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Effect of vegetation distributions on water levels of the Overijsselse Vecht

MASTER THESIS

JOERI MASSA

Effect of vegetation distributions on water levels of the Overijsselse Vecht

Master Thesis

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Cover image
Aerial picture of the high water on the Overijsselse Vecht taken in Ommen in May 2014.

Preface

This thesis is the final part of my study Civil Engineering and Management, specialisation in Water Engineering and Management at the University of Twente. During this research I was concerned with hydraulic modelling, the effect of vegetation on river processes and the management of a river. It was a great experience to work on such a topical and relevant subject, at the interface of technology and management. That is exactly what I like about this study. At the same time, it was a challenge to immerse myself in hydraulic modelling.

I would like to thank Linda and Jeroen for the introduction to this subject, their advices and for our weekly meetings. I would also like to thank Denie and Matthijs, who were always available to answer questions, give advice or reflect on the process.

In addition, I would like to thank Herm Jan aan het Rot for the pleasant cooperation during our study. I would like to thank my girlfriend Carlijn for the help and distraction during the past months, which have not always been easy. Finally, I would like to thank my parents for their everlasting support and interest in what I do.

With this master thesis, I am finishing my time as a student. I have had the opportunity to become acquainted with a wonderful field of expertise and hope to be able to use my knowledge as a professional in water management.

Joeri Massa
Nijmegen, September 2019

Abstract

Highlights

- An existing hydraulic 1D model of the Overijsselse Vecht is extended to an 1D-2D model;
- Different vegetation data sources are used to describe the floodplain vegetation, which results in considerably large differences in the calculated water levels;
- Mixing classes can be a suitable alternative method to classify vegetation, however the mixing classes as defined in this research lead to a large overestimation (15-23 cm) of maximum water levels;
- Vegetation perpendicular to the flow direction causes water levels to rise due to the blockage effect;
- The discharge capacity of a river increases if wide paths with smooth vegetation are present;
- The calculated water levels contain some uncertainties, but the model appears to be suitable for a qualitative exploration of the effects of vegetation distributions on the water levels.

In the floodplains of the Overijsselse Vecht various types of vegetation can be found. From the 'Vechtvisie' there is a demand for nature restoration and development on the one hand, while on the other hand flood safety must be guaranteed. Changing vegetation means changing the hydraulic resistance, which affects the discharge capacity and the water levels along the Overijsselse Vecht. From the perspective of Regional Water Authority (R.W.A.) Vechtstromen, there is a demand for an instrument that can calculate the impact of the spatial variation in vegetation on water levels. This instrument can be used to determine when and where natural development is permitted and when action is required from a flood point of view.

In this study, an existing hydraulic one-dimensional (1D) model was extended to a 1D-2D model. This was done by removing the winter bed from the one-dimensional cross-sections and replacing it with a two-dimensional grid. In this grid it is possible to schematize the spatial variation in a roughness grid. For the winter bed within the study area (the management area of R.W.A. Vechtstromen), vegetation classes have been defined, which are linked to a hydraulic roughness. This hydraulic roughness is used as input for the roughness grid in the model.

A sensitivity analysis has been performed for the hydraulic 1D-2D model. This showed that the model is more sensitive to the summer bed resistance than to the winter bed resistance. Furthermore, it appeared that the model, in terms of the winter bed resistance, is particularly sensitive to extremely lower roughness-values (-40%). Finally, it became clear that the downstream boundary condition, a Q-h relation, significantly affects the water levels in the final 10 km of the Overijsselse Vecht in the management area of R.W.A. Vechtstromen. As a result, the calculated water levels in this part of the model are less reliable.

With the built 1D-2D model different vegetation scenarios have been simulated. Model runs with an extremely rough scenario and an extremely smooth scenario show that the bandwidth between the peak water levels is in the order of magnitude of 1 m. In addition, the peak of the discharge wave in the rough scenario arrives 21 hours later at the end of the study area. It also showed that the largest differences in water levels and flow velocities between the two scenarios occur in narrower parts of the winter bed. This shows that these narrower sections are more sensitive to roughness changes.

In this research the effect of different vegetation data sources, namely the ecotopes map, LGN map and two vegetation maps based on satellite images (2017 and 2018), were compared. The LGN map

shows the dominant vegetation on a lot, there is no variation within the lot and the less common vegetation types are neglected. As these are often the rougher vegetation species, a structurally lower water level is calculated compared to the model run with the ecotopes map (4-8 cm). The LGN map is not suitable as a data source for this model because of its classification method. There are also considerable differences between the model run with the ecotopes map and the model runs with satellite images, in particular the water levels in the model run with the satellite image of 2017 deviate (4-14 cm compared to the ecotopes map, 3-12 cm compared to the other satellite image). The deviation between the satellite image of 2018 and the ecotopes map is much lower (0-4 cm). Due to the significant differences between the two satellite images and its relative novelty, satellite images do not appear to be a suitable alternative to the ecotopes map at the moment. If the accuracy increases however, this could be a suitable alternative because of frequency of the satellite images.

A method in which the lots in the floodplains of the Overijsselse Vecht are assigned a mixing class results in a large overestimation of the water level (15-23 cm). This has to do with the worst-case assumption of the roughness value of a mixing class, where the amount of rough vegetation is rounded up and the roughest type of vegetation (*shrubs*) is used in the calculation of the roughness mixing class. This roughness value often does not correspond to the actual roughness of a lot. It was also investigated how large the variations within the mixing classes can be, which showed that for the chosen vegetation distributions, the deviation in maximum water level is always within 5 cm. A higher water level only occurs when rough vegetation blocks the flow. This shows that if agreements are made with lot owners about the permitted amount of vegetation, the mixing class method can be used to determine the roughness of a lot, but also gives the owner the freedom to organise the lot. However, it is advisable to define other mixing classes than those used in this study.

Different vegetation distributions have been studied with the 1D-2D model. This showed that two aspects must be taken into account if designing the winter bed: (1) the water level rises rapidly if vegetation blocks the flow and (2) the creation of wide flow paths results in higher flow velocities and lower water levels. Vegetation in the river bank does not result in higher maximum water levels as long as there is room for flow paths behind the bank. Rougher vegetation in storage parts of the floodplains barely affects the water levels.

The 1D-2D model calculates higher water levels (15 and 50 cm) compared to the 1D model. This difference may be caused by underestimating physical processes (e.g. the lack of a storage part of the winter bed) and the lower winter bed roughness in the 1D model. Around the weirs, the 1D-2D shows a more realistic result, because there are no jumps in the water level. The difference between the two models quickly diminishes in the last kilometer of the area of R.W.A. Vechtstromen, because the water level in the 1D-2D model adapts to the lower water levels in the last part of the model (which is schematized in 1D).

Due to the strong influence of the Q-h relation and the uncertainty in the measurement data used in the calibration, there is considerable uncertainty in the water level calculated by the 1D-2D model, which is larger in the downstream part (due to the Q-h relation), but difficult to quantify. It is recommended to validate and if necessary improve the quality of the measurement data. It is also recommended to locate the model boundary further downstream and to extend the 2D grid, so that the transition from 1D-2D to 1D does not take place in the study area. Although a quantitative analysis of the water levels is difficult due to the uncertainties in the model, the model appears to be suitable for a qualitative exploration of the effects of vegetation distributions in the floodplains on the water level of the Overijsselse Vecht.

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1 Introduction

1.1 Background

The River Vecht (*Dutch: Overijsselse Vecht)* is a river that originates in Germany (near the village Darfeld) and flows through the Dutch province Overijssel to the River Zwarte Water, which discharges in the Lake Zwarte Meer (Figure 1). The River Vecht has a large winter bed, with floodplains that can discharge water in case of high water. These floodplains contribute to the discharge capacity of the river to a considerable degree. Vegetation is present in the floodplains. The hydraulic roughness, important for the calculation of water levels, is dependent on the vegetation type that is present.

The River Vecht from the German border to the village Varsen is managed by Regional Water Authority (R.W.A., *Dutch :Waterschap*) Vechtstromen (Figure 1). Inside the management area of R.W.A. Vechtstromen, the River Vecht is partly surrounded by regional flood defences. This means that requirements are set for the maximum permissible water levels in order to meet the safety standards (Waterschap Vechtstromen, 2017a). Estimating the flow resistance is of great importance for river managers, since it influences the discharge capacity of the river significantly (Järvelä, 2002).

At the moment, the lots (areas of land that can be distinguished based on their owners) in the floodplains either have an agricultural function or a nature function, but these functions are shifting. In 2009 the 'Vechtvisie' was presented, a vision that aims to transform the River Vecht into a safe, semi-natural river. One of the factors that will be used to assess this vision is the Natura 2000 tasking (Waterschap Vechtstromen, 2017a). For example, there are tasks for the restoration of certain vegetation species. Specifically for the river basin of the Vecht, a number of characteristic species have been identified that should be preserved and, where possible, expanded (Waterschap Vechtstromen, 2017b).

The functions of the lots in the floodplains can change over time, due to the restoration of nature or because the owners of the lot want to change the arrangement of the lot. Vegetation types have a specific hydraulic resistance due to their different characteristics. Changes in the function of lots can therefore lead to a significant increase in hydraulic resistance, which is at the expense of the discharge capacity and leads to an increase in the water level.

From the flood safety point of view, R.W.A. Vechtstromen therefore would like to gain more insight in the hydraulic resistance and development of vegetation in the floodplains. It is desirable that an analysis of the present vegetation can be carried out as quickly as possible. In addition, it is important to have easily manageable vegetation classes, with which, on the one hand, the roughness can be properly assessed and, on the other hand, freedom is given to the owners to manage the lot. This is advantageous for R.W.A. Vechtstromen as well, as less strict monitoring is required. Finally, it is necessary to gain insight into the effect of different vegetation distributions on the water levels, so that critical situations can be recognised. With the above mentioned aspects, it is possible to achieve better agreements with the owners of the lots, so that the developments in the lots are in line with the intended safety and nature goals.

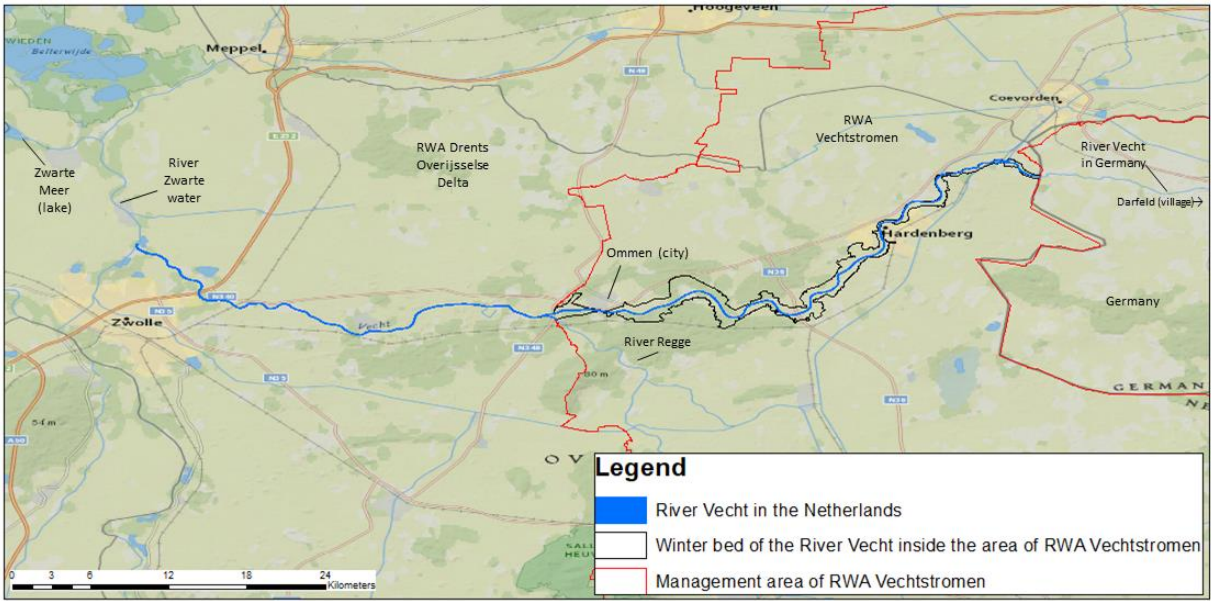

Figure 1. Map of the area of R.W.A. Vechtstromen (Adapted from Esri, 2019).

1.2 State of the art

Research into the hydraulic resistance of channels and its effect on hydraulic variables has been going on for a long time. In 1769, a formula was established by the French engineer Antoine Chézy, using the Chézy coefficient to describe the wall roughness. A higher Chézy value means a lower resistance, which in fact makes the Chézy coefficient a conductance coefficient (Ribberink et al., 2017). Other descriptions with a constant roughness coefficient are the Darcy-Weisbach equation (1845) and the Manning equation (1889). Later descriptions followed in which the Chézy coefficient (Strickler, 1923 and White-Colebrook, 1938) and the Manning coefficient (Bos & Bijkerk, 1963) were no longer constant, but water depth-dependent.

More recently, research has been done into the influence of the properties of vegetation on the hydraulic resistance. The flow resistance of vegetation depends on plant mechanical properties, topology, age, seasonality, foliage, porosity, density and patchiness (Aberle & Järvelä, 2013). An often made distinction is based on the degree of submergence. Kleinhans (2014) distinguishes three types of flows: flow over well-submerged vegetation, flow over and through submerged vegetation and flow through emergent vegetation. In case of well-submerged vegetation, the roughness coefficient can be approached by a constant Manning coefficient (Augustijn et al. 2008). For flow through emergent vegetation, Petryk & Bosmaijan (1975) derived an equation.

The flow over and through submerged vegetation is more complex to describe, as the velocities of the flow through the vegetation differ from the velocities of the flow over the vegetation. There is also a transitional zone and a zone in which the flow rate is influenced by the bottom roughness (Baptist et al. 2007). There are several descriptions for flow over and through submerged vegetation. Some examples are the equation from the vegetation handbook of Rijkswaterstaat, in which the resistance is expressed in a Chézy coefficient (Van Velzen et al., 2003a, 2003b), the equation of Huthoff (2007) and the equation of Baptist et al. (2007), established by using genetic programming.

Besides the characteristics of vegetation, there is another aspect that affects the water level, namely the distribution of vegetation. Luhar & Nepf (2013) found that a different spacing of the same channel blockage affects the velocity. The velocity in the channel is lower if vegetation is distributed in multiple small patches compared to a situation where vegetation is present in large contiguous blocks, because interfacial area increases in case of multiple small patches (Luhar & Nepf, 2013). Bal et al. (2011) investigated three different vegetation patterns. They found a significant difference in Manning-values between a pattern where a bottleneck was created and a pattern where there was no bottleneck created. Makaske et al. (2011) investigated different stages in vegetation development on the reach scale of a lowland river. They found that water levels are more sensitive to an increase in hydraulic roughness in narrow sections.

Hydraulic models are often used to calculate water levels on a river, including the hydraulic roughness. On the scale of a river, often 1D and 2D models are used. 1D models describe flow interaction only in streamwise direction (Huthoff, 2007). The flow velocity in 2D models is depth-averaged. A hybrid form of 1D and 2D models is also used, the so-called 1D-2D models (Huthoff, 2007). In 1D-2D models, the main channel is schematized in one dimension and the floodplains are schematized in two dimensions. The vegetation descriptions, including the characteristics of the vegetation, are often not included in hydraulic models (Kiczko et al., 2017). The drag force on individual plants is translated into a roughness coefficient in a uniform flow formula (Manning, Chézy, or Darcy) (Shields Jr. et al., 2017). The vegetation handbook (Van Velzen et al., 2003) provides Chézy-coefficients for several types of vegetation classes and also a formula to calculate a combined roughness if multiple types occur on a piece of land. The data of the vegetation handbook is often used for Dutch rivers.

The vegetation of Dutch water systems is described in ecotopes maps (Willems et al., 2007). Remote sensing is nowadays often used to detect vegetation types. Geerling & Penning (2018) adapted the method used by Zhu et al. (2012) to detect vegetation changes based on the Normalized Difference Vegetation Index (NDVI) value. In this way, on the basis of satellite images, it is possible to create a vegetation map.

1.3 Problem statement

Based on the available vegetation data sources, changes in vegetation and the hydraulic roughness over time can be determined. To evaluate the effect of these changes on the water levels along the River Vecht, the information must be coupled to a hydraulic model. At the moment R.W.A. Vechtstromen uses a one-dimensional (1D) SOBEK 2 model. This model schematizes the River Vecht using cross-sections. In these cross-sections, the roughness of a floodplain is described by a single roughness value. There is no spatial variation of the hydraulic roughness over the width of floodplains in the 1D-model. Over the length there is also no spatial variation of the hydraulic roughness, until a new cross-section is reached. However, vegetation can vary over the width and length of the floodplain. Information from ecotopes maps and satellite images can show this spatial variation, but in the currently used 1D-model this information is simplified to one value for a floodplain per cross-section. To use the information of the vegetation data sources without simplifying it to roughness values in cross-sections, either an existing model must be extended to a 1D-2D model or a new (1D-)2D model must be built.

This hydraulic 1D-2D model is a missing link in the workflow (Figure 2) that R.W.A. Vechtstromen can use to support the management decisions regarding vegetation in the floodplains of the River Vecht. The steps in this workflow are as follows. Vegetation in the floodplains can be found in the vegetation data sources. Hydraulic roughness maps can be made, based on ecotopes maps and satellite images. A method to make these vegetation data-based roughness maps is known, however the maps have yet to be made. The hydraulic roughness maps can be used by the model to be built as input for the hydraulic roughness of the River Vecht.

The calculated water levels can then be compared to the safety standards. If the calculated water levels are higher than the safety standards, an intervention is needed. R.W.A. Vechtstromen can agree upon the owners of the lots to realize a change in vegetation that is necessary to meet the safety standards. It is also possible that no intervention is needed. In that case, the workflow can be repeated after a certain time with new up-to-date vegetation data. The process of comparing the water levels along the River Vecht with the safety standards and making agreements with the owners of the lots in the floodplains about vegetation change is called the management decision making process. For R.W.A. Vechtstromen, it is important to know how to interpret the results of the hydraulic model to be built, in order to reach correct decisions.

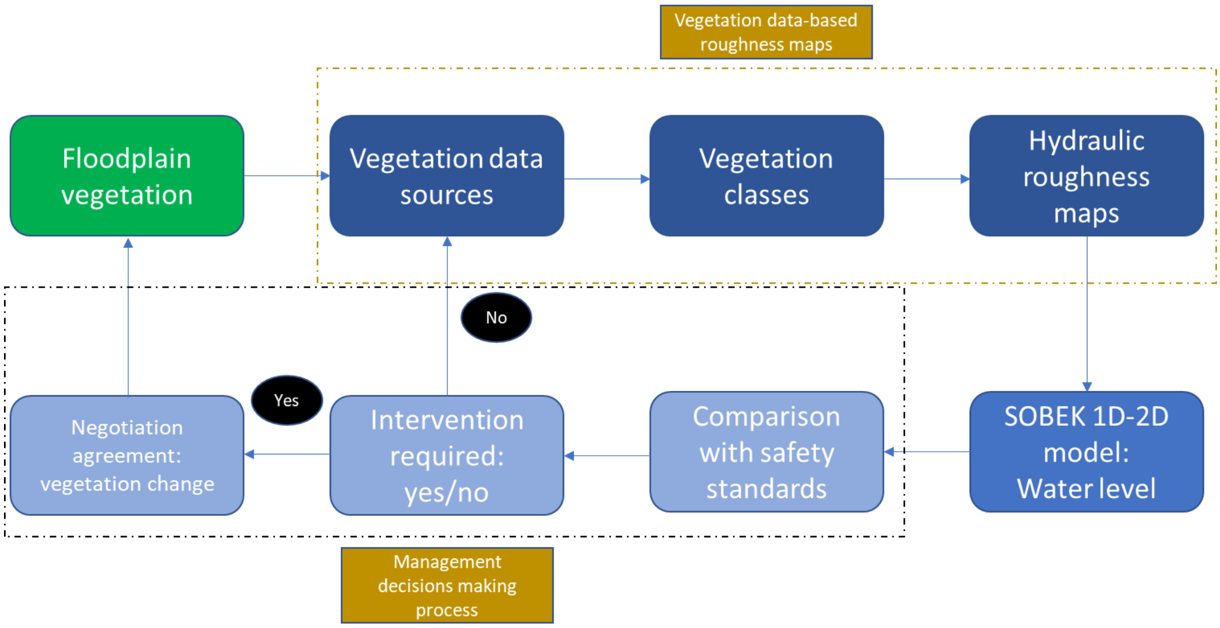

Figure 2. Workflow that shows the different steps to determine if an intervention in the vegetation in the floodplains is needed regarding the safety standards.

1.4 Research objective

The problem statement leads to the following research objective:

"To investigate the possibility of using a hydraulic 1D-2D SOBEK 2 model for the calculation of the water levels along the River Vecht and to support the management decisions making process regarding the management of vegetation in the floodplains"

1.5 Research questions

In order to achieve the research objective, five research questions are formulated to guide the research. The relation between the research question and research objective is shown in Figure 3. The research questions of this study are as follows:

1. To what extent is the 1D-2D model valuable as a tool for Regional Water Authority Vechtstromen regarding the sensitivity of the results to uncertain parameters?
2. What is the effect of extreme vegetation scenarios on the water levels along the River Vecht?
3. To what extent are the available vegetation data sources valuable to describe vegetation situation in the winter bed of the River Vecht?
4. To what extent are mixing classes valuable as a method to determine the permissible amounts of vegetation on lots?
5. What is the effect of different vegetation distribution scenarios on the water levels along the River Vecht?

Before model simulations can be done, a number of steps need to be taken. First, a model must be built and then be calibrated and validated. Next to this, suitable vegetation classes, both homogeneous and mixing classes, must be determined for the floodplains in the management area of R.W.A. Vechtstromen. Based on this, vegetation distribution scenarios can be developed, which can be used as input for the model simulations.

Two types of model simulations are performed: model simulations for the sensitivity analysis (research question 1) and model simulations with the vegetation distribution scenarios. The results of the latter will help to answer the other research questions (2-5). By answering these research questions, the research objective can then be achieved.

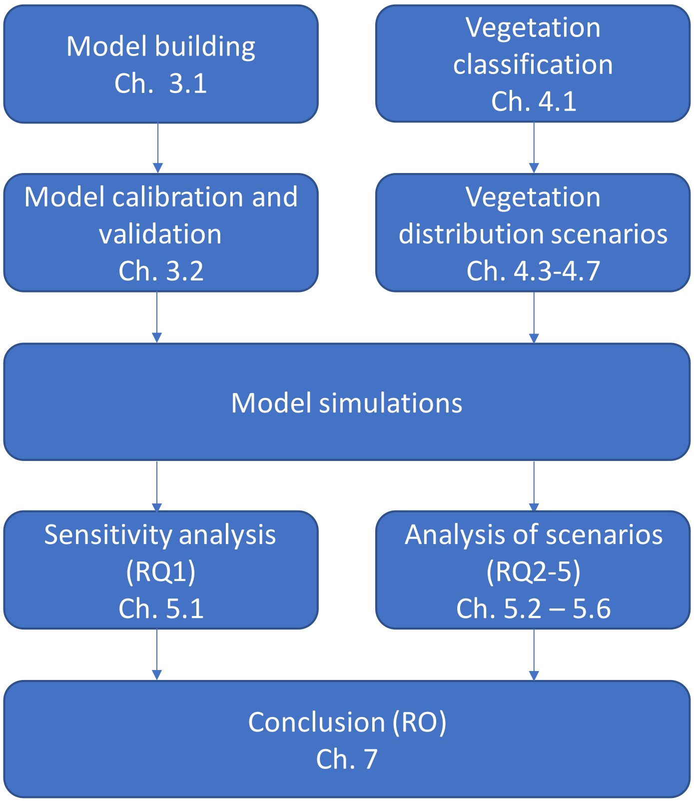

Figure 3. The relation between the research objective (RO), the research questions (RQ) and other research activities.

1.6 Thesis outline

This thesis is organised as follows. The study area, existing hydraulic model and data sources will be discussed in chapter 2. The model set-up, calibration and validation can be found in chapter 3. The methodology of this research is described in chapter 4. The results of the model runs are discussed in chapter 5. The discussion can be found in chapter 6. Finally, the conclusion and recommendations are presented in Chapter 7 and 8.

2 Study area, hydraulic model and data sources

This study focuses on the winter bed of the River Vecht within the management area of Regional Water Authority Vechtstromen. In this chapter a general description of the study area is given first. The existing hydraulic 1D SOBEK 2 model, currently in use by R.W.A. Vechtstromen, will then be discussed. Finally, an overview of all the data that will be used in this study is presented.

2.1 River Vecht

The River Vecht flows into the Netherlands near the German village Laar. This is where the management area of R.W.A. Vechtstromen starts. At the village of Varsen, near Ommen, the River Vecht flows out of the management area of R.W.A. Vechtstromen (to the management area of R.W.A. Drents Overijsselse Delta). The most important urban areas along the River Vecht in the area of R.W.A. Vechtstromen are the cities Hardenberg and Ommen (Figure 1), and the villages Gramsbergen and Mariënberg.

The length of the River Vecht within the management area of R.W.A. Vechtstromen is 35.8 km (the total length of the river is 167 km, of which 60 km is in the Netherlands). Along the river there are 4 weirs, namely the weirs at De Haandrik, Hardenberg, Mariënberg and Ommen. The weir at Vilsteren is located just outside the management area of R.W.A. Vechtstromen. Because of this, the River Vecht can be subdivided into five reaches within the area of R.W.A. Vechtstromen.

The River Vecht is a rain river and has a fluctuating discharge throughout the year (Waterschap Vechtstromen, 2017a). During the winter months a discharge of 100-200 m^3/s, depending on the location, is not uncommon, while the discharge in the summer is much lower. In the summer, the discharge at De Haandrik can be in the order of 1-2 m^3/s. Discharges for different return periods are presented in Table 1 to give an indication about the fluctuations throughout the year. The discharge at which the winter bed starts to flow along also varies per location, but is around 80 m^3/s. This means that only a few days a year water flows through the floodplains of the River Vecht.

The current safety standard is defined based on a return period of 200 years (Waterschap Vechtstromen, 2017). The derivation of this discharge wave is discussed in section 2.2.3. The River Vecht must be able to discharge this amount of water at the indicated locations.

Table 1. Discharges [m3/s] for different return periods at different location along the River Vecht (Van der Scheer, 2015).

Return period	De Haandrik	Ommen	End of management area op R.W.A. Vechtstromen
347 days a year	0.5	0.7	2.4
80 days a year	23	35	53
1 year	116	169	239
200 years	249	355	500

The winter bed of the River Vecht is bordered by natural heights and dikes (elevated roads). The bed level of the River Vecht decreases within the management area of R.W.A. Vechtstromen from approximately 6 m +NAP to -0.5 m +NAP. Within the winter bed, some natural heights are present. These natural heights do not flood in case of high water. At some location, summer dikes are present next to the main channel of the River Vecht.

In the floodplains of the River Vecht there is a wide variety of vegetation, with some rare species that only occur in the Vecht Valley. Along the upstream part of the Vecht River, mostly grasslands and agricultural lands are found in the floodplains. More downstream occurs proportionally more forest, shrubs and herbaceous vegetation (Figure 4).

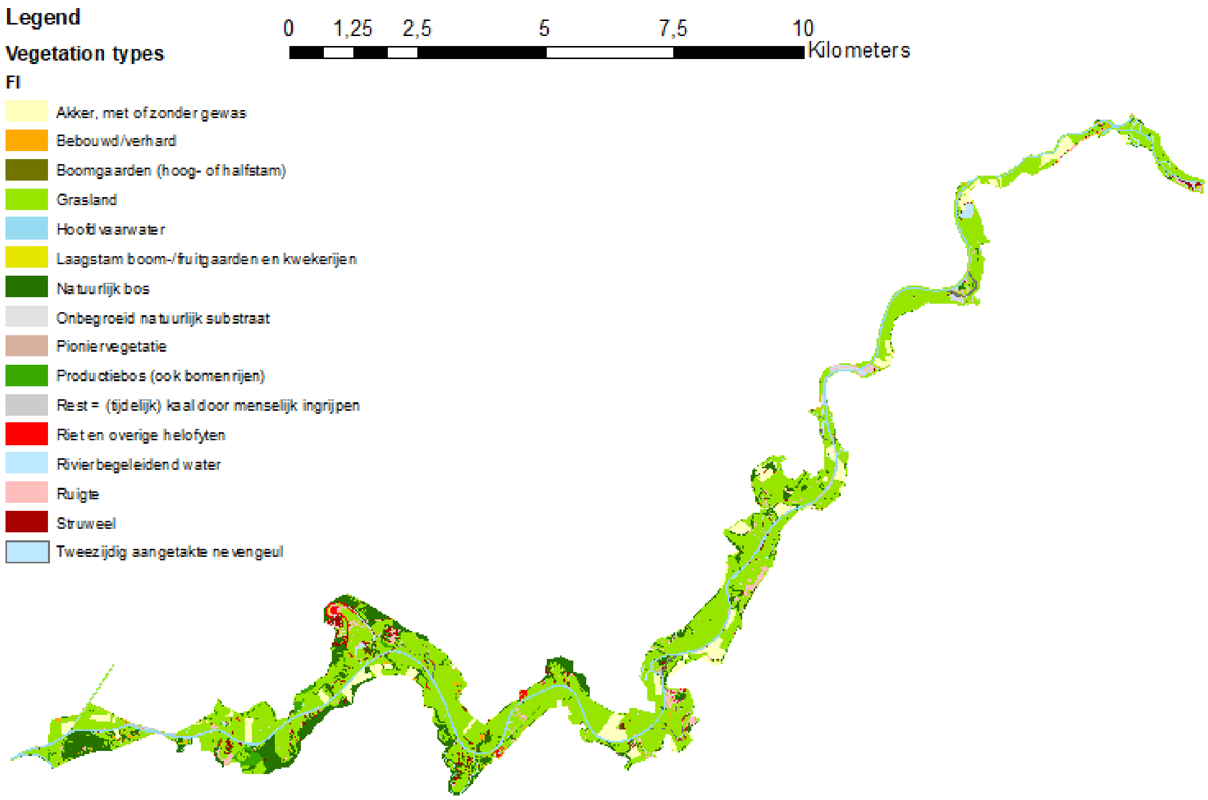

Figure 4. Vegetation in the floodplains of the River Vecht in the ecotopes map.

2.2 Hydraulic 1D SOBEK 2 model

Currently, a 1D hydraulic SOBEK 2 model is used by R.W.A. Vechtstromen. The network, cross-sections and boundary conditions will be used in this research. In this section, the one dimensional SOBEK model is described in its current state.

2.2.1 Network

In the network of the River Vecht from Emlichheim to the weir at Vilsteren, six side channels are included. These are the Flutmulde in Germany and the side channels at the Loozensche Linie, Uilenkamp, the weir of Mariënberg, Beerze and the weir of Junne. The Vechtpark at Hardenberg is also included in the network. Three side channels of the Vecht flow through this park, which flow into the Vecht again at the end of the park.

Besides the inflow of the River Vecht from Germany (included as the upstream boundary condition at Emlichheim), several lateral streams flow into the River Vecht. This network includes a total of 18 lateral flows, of which the River Regge, Afwateringskanaal, Ommerkanaal, Radewijkerbeek and Mariënberg-Vechtkanaal are the largest in terms of discharge.

