted from multiple points over the length of the channel and afterwards be connected to create a length profile. However, the points are not extracted from the exact middle point a grid cell. Furthermore, the elevation model is slightly adjusted to support the scheme to become well balanced using a piecewise linear reconstruction of the bed level (Horvath et al., 2011; Kurganov & Petrova, 2007). In this scheme the adjacent grid cells share the same corner points and edge centre points, the bed level is continuous in x, y-direction and the grid cells consist of a linear slope in x, y-direction (Figure 37) (TYGRON, 2019).

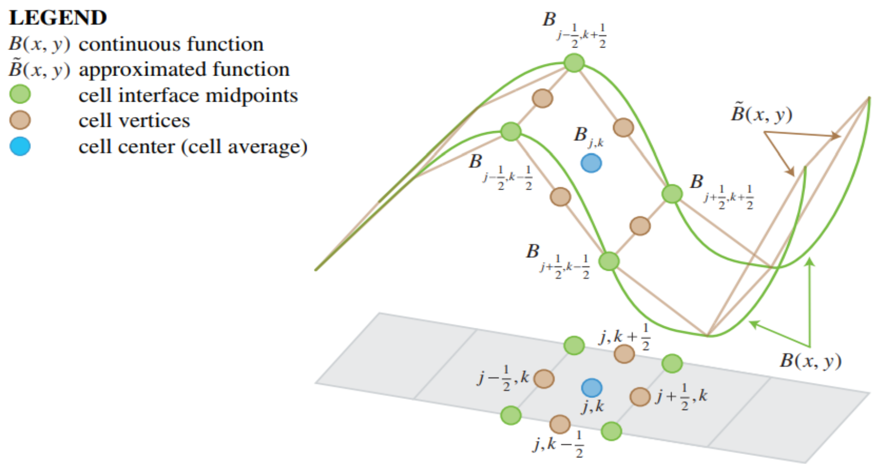


Figure 37: The 2D linear piecewise reconstruction for connecting the bed level with the square grid cells with the 2D scheme (Horvath et al., 2011).

With this method, the new centre point is placed higher/lower when the bed level slope is not linear within the cell (which occurs in irregular geometries). Since the bed levels are not extracted from the exact middle point of the grid cell this may deviate from the reconstructed bed level which is used for the simulation of the water depth. The simulated water level in TYGRON can, therefore, deviate from the actual water level. This effect increases for larger grid cell sizes since the bathymetry is discretised over a larger area containing a larger difference in bed level. Since the water level is the sum of the bed level and the grid averaged water depth this results in irregular water levels in the length profile.

9.1.4. Influence downstream boundary condition

The location of the downstream boundary condition in TYGRON is at Hardenberg (~15 km from the upper BC) and in SOBEK at Vilsteren (~45 km from upper BC). The location of the downstream boundary condition causes that the simulated water levels in the TYGRON model are significantly influenced. The downstream boundary condition influences the simulated water levels since it creates significant backwater effects in the modelled range (Pappenberger et al., 2006). In this study, the inlets remove water from the model by pumping water at a defined rate (i.e. negative inlets or outlets). Since water is pumped away, the simulated water levels are not the result by solving the flow based on the shallow water equations in the computational grid. The influence of the downstream boundary condition is directly visible in the shape of the discharge wave (Figure 17). The steep shape of the discharge wave is the result of constant outflowing discharge at a constant rate. In TYGRON it is not possible to create a project larger than 30x30 km. River studies which exceed this area cannot be created in TYGRON and therefore the simulated water levels are always in the reach of the backwater effects of the downstream boundary condition.

9.1.5. Manning vs. Chézy

In TYGRON hydraulic roughness is described by the Manning coefficient while the SOBEK model is calibrated with the Chézy coefficient. The TYGRON and SOBEK models include important differences due to their different applied hydraulic roughness methods. First, if the discharge is increased, different water levels will result from the two approaches (Huthoff & Augustijn, 2004). Secondly, Manning is a true measure of hydraulic roughness backed with empirical data and Chézy is a measure of relative roughness height dependent on the hydraulic radius. The different theoretical approach and composite channel characteristics may cause that the converted hydraulic roughness deviates locally since the Chézy roughness is converted based on two locations. As a result, this may also lead to a deviation of the simulated water levels from both model results.

In addition, sidewall effects are included in the momentum equations in SOBEK while this is not included in TYGRON (comparing Equations 4 & 5 with 7 & 8). A channel is considered wide when the width is 10 times larger compared to the depth (Chow, 1959). In case of the Overijsselse Vecht sidewall effects may influence the simulated water levels at the slope of the main channel. This is because the simulated water depth is approximately 3.6 m compared to 20 m width (in the 1/4Q scenario). Since hydraulic friction in TYGRON is only described by the Manning coefficient, the simulated water levels are expected to be more influenced by adjustments of this coefficient, which is in line with the results of the sensitivity analysis (Figures 30 & 31).

9.1.6. Simulated inundation area

Jowett & Duncan (2012) present in their study that accurate calibration of 2D models is difficult and a limitation to their utility in contrast to 1D models. As presented in this study, flood images are used as validation of the flood event of 2018. Using satellite images to calibrate or validate the 2D model includes the prediction of the inundated surface as result from the simulated flood event and can be used as a good alternative of point calibration and validation of a 2D model (Horritt, 2000; Liu et al., 2019). However, the used images do not present quantitative information related to the inundated area of the flood of 2018. The used images of the 2018 event can only be used to qualitatively validate the performance of the simulated inundation based on the local inundation captured by the images.

Despite the overestimation of the flood event of 2018 in TYGRON, the model shows potential in simulating free surface flow in the floodplains. Compared to the performance of SOBEK, the horizontal flow components in the floodplains are underestimated and are difficult to relate to the flood images. The suitability of a hydrodynamic model depends on the type of model, the complexity of the scenario and the goal of the assignment. Generally, 2D models are used to predict complex changes in flow patterns such as floodplains where 1D models show inaccuracies in predicting floodplain flow due to the missing horizontal flow components (Jowett & Duncan, 2012). The 1D/2D approach in SOBEK is fit to predict flow in the floodplains. However, the accuracy of the predictions varies with the grid cell size in the floodplains. This corresponds with other studies that compare floodplain flow in 1D/2D and 2D models, which conclude that 1D/2D models show comparable results but 2D models are slightly more accurate and computation time takes longer (Finaud-Guyot et al., 2011; Marzocchi et al., 2014; Vanderkimpen et al., 2008).

9.1.7. Simulated flow velocities

The performance of the flow velocities is qualitatively analysed in the bend at Hardenberg. In literature flow velocities in river bends gradually increase towards the outer bend (Luchi et al., 2011; Sukhodolov, 2012). TYGRON tends to reach this statement. However, it simulates an overshoot in flow velocities at the edges of the main channel.

In SOBEK the flow velocities in the main channel are depth and width averaged. In the floodplains, the simulated flow velocities are dependent on the used resolution. The 25x25 m grid cell sizes used in SOBEK results in an over-discretization of the bathymetry and therefore the discharge distribution and flow velocities in the floodplains. With the used grid cell size in SOBEK, a general estimation of the flow velocities can be made.

Small grid cell sizes and steep edges result in an overshoot in the flow velocity estimation between the cells in TYGRON (Figure 28). The overshoot is inherent to the used algorithm in the 2D scheme which is currently under development at TYGRON (TYGRON, 2019). Part of the development is to include a second velocity estimation which decreases the velocity overshoot based on the fourth-order discretization of Runge & Kutta (Butcher, 1996). The values of the flow velocities are of the same order as in SOBEK. However, there are no velocity measurements available so the values cannot be validated.

Lin et al., (2006) described that 2D models typically use grid cell sizes between 5x5 m and 20x20 m. TYGRON can use a grid cell size of 2x2 m (and even smaller). However, such small grid cell sizes may result in new problems in hydrodynamic modelling (e.g. overshoot in flow velocities/water depths at steep edges). TYGRON can simulate flow in a high resolution within a few hours. However, only a square grid can be used in TYGRON which increases the influence of numerical viscosity on the simulated water levels in a meandering river profile. Small grid cell sizes may decrease the influence of the numerical viscosity, but it also decreases the numerical friction in the grid itself. It is therefore advisable to analyse whether simulating flow in such a high resolution is beneficial in river studies and how the simulated water levels relate to the influence of numerical friction and viscosity at small grid cells and computation time in small grid cell sizes (e.g. 2x2, 1x1 and 0.5x0.5 m).

9.2. Limitations

The limitations are divided into the limitations of the used data in this study and the practical limitations as a result of the model performance of TYGRON.

9.2.1. Data limitations

The Overijsselse Vecht contains several lateral discharges which are measured in the period 1997-2015 (Figure 5). However, the measured discharge data contains ±40% uncertainty (without applying too much statistics) (R.W.A. Vechtstromen, 2015). This means that the design discharges (which are based on these measurements) contain the same uncertainty. In this study, the design discharges are used to feed the hydrodynamic model and the design water level downstream at weir De Haandrik is used to calibrate the hydrodynamic model. Due to the large uncertainty in the discharge data, it is also uncertain if the model is properly calibrated. Besides, the design water levels that are used to calibrate the simulated water levels in TYGRON probably do not correspond to the discharge event of the same return period. To identify the uncertainty in the used discharge and water level data used as upstream (measured downstream at weir De Haandrik) and downstream (measured downstream at weir Hardenberg) boundary condition, the linear relation and strength of the relation between are calculated between the discharge and water level sets.

Figure 38 presents the correlation between the measured discharge and water level downstream of weir De Haandrik which are used to determine the design discharge and design water level. The linear relation and strength of the relation among the discharge and water level sets at weir De Haandrik are 0.857 and 0.734, respectively. With an acceptable degree of uncertainty, it can be stated that the design discharge (which feed the hydrodynamic model) and design water level (which is used to calibrate the hydrodynamic model) at weir De Haandrik can be related to the same return period. Furthermore, the SOBEK model is calibrated based on the design water level downstream at four weirs (De Haandrik, Hardenberg, Mariënberg, Junne and Vilsteren). Since the hydraulic roughness corrects water levels at all four points in SOBEK and only for one point in TYGRON, the minimal difference between the design water level and the simulated water level is easier reached in TYGRON. This also means that the calibration of the TYGRON model is subjective to the design water level at weir De Haandrik.

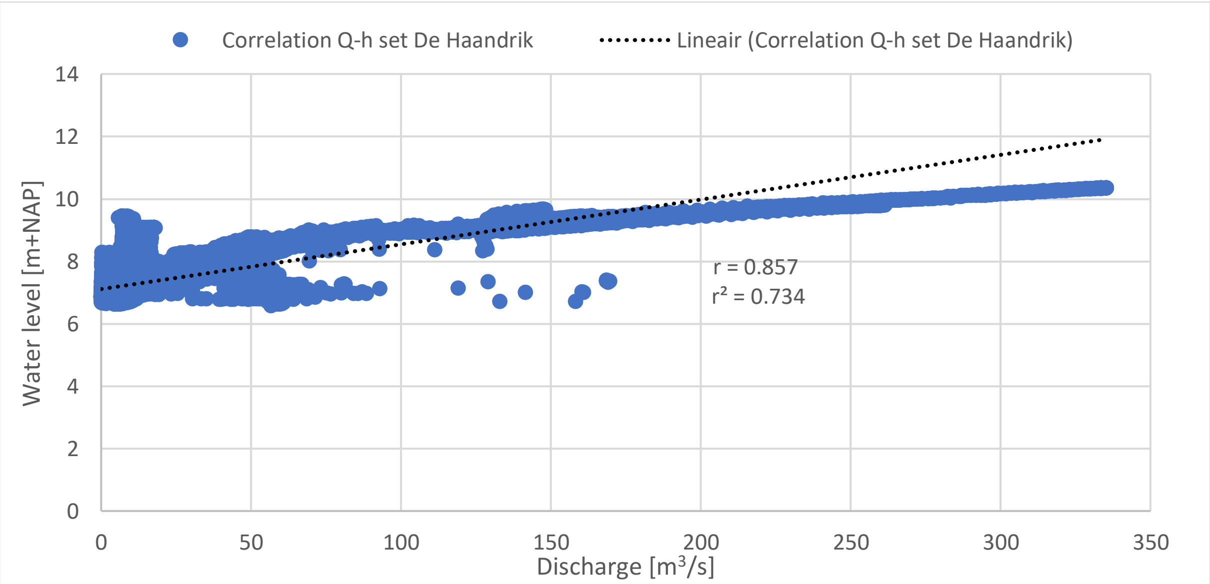


Figure 38: Correlation between the discharge and water level set used to define the design discharges and water levels at weir De Haandrik.

The downstream boundary condition in TYGRON is based on the design discharges and water levels downstream at weir Hardenberg and extrapolated for discharges larger than 150 m^3/s. Figure 39 presents the correlation between the measured discharge and water level downstream of weir Hardenberg and the used Q-h relation as a downstream boundary condition. The linear relation and strength of the relation among the discharge and water level sets at weir Hardenberg are 0.767 and 0.589, respectively. The discharge and water level sets show a linear relation. However, the strength of the relation is of a moderate level based on the rule of thumb. At extreme discharge events (e.g. T10) the simulated water levels in TYGRON are probably also overestimated based on this relation. The uncertainty that the Q-h relation at Hardenberg may result in overestimated flood conditions of the Overijsselse Vecht should be incorporated when analysing extreme flood events simulated by TYGRON in this study.

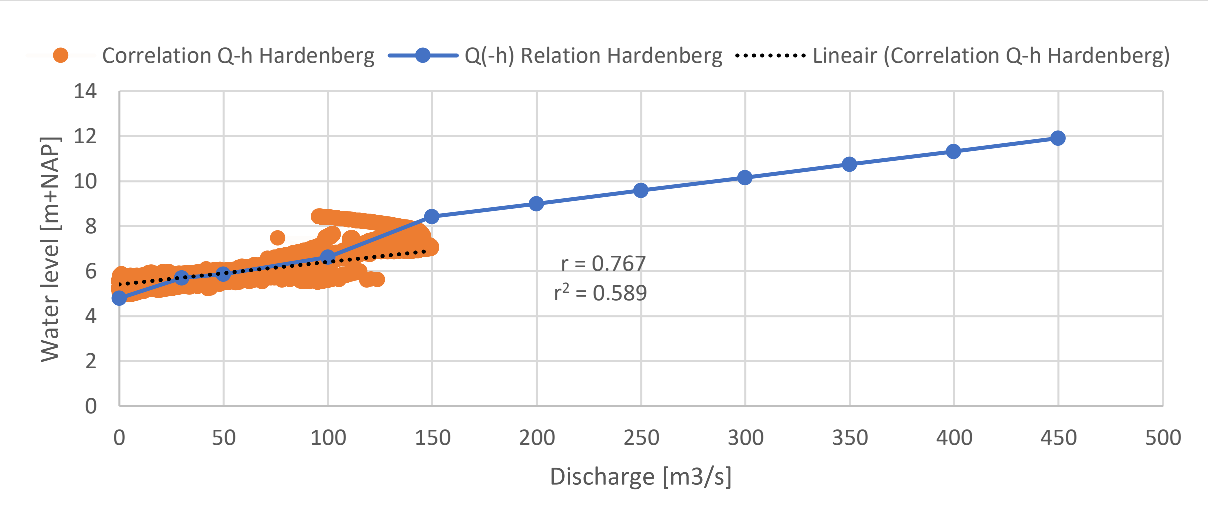


Figure 39: Correlation between the discharge and water level used to determine the design discharge and water level at weir Hardenberg. The linear line has the same slope compared to the extrapolated discharges from 150 m^3/s but the event may be overestimated and hence the Q-h relation.

To validate SOBEK and TYGRON with the uncertain discharge data, the models are validated by simulating the historical flood event of 2018 and compare the simulated inundation with the images of the event. Next to the discharge data, water level measurements at the crossing Almelovechtkanaal of the 2018 event are used to validate the simulation. The used measured discharge data between 1 January 2018- 14 January 2018 at weir De Haandrik is extended to the left side to create a full discharge wave (Figure 18). This means that the discharge before the event of January 2018 contains uncertainty in the used hydrodynamic model. This manual addition to the measurement data can still be used to validate the discharge event. The reason for this is 1) the maximum simulated water level at the peak of the wave is included in the discharge measurement and 2) the extension is used to fill the main channel of the hydrodynamic model before the wave reaches its highest point and to create the shape of the complete wave.

To validate the simulated inundation in TYGRON and SOBEK three images and two videos of the flood event of 2018 are used as a reference. The images give insight into which areas are flooded by the event. The exact flooded area cannot be related to the images. Therefore, the images can only be used as an indication of the simulated inundation. Satellite or aerial images at the day of the flood can provide a better reference of the flooded area during the historical event since the inundated area can be estimated (Horritt, 2000; Liu et al., 2019). The used images in combination with the measured water level at the crossing Almelo-Vechtkanaal can, therefore, be used to validate the inundation at the historical event of 2018.

Furthermore, there are no velocity measurements in the Overijsselse Vecht. The performance of the flow velocities is therefore qualitatively analysed in the main channel and floodplains at Hardenberg.

Measured flow velocities in the main channel and floodplains can be used to verify the ability to accurately simulate flow velocities in SOBEK and TYGRON. In this study, only the major differences between the two simulated flow velocities can be described.

9.2.2. Practical limitations

As mentioned in (Section 9.1.3.) water levels are not a result output in TYGRON. This is a practical limitation to the applicability of TYGRON in a river study. In a river study, accurate simulation of water levels is required to indicate the effects of extreme flood scenarios or a measure. Implementing water levels as result type and present them in a length profile may increase the applicability of TYGRON because backwater effects can then be identified quickly.

Structures in TYGRON are point-based or line-based. Inlets (point-based structures) are used in the TYGRON model to function as boundary conditions by adding/removing water to the system. However, the inlets cannot be used properly as boundary conditions because:

1) An inlet can only contain 100 timesteps values (e.g. 50 discharge and 50 timesteps)
2) Water will flow along the inlet since the point-connection does not cover the full width of the channel.
3) Discharge Q cannot be coupled with water levels h to create a Q-h relation.

In discharge conditions where water also flows in the floodplains, the inlets may not drain all water from the system resulting in an overestimation of the flood event. A similar problem occurs with line-based structures (e.g. culverts, weirs, and pumps). By river weirs, not all water can flow from the entry-point, over the weir, to the exit-point which causes that not all water can flow over the weir in the downstream direction. Since the weirs are not implemented over the full width of the channel, only part of the simulated discharge will flow over the weir, which relates to the lower discharge over the weir in TYGRON. This limits the use of discharge scenarios, where the water levels are fully maintained by the weirs. In the preview of the new version of TYGRON (of 9 May 2020) an update is implemented for hydraulic structures (e.g. weirs, inlets etc.). In this update, structures can simulate flow over an area instead of one cell point. In the update, the structures are divided over the width of a channel and account for a proportional division of flow at the area of the connected grid cell. Furthermore, an inlet can now contain 10,000 time-steps instead of 100. The new update is not validated but it is expected that this will improve the performance of TYGRON in a river case.

Weirs in SOBEK can include a PID-controller which maintains the upstream water level or flow over the weir. In TYGRON weirs have a static height which needs to be calibrated. Changing the weir height limits the use of using actual weir height of weir De Haandrik and Hardenberg. A PID-controller may improve the functionality of weirs in TYGRON as it decreases the uncertainty of using the wrong weir height if the PID-controller is calibrated correctly.

The grid cell size used in this research is 2x2 m. TYGRON reduced the overload of their system by restricting the computation time during daytime by one hour (Appendix B4) and is a practical limitation to the utility of the TYGRON model. Using a 1x1 m grid heavily increases the computation time of TYGRON (11 h at 1/4Q and 23 h at T10), resulting in a simulation that can only be done outside working hours or in the weekend. The 2x2 m grid is faster but results in more irregularities in the length profile compared to the 1x1 m grid. To give a quick insight into the simulated flow pattern a 3x3 m grid can be used over a 2x2 m grid (15-45 min computation time). Due to linear piecewise reconstruction of the bathymetry, grid cell sizes of 5x5 m contain too large irregularities in the length profile (Figures 34 & 35).

TYGRON is limited to use Manning roughness values as a roughness coefficient. In the SOBEK model, Chézy is used as the roughness coefficient. Therefore, the roughness values of the main channel and floodplains from SOBEK are translated from Chézy to Manning roughness values (see chapter 7). This method translated the roughness values based on one cross-section while the roughness is dependent on the hydraulic radius and differs locally and hence the converted roughness may differ locally.

10. Conclusion

The goal of this thesis is to analyse if TYGRON can be used as a hydrodynamic model for a river study. To achieve this a reference case study is used from R.W.A. Vechtstromen of the Overijsselse Vecht in SOBEK 1D/2D. The TYGRON model is set up and calibrated based on the reference model and the model performance is analysed in terms of:

RQ1: An accurate simulation of floodwater levels.
RQ2: An accurate simulation of inundation.
RQ3: An accurate simulation of flow velocities.
RQ4: Realistic model sensitivity to the calibrated parameters (hydraulic roughness, weir dimensions and resolution).
RQ5: Implementing a measure in a case study.

The associated five research questions are formulated to achieve the goal of this thesis. Based on the results and the discussion, each research question is answered and a general conclusion is given at the end.

10.1. RQ1: Accurate simulation of water levels

What is the performance of TYGRON to accurately simulate water levels, when TYGRON is setup based on the reference case of the Overijsselse Vecht in SOBEK?

The performance to accurately simulate water levels is analysed for TYGRON by making a comparison with the reference case of the Overijsselse Vecht in SOBEK. For this study, the 1/4Q (bank full state) and T10 (flood that occurs 1/10 years) discharge scenarios are used for calibration of the hydraulic (Manning) roughness.

It can be concluded that based on this comparison TYGRON cannot accurately simulate water levels within realistic parameter settings. This is because the simulated water levels in TYGRON are possibly influenced by the combination of the following aspects: 1) weirs are not correctly coupled to the Digital Elevation Model and computation grid, 2) the upstream backwater effects of the downstream boundary condition and 3) the influence of numerical viscosity caused by the square grid shape in the meandering river profile of the Overijsselse Vecht. Moreover, water levels cannot be retrieved directly as an output parameter from the TYGRON output because water levels are considered as the sum of the simulated water depth (based on the reconstructed bed level) and the bed level of the selected location (bed level based on input data) (i.e. the actual simulated water level deviates since the bed level may be shifted higher or lower compared to the reconstructed bed level). The aspects mentioned above result in a deviation of the simulated water level compared to the expected simulated water level from SOBEK.

10.2. RQ2: Accurate simulation of inundation

What is the performance of TYGRON and SOBEK to accurately simulate inundation, based on data from the historical flood event in 2018, in the Overijsselse Vecht?

TYGRON simulates inundation in the floodplains with a higher resolution compared to the SOBEK case. Nevertheless, the TYGRON model overestimates the water levels and flood extent. For the 2018 flood event, TYGRON predicts that the residential building (De Haandrik 9) is not inundated, which is not the case in SOBEK. Recalibration of the weir height is required in TYGRON to get a more accurate result of the inundation. This implies an instability of TYGRON since simulating different discharge scenarios requires different parameter sets.

From this analysis, it can be concluded that TYGRON overestimates the simulated inundation and that it is difficult to relate the simulated inundation to the recorded inundation in detail with the SOBEK model. The simulated water level in the SOBEK model at the crossing Almelo-De Haandrik is the same as the measured water level. Based on this can be stated that SOBEK is fit to predict simulated water levels at a selected point but only an indication of the inundation can be presented due to the lower bathymetry accuracy as a result of the large 25x25 m grid compared to the 2x2 m grid in TYGRON.

10.3. RQ3: Accurate simulation of flow velocities

What is the performance of TYGRON and SOBEK to simulate depth-averaged flow velocity profiles in the floodplains?