The most important structures in the River Vecht are the weirs. In total four weirs are present within the area of R.W.A. Vechtstromen. These structures are modelled as they are in the GIS-database of R.W.A. Vechtstromen, including various loops around the weirs, such as fish ladders (Van der Scheer, 2015). Weirs are simulated by a simple proportional control related to the upstream target water level. The four weirs are located in De Haandrik, Hardenberg, Mariënberg and Junne.

The network of the River Vecht, including the side channels, the five largest lateral flows and weirs is schematized in Figure 5.

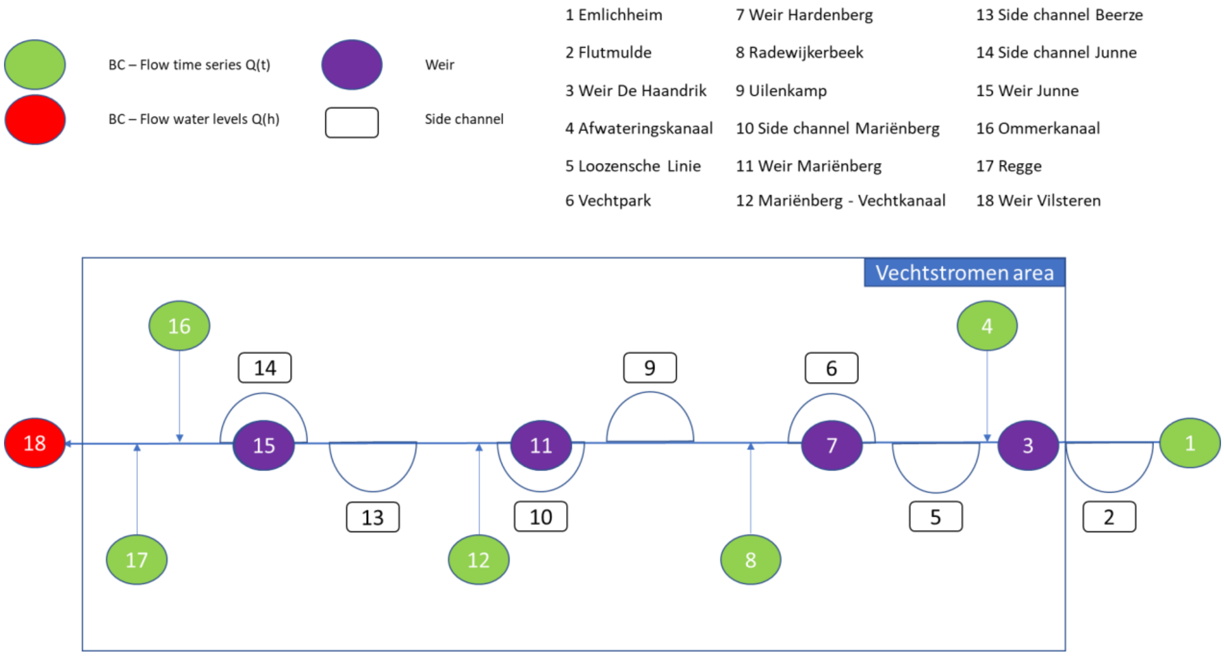

Figure 5. Schematisation of the network in SOBEK 2. Only the five (out of eighteen) largest lateral flows are shown.

2.2.2 Cross-sections

The cross-sections in the existing SOBEK 2 model contain both the main channel and floodsplains. The cross-sections of the main reach of the River Vecht are symmetric (so that different roughness-sections can be defined), while the profiles of the lateral flows and side channels are assymetric (Figure 6). The type of cross-sections that has been used is the YZ-profile, so that different roughness values can be defined within a profile (Van der Scheer, 2015).

The roughness of the main channel is expressed by a Chézy coefficient C. The value of C for the main channel is 35 $m^{1/2}/s$. The roughness of the winter bed is expressed by a Strickler roughness k_n of 0.31 m. In SOBEK 2, a Chézy value is calculated from the Strickler roughness and hydraulic radius R [m] using Eq. (1)(Deltares, 2013).

$$C = 25\left(\frac{R}{k_n}\right)^{\frac{1}{6}} \qquad \text{Eq. (1)}$$

For the side channels and lateral flows, a Bos & Bijkerk parameter of 34 s^{-1} is used. SOBEK 2 calculates a Chézy value with the Bos & Bijkerk parameter γ [s^{-1}], the water depth h [m] and the hydraulic radius R [m] using Eq. (2) (Deltares, 2013).

$$C = \gamma h^{\frac{1}{3}} R^{\frac{1}{6}} \qquad \text{Eq. (2)}$$

The values for the Chézy coefficient, Strickler roughness and Bos & Bijkerk parameter as mentioned above are used in the one dimensional SOBEK 2 model for large discharge events (T=1, T=10, T=100 and T=200). These values gave the best fit during the calibration of the model (Van der Scheer, 2015).

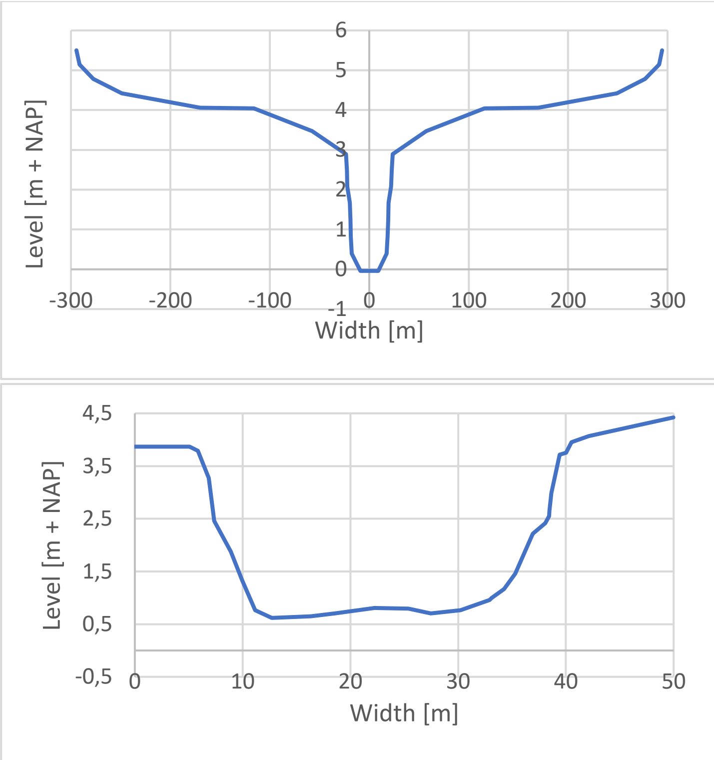

Figure 6. Cross-sections in the 1D hydraulic SOBEK model: a symmetric main channel cross-section (upper) and a asymmetric side channel (lower).

2.2.3 Boundary conditions

The downstream boundary condition is a Q-h relation (Figure 7). The water level is determined by the model based on the calculated discharge. This Q-h relation is based on historical measurement data of the high water event of 1997-1998 at the weir at Vilsteren and several model runs. For discharges larger than 550 m^3/s, the Q-h relation is extrapolated.

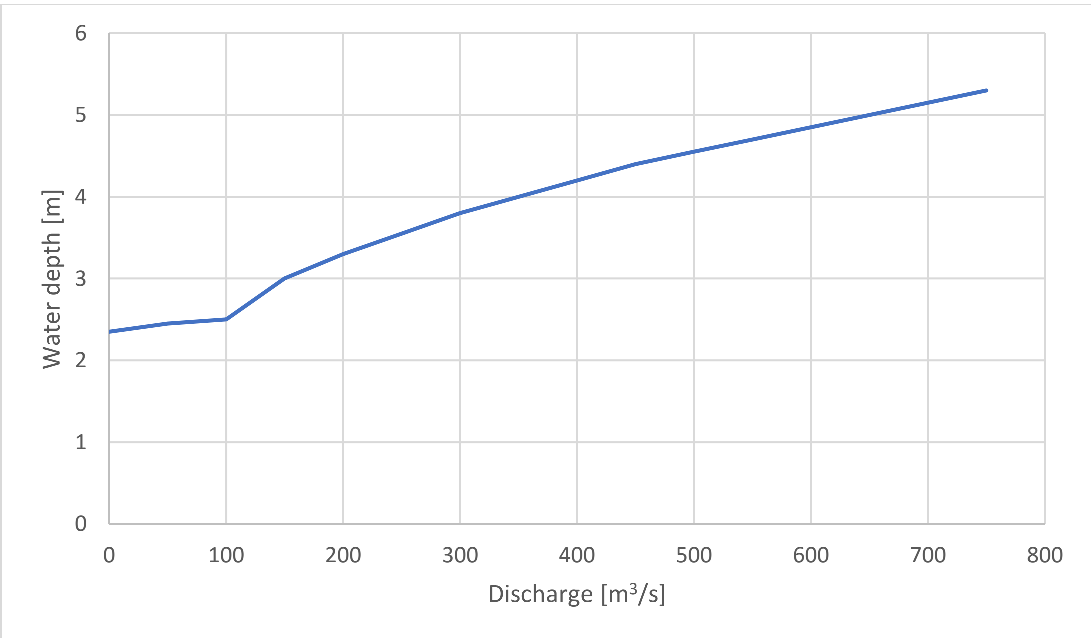

Figure 7. Downstream boundary condition (Q-h relation).

The upstream boundary condition is a Q-t discharge series. The lateral flows are Q-t discharge series as well. Multiple events are defined by R.W.A. Vechtstromen, based on return periods varying from 95% of the time in a year (8322 hours) to once in 200 years. For every event, Q-t discharge series are defined for the upstream boundary condition and the 18 lateral flows. The events are based on measurement data of the period 1997-2015 (Van der Scheer, 2015), although in none of the measuring stations there is data measured during the entire period. At Emlichheim, only 23% of the time measurement data are available.

The design scenario T=200 has a return period of once every 200 years. This extreme scenario is the design discharge for flood defences in the area of R.W.A. Vechtstromen (Waterschap Vechtstromen, 2017a) and will therefore be used in this study to calculate the scenarios. Furthermore, there are also other non-annual design situations with return periods of once in 10, 25 and 100 years respectively, and annually occurring design situations with repetition times of 1 (T=1) 15 (1/2 Q), 80 (1/4Q) and 347 (1/100Q) days per year respectively. No measured water levels are available for the design situations T=25, T=100 and T=200, as the period with measurement data is short. The design situations T=10 and T=1 are therefore used for the winter bed calibration and validation respectively. For the summer bed calibration the situation ¼Q is used.

The water levels associated with a certain return period did not necessarily occur when the discharge with the same return period occurred. The two data sets are separate data sets. The events, with their measured discharge and measured water levels, are therefore theoretical events.

The shape of the discharge wave is based on earlier studies (Van der Scheer, 2015). In the design situation 1/4Q, a constant discharge is used as the upstream boundary condition and the lateral flows. In the less frequent design situations the wave starts with the value of the design situation 1/4Q and then increases to a peak value that depends on the design situation. Figure 8 shows the shape of the discharge waves for the upstream boundary condition (Emlichheim) and the five largest laterals in the design situation T=200. The peak at Emlichheim occurs 32 hours later than the peak at the laterals. For the other non-stationary discharges, the pattern is the same, except for the difference in peak discharge between Emlichheim and the lateral flows. This increases as the event occurs more frequently, to 48 hours in the T=1 situation. The peak values for Emlichheim and the five lateral flows in the design situations that will be used can be found in Table 2.

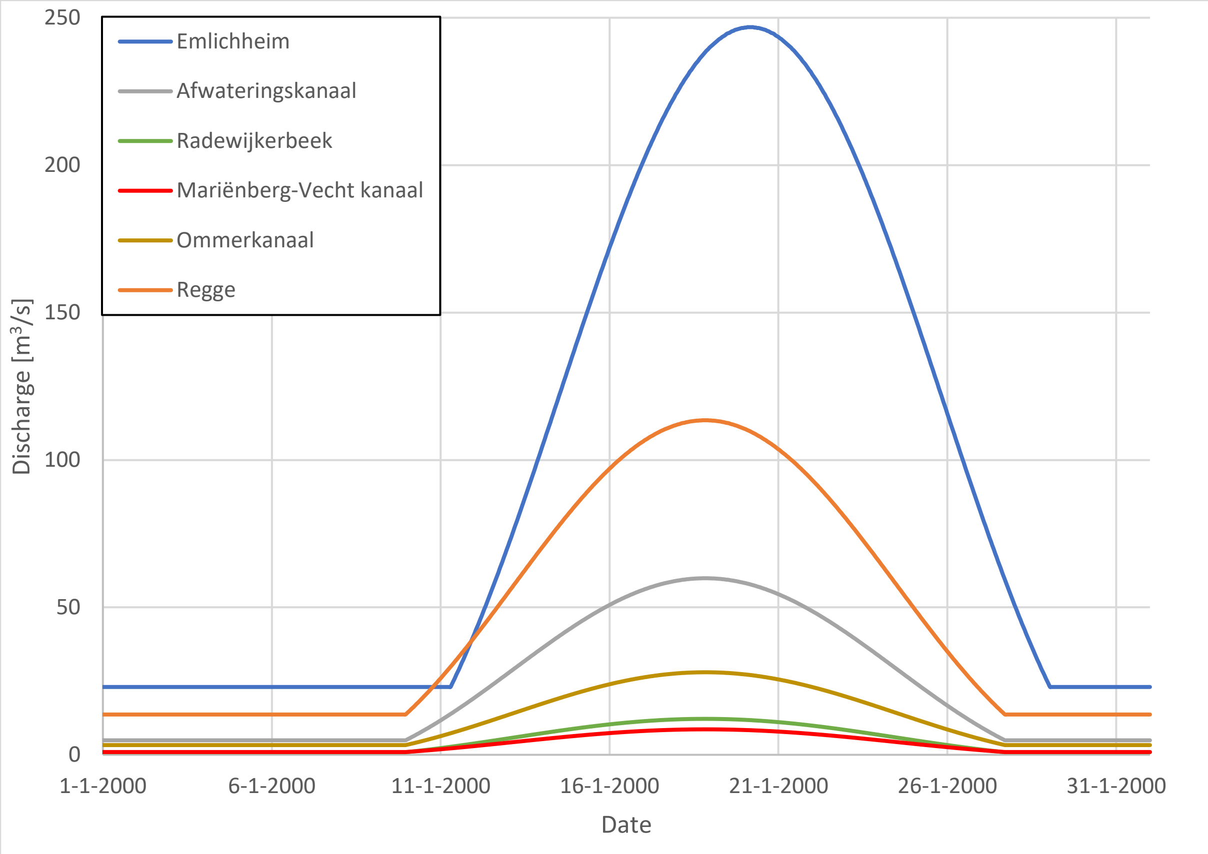

Figure 8. The upstream boundary condition (Q-t relation) and five largest lateral flows (T=200).

Table 2. The peak values of the discharge waves [m³/s] at the upstream boundary condition (Emlichheim) and the five largest lateral flows used for the design situations.

Location	¼Q	T=1	T=10	T=200
Emlichheim	23.00	115.00	199.00	246.80
Afwateringskanaal	4.90	27.48	42.06	59.88
Radewijkerbeek	0.88	4.89	8.76	12.18
Mariënberg-Vecht kanaal	0.93	3.79	6.86	8.63
Ommerkanaal	3.29	14.28	20.20	27.99
Regge	13.65	54.06	82.26	113.46

2.3 Available data sources

During this research different data sources will be used (Table 3). In this section the available data sources are described and it is explained how they will be used in this study.

Table 3. Overview of the data sources that will be used in different steps or elements of this research.

	AHN 2 (2.3.1)	Ecotopes map (2.3.2)	LGN map (2.3.3)	Satellite images (2.3.4)	SNL map (2.3.5)	Cadastral data (2.3.6)	Data Van Velzen et al. (2003a) (2.3.7)
Homogenous vegetation classes		x					x
Mixing classes		x			x	x	x
Calibration/ validation		x					x
Elevation grid (reference model + scenarios)	x						
Roughness grid (reference model)		x	x				x
Roughness grid (scenarios)		x	x	x			x

2.3.1 AHN 2

AHN 2 (Algemeen Hoogtebestand Nederland) is the second version of the digital elevation map of the Netherlands. In this study, the map with a resolution of 5×5 m will be used. The data for AHN 2 were collected in the period 2007-2012. The AHN contains detailed and accurate elevation data with an average of eight elevation measurements per square meter. Height is measured using laser altimetry: a technique in which an airplane or helicopter uses a laser beam to scan the earth's surface. The measurement of the duration of the laser reflection and of the position of the aircraft together give a very accurate result (Actueel Hoogtebestand Nederland, 2019). In this study, the AHN 2 is used to create the elevation grid.

2.3.2 Ecotopes map

The ecotopes map is a GIS file dating from February 8, 2017 (based on date of that year). The file consists of polygons that contain information about the vegetation present in the winter bed of the River Vecht. At a number of locations, the ecotopes map was adjusted manually, because it was known that the vegetation shown was not correct (L. van der Toorn, personal communication, 2019). These adjustments can be found in Appendix 1. Ecotopes maps have been created to meet the demand for instruments that support the design of water systems (Willems et al., 2007). For this reason, the ecotopes map will be used as a reference source for vegetation in this study. The ecotopes map is one of the sources that will be used to determine the vegetation classes for the River Vecht. The model will also be calibrated using this vegetation data source. Unless stated otherwise, in this study the ecotopes map will be used for the roughness grid of the 1D-2D model.

2.3.3 LGN 5 map

The LGN 5 (Landelijk Grondgebruik Nederland) map is a map that shows the land use in the Netherlands. It is a raster with a resolution of 25 × 25 m (Wageningen University & Research, 2019). The fifth version of the LGN map is based on data from the period 2003-2004. The LGN map shows one land use per lot, if more than one land use is present, the most common one is taken. The LGN map will be used as an alternative to the ecotopes map in this study. The LGN map is also used to complete missing data in the ecotopes map.

2.3.4 Satellite images

A vegetation map of the River Vecht can be made on the basis of satellite images. Based on the Normalized Difference Vegetation Index (NDVI) value, the change in vegetation type can be determined using the method by Geerling and Penning (2018). If there is a systematic deviation in the NDVI- value, the vegetation is likely to have changed with respect to the reference source. The ecotopes map is used as test- and training data for the classified satellite images (E. Penning, personal communication, August 27, 2019). The resolution of the maps is 30×30 m (Landsat satellite). Two classified satellite images are provided by Gertjan Geerling (Deltares) and will be used in this study, one from August 2017 and one from September 2018. The satellite-based vegetation maps will be used as an alternative to the ecotopes map in this study.

2.3.5 SNL map

SNL (Subsidiestelsel Natuur en Landschap) types are nature types, often consisting of several types of vegetation, for which a subsidy can be requested (Bij12, 2019). The SNL map consists of polygons that indicate which vegetation management type is present at that location. The SNL types consists of different vegetation types, so the SNL map can be used to derive frequently occurring vegetation combinations. This will be used to determine the mixing classes.

2.3.6 Cadastral data

The cadastral data distinguishes lots, including the owners. The lots can be used to divide the winter bed of the River Vecht into smaller areas. This is used, among other things, to determine the mixing classes. The lots will be used as management units in this research. Adjacent lots of the same owner have been merged into one lot.

2.3.7 Data Van Velzen et al. (2003a)

The vegetation handbook written by Van Velzen et al. (2003a) describes the Nikuradse coefficient and Chézy coefficient for common vegetation species in the floodplains. These roughness values are taken into account when determining the vegetation classes. Furthermore, this data is used to link a roughness value to a vegetation class. The manual also describes a method for calculating the roughness of combined vegetation types on a lot that will be used for mixing classes.

3 Model set-up, calibration and validation

In this chapter the hydraulic 1D-2D SOBEK 2 model used in the remainder of this research is discussed. It was decided to extend the existing hydraulic 1D SOBEK 2 to a 1D-2D model. Compared to building a new 1D-2D or 2D model, this existing 1D model has the advantage that the basis for this model is already available. In addition, R.W.A. Vechtstromen has more knowledge to work with this model (compared to other existing models), the model is focused on the management area of R.W.A. Vechtstromen and data for the boundary conditions and laterals are available.

First of all, it is described which adjustments have been made to extend the existing 1D model to a 1D-2D model. Then the calibration and validation is discussed. Finally, the suitability of the model for scenario analysis (described in chapter 4) is discussed. The aim of these steps is to provide a calibrated and validated 1D-2D hydraulic SOBEK model that can be used in the remainder of this research. The determination of the vegetation classes that are mentioned in this chapter will be described in section 4.1.

3.1 Model set-up

A number of steps need to be taken to convert the existing one dimensional model into a 1D-2D model. These steps are described in this section. The actions for converting the existing model into a 1D-2D model will only be carried out for the trajectory of the River Vecht inside the area of R.W.A. Vechtstromen (German border – Varsen). First, the winter bed is removed from the cross-sections. To be able to model two-dimensionally in SOBEK 2, an elevation grid and a roughness grid need to be created.

3.1.1 Removal of the winter bed from cross-sections

First, the cross-sections of the one-dimensional SOBEK model inside the management area of R.W.A. Vechtstromen (Figure 5) are modified. The flow through the winter bed will be modelled using the two-dimensional grid. If the winter bed is also present in the cross-sections, the capacity of the winter bed is counted twice. To prevent this from happening, the winter bed has been removed from the cross-sections (Figure 9). This could not be done automatically, since the structure of the cross-sections is not uniform. For that reason, the cross-sections are analysed separately to determine the point at which the main channel becomes the winter bed.

3.1.2 Removal of a side channel

After the winter bed was removed from the cross-sections a first test-run was done. This showed that at a side channel 20.5 km downstream of the German border, there was an instability in the model, causing an unrealistic jump in the water level along the River Vecht. It was tried to solve this in a number of ways. Eventually the best option was to remove the side channel. As there was no lateral flow here and the channel is relatively narrow, it is assumed that the removal will not lead to large differences in the water level, but solved the instability.

3.1.3 Elevation grid

The flow through the floodplains of the River Vecht is modelled with a two-dimensional grid. This grid has the shape of the Vecht valley. The winter bed of the Vecht is partly bounded by dikes (roads elevated to dikes), and for the rest bounded by natural heights.

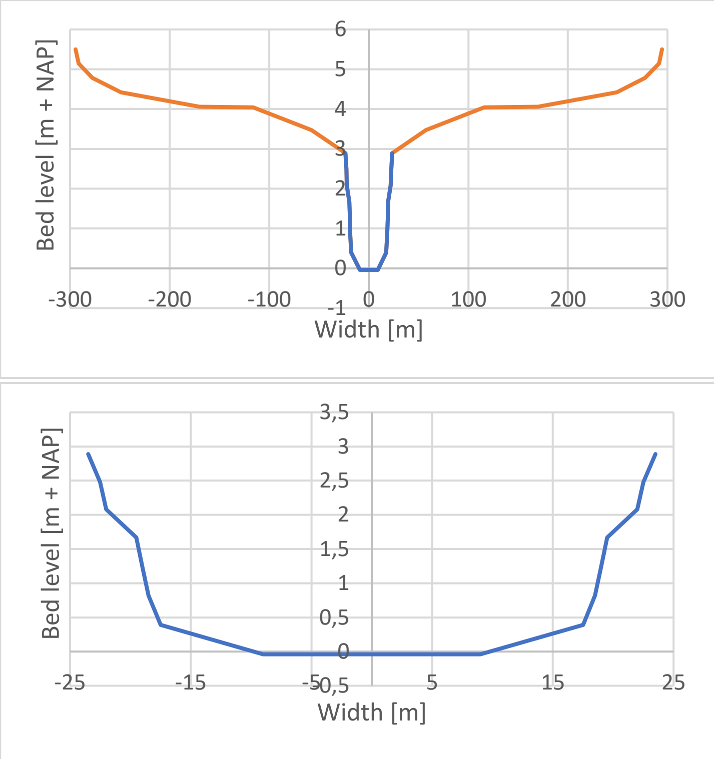

Figure 9. A cross-section in the 1D-2D part of the hydraulic SOBEK model: the original main channel cross-section (upper) where distinction is made between the main channel (blue) and winter bed (orange) and the same cross-section after removing the winter bed (down).

The elevation grid is made on the basis of the AHN2 map (Dutch elevation map), a raster dataset with a cell size of 5×5 meter. In the AHN2 5×5 meter map, the summer dikes of the River Vecht are clearly visible. However, in SOBEK 2, 25×25 meter cells are used, which means that the dike height will be averaged with the surrounding (lower) values as soon as the raster will be converted to a 25×25 meter grid, which will be done later (final paragraph). The cells next to the river will have a lower value than the summer dike and as a consequence water will flow into the floodplains at lower discharges than is possible with the presence of the summer dikes. To prevent this, the whole main channel of the River Vecht in the elevation grid has been raised to the height of the summer dikes. The summer dikes on both sides of the River Vecht do not necessarily have the same height. Points (with height information) on both sides of the River Vecht were used for the interpolation, in which the cells were given a value based on the distance to the points (inverse distance weighting).

In SOBEK 2, there is a vertical connection between the 1D cross-sections and the 2D grid. Water in the 2D grid starts to flow when the height of the 2D grid is equal to the water level in the 1D model. By assigning the height of the summer dikes to the grid at the location of the main channel (green line, Figure 10), water in the 2D grid will only start to flow if the water in the 1D model is at the level of the summer dikes (Figure 10).

The additional advantage of raising the main channel to the summer dike height in the 2D grid is that the 'double storage' of the 1D-2D model is reduced (red arrow versus green arrow in Figure 10). The water that flows in the 2D grid at the location of the main channel is taken into account twice: both in the 2D grid and the 1D model. Because the channel is higher in the 2D grid after processing, less water flows into the grid above the 1D cross sections and the ‘double storage’ is reduced.

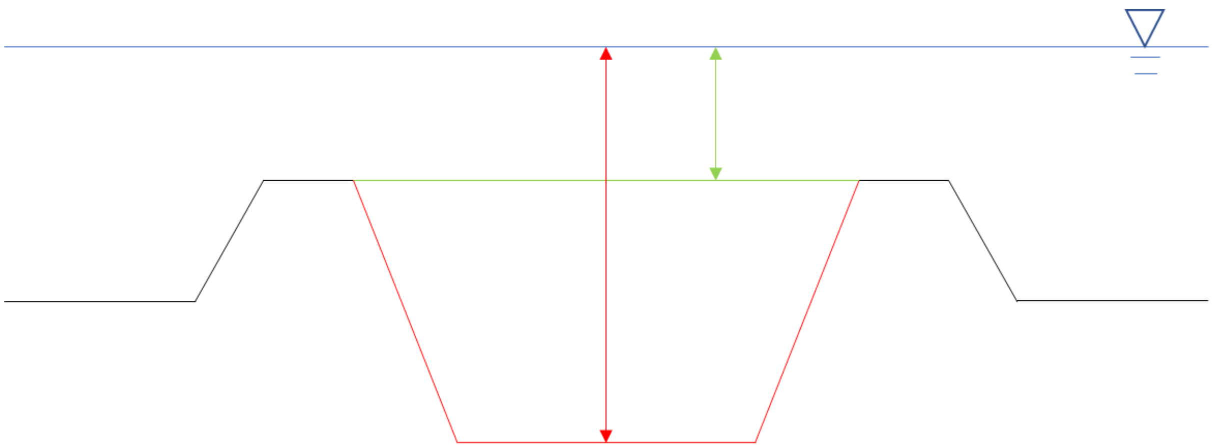

Figure 10. Schematisation of the raising of the main channel in the elevation grid: the black lines represent the winter bed and summer dikes, the red lines represent the original bed level of the main channel in the grid. Water will flow in the grid, as soon as the water level in the 1D-part is as high as the bed level in the grid. The green line represents the raised bed level (to the height of the summer dikes). The arrows show the height of the storage that is counted in both the 1D-part and the 2D grid.

After this processing, the missing cells (no-data) were interpolated and the AHN2 height map was converted into a 25×25 m grid (Figure 11). A 25×25 meter grid will be used instead of a 5×5 meter grid, since the used software (SOBEK 2) is not able to run with a 5×5 meter grid. The effect of raising the height of the grid at the location of the main channel to the height of the summer dikes does not get lost by this grid conversion, since the River Vecht is sufficiently wide. After a flood wave, the floodplains will not remain filled with water (except for isolated sinks), as there are locations without a summer dike, where the water can flow back into the main channel.

3.1.4 Roughness grid

The ecotopes map of February 2017 is used to make the roughness grid (A, Figure 12). This ecotopes map is a shape file, that contains polygons with information about the vegetation. At some places in the floodplains of the River Vecht (the locations marked as storage parts), no data was available in the ecotopes map. Where no data was available, the ecotopes map was completed with LGN (land use map) data (B, Figure 12). A raster (25×25 m) with roughness codes (used to link a vegetation type to a roughness-value) in the floodplains of the River Vecht is generated (C, Figure 12), which is then converted into a grid with the corresponding Chézy-values (D, Figure 12).

The Chézy value depends on the water depth, however in SOBEK 2 it is not possible to properly enter a depth-dependent Chézy value in the 2D grid. For the 2D grid, the only options are to use a constant Chézy coefficient, a Manning coefficient or the White-Colebrook formula. The latter uses the Nikuradse roughness coefficient k_n to calculate the Chézy value at a certain water depth, but this Nikuradse roughness coefficient is also dependent on the water depth (Van Velzen et al., 2003). Therefore, the Chézy coefficient at a water depth that is representative for the River Vecht will be used. This representative water depth will be the calibration parameter for the winter bed calibration (section 3.2.2).

In the original cross-sections of the River Vecht, the hydraulic roughness is described using a Chézy coefficient for the main channel and a Strickler roughness height for the winter bed. Since the winter bed is removed from the cross-sections, in the new cross-sections only the Chézy coefficient of the main channel is used. This Chézy coefficient of the main channel is calibrated (section 3.2.1). In the original cross-sections of the side channels and lateral flows the hydraulic roughness is expressed by a Bos & Bijkerk parameter of 34 s^{-1}, which remains unchanged in the new cross-sections.