It can be concluded that TYGRON tends to predict gradually increased flow velocities towards the outer bend in the main channel, as expected based from the literature (e.g. Luchi et al., 2011; Sukhodolov, 2012). However, the flow velocities in TYGRON have an overshoot at steep edges of the main channel which is inherent for the used computational scheme and increases for small grid cell sizes (TYGRON, 2019).

SOBEK simulates flow velocities in the main channel by averaging over the depth and width, while the flow velocities in the floodplains are over-discretised by the 25x25 m grid. Despite the flow velocity pattern is not correct in SOBEK, the flow velocity values are comparable with the TYGRON case. Furthermore, the effect of local change in bathymetry on the simulated water levels is not well captured in SOBEK as the bathymetry accuracy is lower due to the large 25x25m grid.

This leads to the conclusion that TYGRON can simulate local changes in the flow velocity pattern in more detail compared to SOBEK, but the physical properties in a river bend and floodplains are still not well captured in both models.

10.4. RQ4: Realistic model sensitivity

To what extent are the maximum simulated water levels from TYGRON and SOBEK sensitive to changes of the calibrated parameters (i.e. floodplain roughness, weir dimensions and resolution)?

This study has shown that TYGRON is more sensitive to changes in the floodplain roughness compared to SOBEK. One reason for this is that TYGRON overestimates the water levels for the discharge scenarios T1 and T10 which result in a larger influence of the hydraulic friction in the floodplains. Another reason is that low roughness values correct for high water levels from numerical viscosity. This results from the square grid which does not follow the course of the meandering main channel of the Overijsselse Vecht and limits the flow distribution in the streamwise direction.

The simulated water levels in TYGRON are sensitive to changes in the weir dimensions. The upstream weir threshold water level is not maintained during the simulation of the discharge wave since the weir height and width are static. The upstream weir threshold value in SOBEK is maintained by the PID-controller and is therefore not sensitive to changes of the weir's dimensions. Analysing the flow over the weir also proves that the weirs in TYGRON are not correctly implemented. Weirs in TYGRON are connected to the 2D grid with the entry and exit point connected to the centre point of one grid cell. Therefore, flow is simulated past the entry and exit points, which cause that the hydraulic jump is not present at weir De Haandrik (where this should be the case in the 1/4Q scenario). A new update in TYGRON (9 May 2020) let weirs interact with a surface instead of just grid centre points and may improve the discharge distribution over the weirs.

Based on the resolution analysis can be concluded that the simulated water levels are highly sensitive to the used grid cell size. Irregularities in the length profile are decreased when using a 1x1 m grid over a 2x2 m grid. However, computation time is increased from 1 hour to 6 hours. In the used case a 2x2 m grid results in a balance between computation time and resolution in which a quick indication of extreme floodwater levels can be interpreted. The water levels show an irregular pattern simulated by the 5x5 m grid since the reconstructed bed level deviates more from the bed level selected by the measuring tool when the grid cell size is increased.

10.5. RQ5: Implementing a side-channel

How easy is it to implement a side-channel in TYGRON compared to SOBEK based on the design principles of Rijkswaterstaat?

From this analysis can be concluded that in TYGRON it is easy to implement a measure and to show its effects. The hydraulic effects (e.g. flow direction, flow velocity and water depth) can be predicted by the TYGRON model and presented attractively in a time-lapse. Interoperability is facilitated in TYGRON by the option to exchange geodata such as height elements (GeoTIFF) and object elements (GeoJSON). This makes it possible to design a measure in another software program (e.g. GIS or AutoCAD) and implement and analyse different design states in TYGRON quickly.

However, by making use of the tools presented in the TYGRON model itself, only absolute and relative heights can be changed, which makes it difficult to create exact channel dimensions and change to a previous state after adjustments are made. In SOBEK a channel is easily created by two interconnecting nodes in 1D, but it takes more effort to adjust within the 2D connection. Compared to SOBEK, TYGRON has the advantage to quickly implement different design scenarios and analyse the hydraulic effects, where SOBEK requires more actions to implement a new design scenario.

10.6. General conclusion

"To what extent can TYGRON be used as a hydrodynamic model in river studies based on a comparison in model performance with the reference case of the Overijsselse Vecht in SOBEK?

Based on the model performance aspects for a river study; 1) accurate simulation of floodwater levels, 2) accurate simulation of flow velocities, 3) accurate simulation of inundation, 4) realistic model sensitivity on the calibrated parameters and 5) implementing a measure, it can be concluded that TYGRON is not yet suitable for a river study. The absence of simulated water levels as result output, incorrect simulation of flow scenarios where the water levels are significantly influenced by river weirs, the non-optimal functioning of boundary conditions and the influence of numerical viscosity are the main aspects why TYGRON is not yet suitable for accurate flood prediction studies.

Including water levels as result type and improving weirs in the 2D scheme will improve the performance to simulate water levels in weir dependent river systems in TYGRON. Furthermore, the influence of numerical viscosity will probably decrease with decreasing grid cell sizes as this improves the flow distribution in the streamwise direction. However, this may lead to calibrated roughness values out of the range of typically used roughness values (e.g. table of Chow, (1959)). It can be concluded that TYGRON excels as a 2D hydrodynamic model in terms of resolution because it can simulate in 1x1 m grid cell sizes, while other 2D models generally use grid cell sizes between 5x5 - 20x20 m. Although small grid cell sizes increase bathymetry accuracy and probably improve flow distribution over the grid cells in the downstream direction, it may also include new problems in hydrodynamic modelling (e.g. overshoot in flow velocities/water depths at steep edges), which are not described in literature yet.

Flow patterns in floodplains and extreme flood scenarios can be simulated fast and predicted in a high resolution despite the irregularities in the length profile. TYGRON gives additional value to projects where a quick indication is needed of the flow pattern in extreme flood events. In such scenario's other models lack in computation time (2D models), capturing horizontal flow components (1D models) and quickly analysing and setting up different design measures (1D/2D models).

11. Improvements, potential and recommendations

In this chapter, the points of improvements and potential of this study are presented followed by the recommendations.

11.1. Points of improvement

The improvements focus on what could be done differently in this study are based on the limitations described in section 9.2 and presented in this section.

11.1.1. Model improvement

It was not possible to create the same boundary conditions from SOBEK in TYGRON. Especially in river studies, the boundary conditions must be correctly implemented in the hydrodynamic model since they are used to define the flood condition. Since TYGRON was not originally developed for a river study the boundary conditions are approached differently compared to SOBEK. The TYGRON model can be improved by 1) analysing beforehand which methods are most beneficial to define a Q(-t) and Q-h relation in a 2D hydrodynamic model and 2) how this can be implemented in the TYGRON platform.

In this study, TYGRON is calibrated based on the table of Chow, (1959). Applying the table of Chow, (1959) did not result in appropriate results when calibrating the hydrodynamic model since the influence of numerical friction and viscosity is not considered in this approach. Using lower roughness values than which is described by Chow, (1959) may result in a better approximation of the design water levels but the used hydraulic friction may result in an unrealistic value compare to other studies.

The used case study is bound between the German border and just after weir Hardenberg. Because flow is also simulated along weirs, TYGRON is not useful for discharge scenarios where the water is only flowing over a weir. The question arises if TYGRON can be used within two weir sections or in a river case without the influence of weirs. In this study, the 1/4Q and T10 are simulated without weirs in which the 1/4Q still results in large water levels. This indicates that the unexpected water slope in the 1/4Q scenario is not fully related to the malfunctioning of weirs in TYGRON. It would be interesting to analyse how TYGRON performs in a river section which is not influenced by weirs.

11.1.2. Data improvement

This study used the case study of the Overijsselse Vecht from R.W.A. Vechtstromen as a reference model. Discharge/water level measurements of Overijsselse Vecht are scarce and uncertain (R.W.A. Vechtstromen, 2015). In terms of extreme flood analysis, only discharge and water level data are available of the 1997 flood event ($1/10^{th}$ flood frequency) measured at the bridge in Ommen. Scarce discharge data limits the possibilities for calibration and validation and induces uncertainty in predicting extreme flood events. The case study of the Overijsselse Vecht prevents the validation of the hydrodynamic model because of this uncertainty. The question arises whether TYGRON or SOBEK performs equally well in a case study where sufficient discharge and water level measurements are available.

The floodplain inundation is validated for the flood event of 2018. Five images of the flood event are used at De Haandrik and Hardenberg. However, quantitative values such as the total inundated area during the flood event cannot be related to the used images. Satellite images can be used as a better alternative and are proven to be effective to validate simulated inundation areas (Cicala et al., 2016; Horritt, 2000; Liu et al., 2019).

11.2. Potential of this study

This study analyses the additional value of TYGRON as a 2D hydrodynamic model. The choice of using a certain hydrodynamic model depends on the complexity of the project and the goal of the assignment which are captured in the following aspects of model performance: 1) accurate simulation on of flood water levels (Warmink et al., 2011), 2) accurate simulation of inundation (Horritt, 2000; Liu et al., 2019), 3) accurate simulation of flow velocity (Luchi et al., 2011; Sukhodolov, 2012), 4) realistic model sensitivity to the calibrated parameters (Hall et al., 2009) and 5) implementing a measure (Ministerie van Verkeer en Waterstaat, 2007; Wolters et al., 2001).

R.W.A. Vechtstromen already uses TYGRON for dike breach studies because they require 1) setting up the initial model and interpreting the results quickly, 2) high-quality simulation of the two-dimensional flow components in the floodplains and 3) attractively present and share the results with their stakeholders. TYGRON is a relatively new hydrodynamic model in the market and is constantly under development. Nevertheless, TYGRON is originally set up for predicting rainwater/overland flow based on the shallow water equations for urban and rural purposes and not set up to be applied in a river case study. This study contributes to the applicability of TYGRON for R.W.A. Vechtstromen since it tests the performance of TYGRON in a more general concept of a river study than only for rainwater/overland flow.

Furthermore, this study analyses practical and hydrodynamic issues concerning the initial setup of TYGRON for a river study and gives additional value for the users (e.g. Regional Water Authorities, consultancies, and universities) of TYGRON. During this study, several bugs were found and solved. For example, the inlet contained a bug in the time/discharge interpolation which only occurs at long time/discharge series (in terms of weeks). Figure 40 presents the inlet bug which results in a sudden decrease in water levels around timeframes 37 and 145. By the quick response of the software engineers of TYGRON, this bug was solved. Another example is the flow simulating past weirs in wide river sections. In the new update (9 May 2020) of TYGRON structures can connect over an area and therefore they can be implemented over the full width of a channel. However, from this study, it remains unclear if the new update results in a better simulation of flow over a weir in a wide river section.

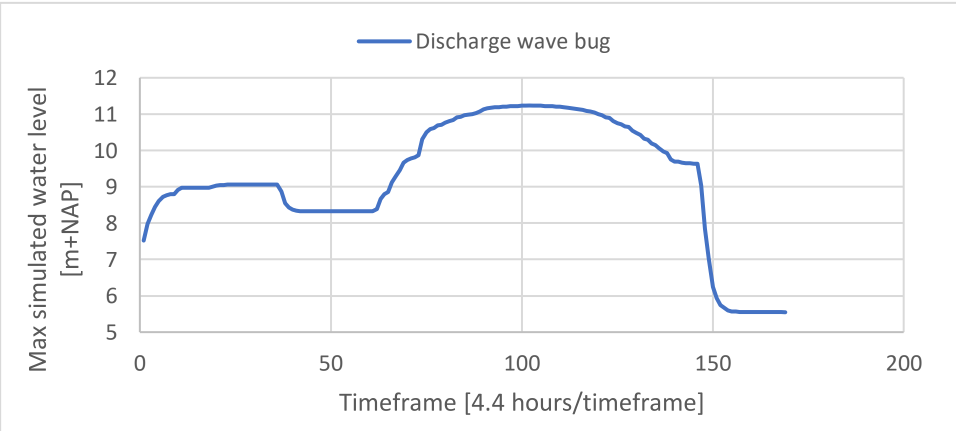


Figure 40: Discharge wave bug which was resolved by the update of 9 May 2020. This ug includes imbalances at long time series (a month) resulting in that some inlets where turned off.

During this study, a problem arose in which it was not possible to include more than 100 time-steps in an inlet. An inlet was used to function as an upper/lower boundary condition. Generally, in a river study, long time series are used to define a discharge condition, which limits the simulation of a discharge wave over a month when an inlet is used. The software engineers of TYGRON replied to the request to change the interaction of hydraulic structures (e.g. weirs) by adding an areal connection with the DEM and the request to include longer time series in inlets based on this study. However, the potential of the weir and inlet updates were not compared in this study due to a time limit.

11.3. Recommendations

The recommendations are divided into recommendations for improving the practical issues in the TYGRON model, recommendations for further research and recommendations for TYGRON users.

11.3.1. Improving practical issues in TYGRON

1) Since 9 May 2020, TYGRON developed a new update for structures in which flow over the structure can be simulated over an area instead of one connected grid cell. It is recommended to verify if the update improves the simulation of flow over a river weir in TYGRON and if this increases the performance to simulate water levels in a weir dependent river case. It is also recommended to compare how other 2D models have implemented structures in their 2D scheme and what the differences are concerning flow distribution over and past the structure.

2) The TYGRON model estimates an overshoot in flow velocities at steep edges of the main channel at small grid sizes. Currently, TYGRON is developing a second velocity estimation based on Runge & Kutta (TYGRON, 2019). It is recommended to verify under which grid cell sizes this problem occurs and what the influences are on computation time when implementing the new velocity estimation.

3) It is recommended to include water level as a result type in TYGRON and add in a length profile to study backwater effects quickly.

4) TYGRON can only use a square computational grid. Using grid shapes like curvilinear and triangular grids may improve flow distribution in the main channel (curvilinear grid) and capture complex geometry (triangular grid) (Bomers et al., 2019). It is recommended to analyse how beneficial alternative grids are in the TYGRON platform as this may increase accurate flood water level prediction. It is also recommended to adjust different grid cell sizes locally in the calculation grid (i.e. to define a high resolution in the main channel and a lower resolution in the floodplains).

5) Hydraulic roughness in TYGRON is described by the Manning coefficient. This coefficient is the true measure of absolute wall roughness and applicable to determine composite roughness with a constant value. However, this value may differ locally due to different geometric characteristics. Although Manning is the true measure of wall roughness and applicable in composite roughness scenarios in rivers, it is recommended to include other roughness methods in TYGRON (e.g. Bos-Bijkerk, Chézy, Nikuradse, Strickler and White-Colebrook).

6) The height of the weirs in TYGRON is not dependent on the discharge distribution or upstream water level. The weir height of river weirs is generally automatically changed to manage the discharge distribution and thereby the water levels in the river. A PID controller can fulfil this function since it applies a correction of the weir height based on the Proportional, Integral, and Derivative terms. It is recommended to implement an option as a PID controller, which let the weirs interact with the simulated water levels.

7) Currently, an inlet in TYGRON can only consist of 100 timesteps. It is recommended to increase the number of timesteps which can be inserted to an inlet. This may lead that an inlet can be used as upstream and downstream boundary condition with long (a month) hourly time-series. (This recommendation is included in the update of 9 May 2020 in which, hydraulic structures can now include a total of 10,000 timesteps instead of 100 timesteps).

8) At the moment, TYGRON can create a model area of 30x30 km. River studies longer than 30 km are therefore not possible. It is therefore recommended to increase the maximum applicable model area to a larger value (e.g. 100x100 km)

11.3.2. Further research topics

1) In this study, it is concluded that the simulated water levels in TYGRON are partly dependent on the high influence of numerical viscosity as a result of the meandering pattern of the Overijsselse Vecht which cannot be correctly captured by the square grid shape. TYGRON can simulate in a high resolution and small grid cell sizes may improve the discharge distribution, over the grid cells, in the streamwise direction. Therefore, it is recommended to analyse to what extend decreasing grid cell sizes improve the discharge distribution in a river case scenario in TYGRON.

2) TYGRON solves flow based on the shallow water equations in a square grid with a high resolution (< 5x5 m). Typically 2D hydrodynamic models use grid cell sizes between 5x5 – 20x20 m (Lin et al., 2006). Using grid cell sizes smaller than 5x5 m may include new problems in hydrodynamic modelling (e.g. overshoot in flow velocities at steep edges). Additional research is recommended to verify the difference in the performance of a high-resolution grid compared to a low-resolution grid. Hereby, it is recommended to analyse which problems occur at small grid cell sizes and how this influences the model performance in general.

3) This is the first time that the performance of TYGRON is analysed a river case study. It is recommended to test if the same results concerning the accurate simulation of floodwater levels, inundation and flow velocities will follow from another case study. The case of the Overijsselse Vecht contains an uncertainty of ±40% in the discharge measurements (R.W.A. Vechtstromen, 2015). Hence, it could not be concluded if TYGRON can predict accurate flood water levels or inundation. It is recommended to use a case where sufficient discharge and water level measurements are available to analyse the predictive performance of TYGRON.

4) The project area contains two river weirs. Since weirs are not properly implemented in TYGRON, it limits the prediction of accurate flood water levels in TYGRON for weir dependent flow scenarios. It is recommended to analyse if an accurate prediction of flood water levels can be made in a river section without the influence of weirs, so this uncertainty is excluded.

5) The use of a certain hydrodynamic model depends on the goal of the assignment. This study compares TYGRON (2D) and SOBEK (1D/2D). It is recommended to compare TYGRON with other 2D hydrodynamic models to analyse if the TYGRON performs equally well for the same purposes (e.g. predicting overland flow and vegetation analysis).

6) Calibration methods for 1D hydrodynamic models are well-developed and reproducible, however empirical (Jowett & Duncan, 2012). Accurate calibration of 2D models is a limitation in their usefulness since calibration is executed against distributed flow data (Jowett & Duncan, 2012). Satellite images of flood events may improve the calibration and validation of simulated inundation areas from 2D hydrodynamic models (Horritt, 2000; Liu et al., 2019). Additional research is recommended to calibrate and validate simulated inundation areas with satellite images in TYGRON.

11.3.3. Recommendations to TYGRON users

1) TYGRON cannot be used for the prediction of flood water levels, where the influence of weirs is significant. In some cases, it is not required to simulate flood water levels with high accuracy. Figure 41 presents a flowchart, which fills the gap where TYGRON may give added value in a river study. TYGRON can give added value to projects where a quick indication is needed of the flow pattern in extreme flood events (and probably also for low and average flood conditions after the update of 9 May 2020). This results in rapid river studies where a complex flow simulation is required on a local scale. In such scenario's other models fail in computation time

(2D models), capturing horizontal flow components (1D models) and quickly analysing and setting up different design measures (1D/2D models).

2) It is recommended to analyse which options are available for creating a Q(-t) and Q-h relation in TYGRON for the upstream and downstream boundary conditions, respectively. For TYGRON users it is recommended to analyse 1) which methods are most beneficial to define a Q(-t) and Q-h relation compared with other 2D hydrodynamic models, 2) how this can be implemented in the TYGRON platform and 3) what the differences are with the used method in this study.

3) Changing the resolution directly affects the simulated water levels since the influence of numerical friction and bathymetry accuracy is hereby also changed. It is therefore recommended to calibrate the used TYGRON model for each resolution independently as this may lead to more accurate simulations.

4) In TYGRON bridges are not considered as a hydraulic structure and is therefore not incorporated in the flow simulation (Appendix B3). When a bridge crosses the channel, it results in a hydraulic jump at the location of the bridge. It is recommended to remove all bridges from the TYGRON model which cross the channel of interest.

5) Calibration of the weir height is necessary in a case where weirs are in located the main channel. Generally, river weirs have an interactive height which controls the discharge over the weir or upstream water level. Therefore, it is recommended to calibrate the weir height between the maximum and minimum levels and compare them with the real weir heights in the concerned flood scenario.

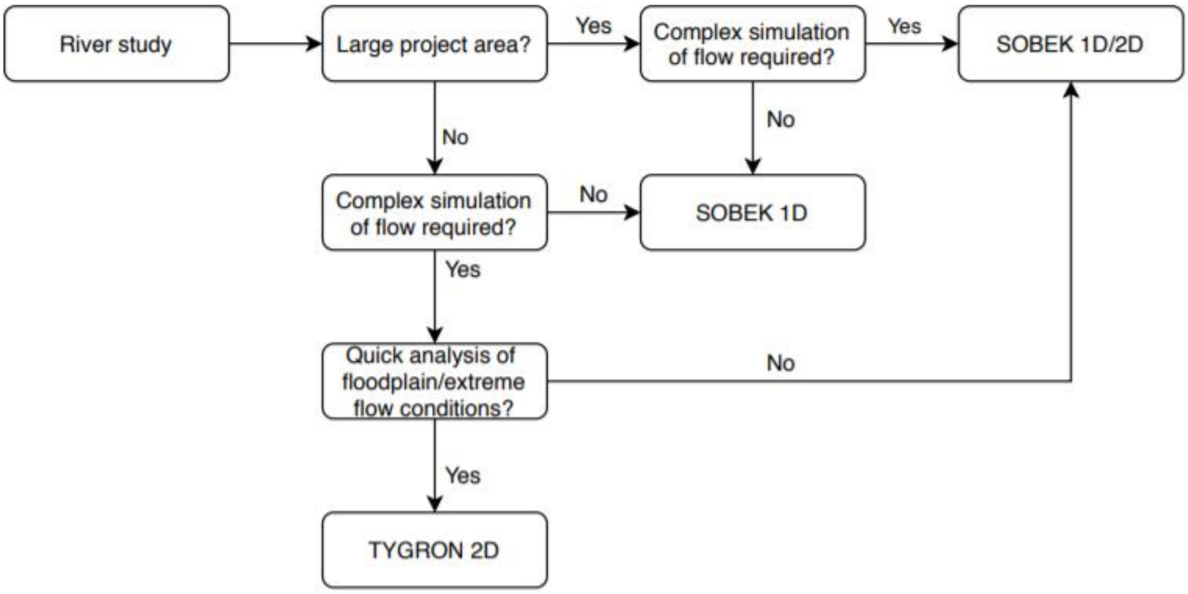


Figure 41: This flowchart describes where TYGRON may show potential in a river study, which is dependent on future developments in TYGRON concerning the accurate simulation flood water levels, inundation and flow velocities.