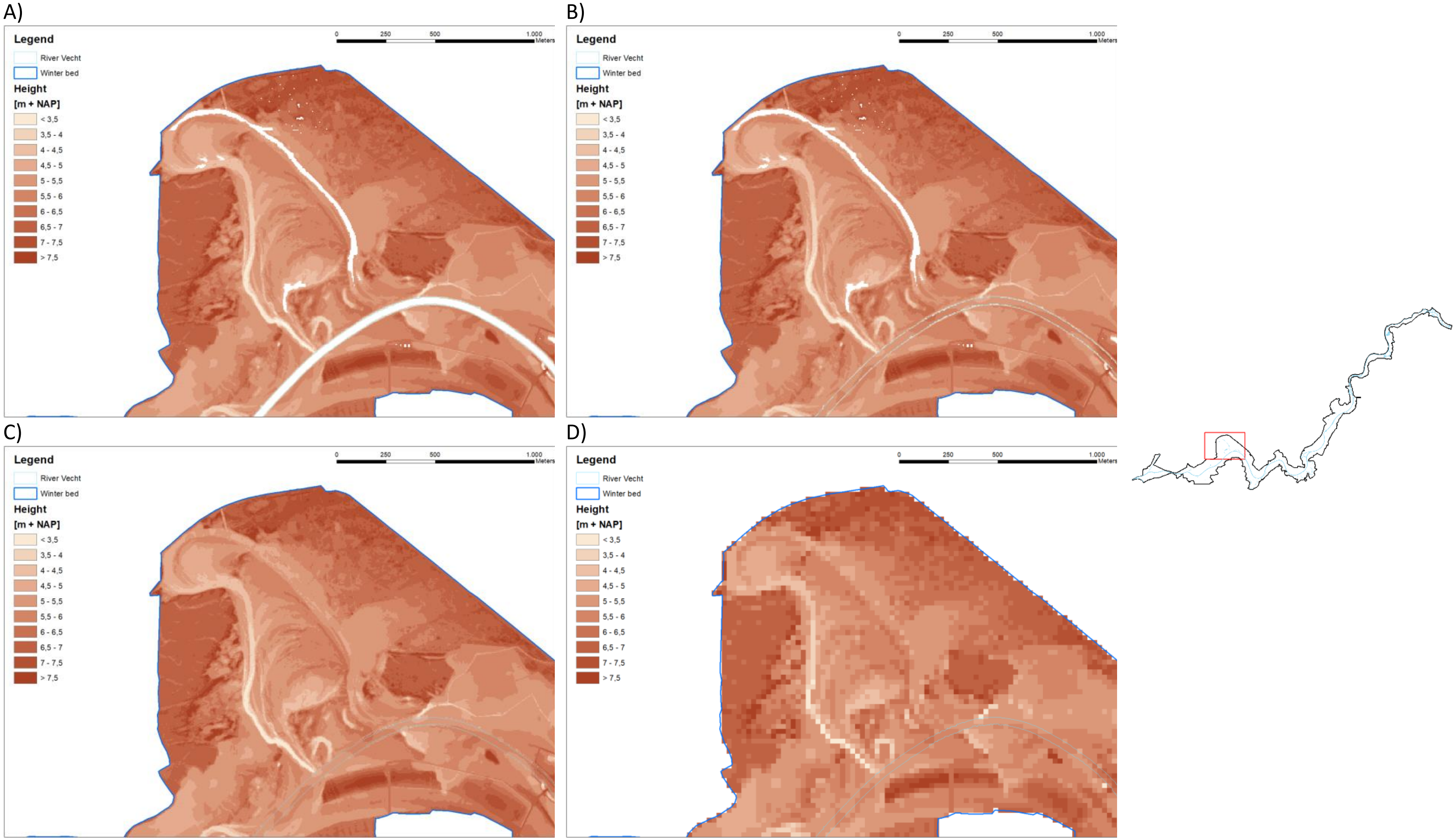

Figure 11. The process of generating an elevation grid for the hydraulic 1D-2D model. First, the missing values of the main channel in the AHN map (A) are replaced by the values of the height of the summer dikes surrounding the main channel (B). After this, the remaining no-data values are interpolated (C). Finally, the 5×5 m height map is converted in a 25×25 m grid (D).

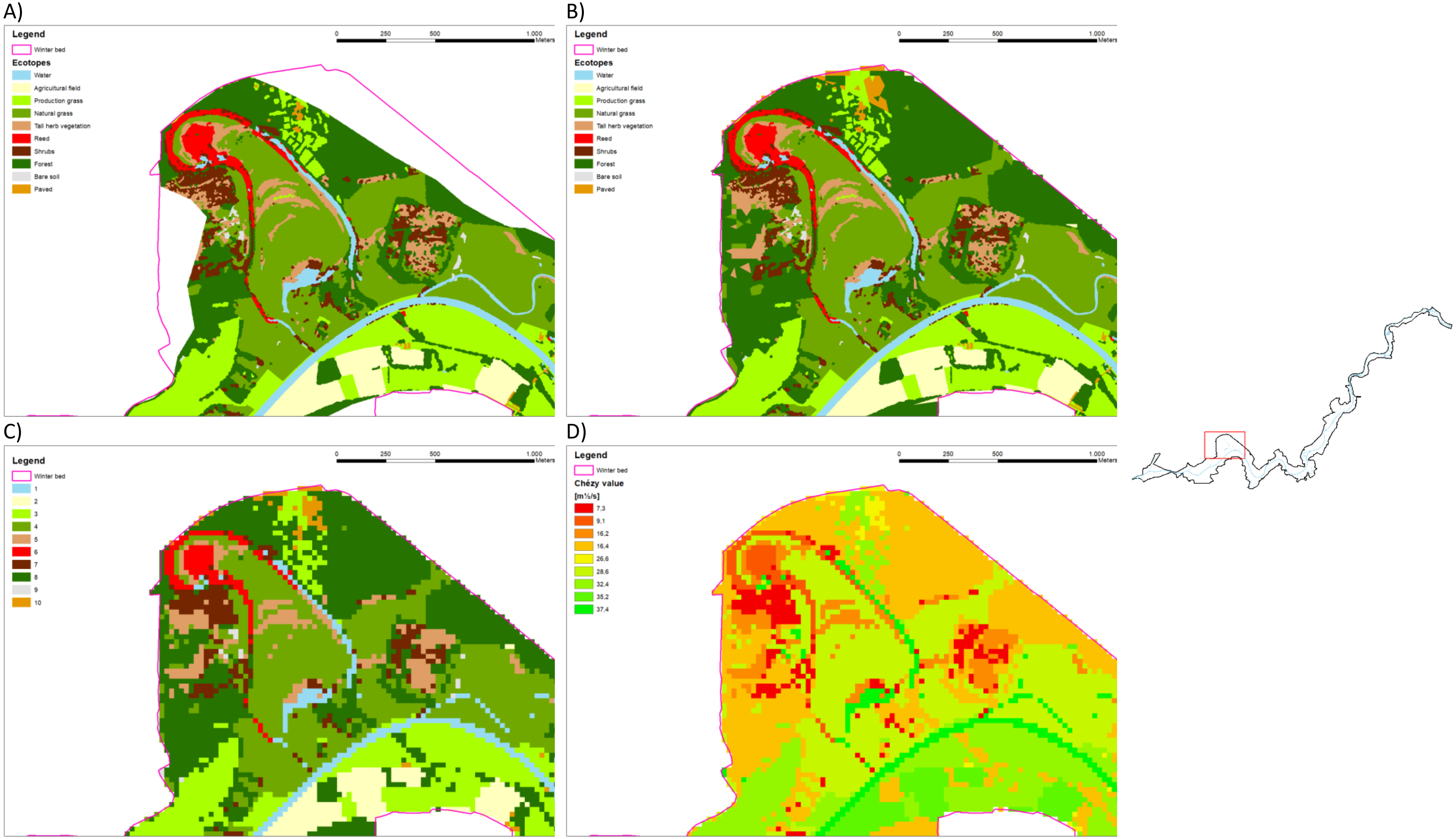

Figure 12. The process of generating a roughness grid for the hydraulic 1D-2D model. First, the ecotopes map (A) is completed with data from the LGN map, resulting in an ecotopes map with data for every location in the winter bed (B). The ecotopes map is then converted into a raster (25×25 m) with codes corresponding to the vegetation classes (C), which is then converted into a grid with Chézy values (D).

3.2 Calibration and validation

In this section, the calibration and validation of the developed model will be discussed. The calibration and validation will be performed by following three steps. First, the hydraulic roughness of the main channel (Chézy coefficient) is calibrated. After that, the winter bed roughness is calibrated. Finally, the model is validated. It is decided not to calibrate the Bos & Bijkerk coefficient of the side channels and the Strickler coefficient of the winter bed outside the 1D-2D part (where the winter bed stayed in the cross-sections), because it is assumed that these roughness parameters have a relatively small impact on the water level.

The following discharge waves (section 2.2.3) are used during the calibration and validation:

- Main channel calibration: ¼ Q. During this event, water only flows through the main channel, so the winter bed roughness does not influence the water level and only the effect of the roughness of the main channel on the water level is calibrated.
- Winter bed calibration: T=10. Water flows through both the main channel and the winter bed, so the winter bed roughness now does influence the water level. This the event with the largest return period for which measuring data is available.
- Validation: T=1. Water flows through both the main channel and the winter bed.

For the main channel calibration, the Chézy coefficient will be varied between values of 45 $m^{1/2}/s$ and 25 $m^{1/2}/s$. These Chézy values correspond to roughness coefficients ($c_f = g/C^2$) within the range of 0.005 (sand with stones) to 0.016 (vegetated channel bottom) (Hoekstra, 2012). This has been done, because the Chézy values in this range are considered as physically realistic values for the main channel of the River Vecht. The Q-t discharge series that are used for the main channel calibration belong to the ¼ Q event (with a return period of 80 days a year).

The winter bed roughness (based on the ecotopes map) is calibrated by varying the representative water depth parameter. As stated before, in SOBEK 2 it is not possible to assign a water depth dependent Chézy coefficient to the 2D grid. This means that a representative water depth needs to be determined, so that the associated Chézy coefficients can be used as the roughness value. During the T=200 event (which will be used for simulations), maximum water depths of around 2 meters are expected. For this reason, the representative water depth will be varied between 1 meter and 2 meters. The corresponding Chézy coefficients for every vegetation type can be derived from the roughness curves (Figure 17). These coefficients are used for the roughness grid. The Q-t discharge series that are used for the winter bed calibration belong to the T=10 event. Finally, the model is validated using the T=1 event. The calibration parameters are not changed during the validation.

During the calibration and validation, the water levels predicted by the model are compared with the water levels that belong to the used return period at five locations. The five locations that are used to compare are the downstream side of the four weirs (De Haandrik, Hardenberg, Mariënberg and Junne) and the bridge at Ommen. These locations are used, because measured data is available here.

The calibration and validation will be evaluated by the root-mean-square error (RMSE). The RMSE-value is a measure of accuracy, which can be used to compare the calculated water levels with the measured water levels. The closer the RMSE-value comes to 0, the more accurate the calculated value is. The RMSE-value cannot get lower than zero, so the aim is to obtain the lowest possible RMSE-value.

3.2.1 Main channel calibration

The model-run with a Chézy value of 35 $m^{1/2}/s$ gave the best result. The RMSE value of this run was closest to 0 (Table 4). The deviation from the measured value was no more than 0.13 m for the measuring points, except for the measuring point at the Junne weir (0.26 m). Figure 13 shows the maximum water levels after the main channel calibration in the longitudinal direction. It can be seen that the model approximates the measured water levels well except for the measuring point at the weir at Junne (fourth measuring point in longitudinal direction). It can also be noticed that the water level slope between the fourth and fifth measuring point is lower than the water level slope between the other measuring points, which may indicate that one of the two last measuring points inaccurate water levels.

Table 4. RMSE-values [m] after the main channel calibration for different Chézy-values [$m^{1/2}/s$].

C – value [$m^{1/2}/s$]	**25**	**28**	**30**	**31**	**32**	**33**	**34**
RMSE [m]	0.319	0.233	0.192	0.174	0.163	0.155	0.150
C – value [$m^{1/2}/s$]	**35**	**36**	**37**	**38**	**40**	**42**	**45**
RMSE [m]	0.145	0.146	0.146	0.150	0.163	0.177	0.203

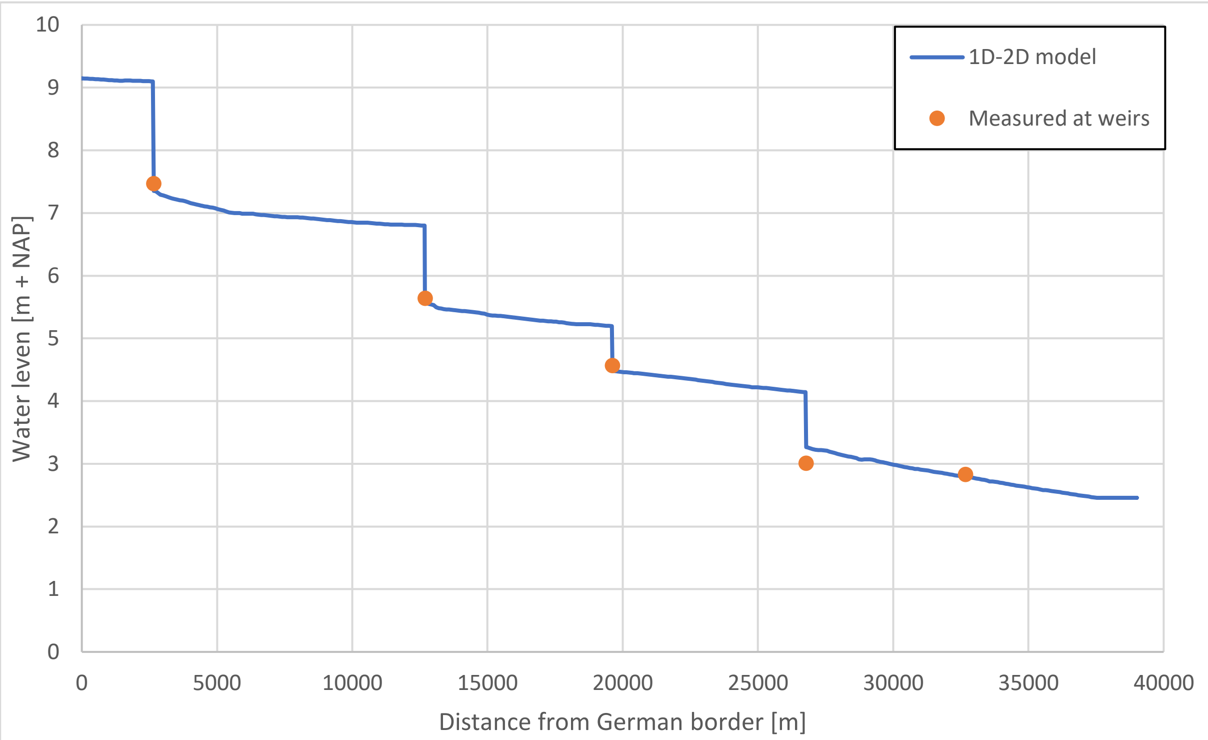

Figure 13. The maximum water levels of the River Vecht in longitudinal direction after the main channel calibration (T=¼Q).

3.2.2 Winter bed roughness calibration

The water level during the winter bed calibration turned out to be little sensitive to the representative water depth. The RMSE-value varied between 37 and 40 cm, while the representative water depth was varied between 1 and 2 metres. The model run with a representative water depth of 1.5 m gave the best result. Remarkable is the clear difference between the measuring points: at the weirs at De Haandrik, Hardenberg and Junne the water level was calculated with relatively small deviations from the measured values (underestimates of respectively 4 cm, 8 cm and 4 cm), while the deviation at Mariënberg and Ommen is much larger. Here the water levels are overestimated by 60 cm and 62 cm respectively. This is also evident in the longitudinal profile (Figure 14). However, also here it is noticeable that the slope between the water levels at the different measuring points is very different. The fourth measuring point (Junne) seems to deviate from the third and fifth measuring points.

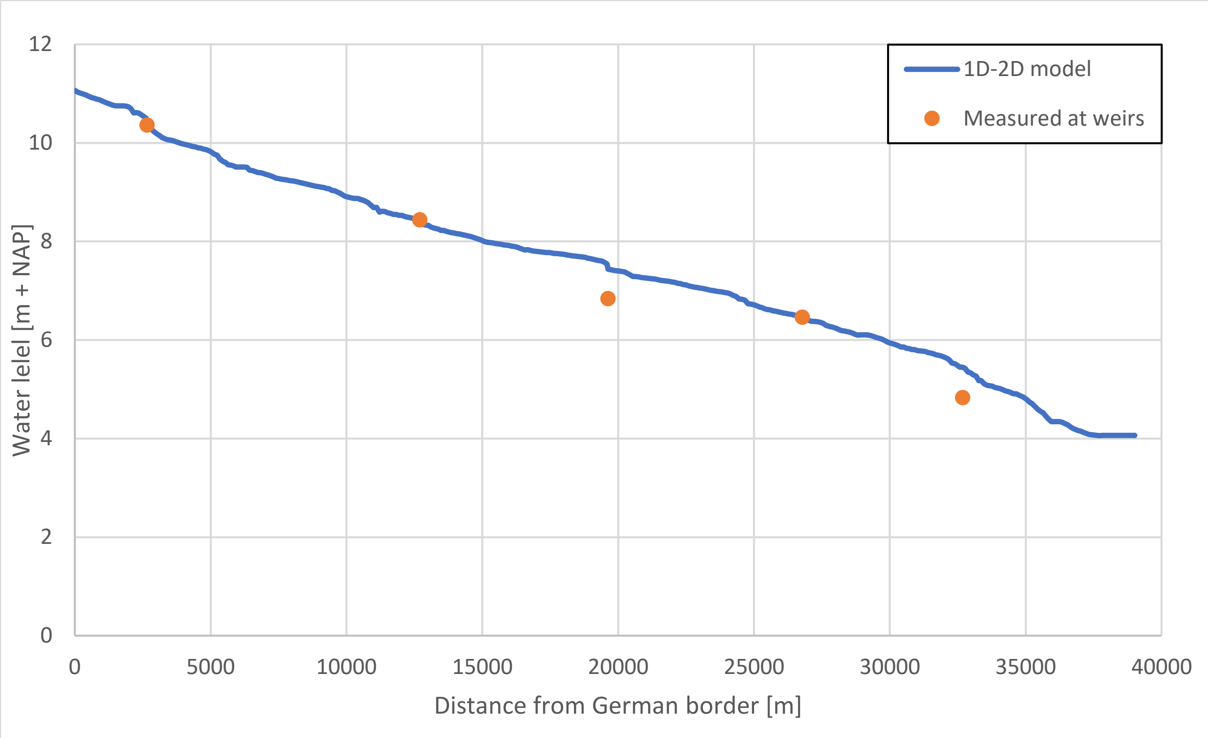

Figure 14. The maximum water levels of the River Vecht in longitudinal direction after the winter bed calibration (T=10).

3.2.3 Validation

A Chézy-value of 35 $m^{1/2}/s$ and a representative water depth of 1.5 m to determine a Chézy coefficient for floodplain vegetation resulted from the main channel and winter bed calibration. From the validation run followed differences in maximum water levels in the order of 30 cm, except at the Junne weir where there is an underestimation of 59 cm (Table 5). The longitudinal profile (Figure 15) shows that the water level is generally underestimated, with the exception of the weir at Mariënberg. Also at the measuring points of the T=1 event it is noticeable that there is a considerable difference in the water level slope between the different measuring points. Again it is the fourth measuring points that seems to deviate from the other measuring points.

Table 5. Difference in maximum water levels [m] compared to the measured water levels and the RMSE-value [m] after the validation (T=1).

De Haandrik	Hardenberg	Mariënberg	Junne	Ommen	RMSE
-0.21	-0.28	+0.04	-0.59	-0.18	0.318

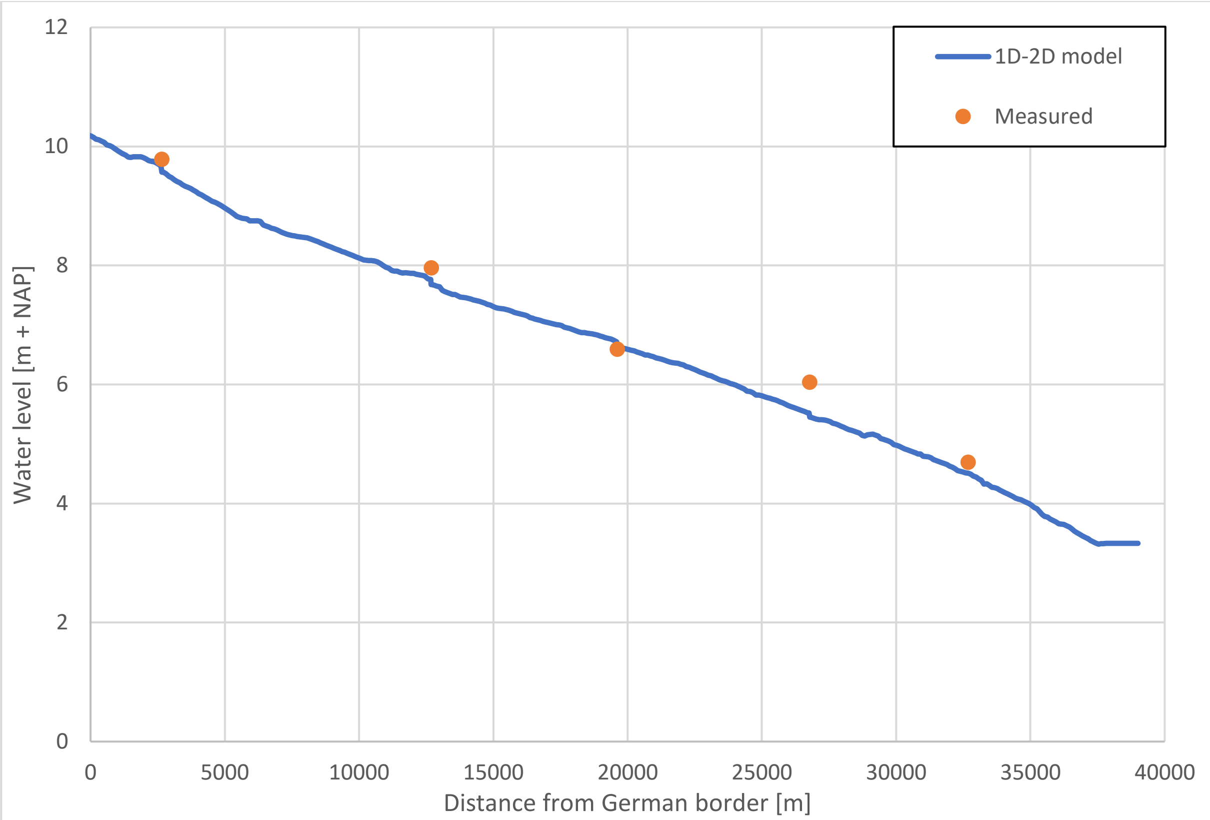

Figure 15. The maximum water levels of the River Vecht in longitudinal direction after the validation (T=1).

3.2.4 Conclusion

The calibration resulted in a main channel Chézy-value of 35 $m^{1/2}/s$ and a representative water depth of 1.5 m to determine a Chézy coefficient for floodplain vegetation. These calibrated parameters will be used in the remainder of this research. As described before, the calibration and validation was done on the basis of the ecotopes map. The model with the ecotopes map as input for the 2D grid and the roughness values as described above will be called the *reference model* (or *reference map* if only the 2D grid is mentioned) in the remainder of this thesis.

3.3 Suitability of the model for scenario analysis

The hydraulic 1D-2D SOBEK 2 model is able to model maximum water levels for an extreme event, but with a considerable degree of uncertainty. During the winter bed calibration and validation, significant deviations from the measured water levels were modelled. In general, the deviations are within 30 cm, but there are also deviations up to 60 cm calculated.

It is remarkable that in the case of annual events (¼Q and T=1) the model generally underestimates the maximum water level, while in an extreme event (T=10) the maximum water level is overestimated. Since the remainder of the study is concerned with an even more extreme event (T=200), it is more likely that the model will overestimate the maximum water levels.

One reason that significant deviations from the measuring points occurs are the three downstream measuring points (Mariënberg, Junne and Ommen). The water level slope in the Mariënberg-Junne section is much less steep than the water level slope in the Junne-Ommen section. Since the used roughness parameters (main channel roughness and representative water depth) do not vary in longitudinal direction, it is difficult to approach the measured water levels at all three measuring points. The difference in water slope between the measuring points seems to be caused by an inaccuracy in the measured maximum water levels at the Junne weir. In all three longitudinal profiles (Figure 13 - Figure 15) the measured maximum water level at this measuring point causes a deviation from the other measuring points. Because this measuring point is one of the five points that is included in the calibration, it can partly explain the deviations at other measuring points.

In addition, it should be noted that theoretical discharge waves based on data measured in the period 1997-2015 (section 2.2.3) were used during the calibration, whereby the measured maximum water level did not necessarily occur at the same time as the measured maximum discharge. These uncertainties in the data used also cause uncertainty in the modelled water levels.

Considering the above aspects, the absolute water levels modelled by the hydraulic 1D-2D SOBEK model should be interpreted with caution, as they might deviate from the actual water level. In the remainder of this study, however, relative differences in water levels, between different scenarios, will be examined. The model is suitable to be used for these purposes.

In the discussion (Chapter 6), the consequences of the model schematisation and the method of calibration will be discussed in more detail.

4 Methodology

This chapter describes the methodology of this research. First, the determination of the vegetation classes is discussed (section 4.1). These classes are used in this study to link hydraulic roughness to vegetation, in order to make a roughness map (vegetation data-based roughness maps in Figure 2) that can be used as input for the hydraulic 1D-2D SOBEK 2 model (chapter 3) to describe the hydraulic roughness. Model runs will then be performed and analysed (Chapter 0), in this chapter (section 4.2 - 0) it is described how the scenarios are designed and which adjustments to the height grid and the roughness grid have to be made, so that the scenarios can be run by the 1D-2D hydraulic SOBEK model. These model runs will contribute to answering the research questions (Table 6). The answers to the research questions will then be used to achieve the research objective.

Table 6. Model runs that will be done in this research in order to answers the research question (RQ).

Model run	RQ	Section	Short description
Sensitivity analysis	1	4.2	The boundary conditions and roughness values are changed with -40%, -20%, +20% and +40% with respect to the values in the *reference model* (T=200).
Extreme vegetation scenarios	2	4.3	An extremely rough scenario and an extremely smooth scenario will be compared to the *reference model.*
Vegetation data sources scenarios	3	4.4	Model runs with the LGN map and satellite images will be compared to the *reference model* (in which the ecotopes map is used).
Mixing classes scenario	4	4.5	A model run in which the lots are assigned a mixing class will be compared to the *reference model.*
Variation within mixing classes scenarios	5	4.6	On three lots, four vegetation distribution scenarios that are possible within the margins of the assigned mixing class will be compared to model run with mixing classes.
Planned projects scenarios	-	0	The effect of changes in vegetation and height in the planned projects at Karshoek-Stegeren and Rheezermaten will be evaluated.

4.1 Vegetation classes

Below is described how the vegetation is classified. The vegetation classes are based on the vegetation present in the winter bed of the River Vecht within the borders of R.W.A. Vechtstromen. The floodplains of the Vecht River are a fragile Natura 2000 area (Waterschap Vechtstromen, 2017a), not comparable to the rivers managed by Rijkswaterstaat. It is therefore decided to adapt the vegetation classes to the vegetation in the floodplains of the Vecht River, instead of making use of the vegetation classes used by Rijkswaterstaat.

Two types of vegetation classes will be used in this research: homogeneous vegetation classes and mixing classes. The homogeneous vegetation classes will be used to link the vegetation in the floodplains of the River Vecht as described in vegetation data sources to a roughness value. In addition, these classes will be used for a number of vegetation scenarios (described in the sections 4.3 - 0). The classification method using mixing classes is a tool that might be used to give the owners of the lots in the floodplains of the River Vecht the freedom to allocate vegetation on their lots. Lots are assigned a mixing class, with one bundled roughness-value for the whole lot. Within these classes, a certain amount of a vegetation type can be distributed over the lot according to the owner's preferences. The amount of vegetation that can be freely distributed differs per mixing class.

The aim of this section is to determine which vegetation classes (homogenous and mixing) with corresponding roughness values will be used in the remainder of this research.

4.1.1 Homogeneous vegetation classes

An ecotopes map of the winter bed of the River Vecht from 2017 is available. On this ecotopes map, 53 different homogeneous roughness classes can be distinguished, of which 36 classes contain vegetation. Some of these classes contain the same vegetation type and are only distinguished based on their location in the winter bed. Since the location of vegetation is not directly related to the roughness, the classes with the same vegetation are combined. This results in twelve new classes: *production grassland, natural grassland, pioneer vegetation, agricultural land, herbaceous vegetation (*Dutch*: ruigte), reed, low-stem orchard, high-stem orchard, production forest, hardwood riparian forest, softwood riparian forest* and *shrubs.* Some of the vegetation types have similar roughness characteristics or are not common in the winter bed of the River Vecht (Figure 16). In the remainder of this study it is not important that these classes remain separate, as they will not be used separately in vegetation scenarios. Taking these aspects into consideration, the following classes are combined:

- *Pioneer vegetation* is added to the *production grassland* class, since the roughness curves are very similar and the percentage of *pioneer vegetation* is low.
- The classes *low-stem orchard, high-stem orchard, production forest, hardwood riparian forest* and *softwood riparian forest* are combined to one new class: *forest.* This has been done since the percentage of all forest classes, except for *hardwood riparian forest*, are low and the roughness curves are not that different.

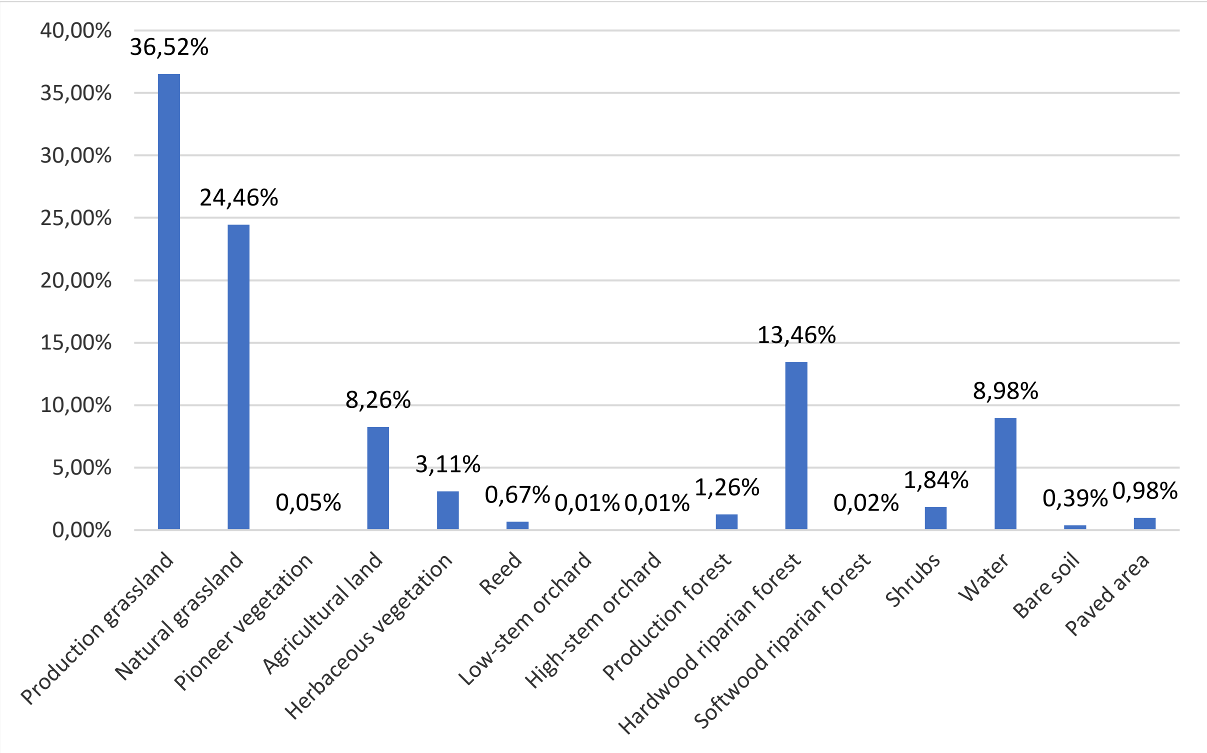

Figure 16. The area of the different vegetation types as a percentage of the winter bed of the River Vecht. The first twelve classes are vegetation classes, the last three classes are non-vegetation classes.