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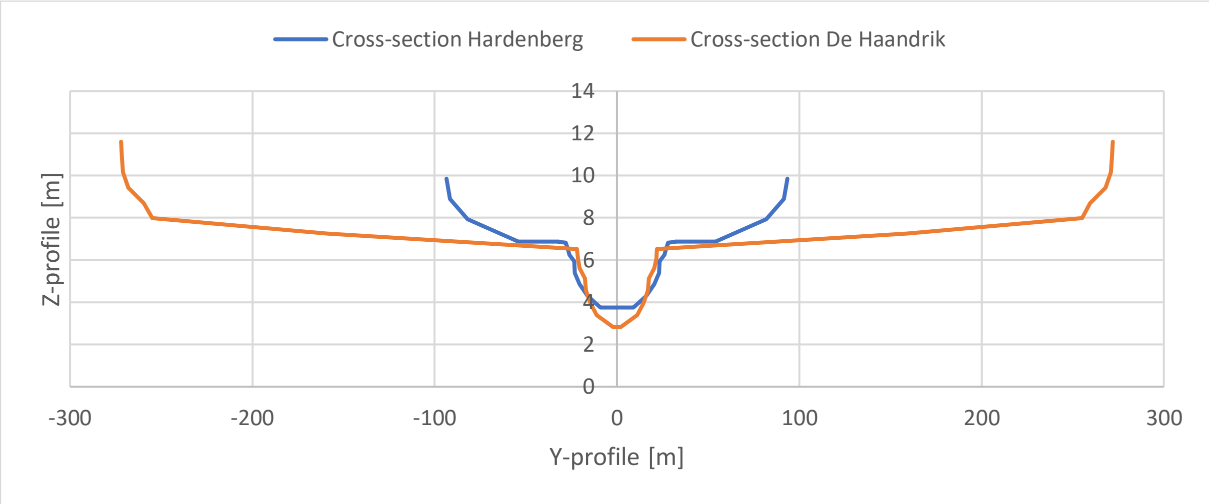
Appendix

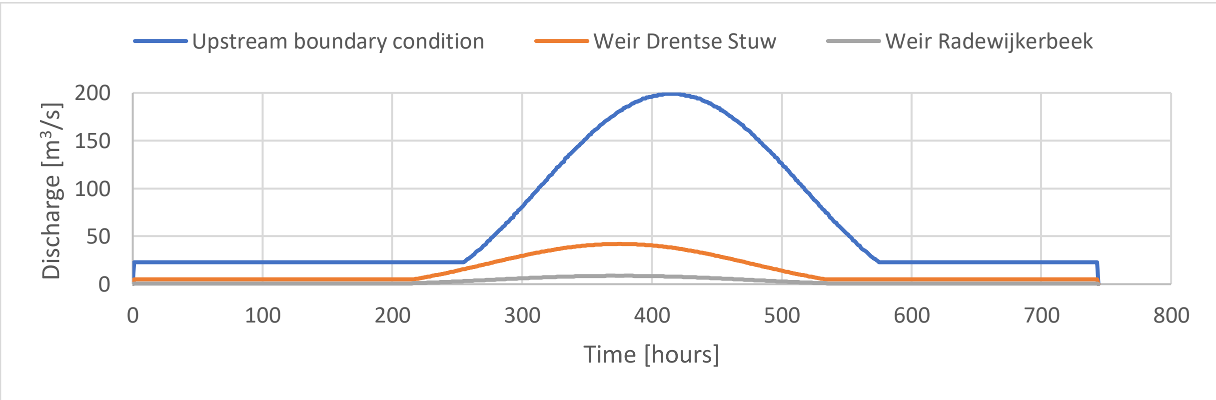
A. Model setup SOBEK

A1. Symmetrical YZ-profile cross-sections

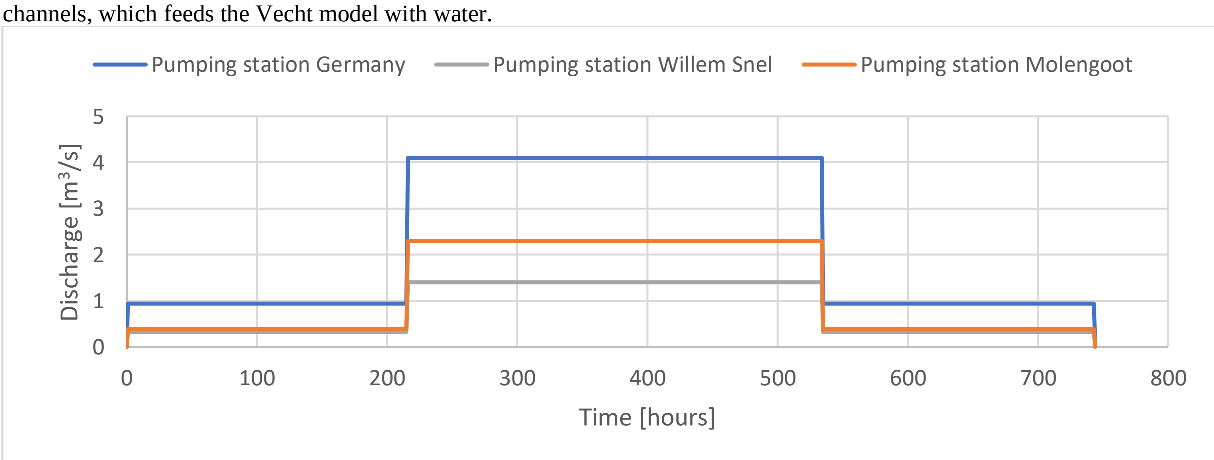


A1. The (symmetrical) cross-section at weir Hardenberg and De Haandrik from SOBEK which are based on the measured bathymetry of the Overijsselse Vecht between the German border and Hardenberg and the AHN2 (digital elevation map of the Netherlands).

A2. Upper boundary condition and lateral flows SOBEK



A2-1. Discharge waves for the T10 scenario (flow in the main channel and floodplains) of the three largest contributing side channels, which feeds the Vecht model with water.



A2-2. Discharge wave of the T10 scenario of three smaller lateral flows.

B. Model setup TYGRON

B1. Attached data sources to the TYGRON-platform

B1. The TYGRON platform uses open data sources to create a user-defined model area. for example, the open data sources provide geo-information like land-use, subsurface types, and a digital terrain model.

(Open) Data sources:	Description	Connection source	More information
BGT	Basis registration of large-scale topography.	PDOK	https://www.kadaster.nl/bgt
BRO	Basis registration of subsurface data.	PDOK	https://www.basisregistratieondergrond.nl/
World Imagery	Satellite map used as a base map for the 3D world.	ESRI	https://services.arcgisonline.com/ArcGIS/rest/services/World_Imagery/MapServer/0
Ocean Basemap	Base map with locations of water bodies.	ESRI	https://services.arcgisonline.com/arcgis/rest/services/Ocean_Basemap/MapServer
DTM	Digital Terrain Model (DTM). Surface without buildings, trees etc.	ESRI	http://www.arcgis.com/home/item.html?id=58a541efc59545e6b7137f961d7de883
AHN2	Actual height map of the Netherlands.	National geo-register	http://www.ahn.nl/index.html
Top10NL	Topographical dataset, used as an addition to the BGT data.	TYGRON/PDOK	https://www.kadaster.nl/-/top10nl
NWB	National road data of the Netherlands.	PDOK	https://www.rijkswaterstaat.nl/zakelijk/zakendoen-met-rijkswaterstaat/werkwijzen/werkwijze-in-gww/data-eisen-rijkswaterstaatcontracten/nationaal-wegenbestand.aspx
BRP	Basis registration of agricultural areas and cultivated crops.	National geo-register	http://www.nationaalgeoregister.nl/geonetwork/srv/dut/catalog.search#/metadata/%7B25943e6e-bb27-4b7a-b240-150ffeaa582e%7D?tab=general
BRK	Basis registration Kadaster, used for the location of parcels.	National geo-register	http://www.nationaalgeoregister.nl/geonetwork/srv/dut/catalog.search#/metadata/40840197-0478-432b-8c76-e99c4da9203f?tab=general
OSM	Open Street Map. Data set consisting of world topography	The instance of Overpass API	https://www.openstreetmap.org/
R.W.A.-data	Several datasets from R.W.A. consisting of hydrodynamic structures and water level areas.	PDOK	https://www.pdok.nl/nl/introductie/-/article/waterschapsdata

B2. Correction to the measured bed level Overijsselse Vecht

The bed level of the Overijsselse Vecht is measured with a radar boat between the German border until weir Hardenberg (see section 2.3.2.). Areas that are not measured need to be manually added in TYGRON. This is done by creating a raster in QGIS with a height attribute and import the raster in TYGRON as GeoTIFF.

The value of the new height is based on the height of the cross-section in SOBEK at the specific location and the bottom level at the end of the measurement. Figure 45 presents an example of the measured Vecht bathymetry in greyscales and some areas near weir De Haandrik that had to be adjusted to the correct the measurements.

B2. A close-up of the measured bathymetry at weir De Haandrik and the crossing with the Almelo Kanaal. In this figure is visible that it was not possible to measure the entire trajectory between De Haandrik and Hardenberg. Manual additions to the bed level were needed to fill the unmeasured area at e.g. weir De Haandrik, (green shape).

B3. Structures in TYGRON

Weirs

A weir is a line-based structure in TYGRON which allows water to flow from a water body with a higher water level to a water body with a lower water level. B3-1 presents the attributes that need to be defined to let the weir interact with the water simulated in TYGRON.

B3-1. In TYGRON a weir is defined by attributes which give certain properties to the object to interact with the simulated flow. The height and width define the weir's dimensions. The weir angle is the top-down orientation of the weir in the model area. The weir coefficient corresponds to the shape of the weir.

Attribute	Unit	Description
WEIR_HEIGTH	m + datum	Height of the weir. Water can flow past the weir when the water level exceeds the weir's height.
WEIR_WIDTH	m	The width of the weir
WEIR_ANGLE	Geo angle (0-360°)	The top-down orientation of the weir
WEIR_COEFFICIENT	[-]	The flow coefficient related to the shape of the weir (varies between 0.865-1.37). Default 1.1 which corresponds to a weir with a sharp top.

The WEIR_HEIGTH attribute in TYGRON is not dynamic (i.e. the weir height does not change to maintain the imposed weir threshold value). During high-water conditions, the weir height should be at a lower level than during low-water conditions to increase the flow over the weir and distribute a large amount of water downstream of the river system. B3-2 presents the maximum and minimum weir heights according to the Geo-information database of R.W.A. Vechtstromen (Geoweb).

B3-2. The maximum and minimum weir heights of weir De Haandrik and Hardenberg.

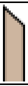
Scenario:	**De Haandrik**	**Hardenberg**
Maximum WEIR_HEIGTH [m+NAP]	9.17	7.10
Minimum WEIR_HEIGTH [m+NAP]	6.96	5.12
Weir threshold value [m+NAP]	9.10	6.80

When a weir is placed in an open channel and forms the only obstruction between the upstream and downstream part of the channel, the bed level needs to be increased to prevent water flowing around the weir, (Figure 46). Hereby, the elevated section causes the water upstream of the weir will be forced to flow over the weir. At relatively low heights (6.9-9.5 m+NAP) the water flows past the weir instead of over the weir. At the higher heights (9.5-12 m+NAP), water will flow over the weir. The elevated area is set on a surface level of 12 m (weir De Haandrik) and 9.5 m (weir Hardenberg) to make sure that all water will flow over the weir.

B3-4. To prevent a weir from leaking water under and past the weir, the elevation at the weir location is increased. The orange rectangle indicates the elevated area and the blue line indicates the weir with entry/exit points. The area is increased to a surface level of 12 m+NAP at De Haandrik and 9.5 m+NAP at Hardenberg.

Changing the weir coefficient to larger values means more water can flow over the weir. The weir coefficient is related to the shape of the weir. The default value of the weir coefficient in TYGRON is 1.1 which correspondents to a weir with a sharp top. B3-5 presents the different weir shapes and their weir coefficients. Since the shape of the weirs at De Haandrik and Hardenberg comply most with the default mode, the weir coefficient is not changed (Figure 47).

B3-5. The shape of the weir is translated to the weir coefficient and therefore influence the water flowing over the construction. In TYGRON the following five weir shapes can be selected:

Icon:	**Shape:**	**Coefficient:**
	Flat top	0.865
	Flat top, rounded corners	0.91
	Sharp top	1.1
	Gentle slope. One-sided	1.3
	Gentle slope. Two-sided	1.37

B3-6. Weir De Haandrik (upper Figure).Weir Hardenberg (lower Figure). Both weirs comply with the default weir coefficient "*Sharp top".*

Inlet

An Inlet is a point-based structure where water can be initialized or removed from the hydrodynamic model. The inlet will add or remove water at a defined maximum rate with optional thresholds. Because an inlet adds or removes water from the system, it can be used to define the upper and lower boundary conditions (see section 3.3.4.). B3-7 presents the attributes of an inlet to create an interaction with the 2D grid and simulated flow in TYGRON.

B3-7. An inlet can provide/deplete a constant flow of water to the system by defining an Inlet_Q. The Upper/lower threshold let water only flow into/out the model until an imposed water level value. The capacity defines a maximum amount of water.