Altogether, this results in seven homogeneous vegetation classes: *production grass, natural grass, agricultural land, herbaceous vegetation, reed, shrubs* and *forest.* Next to this, three non-vegetation classes will be used, namely *water, bare soil* and *paved area.* A roughness curve, based on data from the report of Van Velzen et al. (2003a), is assigned to the seven vegetation classes and three non-vegetation classes (Figure 17). These roughness curves show the Chézy value at different water depths. A detailed description of the determination of the homogeneous roughness classes can be found in Appendix 2.

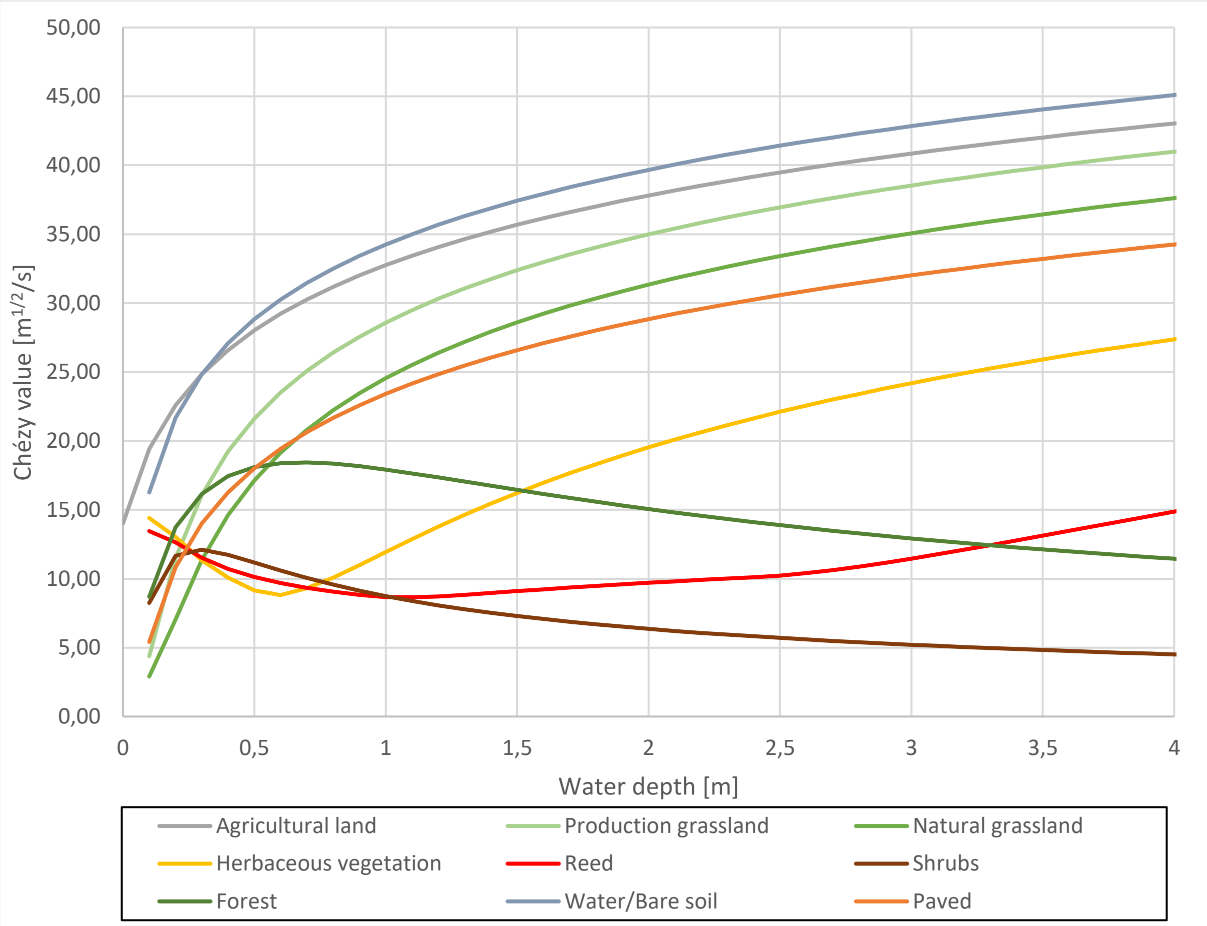

Figure 17. Roughness curves of the homogeneous vegetation classes.

At a water depth of 1 m, the homogeneous vegetation classes of *shrubs* and *reed* are equally rough. Because *shrubs* (5m) generally has a higher vegetation height than *reed* (1 m) (Van Velzen et al., 2003a), the roughness of *shrubs* increases and the roughness of *reed* decreases for higher water depths. The same can be seen for *forest* and *herbaceous vegetation*, whose roughness curves intersect at a water depth of 1.5 m. Since trees generally have a vegetation height (> 10 m) that is much larger than the water depth in the floodplains of the River Vecht, *forest* is not the most rough vegetation class in this research. Finally, it can also be seen that *natural grassland* is significantly rougher than *production grassland*.

4.1.2 Mixing classes

In a mixing class, more than one homogeneous vegetation class is permitted. In order to see what logical mixing classes are for the floodplains of the River Vecht, it was investigated which combinations of vegetation classes occur on the lots in the floodplains of the River Vecht. As a result, there are many different combinations that occur, but only a few combinations that occur frequently. On the basis of the occurring combinations, it was not really possible to define mixing classes. Only two suitable mixing classes follow from this analysis: *Forest-Grassland* (at maximum 50% *forest* and at least 50% of grassland (*production grassland* and *natural grassland*) and *Forest-Shrubs* (at maximum 20% *Shrubs*). These two combinations occur relatively often on the lots in the floodplains of the River Vecht.). A detailed description of the analysis of the occurring combinations of homogeneous vegetation classes can be found in Appendix 2.

In order to obtain suitable mixing classes, another method was used. Based on the expected water depths in the floodplains during a flood wave (T=200), a distinction was made between *rough* vegetation and *non-rough* vegetation. Based on a number of test runs it was determined that the water depths in general vary between 1 and 2 m. Four vegetation classes are considered to be *rough vegetation* classes: *shrubs, reed, herbaceous vegetation* and *forest*, because the Chézy-value of these classes is significantly lower than the other classes at the mentioned water depths (Figure 17). The other classes are considered as *non-rough vegetation* classes. The mixing classes are then based on the distinction between *rough* and *non-rough* vegetation.

The mixing classes are defined in steps of 10%. This step size has been chosen so that many mixing classes are available, but at the same time the roughness curves clearly differ from each other. The following mixing classes are used: *90/10, 80/20, 70/30, 60/40, 50/50, 40/60, 30/70, 20/80, 10/90*. The first number in the names of these classes represents the percentage of vegetation that does not belong to the *rough classes*, the second number represent the percentage that does belong to the *rough classes.*

The roughness of the mixing classes is calculated using the formula of Van Velzen et al. (2003a):

$$C_{mix} = \phi * C_s + (1 - \phi) * C_p \qquad \text{Eq. (3)}$$

Where:

$$\phi = 0.6 \qquad \text{Eq. (4)}$$

$$C_p = \sum_i x_i * C_{ri} \qquad \text{Eq. (5)}$$

$$C_s = \frac{1}{\sqrt{\sum_i \frac{x_i}{C_{ri}^2}}} \qquad \text{Eq. (6)}$$

With:

x_i:	Fraction of the area with vegetation type i	[-]
C_{ri}:	Representative Chézy value of vegetation type i	[$m^{1/2}/s$]
C_p:	Chézy value of the vegetation combination for a parallel pattern	[$m^{1/2}/s$]
C_s:	Chézy value of the vegetation combination for a series pattern	[$m^{1/2}/s$]
ϕ:	Weight factor	[-]

Note that the sum of the fraction of the areas must always be 1, since the Chézy value is calculated for a whole lot. This is important to state, because for other percentages, this formula cannot be used. If for example the sum of the percentages of the areas is approaching zero, then the Chézy value for a parallel pattern (vegetation parallel to the flow direction) would be infinitely low and the Chézy value for a series pattern (vegetation perpendicular to the flow direction) would be infinitely high.

The roughness curves of the mixing classes (Figure 18) are calculated using the Chézy-value of *natural grassland* for the non-*rough classes* (most rough grassland type) and the Chézy-value of *shrubs* (the most rough vegetation class) for the *rough classes*. The roughness curve of *Forest-Grassland* is calculated with 50% *forest* and 50% *natural grassland.* For *Forest-Shrubs*, 20% *shrubs* and 80% *forest* is used to calculate the roughness curve.

If the mixing class *Forest-Grassland* would not exist, the lots that will be assigned this mixing class would belong to mixing class *50/50* (based on the ratio *non-rough*/*rough* vegetation). It can be seen that the roughness curve of mixing class *50/50* is significantly rougher than the roughness curve of *Forest-Grassland.* This confirms that the distinction between both mixing classes is useful. The same applies for the mixing class *Forest-Shrubs*, which has a ratio of 0/100 (*non-rough*/*rough*), which has the same roughness of homogeneous *shrubs* following the current roughness-calculation. This prevents in both cases a significant overestimation of the roughness-values. The Chézy-values of the mixing classes are very low due to the calculation method. The effect of this on the maximum water levels will be examined later in this research (section 4.5)

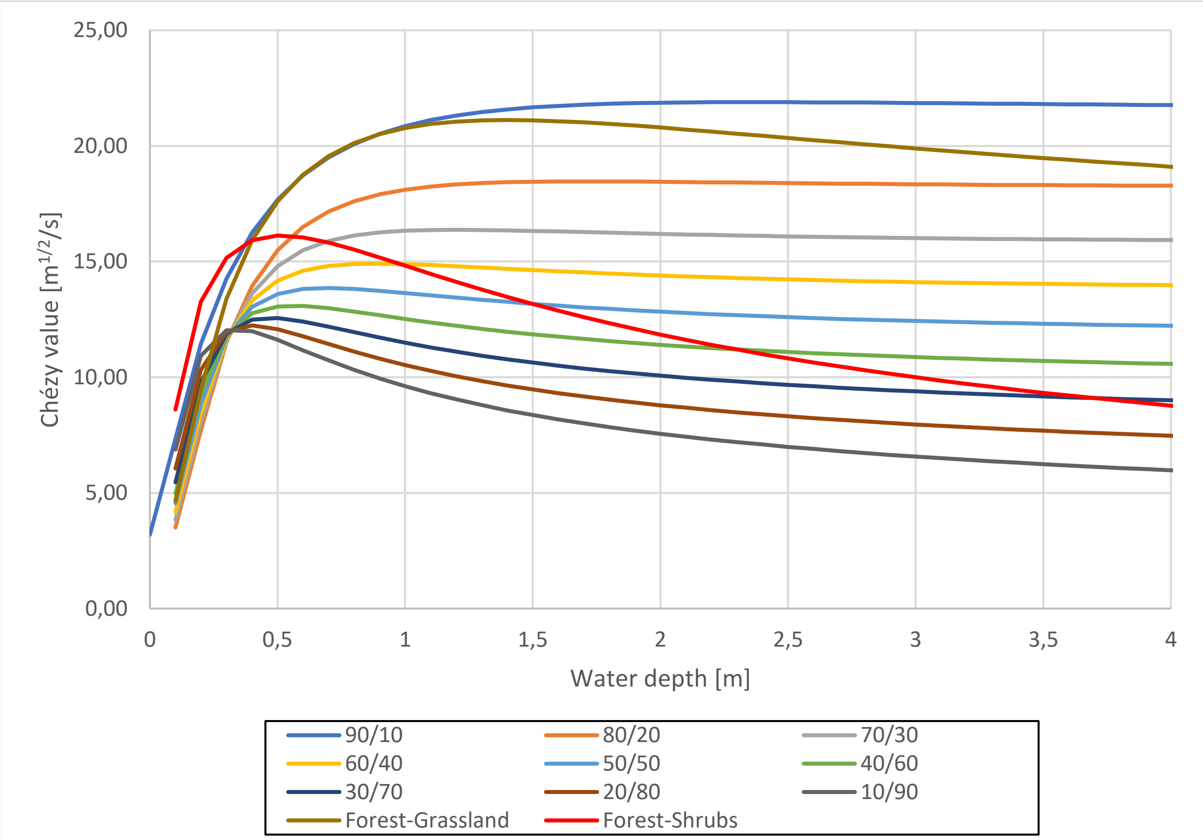

Figure 18. Roughness curves of the mixing classes.

4.1.3 Calibrated roughness-values of floodplain vegetation

From the calibration, a representative water depth of 1.5 m to determine a Chézy coefficient for floodplain vegetation followed. For the defined homogeneous vegetation classes and mixing classes, the Chézy-value at this water-depth is used in the remainder of this research (Figure 19).

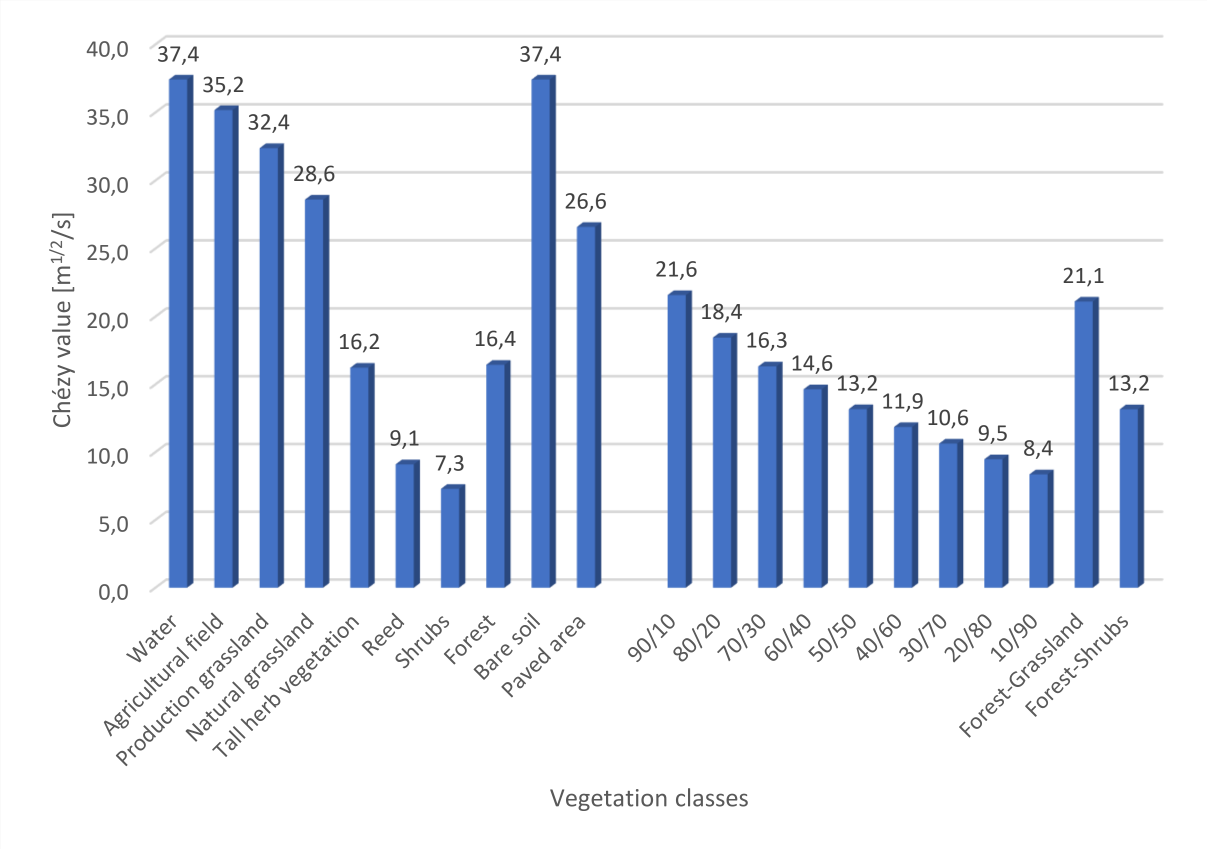

Figure 19. The Chézy-values at the representative water depth h=1.5m.

4.2 Research question 1: sensitivity analysis

A sensitivity analysis will be done in order to find out which parameters or conditions influence the water level the most. Six parameters or conditions are included in the sensitivity analysis: the upstream boundary condition (T=200, discharge wave), the downstream boundary condition (Q-h relation), the main channel roughness (after calibration and validation), 2D winter bed roughness (after calibration and validation), side channel roughness, and the 1D winter bed roughness (outside the area of R.W.A. Vechtstromen, where the winter bed in included in the cross-sections).

The parameters and conditions are changed with -40%, -20%, +20% and +40% with respect to the values in the (calibrated) model (using discharge wave T=200). For the main channel roughness, side channel roughness and 1D winter bed roughness only one number needs to be changed. For the 2D winter bed roughness, all ten roughness values of the classes are changed. At the upstream boundary condition, the whole discharge wave is scaled. The water levels belonging to a certain discharge at the downstream boundary condition are changed to reflect the sensitivity of the model to the downstream boundary condition.

The uncertainty margin in the discharge data used to determine the discharge waves (e.g. T = 200) is in the order of 40%. By investigating the sensitivity of the model to a variation of 40%, the effect of this uncertainty margin on the maximum water level can be determined. The sensitivity to the downstream boundary condition is investigated to determine if and to what extent this boundary condition influences the modelled water levels. The sensitivity to the four roughness-parameters is investigated to gain insight into the sensitivity of the model to the roughness in the 2D grid, in relation to the other roughness-parameters.

4.3 Research question 2: extreme vegetation scenarios

For the rough scenario, all the present vegetation types are changed into s*hrubs*, which is the most rough vegetation class with a Chézy value of 7.3 $m^{1/2}/s$ (Figure 19). In the smooth scenario, the vegetation types are changed into *production grassland.* This vegetation class has a Chézy value of 32.4 $m^{1/2}/s$, making it the smoothest vegetation class (*agricultural land* is not counted as vegetation class here, because the Chézy-value is based on ploughed *agricultural land*).

The maximum water levels along the River Vecht and in the floodplains for the two extreme scenarios will be compared with each other and with the current situation. This will make it possible to determine the bandwidth and how the current situation relates to the extreme scenarios. Bottlenecks with respect to the sensitivity of the water levels to floodplain roughness can be discovered by analysing where the largest differences in maximum water levels occur in the floodplains. Locations where the vegetation has little effect on the water level can also be detected.

4.4 Research question 3: vegetation data sources

The reference map, based on the ecotopes map, will be compared with a roughness map based on the LGN (land use) classification and two roughness maps based on satellite images. The used satellite images are from 1 August 2017 and 30 September 2018. The land use from the LGN map and the vegetation types from the satellite images are divided into vegetation classes as defined before. The following differences in the classifications are noticeable:

- The LGN classification contains more detailed information (more separate classes) than the classification of the ecotopes map for *agricultural land* and *paved* areas. However, this difference is not included in the vegetation classes of this research, as only *agricultural land* and *paved* areas are used as separate classes. On the other hand, the LGN classification does not include *shrubs* and *reed*, which are the two roughest classes. This makes *herbaceous vegetation* and *forest* the most rough classes in the LGN classification. In addition, the LGN classification only shows the dominant vegetation type on a lot.
- On the satellite images, no difference between *production grassland* and *natural grassland* is made. Therefore, a Chézy value for *grassland* is calculated as a combination of the two classes, based on the ratio in the ecotopes map.

The differences between the different vegetation data sources will be analysed, as well as their effect on the calculated water level. Possible differences between the vegetation data sources and the extent of these differences will say something about the usefulness of the vegetation data sources. Both the differences in the data sources as well as the effect on the (maximum) water levels will be taken into account.

4.5 Research question 4: mixing classes

To each cadastral lot in the winter bed, a mixing class has been assigned in this scenario. Lots that consist of 98% or more of one vegetation type will be considered as homogeneous vegetation classes and will not be classified in a mixing class. This was chosen because these small amounts of vegetation (<2%) are often caused by the conversion of the polygons (with vegetation information) into a raster. Next, the mixing classes are assigned according to the following principle: if the amount of *shrubs*, *reed*, *herbaceous vegetation* and *forest* together is below 10% (and above the threshold value of 2%), the lot will be assigned to the mixing class *90/10*. If this percentage is between 10% and 20%, the lot belongs to the mixing class *80/20*. This continues to the mixing classes *10/90*. If the percentage is above 90%, the lot is considered as *shrubs* (since the mixing class *0/100* does not exist, because in terms of calculating the roughness this is equal to the class of *shrubs*). The percentage of vegetation belonging to the *rough*-classes (*shrubs*, *reed*, *herbaceous vegetation* and *forest*) is always rounded up when classifying in mixed classes. In this way, the roughness of lot will never be underestimated.

The roughness can be derived from the roughness curve of the mixing classes (Figure 18). The roughness at the calibrated representative water depth is taken and assigned to the lot. This results in a roughness grid with one uniform roughness value per lot. The model run with this grid will be compared with the results of the run with the reference map. The maximum water levels along the River Vecht will be compared to see if and to what extent the water levels are calculated differently if the lots in the floodplains of the river Vecht are classified according to the principle of mixing classes. Furthermore, it will also be examined whether there are differences in the water levels and flow velocities on the lots in the two scenarios.

4.6 Research question 5: vegetation distribution scenarios

The effect of vegetation distribution scenarios will be determined by investigating possible variations within the mixing classes. This will be done for two reasons. First, it is possible to evaluate the effects of different possible vegetation distributions (within the margins of a mixing class) on the maximum water level. Secondly, the roughness value of the mixing class is based on two vegetation types: *non-rough* vegetation (*natural grassland*) and *rough* vegetation (*shrubs*). Only these two vegetation classes have to be taken into account when designing the scenarios. This makes it possible to better investigate the effect of a certain vegetation distribution. If several vegetation species are present on a lot, as is often the case in the reference model, there are also more variables that can influence the processes that occur. The disadvantage of these vegetation distributions is that they are theoretical distributions, which can only be compared with each other, and with the model run with mixing classes. It does not make sense to compare the results with the *reference model*, since the effects of classifying vegetation in mixing classes also play a role. However, for the purpose of these scenarios, it is not necessarily needed to make a comparison with the *reference model.*

Three lots are chosen to determine the effects of the possible variations within the mixing classes (Figure 20). It has been chosen to use lots that differ from each other in location and properties. For example, it was decided to use a lot situated in a relatively straight stretch of the river, a lot in an inner bend of the river and a lot in an outer bend in the river. It has also been ensured that there is not a lateral flow on all the lots. Finally, the lots have a different mixing class from the other chosen lots. The three lots have the following characteristics:

- The most upstream lot is assigned to mixing class *70/30*. It is located just downstream of Hardenberg. The River Vecht is relatively straight at this point. In the network of the 1D hydraulic model, a lateral flow runs through the lot on the northern boundary.
- The lot in the middle is assigned to mixing class *80/20*. This lot is located in an inner bend of the River Vecht, adjacent to a natural height, which also partly lies within the lot. There are no lateral flows in the 1D network of the hydraulic model that run through the lot. On the other side of the river, a side channel is present.
- The most downstream lots is the largest lot in the winter bed of the River Vecht (in the area of R.W.A. Vechtstromen) is located. This lot is assigned to mixing class *50/50*, because on the lot a nature area with several types of vegetation is located. The lot is located in the outer bend of the River Vecht and on the edges of the lot some natural heights are present. A lateral flow is entering the winter bed of the River Vecht in this lot. There is a side channel located on the lot, where water flows through in case of high water.

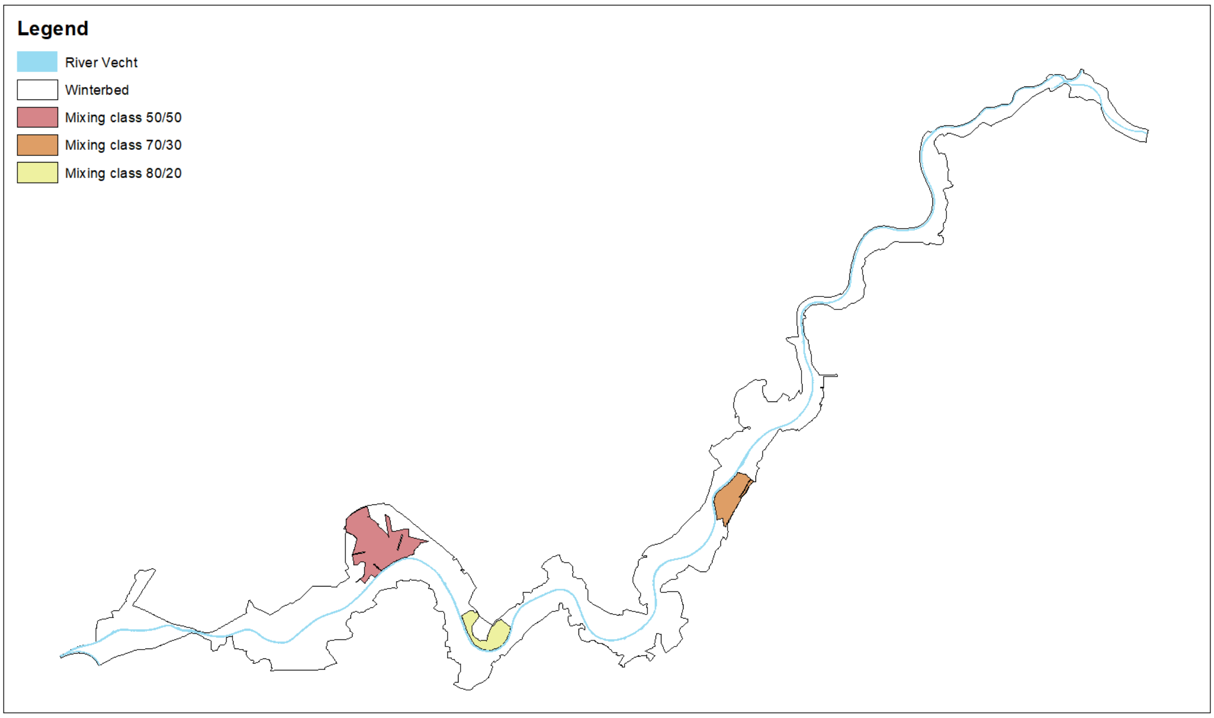

Figure 20. Locations of the three lots that will be used to determine the effect of the variation within mixing classes.

For each lot four scenarios are designed, in which the vegetation distributions over the lot are varied:

- Scenario 1: The rough vegetation is located on the banks of the river, in a line along the river.
- Scenario 2: The rough vegetation is located in the storage parts of the winter bed. This has been determined based on the presence of natural heights on the lot. Less or no flow is expected here, so the rough vegetation is placed here. If this was not enough to reach the percentage, the rough vegetation is placed as far away from the river as possible.
- Scenario 3: The rough vegetation is located in stretches perpendicular to the direction of the flow.
- Scenario 4: The rough vegetation is located in stretches parallel to the direction of the flow.

An example of the four scenarios is presented here (Figure 21). The designs of the four scenarios for all three lots can be found in Appendix 3. These scenarios will be implemented in the hydraulic model as follows. First, the scenarios are designed, taking into account the correct ratio of *natural grassland* and *shrubs* corresponding to the mixing class (Figure 21). Thereupon, the layer with shapefiles of the lots with the mixing classes is overwritten by the designed shape. Next, these shapes are converted into a raster with grid size 25×25 m. Finally, the raster is converted into a roughness grid by using the table with the roughness of each vegetation class to match the vegetation type with the correct roughness.

The results of the model runs will be compared to the results of the model run with a single roughness value for the lots (scenario with mixing classes). The maximum water levels can be compared, in order to determine the deviation from the run with mixing classes. By doing this, the use of single roughness values for mixing classes on lots can be evaluated. In addition to this, it is possible to look at the effects of different vegetation scenarios on the maximum water levels and flow velocities. These insights are useful for R.W.A. Vechtstromen for the management of the vegetation in the floodplains. It can also be used to evaluated whether the modelled processes are realistic, by comparing the results with other studies.

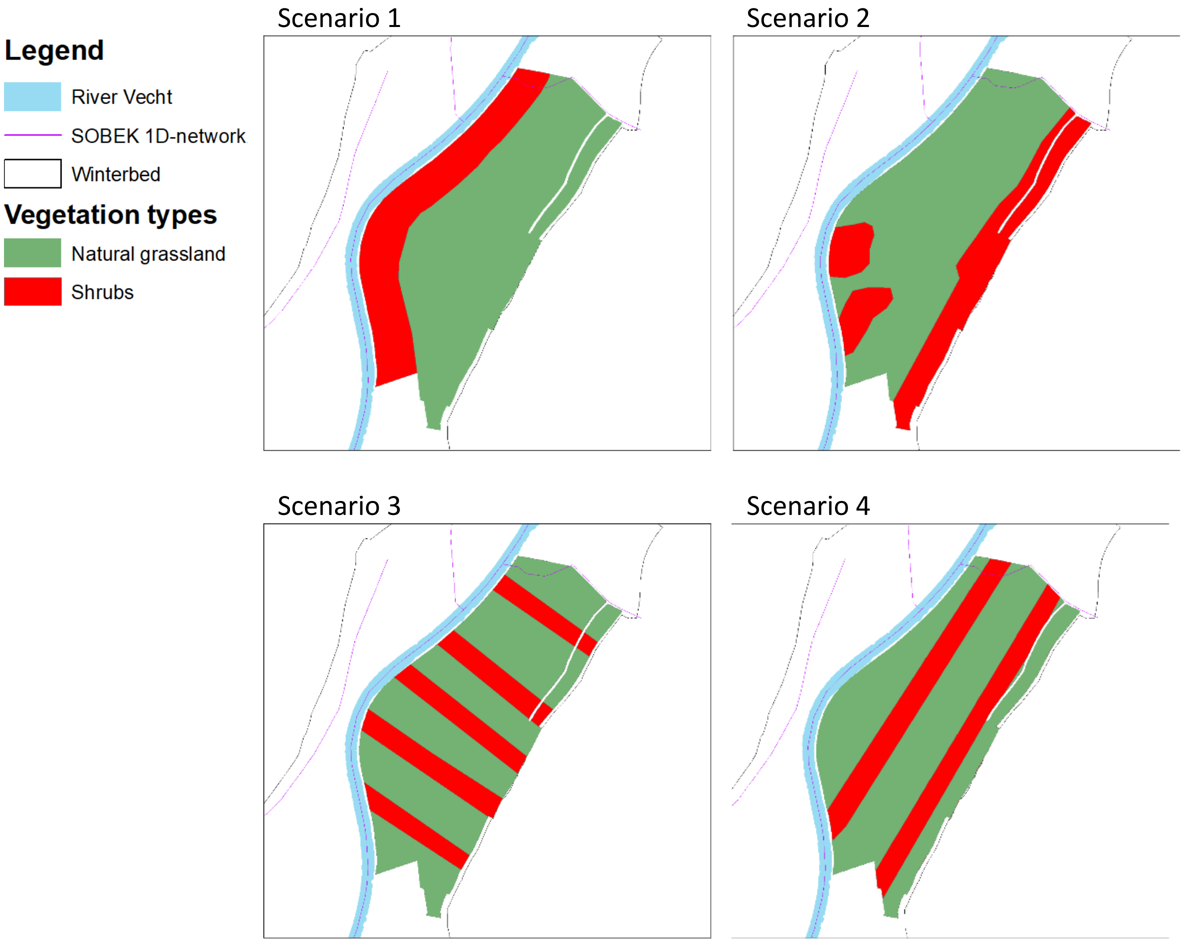

Figure 21. Different scenarios of vegetation distribution on the lot with mixing class 70/30.

4.7 Planned projects

Three scenarios are run: a scenario with the planned measures at Rheezermaten, a scenario with the planned measures at Karshoek-Stegeren and a scenario where all measures are combined. In Appendix 4, the projects are described. In this section, it is described how the projects are implemented in the hydraulic model and how the results contribute to this research.