Attribute	**Unit**	**Description**
INLET_Q	m/s	Defines the maximum amount of water that can flow in or out the hydrodynamic model. If a negative value is used the inlet functions as an outlet.
LOWER_THRESHOLD	m + datum	A lower threshold let water only flow into the model through the inlet till the water level at the point is equal or higher than the threshold value.
UPPER_THRESHOLD	m + datum	A higher threshold let water only flow into the model through the inlet till the water level at the point is equal or lower than the threshold value.
INLET_CAPACITY	m^3	Defines the maximum amount of water which can flow through an inlet.

Bridges

A bridge in TYGRON is initialized as a building interacting with the elevation model. This interaction causes the bed level of the Vecht is raised to the same height as the bridge. By removing the bridge from the model, the bed surface level of the Vecht becomes the bed surface level of the measured bathymetry. All bridges that cross the river Vecht are removed from the case (Figure 48).

B3-8. A bridge in TYGRON is initialized as a building interacting with the elevation model. This interaction causes that the bed surface level of the Vecht is raised by the height of the bridge which is presented in the green ellipse in the upper figure. The red line indicates the bed surface level and the yellow line the water depth summed with the bed surface level. By removing the bridge from the model (Orange rectangles), the bed surface level of the Vecht becomes the bed surface level of the measured bathymetry as is presented in the green ellipse in the lower figure.

B4. Used grid cell size

Multiple simulations were executed with different grid cell sizes ranging from 1x1-5x5 m to define the appropriate grid cell size. TYGRON reduced the overload of their system by restricting the computation time during working hours. The simulation will be cancelled during the working hours when the computation time is longer than one hour. A larger resolution and thereby the use of smaller grid cell sizes are therefore limited for large project areas like the used case study (±15 km river). This restricts the use of grid cell sizes smaller than 2x2 m between 09:00-17:00 in the case of the Overijsselse Vecht. After 17:00 the system allows for simulations with a duration of 12 hours. The number of time frames that can be saved during the simulation is dependent on the grid cell size and output overlays (result types, e.g. max water depth, flow velocity, flow direction). Smaller grid cell sizes and multiple-output overlays limit the number of timeframes that can be saved during the simulation, (B4). A grid cell size of 2x2 m is used to comply with a sufficient resolution and computation time.

B4. The dependency of grid cell size and number of output overlays on the number of timeframes for the simulation of the 1/4Q discharge scenario. In this scenario, a constant discharge of 23 m^3/s is initialized in the model over 5 days.

Grid cell size	Number of output overlays	Maximum number of saved time frames	Computation time
1x1	1	42	2-4 hours
	2	21	
	3	14	
2x2	1	169	45 min – 2 hours
	2	84	
	3	56	
3x3	1	381	15 – 45 min
	2	190	
	3	127	

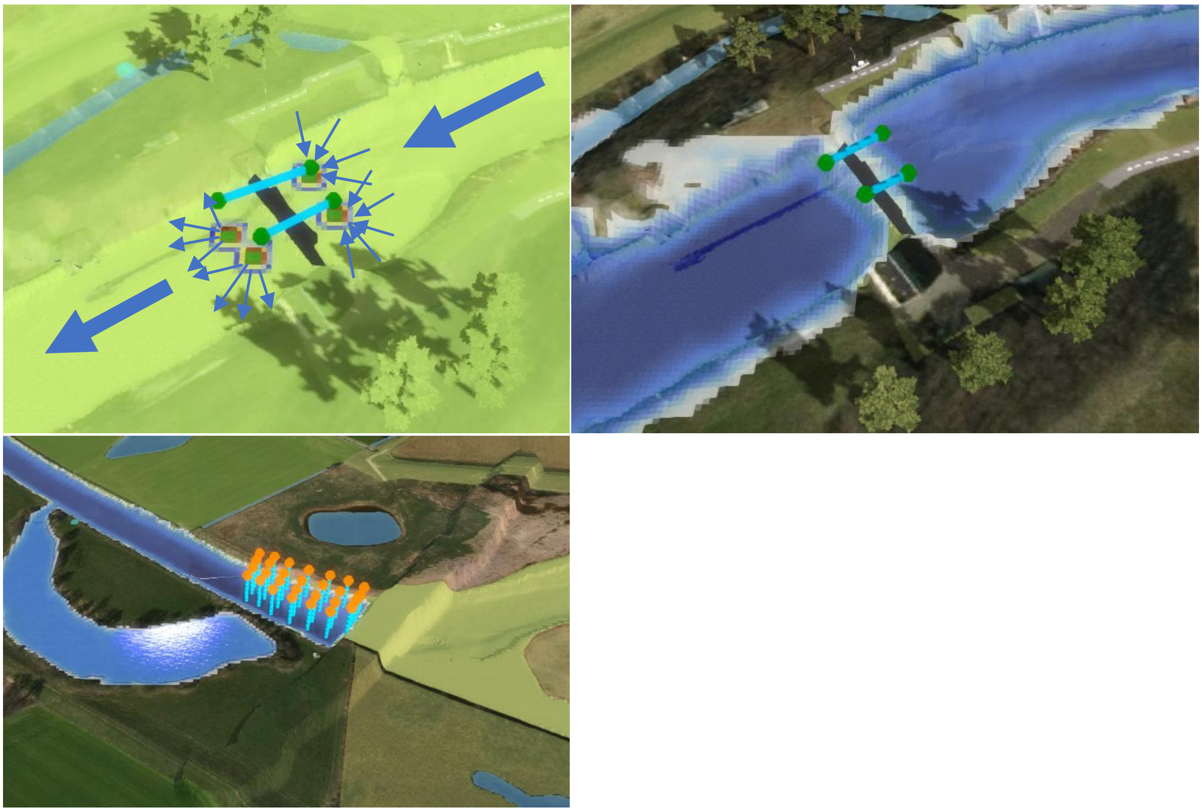
B5. Check before calibration

By simulation of the 1/4Q scenario, only the main channel should be filled with water. However, during the first simulations, the water flows over the main channel to the floodplains, (Figure 49). This results in an inaccurate simulation of the 1/4Q scenario.

B5-1. Simulation of the 1/4Q scenario, with hydrodynamic roughness (Manning) 0.035 $s/m^{1/3}$.

It seems that the weir structure cause that more water is held between the upper boundary and weir De Haandrik than water can flow over the weir in the downstream direction. The elevated area (**Fout! Verwijzingsbron niet gevonden.**a and c) results in an obstruction in the flow pattern, this makes that more water is held upstream than which is flowing over the weir in the downstream direction. The water levels become, due to the obstruction, higher over time and eventually cause the floodplains to inundate.

The elevated area of the weir in combination with the upstream boundary condition cause that the river between the upper boundary condition and weir De Haandrik will function as a basin until the upper threshold at weir De Haandrik reached (9.1 m+NAP). In TYGRON a weir is a line-based construction in which water can flow from the higher entry to the lower entry by an interacting centre point of a grid cell (**Fout! Verwijzingsbron niet gevonden.**a).



B5-2. When water is initialized to the model, it reaches the entry points connected to a grid cell at the weir and exits at the downstream side of the weir (a). The elevated area for the weir (b) and the area between the upper boundary and weir De Haandrik is closed by a dam (c). More water will flow into the area between the weir and the upstream boundary condition than that water can flow over the weir, resulting in rising water levels over time.

Since a weir is only connected by the centre point of one grid cell, it functions as a funnel. The funnel (line-based weir structure) together with the basin (upper boundary condition and elevated heights) cause that more water will come into the system than that can flow over the weir. This results in higher water levels at De Haandrik and eventually in the inundation of the floodplains. A solution to this problem is found by reducing the weir height of weir De Haandrik and Hardenberg. Normally a river weir is dynamic, so the weir can divide the volume of water over the downstream part in larger discharge scenarios and hold water in the upstream regime during lower discharger scenarios by regulating the threshold height. In TYGRON a weir height is not dependent on the upstream water level, so the weir height needs to be calibrated to a value where the actual weir threshold is reached by the simulated water levels.

C. RQ1 simulation water levels

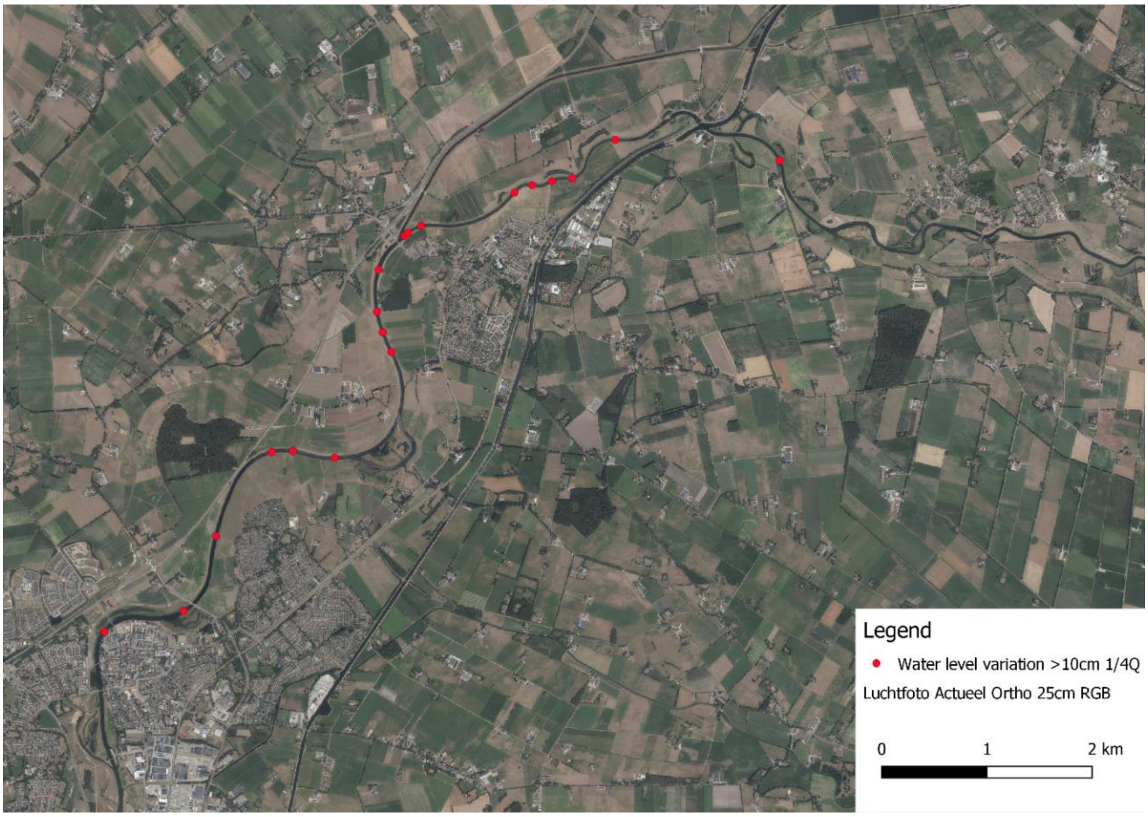
C1. Manning roughness values

In the 1/4Q scenario water only flows through the main channel and in the T10 scenario water will also flows in the floodplains. The SOBEK model is already calibrated and the value of the calibrated main channel roughness corresponds to a Chézy value of 25 $m^{1/2}/s$ for the 1/4Q scenario and 35 $m^{1/2}/s$ for the T10 scenario. The Chézy values of SOBEK are converted to Manning values to compare the results with the calibrated values in TYGRON, (C1). The Chézy roughness values are converted based on the symmetrical cross-section at De Haandrik (Appendix 1.1.1.).

C1. The minimum and maximum hydraulic roughness values described by Chow (1959), for a river main channel and the floodplains. The last column presents the calibrated roughness values in SOBEK to the T10 discharge scenario. The T10 discharge scenario in SOBEK is calibrated with a representative water level of 1.5 meters for Chézy. The Chézy values are converted to Manning values based the symmetrical cross-section is SOBEK.

Natural streams (< 100 ft.):	Minimum Manning value n [$s/m^{1/3}$]	Average Manning value n [$s/m^{1/3}$]	Maximum Manning value n [$s/m^{1/3}$]	Converted Manning roughness SOBEK [$s/m^{1/3}$]
1. Clean, straight, full stage and no rifts or deep pools	0.025	0.030	0.033	0.026
2. Same as above but with more stones and weeds	0.030	0.035	0.040	
3. Clean and winding streams with some pools and shoals	0.033	0.040	0.045	
4. Same as above but with some weeds and stones	0.035	0.045	0.050	
Floodplains:				
1. Grass/open land	0.030	0.035	0.050	0.033
2. Cultivated areas	0.030	0.040	0.050	0.027
3. Scattered brushes	0.035	0.050	0.070	[-]*
4. Light brush and trees	0.040	0.060	0.080	[-]
5. Dense brushes with trees	0.070	0.100	0.150	0.058
*Not defined in the TYGRON case				

C2. Locations difference water level > 10 cm

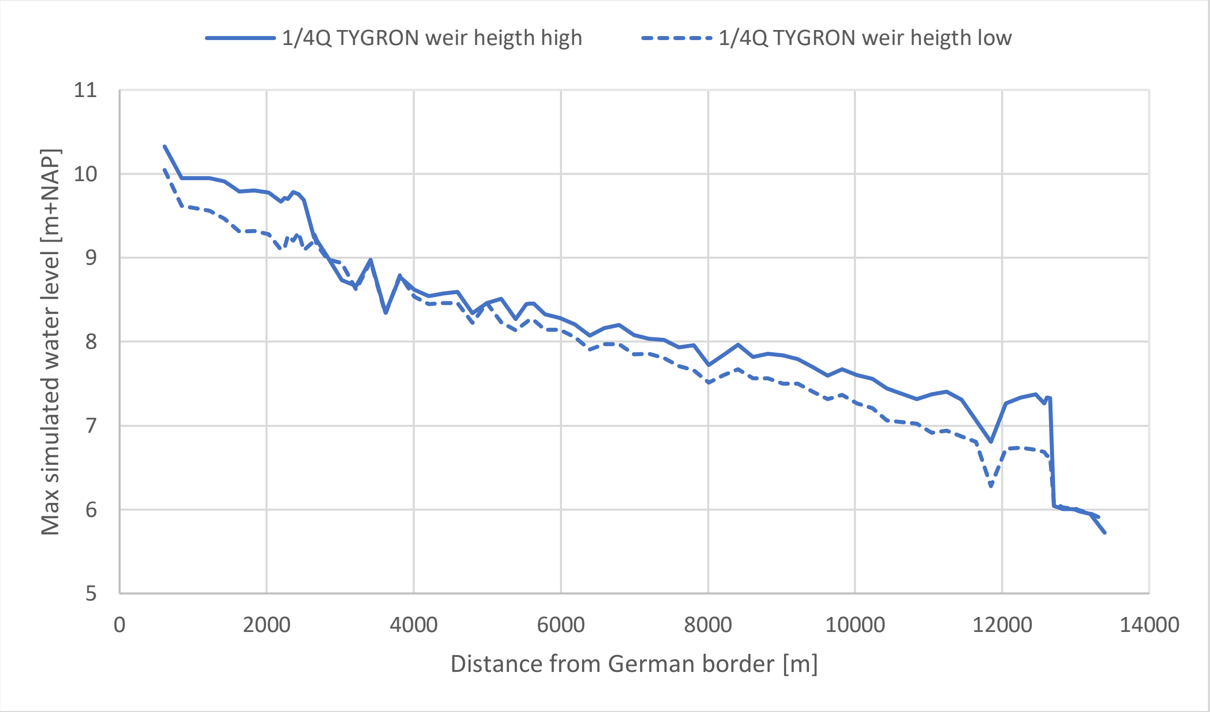


C2-1. Locations where the difference in the simulated water levels are larger than 0.10 m compared with the adjacent observation point in the 1/4Q scenario.

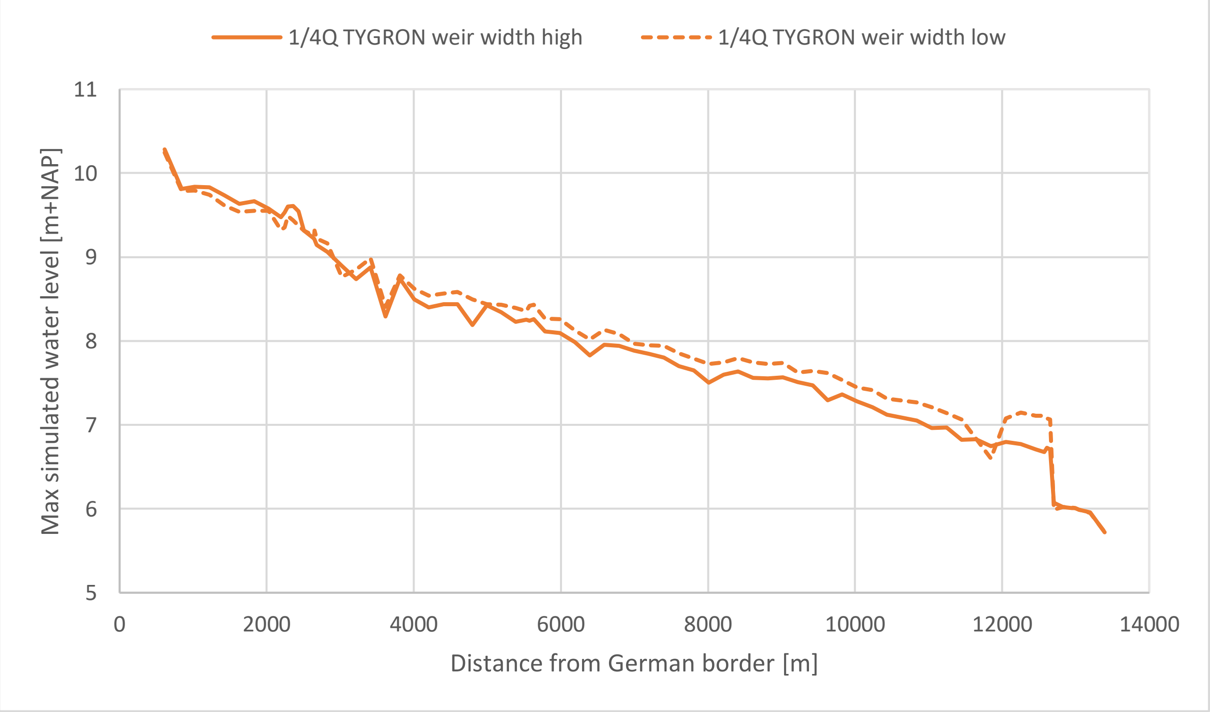
C2-2. Locations where the difference in the simulated water levels are larger than 0.10 m compared with the adjacent observation point in the T10 scenario.

D. RQ3 sensitivity analysis

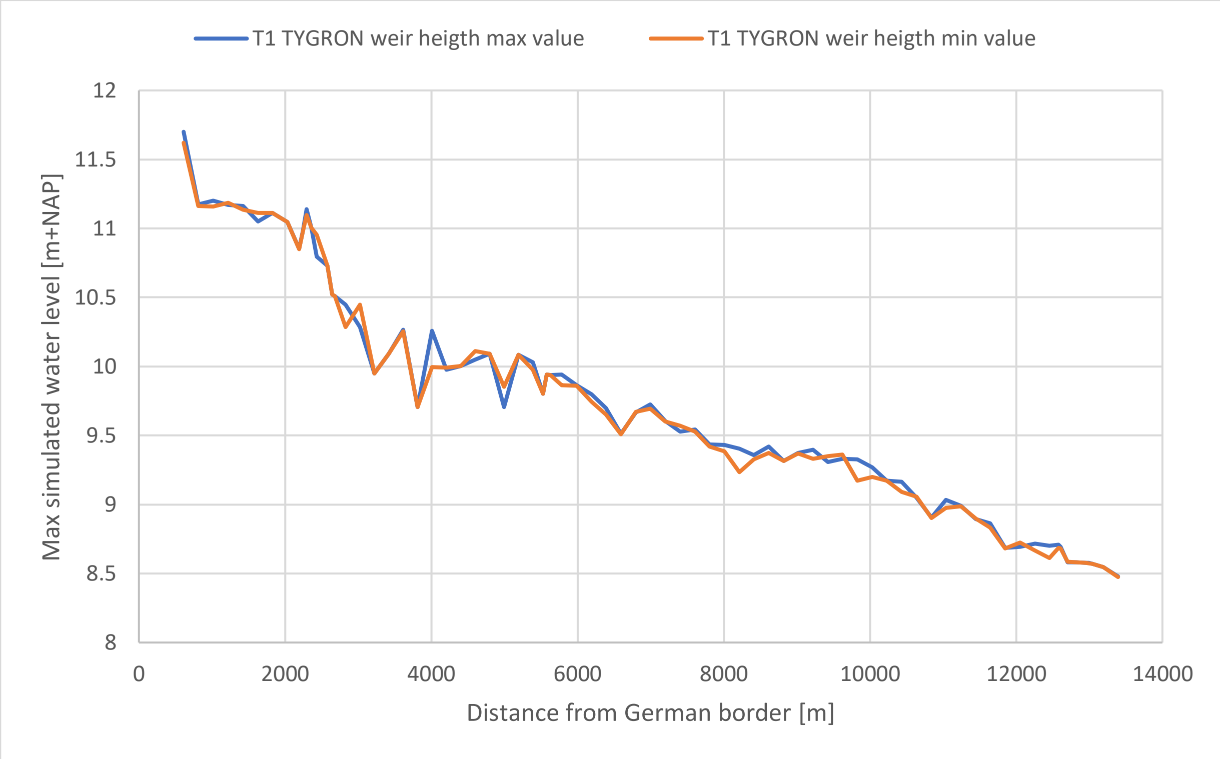
D1. Sensitivity weir dimensions TYGRON



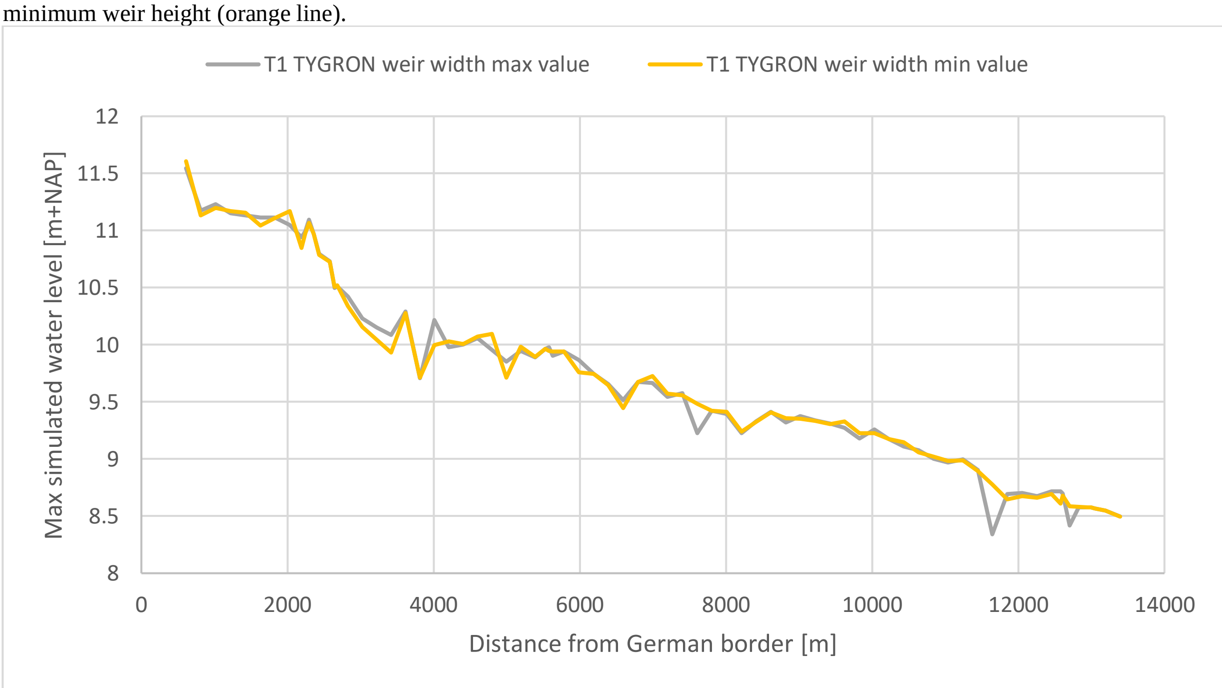
D1-1. Length profile of maximum simulated water levels in the 1/4Q scenario at the maximum weir height (blue line) and the minimum weir height (dotted line).