The measures of the planned projects along the River Vecht can be subdivided in three types of changes in the hydraulic model: changes in the network of the hydraulic model (change of the river course, addition of the side channel), changes in the elevation grid (heightening or lowering the surface level) and changes in the roughness grid (new vegetation type). The necessary changes in the network are not implemented. It is expected that these changes have an impact on the water level. Since the focus of this research is on the effect of vegetation patterns, these changes in the network are not implemented and the course of the river is kept the same. However, it should be taken into account that the results of these scenarios are not the complete measures, but only the effect of the changes in vegetation and elevation. The different measures of the planned projects are implemented as follows:

- Pools: the values of the elevation raster within the polygons of the pools are changed to a specific value (5.1 or 5.2 m + NAP).
- Heighten 20 cm: the values of the elevation raster within the polygons are raised with 20 cm.
- Heighten 20 cm, stroomdalgrasland: Within the polygons, the values of the elevation raster are raised with 20 cm and the vegetation type in the ecotopes map is changed into mixing class 80/20. This mixing class is chosen, because two other areas in the winter bed of the River Vecht where there is 'stroomdalgrasland' have a ratio of natural grassland and rougher vegetation that is around 80/20.
- Lower 20 cm, stroomdalgrasland: The values in the elevation grid are lowered with 20 cm, vegetation type is changed into mixing class 80/20.
- Lower 20 cm, plas-dras: The vales of the elevation grid are lowered with 20 cm. The vegetation type is changed into reed.
- Stroomdalgrasland: The vegetation type in the ecotopes map is changed into mixing class 80/20.
- Forest: The vegetation type in the ecotopes map is changed into forest.

The difference in maximum water levels says something about the effect of the changed vegetation patterns on the water level. The scenario with both projects shows whether and to what extent changes in vegetation at different locations can influence each other.

5 Results of the model runs

In this chapter the results of the model runs are analysed. These analyses will be used to answer the research questions.

5.1 Research question 1: sensitivity analysis

The sensitivity of the model results to the change of the four roughness parameters and the two boundary conditions (BC) was analysed. The maximum water levels along the River Vecht for the four scenarios per parameter (-40%, -20%, +20%, +40%) are compared to the maximum water levels of the reference model (T=200). This is done on all calculation points along the river, from which an average deviation is then calculated (Table 7). This differs from the calibration and validation since there are many more points where the maximum water level can be compared, instead of the five measuring stations that were available with measuring data for calibration and validation.

Table 7. Sensitivity of the hydraulic model to the different parameters; expressed in the average of the differences in maximum water level [m] along the River Vecht on the trajectory German border – Varsen compared to the reference model (T=200).

Changed parameter	-40%	-20%	+20%	+40%
Main channel roughness	0.305	0.145	-0.138	-0.275
Winter bed roughness (2D-grid)	0.322	0.132	-0.085	-0.146
Winter bed roughness (cross-sections)	-0.001	-0.001	0.001	0.001
Side channel roughness	0.016	0.007	-0.005	-0.009
Discharge (upstream BC)	-0.514	-0.245	0.216	0.416
Q-h relation (downstream BC)	-0.035	-0.031	0.099	0.282

The hydraulic model appears to be the most sensitive to variations in the upstream boundary condition. A 40% decrease in the discharge wave causes an average of 50 cm decrease in the maximum water level along the River Vecht, while a 40% increase in the maximum water level causes a rise of more than 40 cm. In other words, this means that the hydraulic model is most sensitive to an increase or a decrease in the amount of water flowing through the river. The model is more sensitive to a decrease in discharge than to an increase. The variations of 40% correspond to the uncertainty margins in the discharge data (Van der Scheer, 2015). The uncertainty in these data can lead to deviations of the order of magnitude of 50 cm.

The hydraulic model is more sensitive to a variation in the main channel roughness compared to the same variation in the roughness of the 2D grid. An increase in Chézy coefficient (meaning that the river becomes smoother and can convey more water) in the main channel causes almost twice as much reduction in the maximum water level compared to the same increase in the winter bed (Table 7). On the other hand, a very large (-40%) decrease in the Chézy coefficients in the 2D grid results in a larger increase in maximum water level than the same decrease in the Chézy coefficient in the main channel, although this difference is not very large (32.2 cm for a change in the winter bed compared to 30.5 cm for a change in the main channel). It is particularly striking that the model is much more sensitive to an extreme decrease (-40%) of the Chézy values in the 2D grid, than when there is a smaller decrease (-20%) or an increase. This means that if the vegetation in the winter bed is actually much rougher than currently estimated, this will result in a much higher maximum water level.

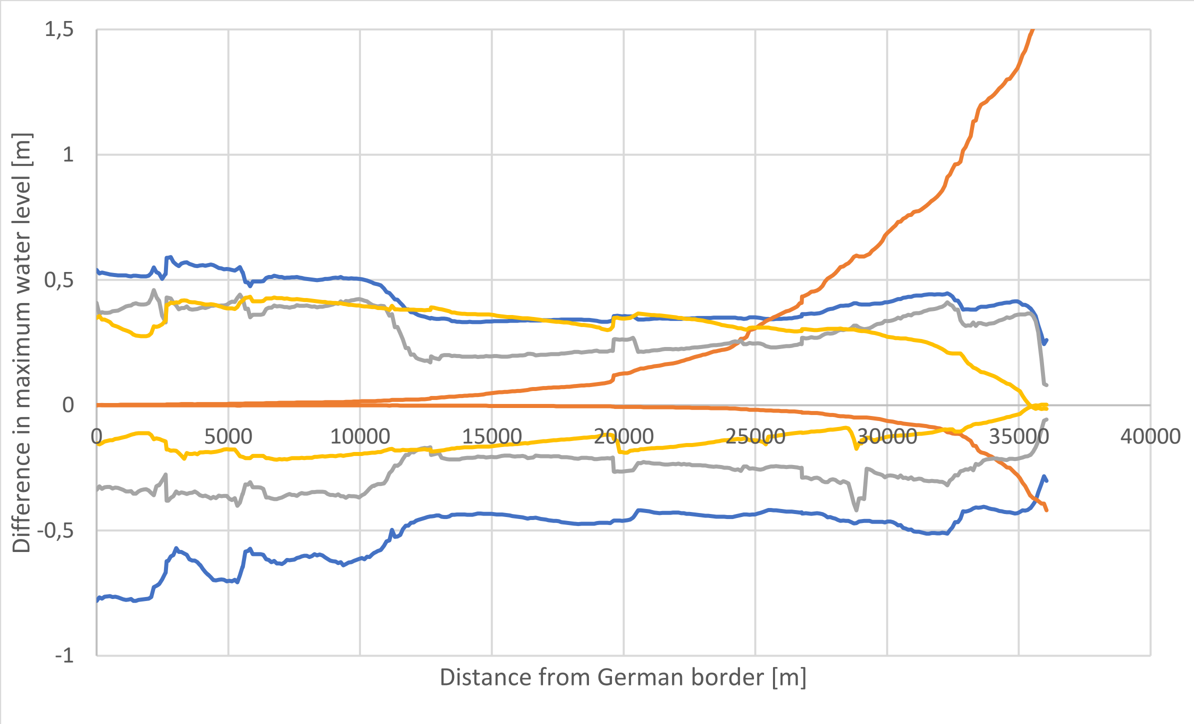

Figure 22. Sensitivity of the hydraulic model to variations of +-40% in the Q-t relation (upstream BC) (blue), the Q-h relation (downstream BC) (orange), main channel roughness (grey) and winter bed roughness (yellow), expressed in the difference in maximum water level [m] along the River Vecht compared to the reference model (T=200).

The hydraulic model is not very sensitive to the side channel roughness and the roughness of the winter bed in the 1D-part of the model (included in the cross-sections). This justifies the assumption that it is not necessary to calibrate these parameters. The model is considerably more sensitive to the main channel roughness and the roughness of the winter bed in the 2D-grid (Table 7).

The average value of the difference in maximum water level for the Q-h relation gives a distorted view. The effect of the changed Q-h relation is only noticeable in the downstream part of the River Vecht (Figure 22). Here, the effect is significantly higher than the average value, which is lower because the boundary condition does not influence the water level in the upstream part. The effect of a lowering in the Q-h relation is only noticeable from 25 kilometres from the German border. The effect of increasing the Q-h relation is noticeable further upstream. In case of an increase of 40% in the Q-h relation the water level is already affected from 15 kilometres from the German border (Figure 22). The water level is affected further upstream in case of an increase in the Q-h relation, because there is a larger difference in water level at the end of the 1D-2D part (Figure 22). This explains why the average values are significantly higher if there is an increase in the Q-h relation (Table 7). The sensitivity to the downstream boundary condition can be explained by the fact that a backwater curve to the water level downstream occurs. It shows that in the downstream section of the river, the boundary condition has a strong influence. This effect must be taken into account when interpreting results obtained in the remainder of this study.

The sensitivity of the hydraulic model along the River Vecht to variations in the upstream boundary condition, main channel roughness and winter bed roughness is relatively constant (Figure 22). However, in the first 10 km, the model is somewhat more sensitive to variations in the discharge and main channel roughness. This part of the River Vecht is narrower than the part further downstream. It shows that the main channel is more dominant in the narrower part of the winter bed.

5.1.1 Conclusion

In general, it can be said that the model is the most sensitive to the upstream boundary condition. In the downstream part of the River Vecht (from 25 kilometres from the German border) the Q-h relation has a larger effect. The hydraulic model is also sensitive to both main channel roughness and winter bed roughness, although this sensitivity is not as large as the sensitivity to the upstream boundary condition. The model is less sensitive to winter bed roughness compared to main channel roughness, unless it involves a strong decrease in Chézy-coefficient (-40%). For both the main channel roughness as the winter bed roughness, a reduction of the Chézy coefficient (a higher resistance) has a stronger effect than the same increase of the Chézy coefficient (a lower resistance). In the case of the winter bed, this effect is more than twice as strong. In narrow parts, the model is more sensitive to variations in the main channel roughness.

It is expected that the dominant effect of the downstream boundary condition in the downstream part of the river will influence the results. As the water level adapts to the water level downstream (backwater curve), it is to be expected that the differences in water levels from about 25 km from the German border will decrease. From this point, the modelled (maximum) water levels are less reliable than the water levels further upstream. At the transition from the 1D-2D to the 1D schematisation (at Varsen, end of the area of R.W.A. Vechtstromen), the differences in maximum water level between scenarios will be around 0, unless there are different maximum discharges in the scenarios that flow out of the area. In that case, the Q-h relation causes different water levels in the 1D trajectory.

5.2 Research question 2: extreme vegetation scenarios

The aim of the extreme vegetation scenarios is to get an idea of the possible effects on the maximum water levels (section 5.2.1), discharge peak (section 5.2.2) and maximum flow velocities (section 5.2.3) along the River Vecht in the area of R.W.A. Vechtstromen. It outlines the bandwidth in which the effects of possible vegetation measures will fall and it is also possible to place the current situation in the winter bed of the River Vecht within this bandwidth.

5.2.1 Bandwidth of the maximum water levels

The difference in maximum water levels along the River Vecht between the two extreme scenarios can be seen as the bandwidth of maximum water levels. The calculated maximum water levels will always fall within these two extremes. The difference in winter bed roughness causes a large difference in the maximum water levels along the River Vecht (Figure 23). The difference between the water levels in the rough scenario and the smooth scenario differs considerably in the longitudinal direction. In the upstream part of the river within the area of R.W.A. Vechtstromen (up to about 20 kilometres from the German border), the difference in maximum water levels varies between 0.8 and 1.2 metres (Figure 23). The positive values of the difference in maximum water level indicate that the rough scenario has a higher maximum water level. In the downstream part, up to 35 kilometres from the German border, this difference decreases. However, the rough scenario still has a higher maximum water level. From 35 kilometres from the German border the difference is negative, which means that the smooth scenario has a higher maximum water level.

The deviation of the rough scenario from the current situation is distinctly larger than the deviation of the smooth scenario from the current situation (Figure 23). It indicates that in the current situation of the winter bed flow paths are present that contribute significantly to the discharge capacity. This corresponds to the large amounts of *production grassland* and *natural grassland,* compared to the amounts of rougher vegetation (*forest*, *herbaceous vegetation*, *reed* and *shrubs*).

The decrease in the difference in maximum water levels in the downstream section (from a distance of 25 km from the German border) is due to the backwater curve to the water levels downstream imposed by the boundary condition (Q-h relation). This has nothing to do with the characteristics of the winter bed of the River Vecht.

5.2.2 Diffusion of the discharge wave

At the transition from the 1D-2D schematisation to the 1D schematisation, at the end of the area of R.W.A. Vechtstromen, there is a clear difference in the discharge wave (Figure 24). Due to the higher roughness coefficient in the rough scenario, water takes longer to propagate. The peak in the discharge wave therefore arrives 21 hours later at the end of the area of R.W.A. Vechtstromen. In addition, more diffusion occurs (the process whereby the peak in the discharge wave becomes less high and spreads more widely). In the rough scenario, the peak is around 2.5% lower.

The difference in the peak of the discharge wave is further increased by the River Regge, which is a lateral flow in the hydraulic model that the River Vecht in the most downstream part of the 1D-2D grid in the model. The discharge wave of the River Regge is different from the discharge wave of the River Vecht. When the peak arrives in the rough scenario, the discharge of the River Regge is already further reduced than when the peak arrives in the smooth scenario. This accounts for 64% of the total difference between the peaks of the discharge waves of the rough scenario and the smooth scenario. The remaining 36% is caused by the lower discharge capacity due to the higher roughness of the winter bed.

Because there is a higher maximum discharge in the smooth scenario, a higher maximum water level occurs in the most downstream part of the River Vecht, from 35 km from the German border. This is because the Q-h relation in this section of the river completely determines the water level.

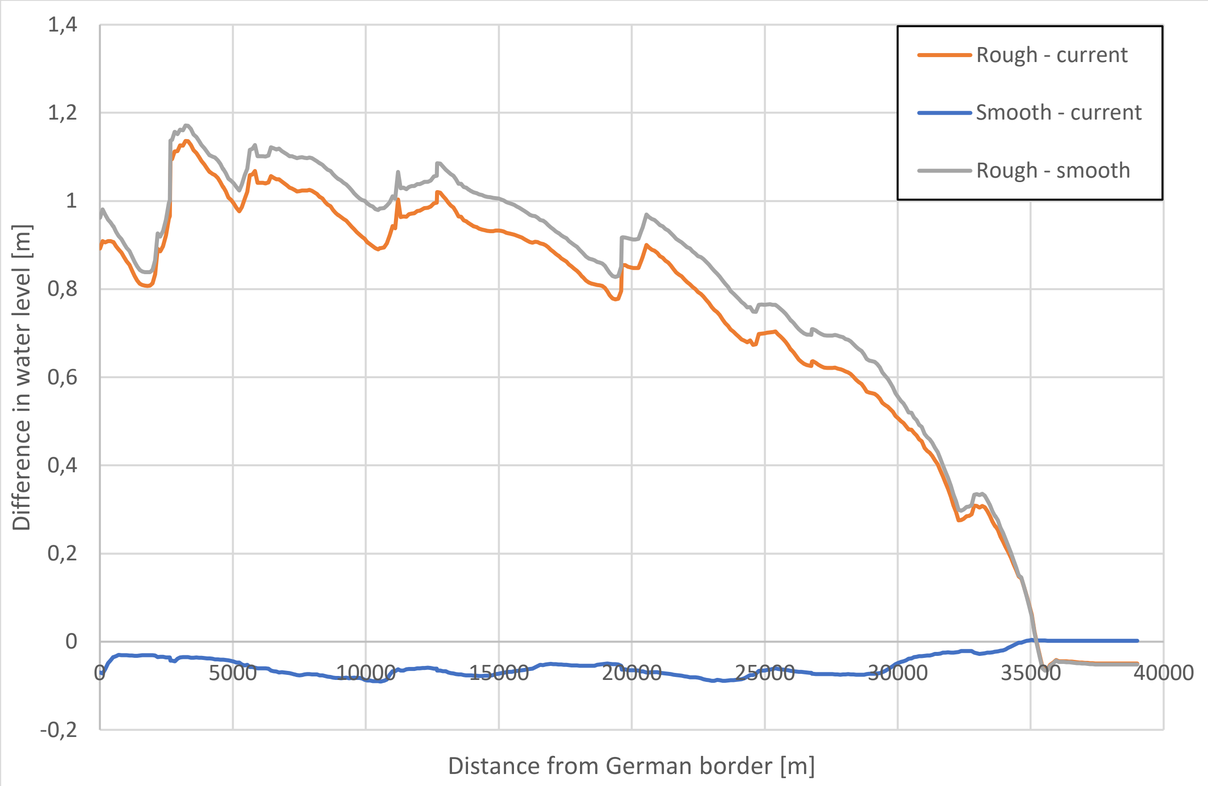

Figure 23. The difference in maximum water level [m] between the rough and smooth scenario and between the rough respectively smooth scenario and current situation.

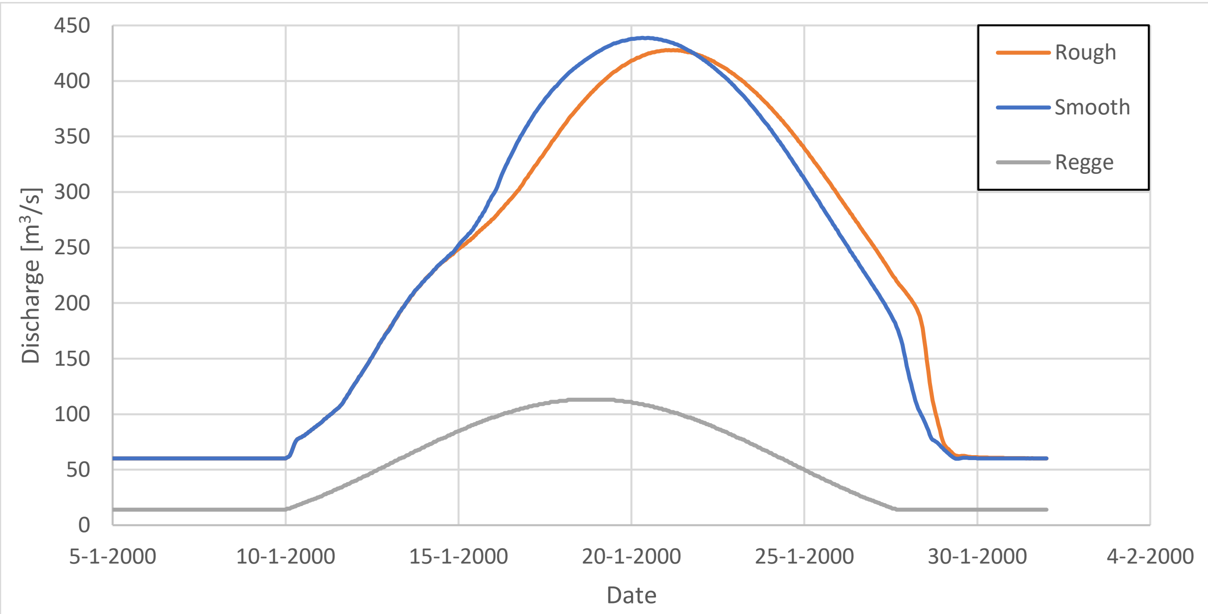

Figure 24. Discharge [m^3/s] at the downstream border of the area of R.W.A. Vechtstromen for the rough and smooth scenario.

5.2.3 Differences in maximum flow velocity

The difference in maximum flow velocity varies strongly along the River Vecht (Figure 25). In the more narrow parts of the winter bed, the flow velocities in the smooth scenario are substantially higher. In the wider parts, this difference decreases. The locations where the differences in maximum flow velocity are the largest indicate the bottlenecks in the winter bed of the River Vecht. A change in the roughness will result in a larger change in the maximum flow velocity (and therefore the maximum water level) than at other locations.

In the outer parts of the winter bed, the maximum flow velocity is higher in the rough scenario (Figure 25). This is due to two reasons: (1) no water flow is present in the smooth scenario, so the flow velocity in the rough scenario is automatically higher, (2) the water depth in the rough scenario is substantially higher due to the blockage of the vegetation, while the water depth in the smooth scenario is very low (and the velocity therefore as well). If the last reason is the case, these parts can be storage parts of the winter bed in the smooth scenario and flowing parts in the rough scenario. It shows that if the vegetation becomes rougher, water will flow at locations where this was not the case when the vegetation was smoother.

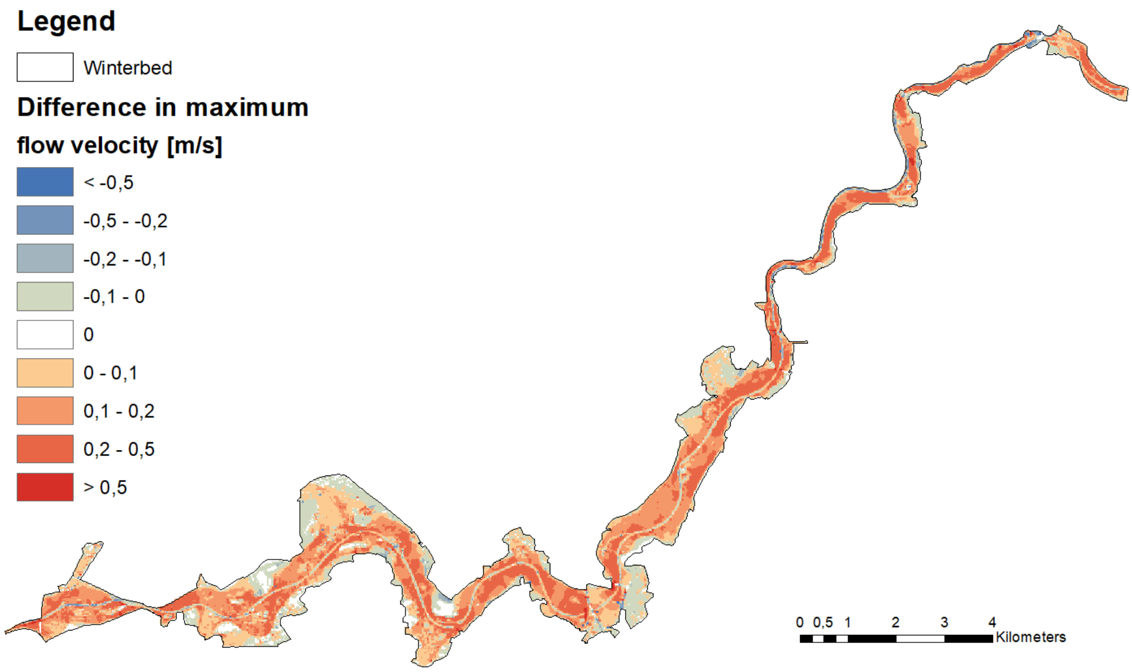

Figure 25. Difference in maximum velocity [m/s] between the rough and smooth scenario. A positive value indicates a higher velocity in the smooth scenario.

5.2.4 Conclusion

From the runs with the extreme vegetation scenarios it follows that the difference in maximum water level along the River Vecht is in the order of 1 meter. This is the bandwidth in which the results in the remainder of this study will fall. The current situation of the winter bed is much closer to the smooth extreme and is therefore relatively smooth. The peak of the discharge wave will be delayed considerably if rougher vegetation is allowed in the winter bed, namely 21 hours.

The difference in maximum flow velocity varies greatly from location to location. Bottlenecks occur in the narrower parts of the winter bed, the difference in the maximum flow velocity is much higher here. Storage areas in the floodplains can become flowing areas if the water level rises, which happens if the vegetation becomes rougher. This shows that storage areas of the winter bed are dynamic, depending on the roughness in the entire winter bed.

5.3 Research question 3: vegetation data sources

In this section the different vegetation data sources are compared. The model with the ecotopes map is used as a reference model. First, the model run with LGN (land use) map will be compared with the reference model. Then the model runs with the satellite images will be compared with the reference model. The satellite images will also be compared to each other. The aim is to come to a conclusion about the suitability of the different vegetation data sources to describe the vegetation in the winter bed for the hydraulic models of the River Vecht.

5.3.1 LGN map versus ecotopes map

If the LGN map is used, a lower maximum water level is calculated (Figure 26). In general, the roughness of the LGN map is lower than the roughness of the ecotopes map. This is because the LGN map shows the most dominant vegetation type on a lot. The rougher vegetation classes are often not dominantly present on a lot, which means that they are lost in the LGN map.

Until 25 kilometres from the German border, the difference in maximum water level fluctuates between 0.04 and 0.08 m. At the peaks of the difference graph (around 10 km, 15 km and 23 km), the vegetation in the LGN map close to the river is smoother compared to the ecotopes map. Around 10 km, where the largest peak is with a difference of around 0,08 m, the river is relatively narrow. At the locations of the peaks, the roughness in the LGN map is lower, mostly because *natural grassland* and *herbaceous vegetation* in the ecotopes map is described as *production grassland* in the LGN map. In the last section of the 2D grid, the maximum water level is higher in the model run with the LGN map. This is because at this location, there is rougher vegetation in the LGN map.

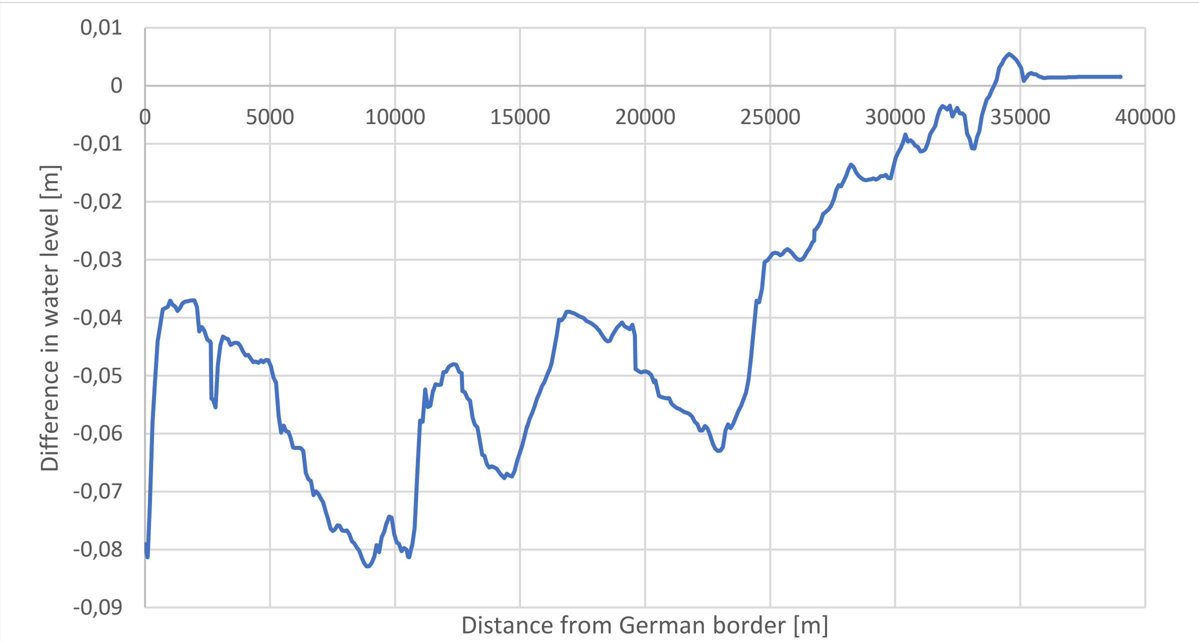

Figure 26. Difference in maximum water level [m] along the River Vecht for the model runs with the LGN map and ecotopes map. A positive value indicates a higher maximum water level during the run with the LGN map, a negative value indicates a lower maximum water level.

If zooming in on the area of Junner Koeland (Figure 27), it can indeed be seen that the hydraulic roughness derived from the LGN map is often lower than the hydraulic roughness derived from the ecotopes map. Differences that often occur are:

- *Bare soil*, *production grassland* or *natural grassland* is marked as *herbaceous vegetation* (dark green (*herbaceous vegetation* in the ecotopes map) or red (*herbaceous vegetation* in the LGN map) in Figure 27).
- *Shrubs* and *reed* in the ecotopes map are classified as *bare soil*, *production grassland* or *natural grassland* (dark green in Figure 27). This happens at all locations where there is *shrubs* or *reed* present in the ecotopes map, which is not a class in the LGN map.
- *Water* in the LGN map is marked as *reed* in the ecotopes map (dark green in Figure 27). This difference occurs mainly in side channels, which locally causes a relatively large difference in Chézy value.
- *Bare soil, agricultural land, production grassland* or *natural grassland* is marked as another of these mentioned types (light green or light orange in Figure 27). This can be the case in both maps for all mentioned classes. The difference in Chézy value is between 2 – 6 $m^{1/2}/s$, which is relatively small. However, if comparing the two roughness grids, 32% of the total winter bed has a difference in Chézy value within this range.

The white areas (Figure 27) indicate that the Chézy value in the roughness grids based on the LGN map and ecotopes map is the same. This is the case in 55% of the total winter bed of the River Vecht.

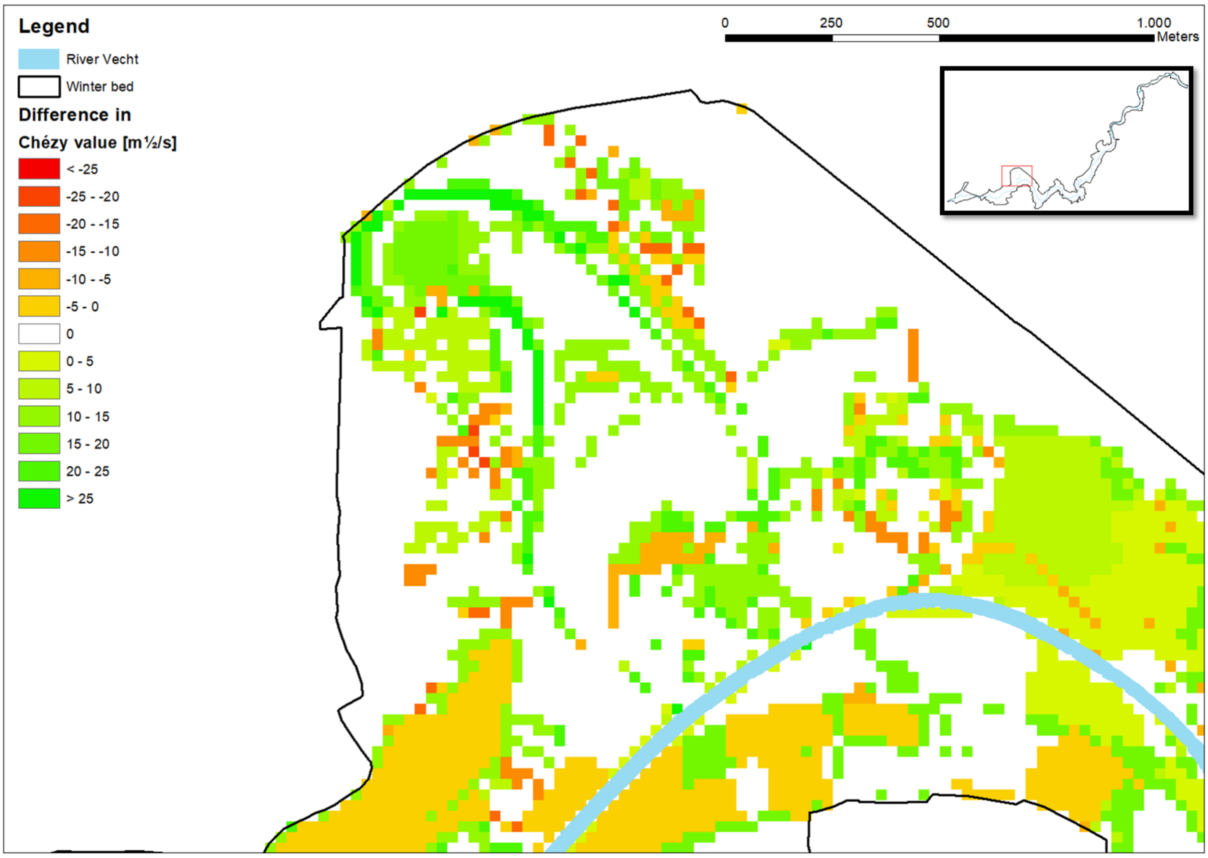

Figure 27. Differences in Chézy value between the LGN map and the ecotopes map. A positive value indicates a higher Chézy value in the LGN map and thus a smoother vegetation type, a negative value indicates a lower Chézy and rougher vegetation type in the LGN map. The same vegetation type is indicated by the LGN map and ecotopes map in the white areas.

Logically, if the Chézy value is higher, a higher flow velocity occurs (Figure 28). The green line through the lot in Figure 28 corresponds to a present side channel of the River Vecht. Here, the vegetation is classified as *reed* in the ecotopes map, while it is classified as *water* in the LGN map. Therefore, a higher flow velocity occurs in this side channel. At some locations where the Chézy value in both grids is the same, a slightly lower velocity occurs in the model run with the LGN map. This is because the flow velocity at other locations is noticeably higher at other location (due to a lower Chézy value in the ecotopes map).

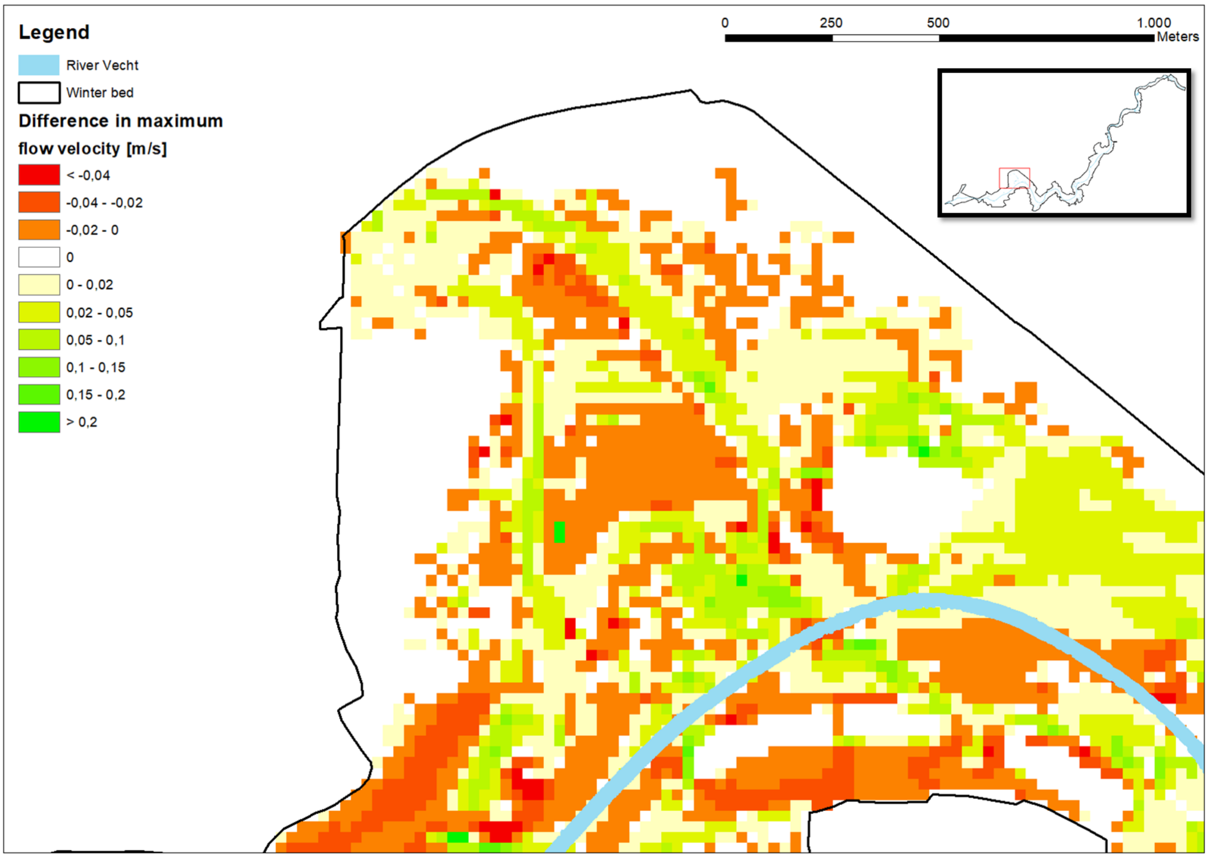

Figure 28. Differences in maximum flow velocity between the model runs with the LGN map and the ecotopes map. A positive value (green) indicates a higher flow velocity in the model run with LGN map, a negative value (red) indicates a lower flow velocity.

5.3.2 Satellite images versus ecotopes map

Looking at the differences between the model runs with satellite images compared to the model run with the ecotopes map (Figure 29), it can be seen that the maximum water level for the model run with the satellite image of 2018 fluctuates between the -4 and 4 cm. However, it should be noted that in the model run with the satellite images from 2018, a jump in the maximum water level along the River Vecht occurred, caused by an instability in the model. The water levels between 17 and 20 km have been adjusted manually, because the peak in the maximum water level would otherwise result in a distorted scale. The differences in water levels between 17 and 20 km with respect to the satellite images from 2018 are therefore not reliable. Looking at the surrounding differences between the model run with the ecotopes map and the model run with the satellite images from 2018, it is to be expected that the differences are in the range of 1-4 cm ((Figure 29). This means that the differences in the maximum water levels along the River Vecht between the two models fluctuates between 0-4 cm.

The maximum water level of the model run with the satellite image of 2017 differs considerably more from the model run with the ecotopes map, namely between the 4 and 8 cm with a peak of 14 cm between the 5 and 10 km from the German border. The difference between the model runs with the two satellite images is also relatively large, with a peak around the 11 cm.

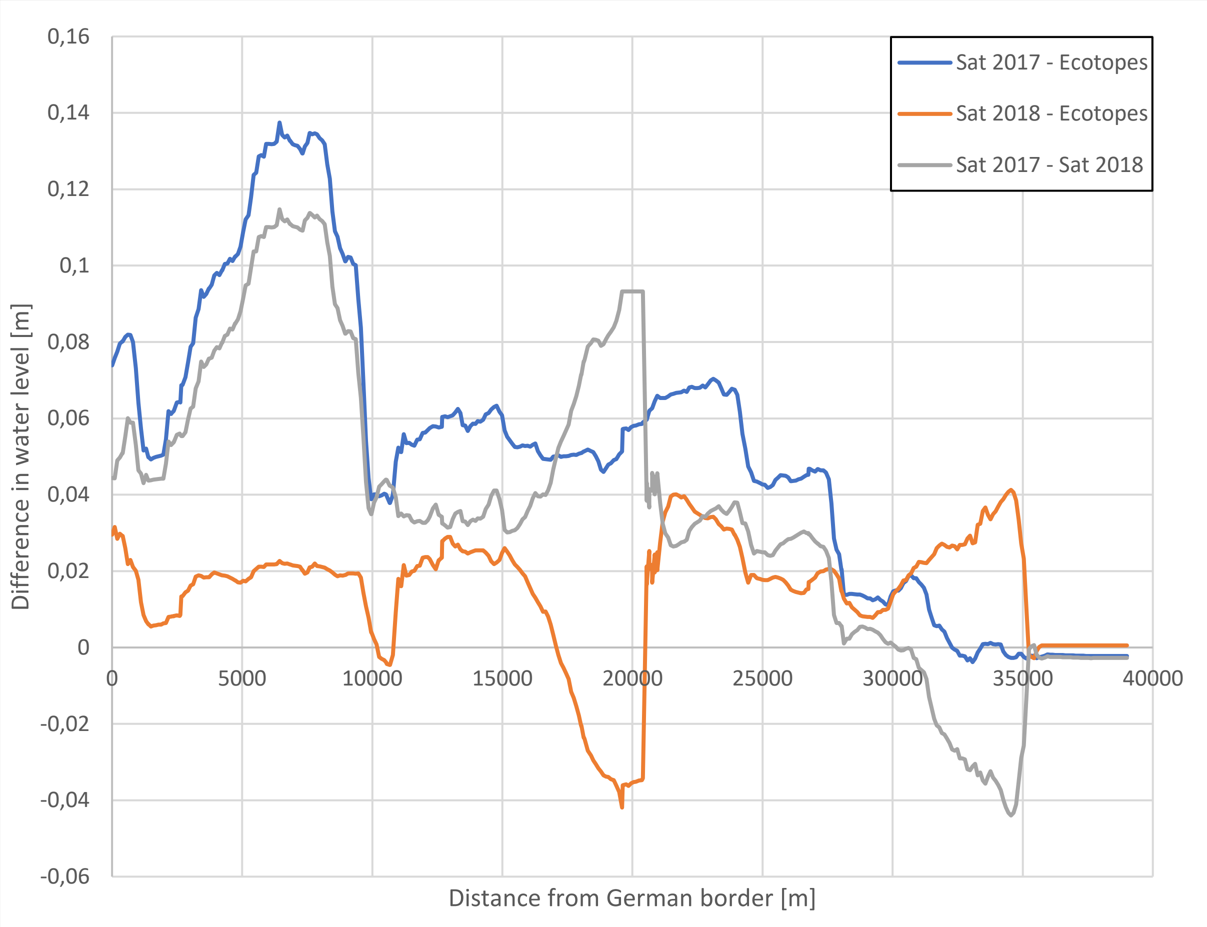

Figure 29. The differences in maximum water level [m] along the River Vecht for the two model runs with satellite images and the model run with the ecotopes map. Between 17 and 20 km the maximum water levels in the model run with the satellite image of 2018 have been adjusted due to instability in the model. Therefore, the differences between the other data sources and the satellite image of 2018 cannot be regarded as reliable in this trajectory.

The roughness grids of the two model runs with the satellite images are for 72% in agreement. The agreement of the ecotopes roughness grid with the two satellite roughness grid is significantly lower with respectively 34% and 33% for 2017 and 2018. This is because in the satellite images there is no difference between production grassland and natural grassland and instead there is only one grass-class, with a different roughness value. If this difference is not taken into account, the satellite images of 2017 and 2018 also correspond for respectively 73% and 72%. This order of magnitude corresponds to the accuracy of the classified satellite images of 75% (E. Penning, personal communication, August 27, 2019). The agreements of the satellite images with the ecotopes map are equally large as the agreement of both satellite images (72%). *Herbaceous vegetation, agricultural land, production grassland* and *natural grassland* are the vegetation types that are observed most differently. It often happens that these classes are classified as one of the other mentioned classes in a different source.

The difference between the ecotopes map and satellite image of 2017 is slightly lower than the difference between the ecotopes map and satellite image of 2018, however the maximum water level between the first two differs significantly more. This can be explained by the location of the differences. In case of the satellite image of 2017, these differences occur more often close to the river, while the satellite image of 2018 differs often further away from the river.

The ecotopes map and the two satellite images were collected within a period two years. It is unlikely that the vegetation has changed much during that period. It is therefore unlikely that the major differences between the ecotopes map and the two satellite images are due to changes in vegetation in the floodplains. In addition, the satellite image of 2017 is the middle data source in chronological order, while this source has the greatest deviation from the other sources.

It could be that the differences arise from the period during the year in which the images and ecotopes map were made. The ecotopes map dates from February 2017, but is based on data of a longer period. The satellite images are based on one moment during the year. The satellite image from 2018 was taken after a dry summer, which could possibly have an effect on the NDVI value and thus the observed vegetation. Furthermore it is known that classification methods contain uncertainties.

5.3.3 Conclusion

The model with the LGN map calculates a lower maximum water level than the reference model. The LGN classification gives one vegetation type per lot and does not include the vegetation classes *shrubs* and *reed* in the floodplains within the area of R.W.A. Vechtstromen. The ecotopes map is more detailed and recognises the rougher classes inside the area of R.W.A. Vechtstromen. For these reasons, the LGN map is less suitable for describing the vegetation in the winter bed of the Vecht River.

Satellite images do show variation within lots. In terms of vegetation classes, this method is also more similar to the method used with the ecotopes map: only the difference between production grassland and natural grassland is not observed. The modelled water levels of the model with the satellite image of 2017 differ considerably from the water levels of other two model runs. The differences between the model runs of the ecotopes map and satellite images from 2018, on the other hand, do not differ that much, with a deviation that fluctuates around 2 cm. The differences observed may be related to the difference in the classification methods, or to the uncertainty within a classification method. The moment during the year can also influence these differences.

Considering that the accuracy of the ecotopes map is improved (section 2.3.2), that the ecotopes map is used as training and test data for the satellite images (section 2.3.4), that no distinction is currently made between *production grassland* and *natural grassland* on the satellite images, and that it is not clear at the moment why the satellite image of 2017 differs from the ecotopes map and the satellite image of 2018, it seems logical to use the ecotopes map at the moment. However, if the accuracy of satellite images is further improved, this method certainly has potential to be used in the future.

5.4 Research question 4: mixing classes

In this section the results of the model run with mixing classes are discussed. First the model run with mixing classes is compared with the reference model. The purpose of this section is to determine how suitable the classification method with mixing classes is for R.W.A. Vechtstromen to calculate the water level.

5.4.1 Mixing classes versus homogenous vegetation classes

Along the whole trajectory of the River Vecht, the maximum water level is higher during the model run with the mixing classes (Figure 30). The difference is fluctuating between the 15 and 23 cm, until it is decreasing in the last kilometres before the 1D-2D part ends. In de downstream 1D section, the maximum water level in the reference model is higher, because a higher maximum discharge flows through the River Vecht in this model and the Q-h relation is dominant here.

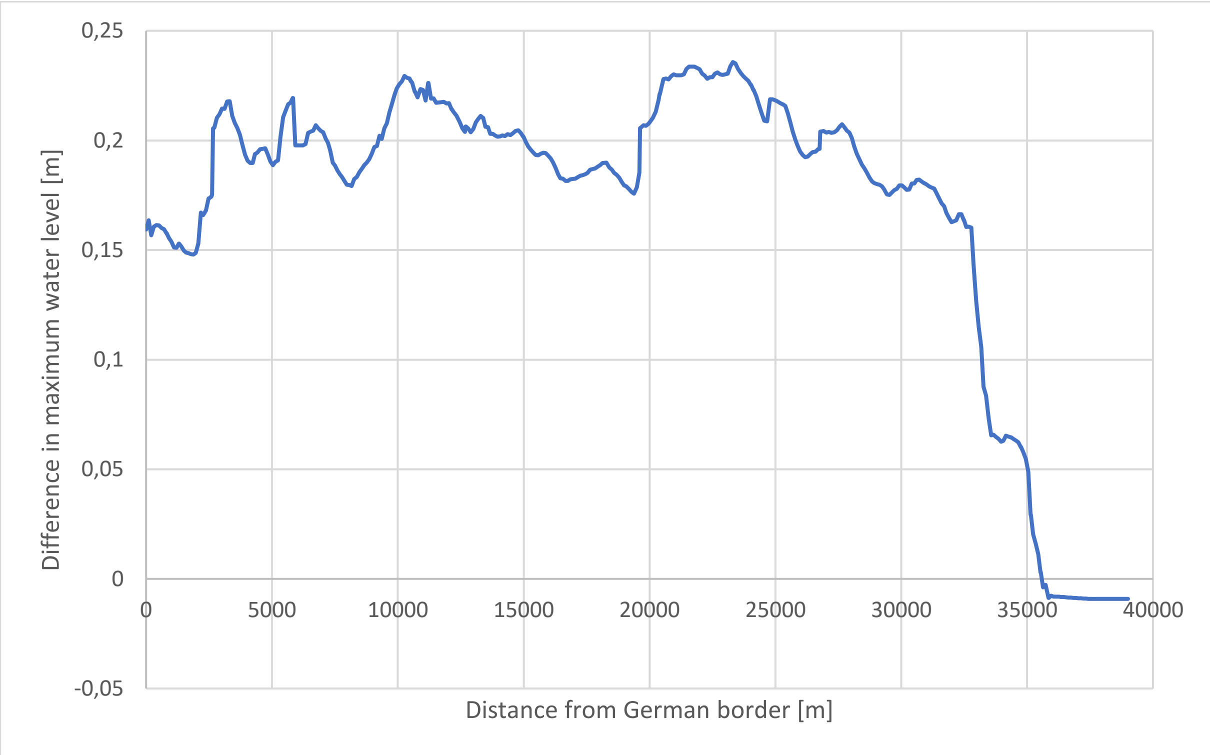

Figure 30. Difference in maximum water levels [m] between the along the River Vecht for the model runs with the mixing classes and ecotopes map. A positive value indicates a higher maximum water level during the run with the mixing classes, a negative value indicates a lower maximum water level.

If comparing the maximum water levels on the 2D-grid for both scenarios (Figure 31), it is also clear that there is a significant difference. A reason for this relatively large difference is the overestimation of the roughness due to two reasons:

- The percentage of vegetation belonging to the *rough-classes* is rounded up when assigning a mixing class to a lot.
- The used roughness for the calculation is the value of the most rough vegetation class, namely *shrubs*. For the *non-rough* vegetation, *natural grassland* is used, which is the most rough class of the *non-rough* vegetation classes.

The maximum possible value is used by the calculation of the mixing classes, which is often not the reality. If there is, for example, a lot with mixing class *80/20* then the calculated roughness is the

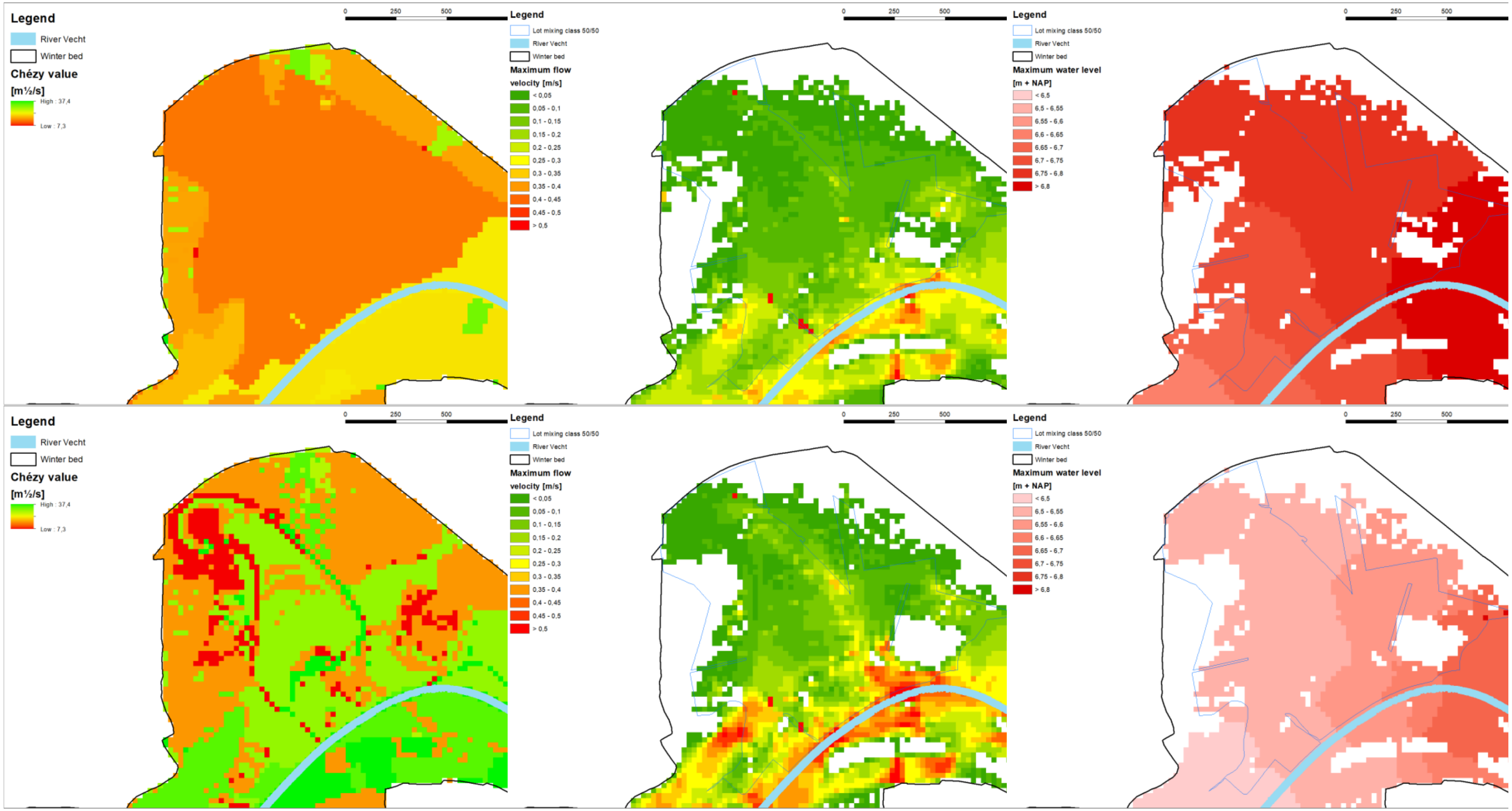

Figure 31. The hydraulic roughness grid, maximum flow velocities [m/s] and maximum water levels [m] in the model run with mixing classes (upper row) and ecotopes map (lower row) on the lot at Junner Koeland with mixing class 50/50.

combination of 80% *natural grassland* and 20% *shrubs.* However, also a lot with 12% of the other *rough* vegetation classes (*herbaceous vegetation, forest* and *reed*) and 88% *production grassland* is assigned to this mixing class.

If the roughness of mixing classes is used, every lot has one uniform roughness for the whole lot. The effect of this is that there is less variation in the flow velocity on a lot (Figure 31). Where the Chézy-value is high, the maximum flow velocity is relatively high in the model run with the ecotopes map compared with the model run with mixing classes. At the locations with a low Chézy-value, the maximum flow velocity is low. However, this is also in the model run with the mixing classes, since the Chézy-value of the mixing class (in this case 50/50, C = 13.2 $m^{1/2}/s$) is also relatively low. In the model run with the mixing classes, less flow paths occur since the roughness-value is high on the whole lot. This also contributes to higher water levels.

5.4.2 Conclusion

The model run with the mixing classes overestimates the maximum water level if this classification method is used to describe the vegetation situation in flood plains of the River Vecht. This is because for the mixing classes the maximum roughness coefficient is calculated, while it often does not reflect the actual situation on the lot. The method as used describes worst-case situation.

This can be seen as a safety margin. However, in the way this is done now, a double safety margin is taken by both rounding up the percentage of *rough* vegetation and using the most rough vegetation classes in the calculation of the roughness. In addition, due to the high roughness, there are no preferential flow paths present on the lot. The used worst-case calculation of the roughness provides a very large safety margin. This safety margin can be reduced by adjusting the definition of the mixing classes. For example more vegetation classes can be introduced, or different homogeneous vegetation classes are used for the calculation of the roughness-value of the mixing classes.

5.5 Research question 5: vegetation distribution scenarios

In this section, the effects of different vegetation distribution patterns on the maximum water level and the maximum flow velocities in the winter bed of the River Vecht are discussed. First, the effect on the maximum water levels of different vegetation patterns that are possible within the mixing classes will be examined and compared to the run with the mixing classes.

In addition, the blockage effect of vegetation, the formation of flow paths, the effect of vegetation in the river banks and the effect of vegetation in the storage areas of the floodplains is investigated. The aim of investigating the effects of different vegetation distribution patterns on the maximum water levels and the maximum flow velocities is to formulate recommendations for R.W.A. Vechtstromen on the planning of vegetation on lots in the winter bed of the River Vecht.

In Appendix 3, a results of the vegetation distribution scenarios can be found.

5.5.1 Effect of variation within mixing classes on the maximum water levels

From the runs with the possible variations within the mixing classes it follows that the model run with the mixing classes in most cases calculates a higher maximum water level (Table 8). Only scenario 3 (0.7 cm) on the lot with mixing class *70/30* and scenarios 1 (3.0 cm) and 3 (0.1 cm) on the lot with mixing class *50/50* calculate a higher maximum water level. The scenarios 3 are designed in such a way that the rough vegetation is perpendicular to the direction of flow and thus has a blockage effect. Scenario 1 on the lot with mixing classes *50/50* is the one with the vegetation in the river bank, however since in this mixing class half of the lot is rough vegetation, this also has a strong blockage effect. In other words, only when the vegetation blocks the flow, a possible distribution of vegetation within the mixing classes will ensure a higher maximum water level. In the other scenarios on these lots, the maximum water level is 1.0 - 4.6 cm lower compared to the model run with mixing classes.

Table 8. The maximum deviations in maximum water levels [m] along the River Vecht of the scenarios compared to the model run with mixing classes.

Lot	Scenario 1	Scenario 2	Scenario 3	Scenario 4
70/30	-0.023	-0.024	0.007	-0.015
80/20	-0.010	-0.046	-0.014	-0.018
50/50	0.030	-0.025	0.001	-0.020

5.5.2 Effect of blocking vegetation on the maximum water levels

It has already been discussed that the blockage effect of vegetation can cause a higher water level compared to the run with mixing classes, here the blocking effect on the water level and flow velocity is explained. If rough vegetation is placed perpendicular to the direction of flow, a blockage effect is created by the rough vegetation. This results in a higher maximum water level compared to the model run with mixing classes. This can be clearly seen in scenario 1 of the lot with mixing class 50/50 (Figure 32). Upstream of the lot, the water level rises due to the presence of a large quantity of rough vegetation in the banks, which is difficult for the water to flow around. Also in both scenarios 3 on the lots with mixing class *70/30* and *50/50*, the maximum water level rises compared to the mixing class model run (Table 8).

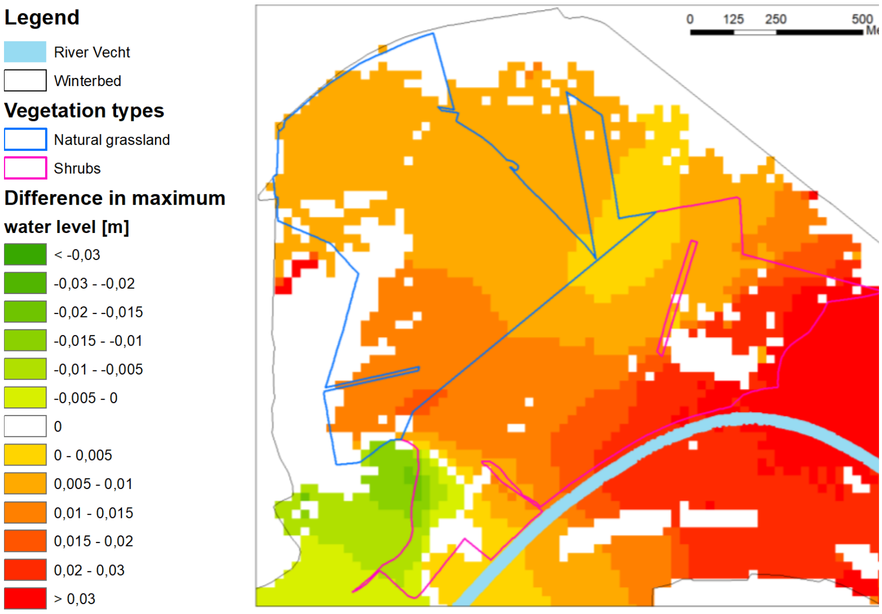

Figure 32. Difference in maximum water levels [m] for scenario 1 on the lot with mixing class 50/50 compared to the model run with the mixing classes..

5.5.3 Effect of flow paths on the maximum water levels

The blockage effect does not always lead to a higher water level. In scenario 3 of the lot with mixing class *80/20*, the maximum water level is lower than the model run with mixing classes (Table 8). This is because water can flow on the other side of the river and around the lines with rough vegetation. The maximum flow velocity inside the areas with rough vegetation is lower, but around it higher maximum flow velocities occur (Figure 33, scenario 3). For this reason, there is no higher water level compared to the model run with mixed classes.

The existence of flow paths that reduce the maximum water level can also be seen in scenario 3 of the lot with mixing class *50/50*. Despite the fact that the rough vegetation here is perpendicular to the direction of flow, the maximum water level is hardly higher (0.1 cm) compared to the model run with mixing classes. The reason for this small difference is that the tracks with rough vegetation are surrounded by tracks with much smoother vegetation. These tracks with smooth vegetation have considerably higher flow velocities compared to the tracks on the same location in the model run with mixing classes, with the uniform roughness of the mixing class *50/50* (Figure 34, scenario 3). In this case, the blocking effect of the rough vegetation is almost eliminated by the creation of flow paths.

The presence of lines with natural grasslands make sure that the maximum water level is lower compared with the model run with mixing classes. In these areas, higher maximum flow velocities can occur and water can be discharged faster (Figure 34, scenario 4 and Figure 35, scenario 4).

The most effective are the flow paths when they are parallel to the flow direction. Scenario 4 always leads to a lower maximum water level compared to the model run with mixing classes. Here, tracks with rough vegetation and tracks with smooth vegetation are present in the flow direction (Figure 34, scenario 4). In scenario 1 and scenario 2 on the lot with mixing class *70/30*, wider tracks with smooth vegetation (and higher maximum flow velocity) are present compared to scenario 4 (Figure 35). Lower maximum water levels therefore occur here (Table 8).

5.5.4 Effect of vegetation in river banks on the maximum water levels

Rough vegetation on the banks of the river does not necessarily lead to higher maximum water levels (Table 8). As long as it is possible for water to flow over tracks with smooth vegetation (Figure 33, scenario 1 and Figure 35, scenario 1), rough vegetation on the banks does not result in higher maximum water levels. The investigated scenarios show that as long as the stretch of smooth vegetation is wider than the stretch of rough vegetation, no higher water levels occur compared to the model run with mixing classes. However, as described above, when this vegetation has a blocking effect, higher maximum water levels will occur.

5.5.5 Effect of vegetation in storage parts of the floodplains on the maximum water levels

When vegetation is placed in the storage areas of the river, the lowest maximum water level is always calculated compared with the other scenarios and the model run with mixing classes (Table 8). In scenario 2, with rough vegetation in the storage areas of the lots, these relatively low maximum water levels occur, because water can flow easily over the non-rough parts (Figure 33, scenario 2). In terms of not increasing the water levels along the river, it is the best choice to place rough vegetation in the storage areas.

5.5.6 Conclusion

The model runs with the variations that are possible within the mixing classes show that deviations in maximum water levels do not exceed 5 cm. Moreover, the maximum water level is only higher in the case of blocking vegetation. In other cases, there may be flow paths on the lot, so that water can be discharged more easily. The uniform roughness value for the entire lot of a mixing class is therefore a safety margin in itself, as it can result in less clear flow paths. The advantage of this safety margin is that it does not result in an extreme overestimation of the maximum water level, as has been discussed in section 5.4. It offers possibilities for custom-made mixing classes, in which a mixing class is adapted to the desired situation. The owner of a lot is then allowed to freely distribute the agreed quantities of vegetation over the lot, as long as this does not cause a blockage effect.