D1-2. Length profile of maximum simulated water levels in the 1/4Q scenario at the maximum weir width (orange line) and the minimum weir width (dotted line).

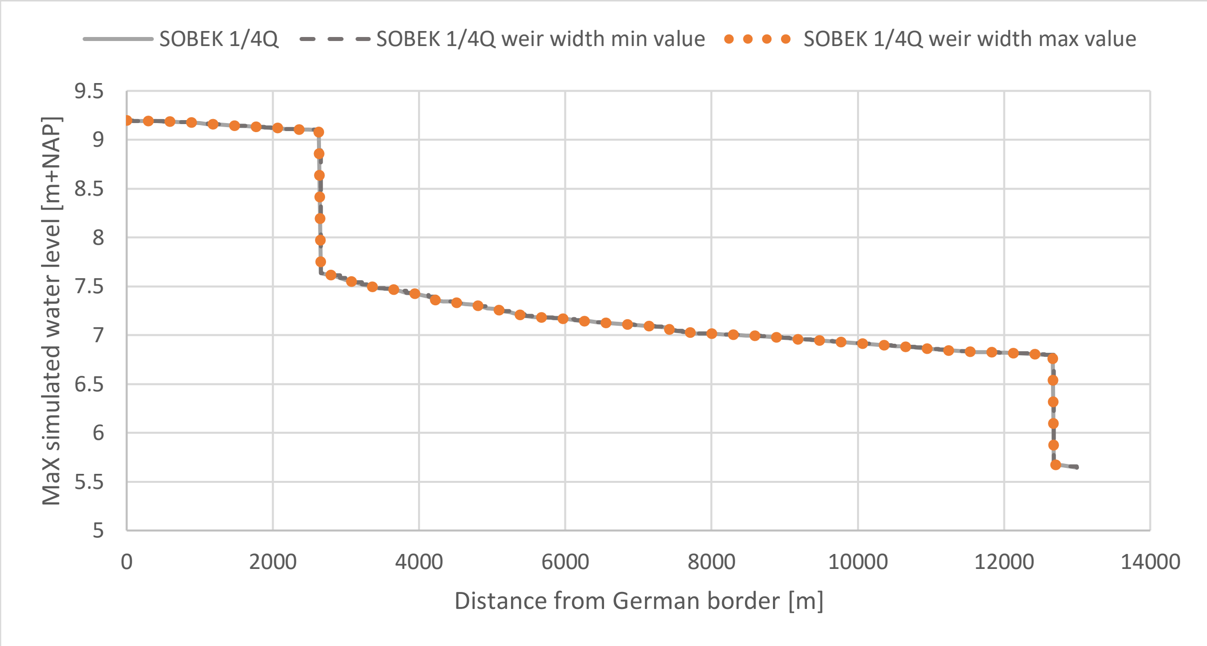


D1-3. Length profile of maximum simulated water levels in the T1 scenario at the maximum weir height (blue line) and the minimum weir height (orange line).

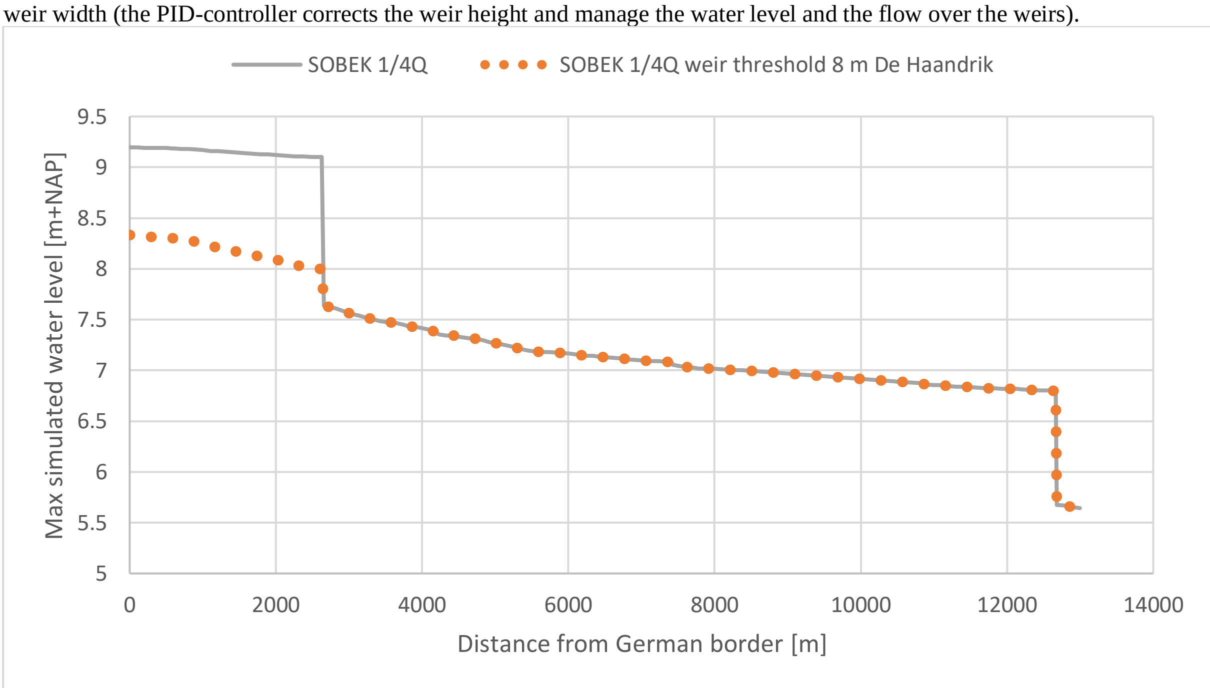


D1-4. Length profile of maximum simulated water levels in the T1 scenario at the maximum weir width (grey line) and the minimum weir width (yellow line).

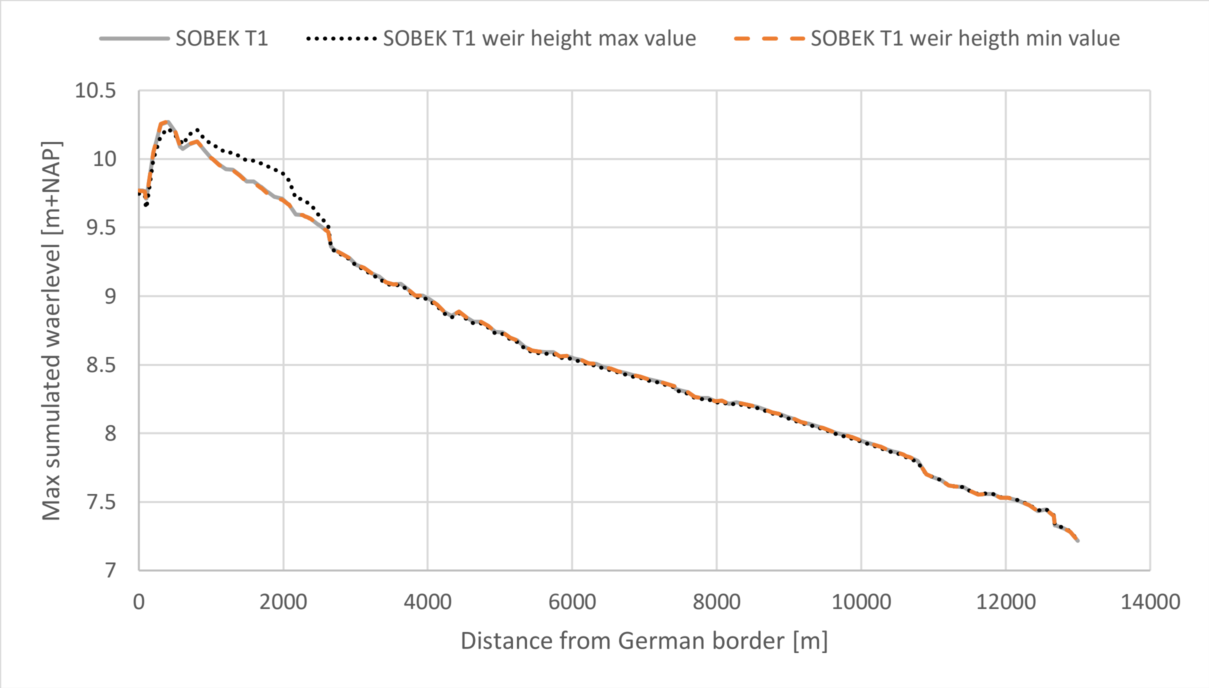
D2. Sensitivity weir dimensions SOBEK



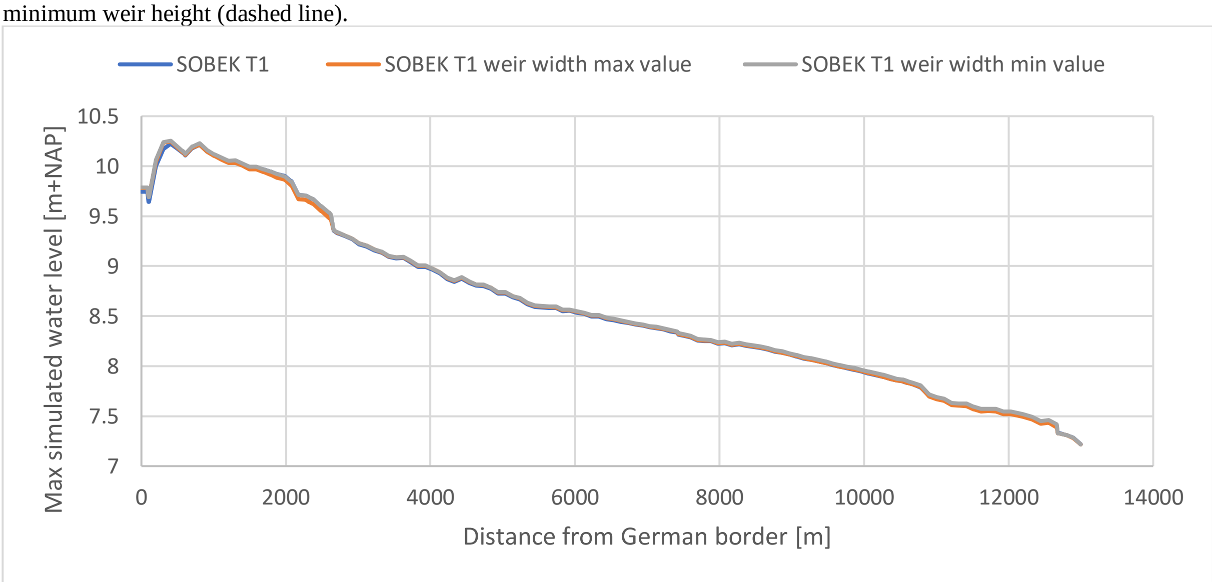
D2-1. Length profile of maximum simulated water levels in the 1/4Q scenario in the maximum weir width and the minimum weir width (the PID-controller corrects the weir height and manage the water level and the flow over the weirs).



D2-2. Length profile of maximum simulated water levels in the 1/4Q scenario (grey line) and in the situation where the upstream weir threshold value is decreased to 8 m (the PID-controller corrects the weir height and manage the water level at 8 m and the flow over the weirs).



D2-3. Length profile of maximum simulated water levels in the T1 scenario at the maximum weir height (dotted line) and the minimum weir height (dashed line).



D2-4. Length profile of maximum simulated water levels in the T1 scenario at the maximum weir width (orange line) and the minimum weir width (grey line).