Furthermore, there are two important aspects of vegetation distributions in the floodplains, namely the blockage effect of rough vegetation and the presence of flow paths. The blockage effect of rough vegetation results in higher water levels, while the presence of flow paths results in higher flow velocities and therefore lower water levels. It is important to note that the effects have been studied in relation to the model run with mixing classes, where the same amount of rough vegetation is present (but included in the roughness-value of the mixing class). If rough vegetation is placed on a completely smooth lot, a higher water level will occur anyway, even though there are wide flow paths and the rough vegetation is placed parallel to the flow direction. However, this higher water level is much lower than when the rough vegetation is placed perpendicular to the flow direction.

5.6 Planned projects

From the model runs with the planned projects, two results follow that are interesting for this research:

- Again, it was showed that the blockage effect of rough vegetation and the presence of flow paths have a distinct effect on the water levels.
- When several vegetation changes are realized, this can cause the water levels upstream to be influenced by the downstream projects as well. The different projects should therefore be modelled together, if they are close to each other. In this case, the effects of the projects are noticeable up to 15 km upstream.

In Appendix 4, a detailed description of the scenarios with the planned projects can be found.

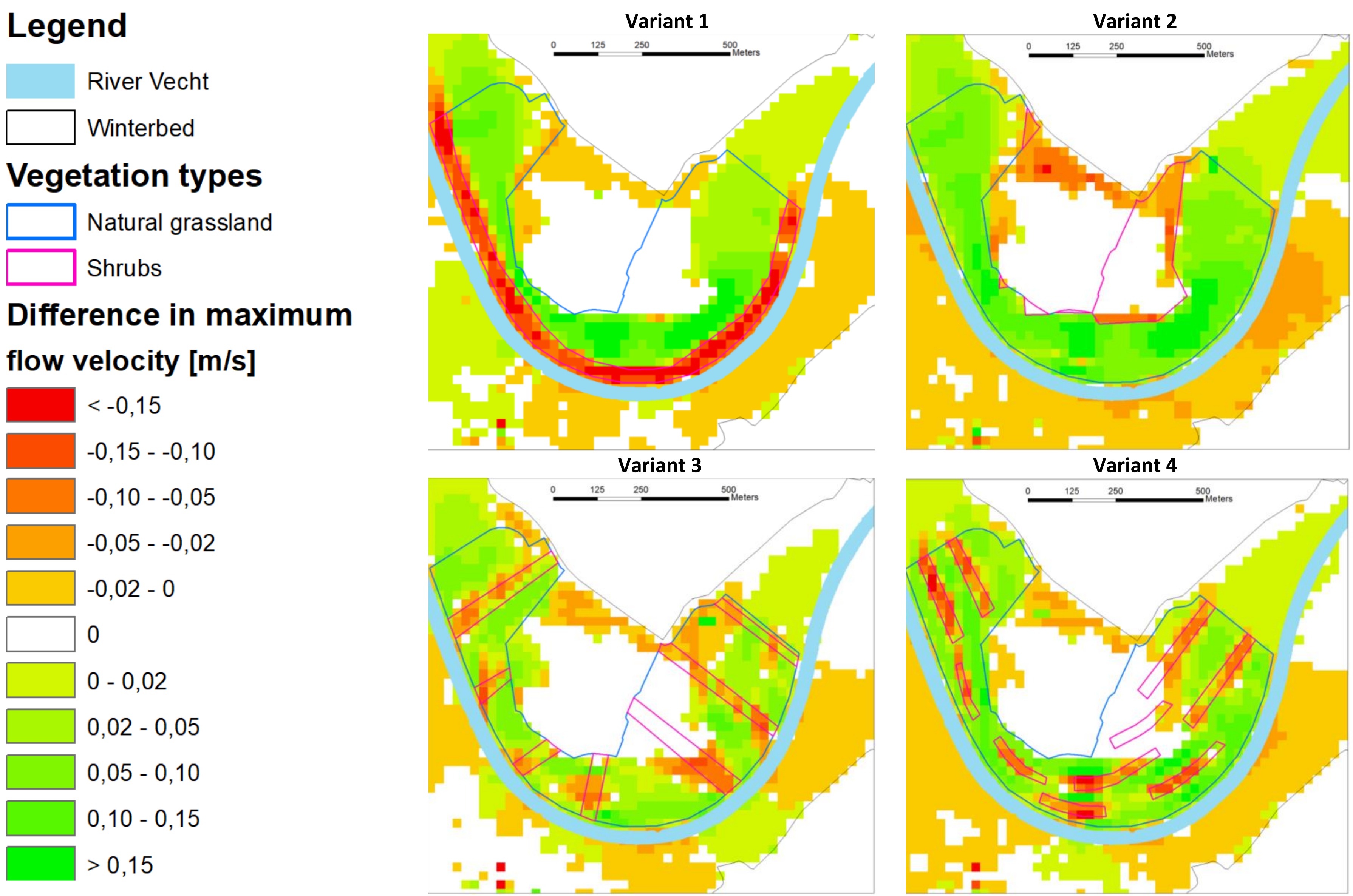

Figure 33. Difference in maximum flow velocity [m/s] for the different scenarios on the lot with mixing class 80/20 compared to the model run with the mixing classes.

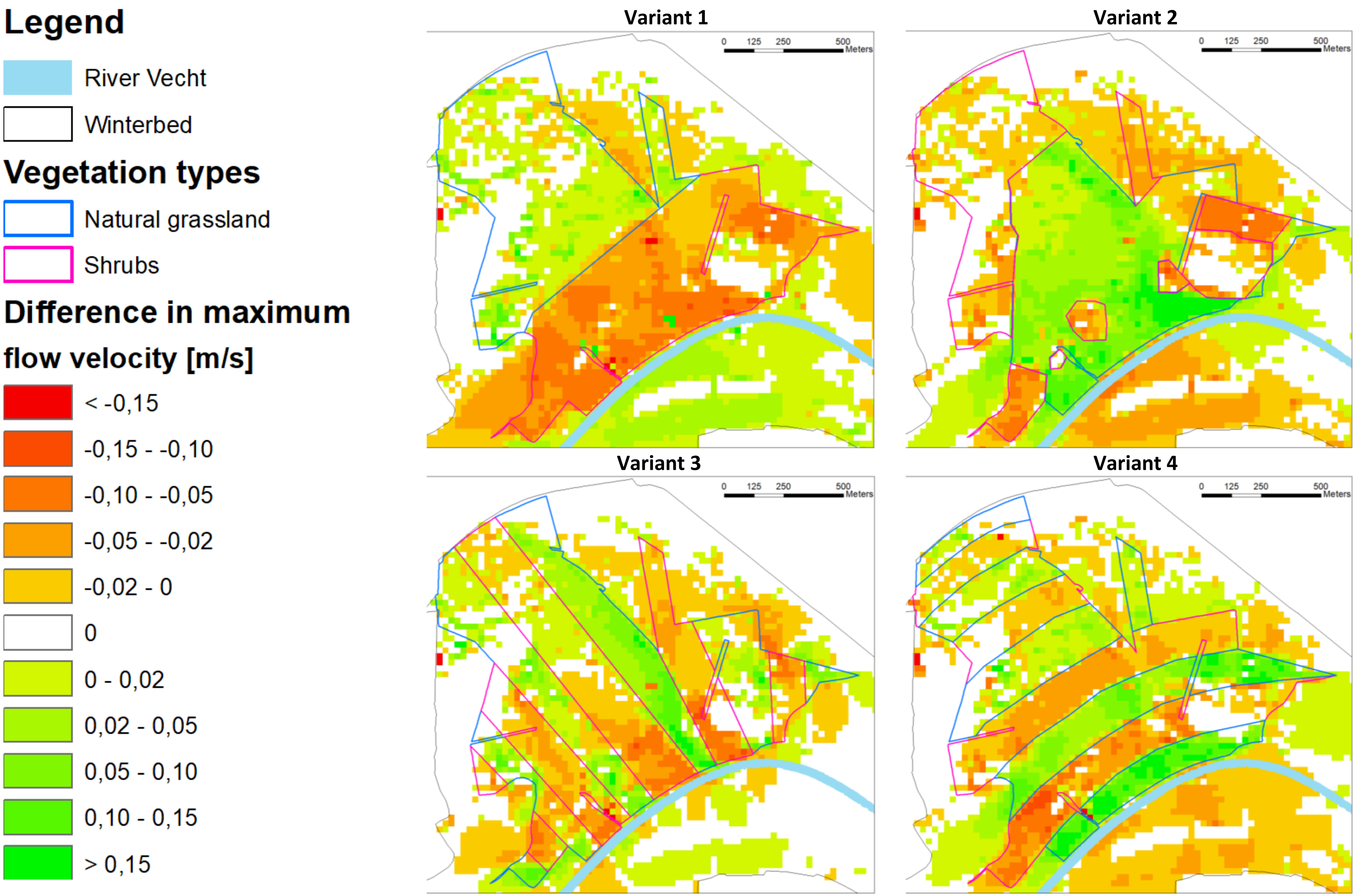

Figure 34. Difference in maximum flow velocity [m/s] for the different scenarios on the lot with mixing class 50/50 compared to the model run with the mixing classes.

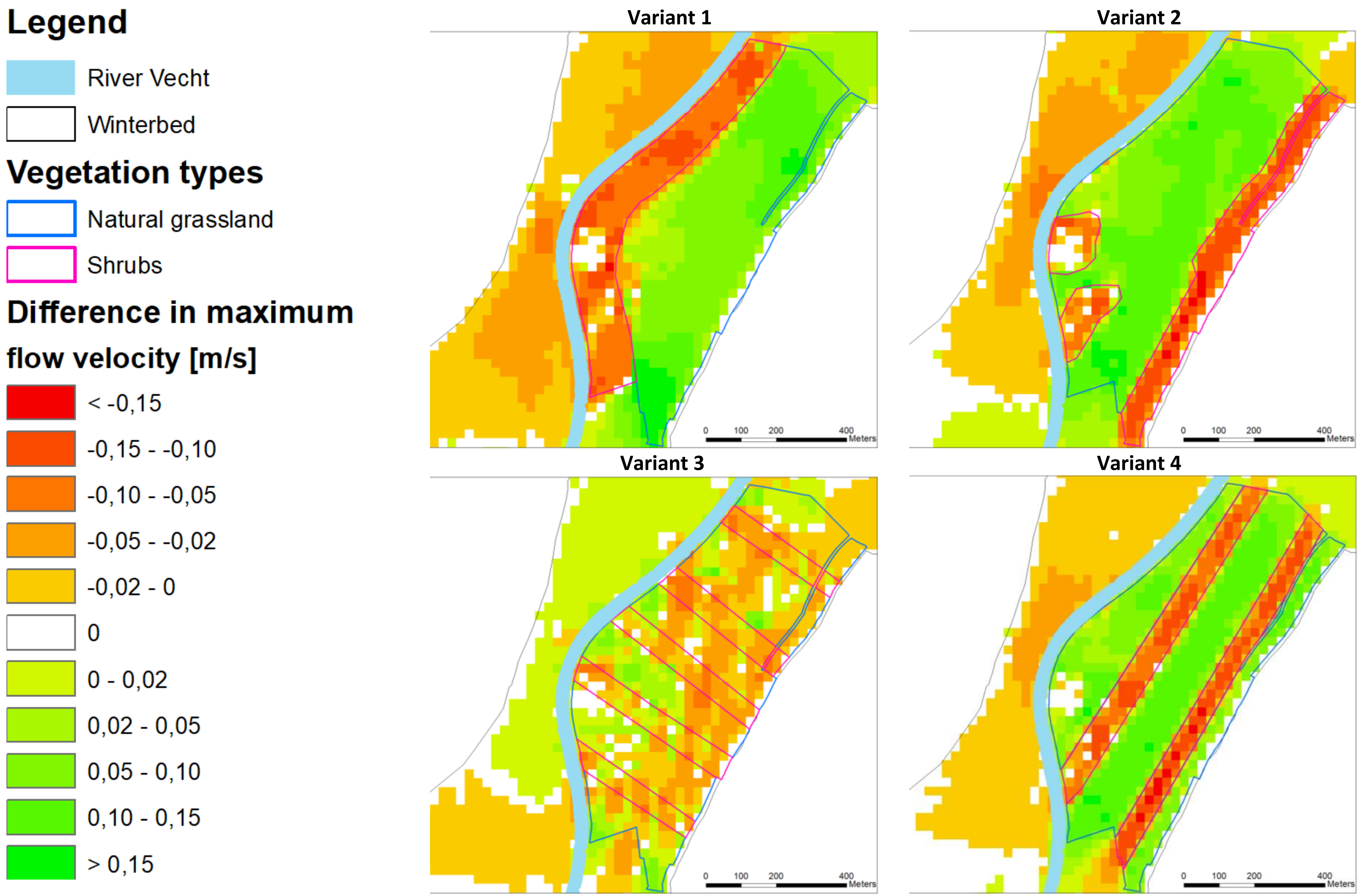

Figure 35. Difference in maximum flow velocity [m/s] for the different scenarios on the lot with mixing class 70/30 compared to the model run with the mixing classes.

6 Discussion

This chapter deals with the issues that should be taken into account by the interpretation of the results. Since this model is an alternative model for the existing hydraulic model of the River Vecht, both models will be compared. This discussion also includes the limitations, points of improvements and possible applications of this research.

6.1 Comparison with the existing hydraulic 1D SOBEK model

As described in the methodology, the 1D-2D model is created by removing the winter bed in the cross-sections of the 1D model and replacing it with a 2D grid. The two models therefore differ in two respects:

1. The schematisation of the flow of water through the floodplains. Because the water in the 1D-2D model flows through a 2D grid, more spatial information is included in the calculation of the hydraulic variables.
2. The coupling between the main channel and the floodplains. In the 1D model, the main channel and the winter bed are one entity (cross section), while in the 1D-2D model, the main channel and the winter bed are two separate, coupled, elements. Water will only flow in the 2D grid if the water level in the 1D summer bed is as high as the bottom level in the 2D grid.

The two models result different maximum water levels along the River Vecht. The 1D-2D model predicts structurally higher water levels than the 1D model (Figure 36). These differences in maximum water level varies between 15 and 50 cm.

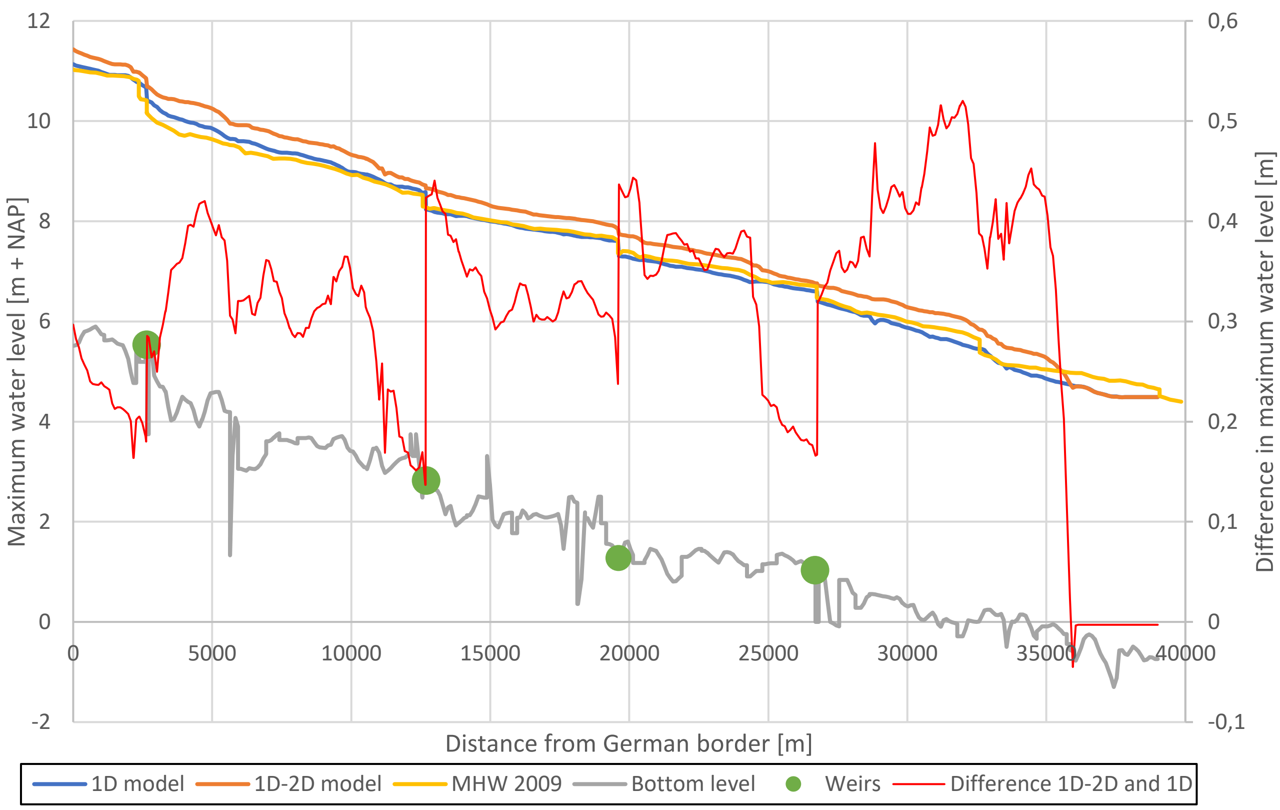

Figure 36. The normative high water levels and the maximum water levels along the River Vecht predicted by the 1D model and the 1D-2D model (T=200).

A reason for a higher maximum water level in the 1D-2D model is that there are storage areas present in the 2D grid, while the winter bed in the 1D model only contains flowing parts. Where the water in the 2D grid is not always discharged directly, this will happen in the 1D model. The 1D model therefore has a larger discharge capacity. This is in accordance to the study by Groot (2009). In this study a 1D-2D model and a 1D model of the River Regge were compared. Groot (2009) also explained this by the occurrence of storage areas in the 2D winter bed.

Another reason for the lower maximum water levels in the 1D model is the choice for roughness coefficient. In the 1D model, the roughness coefficients for the vegetation in the winter bed of Nikuradse roughness heights of 0.2 m (for the part of the winter bed near the river) and 0.31 m (for the outer part). However, when this is converted to a Chézy coefficient using the Strickler formula, these values are less rough than the Chézy values used for *production grassland* (k_s = 0.2 m) and *natural grassland* (k_s = 0.31 m). The winter bed in the 1D model therefore has a much lower roughness coefficient than the 2D grid, in which significant lower Chézy values occur. During the calibration these values gave the best fit, however during the T=200 event a larger discharge flows through the model, since both the 1D model as the 1D-2D model is calibrated with the T=10 event. Because more water flows through the winter bed, the winter bed roughness coefficient becomes more dominant. Given the difference in discharge capacity between the models, this results in a larger difference in maximum water levels.

Around the weirs, the difference in maximum water level between the 1D-2D model and the 1D model is suddenly increasing. A more realistic flow around the weirs can be seen in the 1D-2D model. Here, in case of high water, it is possible that water flows around the weirs in the 2D grid. Therefore, there are no large drops in the water level. In the 1D model, water cannot flow around the weirs. The jumps in the maximum water levels are caused by the high roughness of the weirs. The water levels around the weirs in the 1D-2D model are more realistic since in reality it is also possible that water flows around the weirs in case of high water. The 2D grid (25 × 25 m) seems fine enough to model this flow around the weirs.

It can be seen that from 34.5 km distance from the German border, the difference between the 1D-2D model and the 1D model starts decreasing rapidly. This is because of the transition from 1D-2D schematisation to 1D schematisation in the 1D-2D model, which starts at around 36 km from the German border. After the transition, lower water levels occur, because the discharge capacity of 1D schematisation is larger. From this transition point, the model schematisation are the same. In the trajectory from 34.5 km to 36 km, the water level in the 1D-2D model is decreasing because the water is adapting to the lower water levels in the 1D schematisation (backwater curve).

In literature, not often 1D-2D models are compared with 1D models. For this reason, it is hard to determine which model is performing better. The advantage of the 1D-2D model is that it contains more detailed spatial information. This should in principle lead to more accurate results. However, there is also more uncertainty in the spatial information. According to Betsholtz & Nordlöf (2017), 2D modelling have shown to better estimate flows in complex floodplains. In a 1D model, the frictional losses may be underestimated (Tayefi et al., 2007). Given the variation in roughness in the floodplains of the River Vecht, it is likely that the 1D model underestimates the hydraulic roughness thus the maximum water level during the T = 200 event.

Betsholtz & Nordlöf (2017) also state that the parameters that determine the coupling between the 1D and the 2D domain have a major impact on the results. However, it is not to be expected that this would be the case for this 1D-2D model, as there is no specific parameter. The 1D cross-section and the 2D grid are vertically linked, based on the water level in the cross section and the bottom height of the 2D grid at the locations of the calculation points.

Furthermore, it can be seen that the 1D-2D model structurally calculates higher water levels than the normative high water levels (Figure 36, MHW 2009, which is based on model runs with a different model); the 1D model does not. Although there is uncertainty in the modelled maximum water levels of the 1D-2D model, it seems better able to calculate the water levels during the T=200 event than the 1D model. This would mean that the current flood defences are not sufficient, as they are based on the normative high water levels.

6.2 Limitations of this research

During the various steps of the research, assumptions and choices were made and a limited amount of reliable data was used. This can influence the results obtained. This section discusses the limitations of this research and the impact of these limitations on the obtained results.

6.2.1 Vegetation classification

Different vegetation data sources with classified vegetation are used in this research. The methods to classify this vegetation contain inaccuracies. Knotter & Brus (2010) found an overall accuracy of 69% on an ecotopes map with similar vegetation classes as used in this study. Straatsma & Huthoff (2011) investigated the effect of these inaccuracies on the water level and defined three vegetation classification errors, namely:

1. A classification error, where the wrong ecotope class is assigned to an area.
2. Within class structural variation error, where there is natural variation in vegetation within a polygon, which is lost in the classification.
3. Scale error, where an error occurs because of the scale of the classification. If a smaller scale was chosen, a certain area would have been classified to a different class.

Straatsma & Huthoff (2011) used a two-dimensional hydrodynamic WAQUA model and found, for three distributaries of the River Rhine, variations in the water level of about 0.1 - 0.6 m for the *classification* error, 0.005 - 0.03 m for the *within class structural variation* error and 0.01 - 0.06 m for the *scale* error. The largest effects (mainly in the River IJssel, one of the three River Rhine distributaries) occur in parts of the river where a large fraction of the discharge flows through the floodplains. In the research of Straatsma & Huthoff (2011) a constant discharge of 16,000 m^3/s (T = 1250, of which fractions of approximately 2/3, 1/3 and 1/9 flow through the three distributaries) was used, which is considerably higher than the discharge of the River Vecht. Despite the scale difference, the results can give an indication of the effects of the uncertainty in vegetation data. Straatsma & Huthoff (2011) conclude that the *classification* error generates the largest error. However, this study has attempted to reduce this *classification error* by making adjustments to the ecotopes map.

The model runs with different vegetation data show differences in maximum water level. The differences between the model run with the LGN map and the other model runs can most likely be explained by the method of classification in the LGN map, namely by using the one dominant vegetation type per lot. As a result, the rougher, less common vegetation types disappear and a lower water level is to be expected, which also occurs compared to the other maps. The cause of the differences between the model runs with the ecotopes map and the satellite images is more difficult to explain. The deviation of the model run with the 2017 satellite image is so large compared to both the model run with the ecotopes map and the model run with the 2018 satellite image, that it seems that there are major errors in it. However, due to the low number of different data sources used in this study, this cannot be said with certainty.

The method used in the study to link a roughness value to vegetation classes is taken from the vegetation handbook (Van Velzen et al., 2003). This method is often used for vegetation in the floodplains of Dutch rivers (e.g. Makaske et al. (2011), Straatsma & Huthoff (2011) and Straatsma & Kleinhans (2018)). The current vegetation classes used by Rijkswaterstaat are also the result of combining handbook classes with the correct weighting factors (M. Schropp, personal communication, March 5, 2019). However, there are also other methods of assigning a roughness value to a vegetation class. Querner & Makaske (2012) compared the method of Van Velzen et al. (2003) with three other methods. They found, after recalibration of the main channel roughness, a lower discharge capacity of the entire cross section of the river (main channel + floodplains) when the method of Van Velzen et al.

(2003) was used. Compared to the other methods, the discharge capacity was 2% to 10% lower. Querner & Makaske (2012) conclude that there is not yet sufficient scientific certainty about the hydraulic roughness of floodplain vegetation, so no choice can yet be made between the various methods. Therefore there is no reason to state that the method of Van Velzen et al. (2003) is not appropriate, but it can be stated that this method calculates the lowest discharge capacity of the four methods that were investigated. In the context of this research, it can be said that the calculated maximum water levels would most likely be lower when other methods were used.

It follows from the results that the mixing classes, as defined in this study, lead to an overestimation of the water level. When the current vegetation in the floodplains of the River Vecht is divided into mixing classes, a considerable higher maximum water level is calculated compared to the reference model. The roughness value of most of the lots is overestimated because the roughness is calculated by rounding up the amount of rough vegetation and by using the most rough vegetation types. The scenarios studied do not show whether the formula used to calculate the roughness of a mixing class works, since in almost no case the exact amount of vegetation on the lot is used as input for the formula. In the event of a possible rearrangement of vegetation on a lot, the use of the current mixing classes will in most cases also lead to an overestimation of the water levels. The planned vegetation on a lot will often not come close to the vegetation used in the calculation of the mixing class.

6.2.2 Existing hydraulic 1D SOBEK 2 model

The existing hydraulic model, which is used in this study as the basis for the developed model, has a downstream boundary condition at the Vilsteren weir. The Vilsteren weir is the first weir located downstream of the area of R.W.A. Vechtstromen. The downstream boundary condition is a Q-h relation. The sensitivity analysis showed that the downstream part of the River Vecht in the hydraulic model is very sensitive to this boundary condition. Most results show that the difference in maximum water level between two scenarios decreases from 25 km downstream of the German border. This is due to the fact that the Q-h relation from there affects the water level and the water level will adapt to the water level in the 1D section that is determined by the Q-h relation. It makes the results less usable, as this adjustment does not occur in reality.

The Q-h relation is determined on the basis of measurement data and runs with models of the whole River Vecht (whereby the model does not end in Vilsteren). The Q-h relation is an average of all values. The measured and calculated values at the Vilsteren weir vary up to 20 cm. This is partly due to the phenomenon of hysteresis, which is not taken into account by the Q-h relation. This while increasing or decreasing the water level in the Q-h relation by 20 cm is clearly noticeable in the downstream part in the area of R.W.A. Vechtstromen, with differences in the maximum water level in the order of magnitude of 10 cm. For higher discharges, which have never occurred before and for which there are no measured water levels, the Q-h relation has been extrapolated.

Since the Q-h relation is located on the weir at Vilsteren, the weir operation has not been taken into account. In the case of the model run for the MHW 2009 (Figure 36), this operation is included and it is clearly visible that the model predicts a higher water level in the downstream section than the models with the Q-h relation on the Vilsteren weir.

The cross-sections in the last kilometres before the Vilsteren weir were manually adjusted and widened. This was done because otherwise instability would occur in the downstream section (J. van der Scheer, personal communication, 2019). This causes the Q-h relation to be more upstream (closer to the area of R.W.A. Vechtstromen) in practical terms, which means that the influence of the Q-h relation in the area of R.W.A. Vechtstromen is larger.

6.2.3 Developed hydraulic 1D-2D SOBEK 2 model

The method of using the 2D grid in this study to model the flow through the floodplains of the River Vecht has a couple of limitations. The decision to include only the floodplains in the area of R.W.A. Vechtstromen in the 2D grid leads to a transition from 1D-2D schematisation to 1D schematisation at the end of the area of R.W.A. Vechtstromen. The lower water levels in the 1D schematisation cause a significant drop in water level in the last kilometre of the 1D-2D part, as the water level adapts to the lower water levels. This makes the results in this section unreliable.

The 2D grid has a resolution of 25 × 25 m, while more detailed information, with a resolution of 5 × 5 m, is available. However, the use of this information with a higher resolution is not possible in this study, as the software crashes when a 2D grid of this size and resolution is used. In addition, it is expected that if the software would have been able to process such a grid, this would have increased the computation time drastically.

In SOBEK 2 it is only possible to use the Chézy-coefficient, the Manning-coefficient or the White-Colebrook formula in the 2D grid to calculate the hydraulic resistance (Deltares, 2013). The first two options are constant coefficients, while the hydraulic resistance depends on the water depth. A depth-dependent Chézy coefficient is calculated by the White-Colebrook formula, however a constant Nikurade coefficient must be used as input (Deltares, 2013), while this coefficient also depends on the depth (Van Velzen et al., 2003). In other words, in SOBEK 2 with the vegetation data used, it is not possible to use a depth-dependent hydraulic resistance. As an alternative, the hydraulic resistance at a representative water depth (1.5 m) is used. However, this leads to an underestimation of the hydraulic resistance at lower water depths and an overestimation at higher water depths for most vegetation classes..

A disadvantage of 1D-2D modelling in general is that the models easily become unstable if the water level in the 1D model exceeds the height of lateral structures (Betsholtz & Nordlöf, 2017). During the model making process this was also the case with this model; a side branch of the River Vecht was removed because there was visible instability in the water level and flow velocity at this location. It is likely that a smaller form of instability also occurs at other locations. The effect of this will not result in a significant difference in the water level, but it can cause small jumps in the water level.

6.2.4 Calibration and validation

The discharge events used for calibration and validation are theoretical events, based on discharge data collected in the period 1997 - 2015 (Van der Scheer, 2015). The model was then calibrated by varying the hydraulic resistance to approach as closely as possible the water level associated with the same return period as the event. The disadvantage of this method is that the water levels with which the model results are compared did not necessarily occur at the same time as the discharge occurred. In addition, there is a large margin of uncertainty in the discharge measurements, without much statistics, set at ±40% (Van der Scheer, 2015). Due to the uncertainty in the used data, there is also uncertainty whether the model has been properly calibrated.

The reason that this data is used for the calibration and validation is that there is almost no appropriate data available. The flood event of 1998 is often used for the River Vecht, but there is also a lot of uncertainty in the measurement data belonging to this event. The calibration method is the same as previously performed for the hydraulic 1D SOBEK 2 model.

There are also concerns about the measurement data in the water levels at the Junne weir. As mentioned earlier in the model set-up, the water level in these events seems to be deviating from the water levels at the measuring points around it (Mariënberg weir and Ommen). Taking into account that there are only five measuring points along the River Vecht that can be used for calibration, one measuring point at which the measured water level is uncertain can give a considerably distorted result.

During the winter bed calibration, the representative water depth is calibrated. However, the model was not sensitive to this within the chosen margins. This while the sensitivity analysis showed that the model results are actually sensitive to large changes in the winter bed. This shows that the representative water depth is not the best way to calibrate the winter bed.

6.3 Points for improvement

From the limitations in the previous section follow some points for improvement. Below, the most important challenges for better 1D-2D modelling of the flow through floodplains of the River Vecht are discussed.

6.3.1 Vegetation classification

A higher accuracy in vegetation classification will lead to a decrease in uncertainty. Increasing the classification accuracy to 95% reduces the uncertainty by almost 50% (Straatsma et al., 2013). A first step can be taken by performing model runs with satellite images of other moments. This will make more clear what the variation is between different satellite images. Furthermore, the classification methods will have to be evaluated in order to investigate how they can be improved.

Other methods to link a roughness value to a vegetation class, such as the three alternative methods proposed by Querner & Makaske (2012), can be investigated in order to obtain more insight into the variations that occur with the different methods to determine the roughness value of a vegetation class. The use of the vegetation handbook (Van Velzen et al., 2003) plays a major role in this research and it is therefore of great importance to know whether these data leads to an overestimation of the water level or not.

6.3.2 Hydraulic 1D-2D model

Adjustments have to be made to the hydraulic 1D-2D SOBEK 2 model, or a new model has to be built. The downstream boundary condition in the current schematisation is located too close to the area of interest and therefore has a large impact on the water level. By extending the model, the downstream boundary condition is located further away from the area of R.W.A. Vechtstromen. This has the additional advantage that the operation of the weir at Vilsteren can be taken into account. It is advisable to extend the model to the next weir, namely the weir at Vechterweerd. The distance from this weir to the end point of the area of R.W.A. Vechtstromen is larger than the distance over which the Q-h relation in the current model has an effect.

Furthermore, it is necessary to extend the 2D grid in downstream direction, so that there is no adjustment in water level within the area of R.W.A. Vechtstromen due to the transition from 1D-2D schematisation to 1D schematisation. This adjustment takes place over a shorter distance than the adjustment to the downstream boundary condition, so it is not necessary to extend the 2D grid to the end point of the model. However, it is recommended that the 2D grid be extended well beyond the area of R.W.A. Vechtstromen.

6.3.3 Calibration and validation

In order to better calibrate the model, it is necessary to have reliable data of a flood event, so that there is no need to use a theoretical event. It is a challenge to improve the measuring points along the River Vecht so that discharge and water level measurements can be measured with a higher accuracy at a future high water event. If the measurement data improves, this can reduce the uncertainty because the discharge and water levels occur at the same time, because the accuracy margin on the discharge data decreases and because the water level data at the measurement point on the Junne weir are more accurate.

In addition, it is advisable not to calibrate the winter bed by adjusting the representative water depth, since the model showed insensitive to this. Instead, it is better not to calibrate the floodplain roughness at all, since the roughness is based on data that have been the subject of much research.

6.4 Potential of this research

This study shows that it is possible to use a hydraulic 1D-2D model for the River Vecht to observe the effect of the vegetation in the floodplains of the River Vecht on the water level. This research also shows where bottlenecks can occur in the winter bed of a river when vegetation is becoming rougher, namely in the narrower sections of the winter bed. Furthermore, this study shows that the blocking effect of vegetation causes an increase in the water level and that a sufficiently wide flow paths will have a positive effect on the discharge capacity.

Makaske et al. (2011) investigated different stages in vegetation development on the reach scale of a lowland river. A similar method for converting observed vegetation into a hydraulic resistance is used in the study by Makaske et al. (2011). They found that water levels are more sensitive to an increase in hydraulic roughness in narrow sections. This leads to critical situations with backwater effects that raise high water levels far upstream of the narrow sections. This is in accordance with the observations in scenario 1, which showed that the largest differences in maximum water level occur in the narrower sections of the winter bed.

Luhar & Nepf (2013) showed that a decrease in vegetation resistance and channel blockage, defined as the fraction of a cross-section occupied by vegetation, can result in a reduction in hydraulic resistance and an increase in flow velocity. This is in line with the results of this study, where an increase in the blocking effect of vegetation, similar to the channel blockage in the study of Luhar & Nepf (2013), results in a decrease in flow velocity and an increase in the water level. Furthermore, Luhar & Nepf (2013) found that the same amount of vegetation divided into small patches provides a greater reduction in flow velocity than large continuous blocks of vegetation. This is also in line with the results of this research, since it was found that a wide flow path ensures a lower water level than several narrower flow paths. Bal et al. (2011) investigated similar scenarios and found a significant difference between a scenario with a wide current stream and a scenario with a narrow current stream, in which the latter had a higher hydraulic resistance.

The observed effects of different vegetation distributions are similar to results found in literature. The used approach in this research seems to be a suitable method to monitor the changes in vegetation in the floodplains of the River Vecht and to determine their effects on the water level. This method can also be useful for future studies of vegetation in the floodplains of the River Vecht.

For example, the model can be used to investigate different phases of vegetation development, so that the effects of spontaneous vegetation development on the water level can be investigated. Based on this, it can be determined up to what point freedom can be given to nature and when action must be taken from the safety point of view. These results can contribute to the management decision making process concerning the permitted vegetation in the floodplains. Furthermore, this approach can be used to calculate the effect of (planned) vegetation changes.

Additional research on the mixing classes can also be done using this model. For example, the effect of 'custom-made' mixing classes can be investigated. The roughness of a mixing class can be determined on the basis of the desired percentages of vegetation on a lot. This has the advantage that freedom is still offered to the owners of the lot, but the roughness is not greatly overestimated because a limited number of mixing classes is available.

7 Conclusions

In order to meet the demand of Regional Water Authority Vechtstromen for a hydraulic model capable of calculating the effects of vegetation in the floodplains of the River Vecht, an existing hydraulic 1D SOBEK 2 model has been extended to a 1D-2D model in this study. In the 2D grid, the spatial variation of vegetation along the River Vecht can be taken into account. Vegetation is divided into classes that are determined on the basis of the vegetation in the floodplains within area of R.W.A. Vechtstromen. The model has been calibrated and validated using available events. Five research questions have been formulated to achieve the research goal. Based on the results and the discussion, conclusions can be made to answer the research questions.

7.1 Sensitivity of the model

To what extent is the 1D-2D model valuable as a tool for Regional Water Authority Vechtstromen regarding the sensitivity of the results to uncertain parameters?

The sensitivity analysis shows that the model is sensitive to both the roughness of the main channel and the roughness of the winter bed. In general, a change in the roughness of the main channel has more effect on the water level than a change in the roughness of the winter bed. Unless it concerns an extreme roughening (-40%) of the winter bed, then the model appears to be a lot more sensitive to the winter bed roughness. In case of an extreme roughness of the main channel or the winter bed, the increase of the water level is in the order of 30-32 cm. The sensitivity of the model to winter bed roughness means that it is to be expected that significant differences will occur between the different scenarios.

In general, it can be said that the model is the most sensitive to the upstream boundary condition, however, in the downstream part of the River Vecht (from 25 kilometres from the German border) the Q-h relation has a larger effect. The sensitivity to the upstream boundary condition is not surprising, as this condition determines the amount of water flowing through the model. However, the sensitivity to the Q-h relation is undesirable, as this condition has no impact in reality, but strongly influences the results in the model. The differences between scenarios decrease from 25 km downstream of the German border, because the water level adapts to the water level imposed by the Q-h relation. In order to solve this problem, it is necessary to place the downstream boundary condition further downstream.

Due to the influence of the Q-h relation, the results of the model in the downstream part (from 25 km from the German border) are not reliable. In the upstream part, the influence of the Q-h relationship is hardly noticeable and the results are more reliable.

7.2 Extreme vegetation scenarios

What is the effect of extreme vegetation scenarios on the water levels along the River Vecht?

The bandwidth in calculated maximum water levels along the River Vecht varies around 1 meter. Results will not fall outside this bandwidth, as the extremes of this bandwidth are determined by the roughest and smoothest scenario. The current situation in the winter bed of the River Vecht is much closer to the smooth scenario than to the rough scenario, in other words, the winter bed of the River Vecht is relatively smooth. By roughening the winter bed, the discharge wave can be considerably delayed, in the rough scenario the top of the discharge wave arrives 21 hours later at the end of the area of R.W.A. Vechtstromen.

The difference in maximum flow velocity varies greatly from location to location. Bottlenecks occur in the narrower parts of the winter bed, the difference in the maximum flow velocity is much higher here. Storage areas in the floodplains can become flowing areas when the water level rises, which happens when the vegetation becomes rougher. This shows that storage areas of the winter bed are dynamic, depending on the roughness in the entire winter bed.

7.3 Vegetation data sources

To what extent are the available vegetation data sources valuable to describe vegetation situation in the winter bed of the River Vecht?

Since the LGN map uses the dominant vegetation type on a lot, the two roughest classes, *reed* and *shrubs*, do not occur in the floodplains of the River Vecht. The resolution of this map is also much lower due to the use of one vegetation class per lot. Compared to the ecotopes map, a structurally lower water level is calculated (between 4 and 8 cm), which can be explained by the fact that rougher vegetation types are often less dominantly present and therefore disappear in this data source.

The results of the model runs with the satellite images differ both from each other and from the reference model with the ecotopes map. Of all three, the satellite image of 2017 differs the most. The satellite images calculate differences in maximum water level between 3 and 12 cm, the differences between the model run with the satellite image of 2017 and the model run with the ecotopes map fluctuates between 4 and 14 cm. The differences between the model run with the satellite image from 2018 and the model run with the ecotopes map are clearly smaller, with deviations between 0 and 4 cm. Due to the limited number of data sources, it is not easy to say what the cause of the large deviations is. It was found in literature that there is often a low accuracy (69%) in classification methods. Other causes could be the difference in classification methods (ecotopes map versus satellite images) and the period of the year in which the data was collected.

Based on the method of classification, the LGN map does not seem to be valuable to use for this purpose. On this basis, the ecotopes map and the satellite images appear to be more valuable, while the satellite images have the advantage that they are produced at a much higher frequency. However, this method is still relatively new and, moreover, satellite images themselves appear to differ from each other at the moment. The ecotopes map therefore seems to be the best alternative at the moment. Improving the accuracy and more research into the use of both sources is, however, necessary to provide a better argumentation.

7.4 Mixing classes

To what extent are mixing classes valuable as a method to determine the permissible amounts of vegetation on lots?

The mixing classes as defined in this study result in a strong overestimation of the water level. The worst-case calculation of the water level is an accumulation of safety margins, because the amount of rough vegetation is rounded up and the most rough vegetation species are used in the calculation of the roughness. In addition, the uniform, low roughness of a lot may result in less effective flow paths.

However, when the definitions of the mixing classes are adapted, it is a good method for the water board to give the owners of lots the freedom to manage the lot. The degree of adaptation depends on the desired safety margin.

It should be taken into account that the processes on a lot that occur due to the variation in vegetation on a lot are no longer visible, because a single roughness value is used. This method is therefore only useful if one is interested in the spatial variation in vegetation on a river scale, not if one is interested in the spatial variation in vegetation on a lot scale.

7.5 Vegetation distribution scenarios

What is the effect of different vegetation distribution scenarios on the water levels along the River Vecht?

There are two aspects of the location of the rough vegetation that have a clear influence on the maximum water level: the blocking effect and the amount of space left for flow paths. When rough vegetation strongly blocks the flow, the maximum water level rises rapidly. The maximum water level can be lowered by creating wide flow paths. Vegetation in the banks does not cause the maximum water level to rise strongly, as long as there is room for flow behind the river bank vegetation. If this is not the case and the vegetation on the river banks blocks the flow, the maximum water level will rise. Finally, it must be taken into account that the combined effect of several changes has a different effect than when the changes are calculated separately from each other.

The results found in this study correspond to previous studies. The model seems to be able to properly calculate the effects of floodplain vegetation on hydraulic variables. In addition, the aforementioned effects can be taken into account in the future design of lots in the winter bed of the Vecht River.

7.6 General conclusion

The research objective in this thesis was *to investigate the possibility of using a hydraulic 1D-2D SOBEK 2 model for the calculation of the water levels along the River Vecht and to support the management decisions process regarding vegetation in the floodplains*. The hydraulic 1D-2D SOBEK 2 model seems capable of determining the effects of vegetation in the winter bed on the water levels, however the calculated water levels contain some uncertainties. This makes the used method in this research to seem appropriate, with the challenge of reducing the uncertainty in the various data sources that were used.

8 Recommendations

Based on the conclusions that have been formulated, a number of recommendations can be made. A distinction is made between recommendations for further research and recommendations for the Regional Water Authority Vechtstromen. The recommendations for further research are aimed at improving the modelling of the effect of flood vegetation on the water level. For R.W.A. Vechtstromen, the recommendations focus on the developed model and the organisation of the floodplain areas.

8.1 Recommendations for further research

During this research, uncertain data was used. Uncertainty in data used as input for a model also means uncertainty in the results of a model. For this reason, it is important to reduce this uncertainty. Based on this research, the following recommendations can be made:

1. At the moment, the accuracy of classification methods is low. As a result, the type of vegetation is not always observed correctly. This can lead to considerable differences in the water level. If this inaccuracy in classification methods is reduced, the water level can be predicted more accurately and the effect of vegetation distributions can be better estimated.
2. There are several methods by which a roughness-value can be linked to a vegetation type. When using these different methods, clear differences in discharge capacity are calculated. Further research into these methods can provide clarity about the usability of the methods and reduce the uncertainty in the water level.
3. There is little literature to be found in which the comparison between a hydraulic 1D model and a hydraulic 1D-2D is made. In this study a clear difference in the calculated water levels was found. It is unclear whether this is due to the different way of schematising, or because there are errors in the schematisations of one or both models. More clarity about the cause of the differences between the two types of schematisation can contribute to the successful expansion of 1D models to 1D-2D models.

8.2 Recommendations for Regional Water Authority Vechtstromen

Based on this research, various recommendations can be made for R.W.A. Vechtstromen:

1. It is recommended to do more runs with other satellite images. On this basis, it can be determined whether the deviation of the satellite image of 2017 from the other satellite image and the ecotopes map is an exception, or whether these variations occur more frequently. A margin of uncertainty can also be determined on the basis of the differences that often occur between the various satellite images. Ultimately, more can be said about the usability of satellite images in the context of this study.
2. It is advisable to adjust the mixing classes in relation to the mixing classes used in this study. The current mixing classes often result in a large overestimation of the water level. If this overestimation were smaller, it could still be used as a safety margin. The method described in the vegetation handbook (Van Velzen et al., 2003) can easily be used to calculate a roughness value on the basis of the planned percentages of vegetation on the lot, which can then be used in the model to calculate the water levels, while the owner of the lot has the freedom to set up the lot freely (within the framework of the agreed percentages of vegetation). The combination with a high accuracy of the classification based on satellite images would be very useful. For example, new agreements can be made with the owners of the lots about permitted vegetation and distribution of the vegetation over a lot, expressed in

a mixing class, and from time to time the satellite images can be used to check whether the situation in the floodplains still meets the safety standards.

3. For more reliable results, the model should be extended. The downstream boundary condition should be further downstream, at least at the weir at Vechterweerd. Also the operation of the Vilsteren weir has to be implemented in the model. In addition, it is advisable to let the 2D grid continue a little further, so that the transition from 1D-2D schematisation to 1D schematisation is outside the area of interest (the area of R.W.A. Vechtstromen). Another option is to switch to a 2D model. A 2D model for the entire River Vecht in the Netherlands is currently being developed, which could be a good option for conducting research into the effects of flood vegetation on water levels.
4. To improve the calibration of the model, it is recommended to improve the quality of the discharge data and water level data. It is recommended to choose an event where a reliable discharge wave and reliable water level measurement points are available. In order to better measure a future event, it is advisable to investigate whether the current measuring equipment are functioning properly.
5. In the future, it is recommended that the model is no longer calibrated by adjusting the representative water depth parameter. The model does not appear to be very sensitive to this parameter.
6. With regard to the design of the floodplains, it is advisable not to allow vegetation perpendicular to the direction of the flow, as the blocking effect of vegetation appears to be dominant. In addition, it is recommended to maintain or create flow paths, as this increases the discharge capacity.
7. A similar method as the method used by Makaske et al. (2011) can be useful to determine the permitted development of vegetation based on succession stages. This gives the owners of the lots clarity as to when they can give nature freedom and when interventions are needed.
8. Since the 1D model that is currently in use by R.W.A. Vechtstromen is calibrated in the same way and the same Q-h relation is used as downstream boundary condition, it is also advisable to evaluate this model.

9 References

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Ecotopes map, LGN map, Cadastral data map , SNL map are adapted from Waterschap Vechtstromen. (n.d.). Using ArcGIS.

Satellite images are derived/adapted/verzin een woord from Deltares. (December 20, 2018). Using ArcGIS.

Appendix

Appendix 1: Adjustments to the ecotopes map

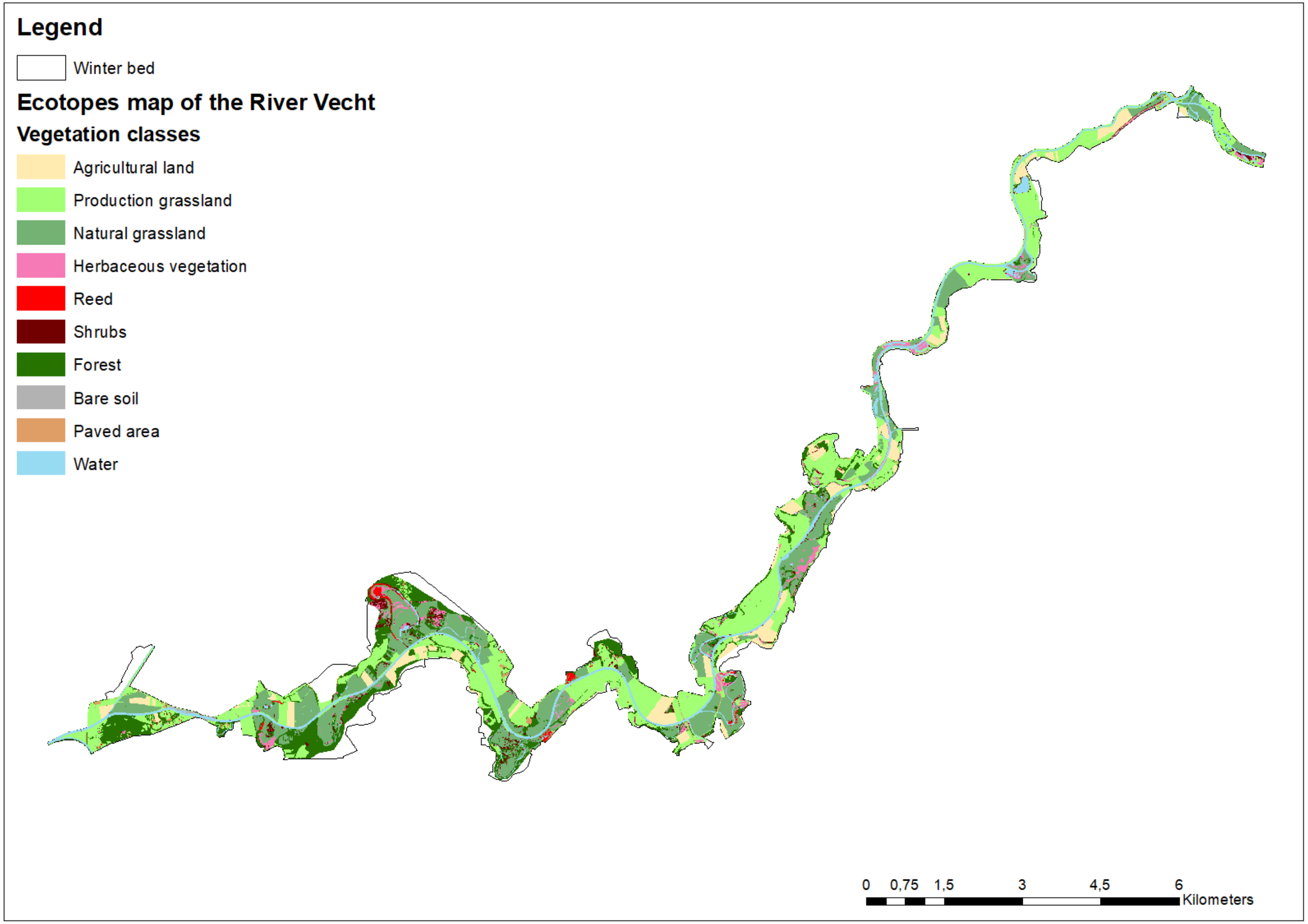

Figure 37. Original ecotopes map classified in homogeneous vegetation classes.

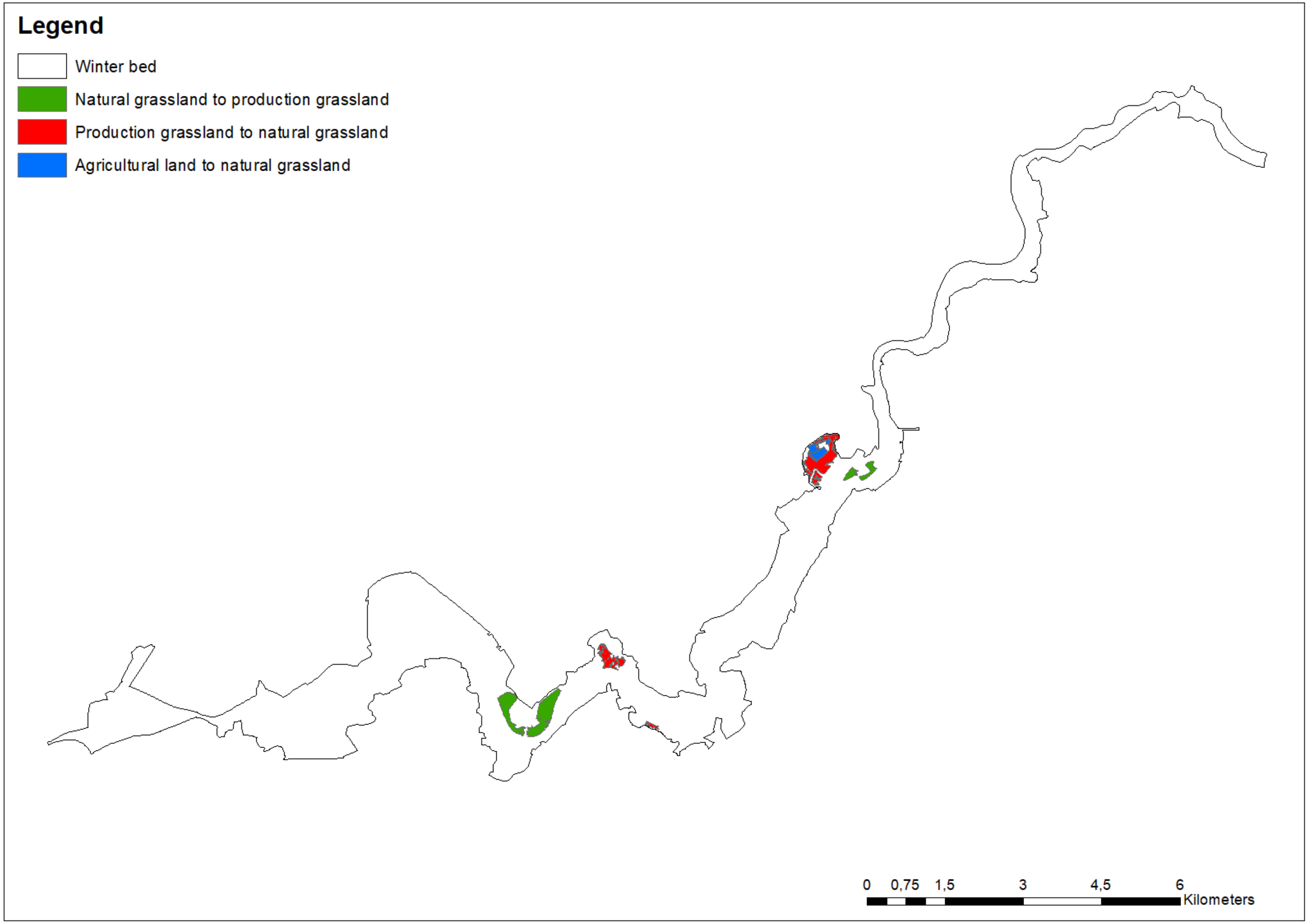

Figure 38. Adjustments to the ecotopes map.

Appendix 2: Determination of vegetation classes

Homogenous vegetation classes

An ecotopes map of the winter bed of the River Vecht based on the situation in 2017 is available. On this ecotopes map, 53 different homogenous classes can be distinguished, of which in total 36 classes contain vegetation. Some of these classes contain the same vegetation type and are only distinguished based on their location in the winter bed. Since the location of vegetation is not directly related to the roughness, the classes with the same vegetation are combined. This results in twelve new classes: *production grassland, natural grassland, pioneer vegetation, field, herbaceous vegetation (*Dutch*: ruigte), reed, low trunk tree orchard, standard tree orchard, production forest, hardwood riparian forest, softwood riparian forest and shrubs.* These classes all contain unique vegetation types. However, some of these vegetation types have similar roughness characteristics or are not common in the winter bed of the River Vecht. Therefore, all of the classes will be analysed on these two criteria, in order to see whether the classes can be combined with others or not.

Looking at the total area of the vegetation types (Figure 39) it can be seen that the most common vegetation types in the winter bed of the River Vecht are *production grassland* (36,52%) and *natural grassland* (24,46%). Next to this, *hardwood riparian forest* (13,46%) and *agricultural land* (8,26%) are common. It can also be seen that there are three non-vegetation classes (*water, bare soil and cultivated area)*, of which *water* (8,98%) is quite common, are present. These classes will be used to describe the location where there is no vegetation present.

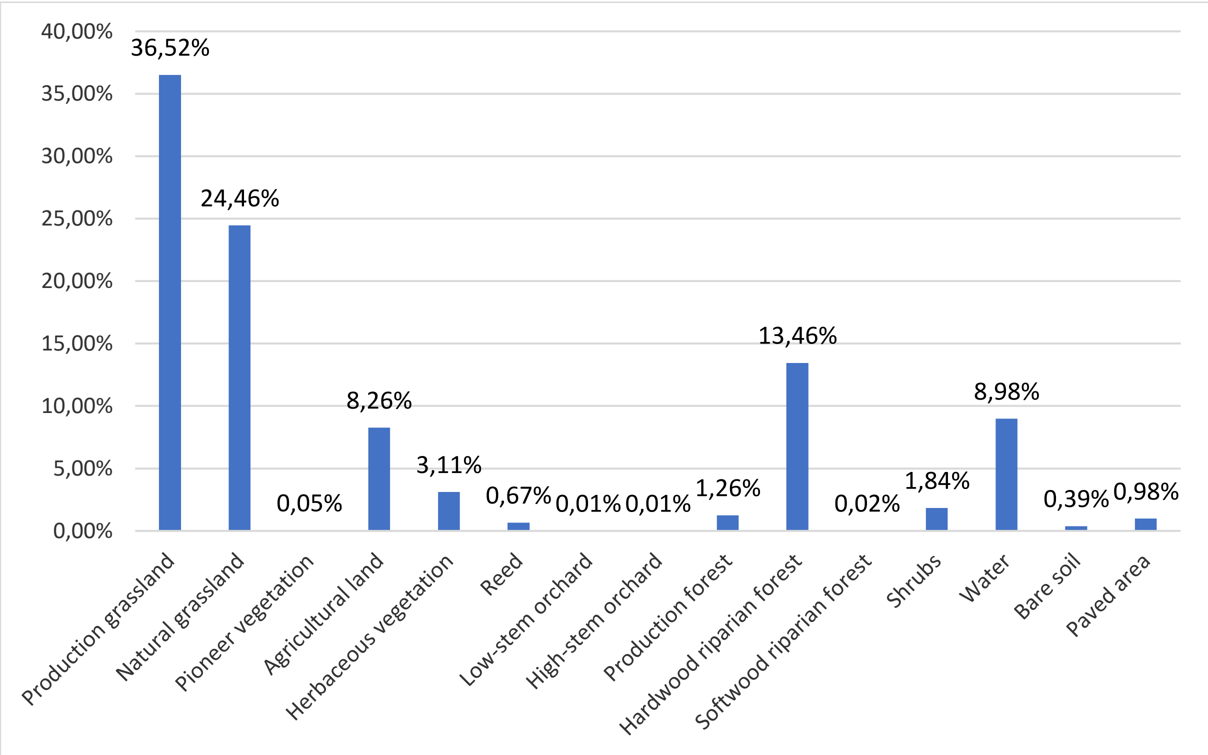

Figure 39. The area of the different vegetation types as a percentage of the winter bed of the River Vecht. The first twelve classes are vegetation classes, the last three classes are non-vegetation classes.

Production grassland and *natural grassland* have similar roughness curves (Figure 40), however the Chézy value of *natural grassland* is somewhat lower than the Chézy value of *production grassland.* Since these two vegetation types are the most common vegetation types in the area of the River Vecht and there are some differences in the roughness values at different water depths, *production grassland* and *natural grassland* will remain as two separate classes. The roughness curve for *pioneer vegetation*

(Figure 40) is very similar to the roughness curve of *production grassland*, except for very low (<0,2 m) water depths. Since *pioneer vegetation* is only 0,05% of the total area, it will be added to the *Production grassland* class. The class *agricultural land* will remain as a separate class, because the roughness of this class differs strongly over the seasons. During the winter, when high water is most likely to occur, often little vegetation is present on agricultural lands. The roughness can then be described using a Nikuradse roughness height of 0,2 m.

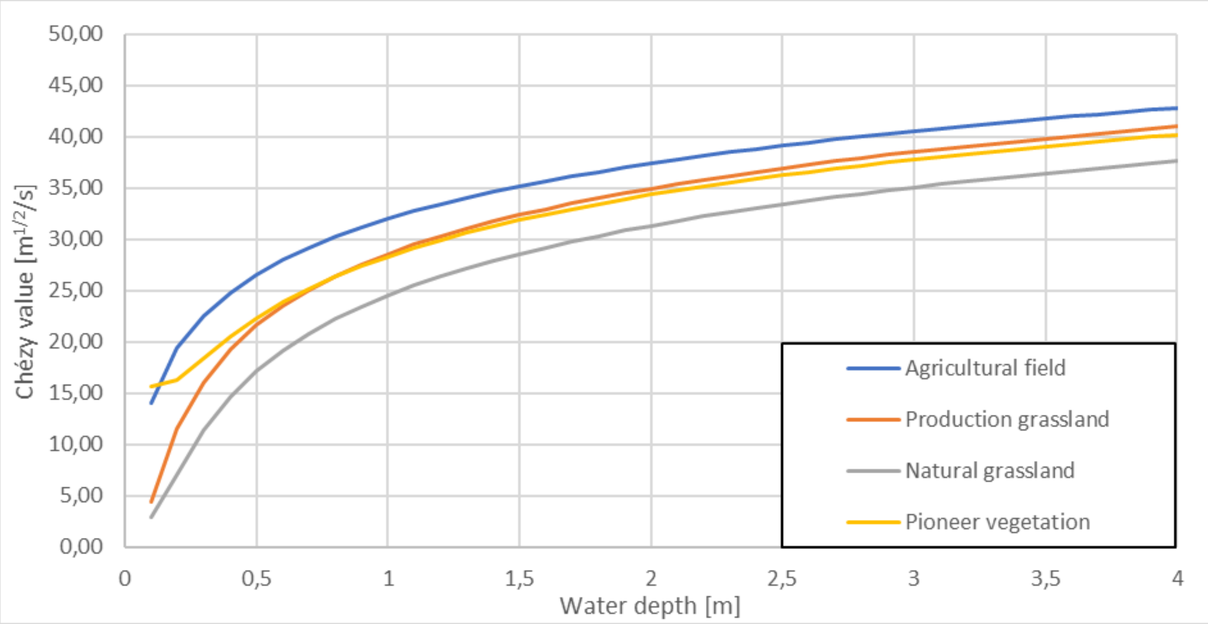

Figure 40. The Chézy values at different water depths for agricultural land, production grassland, natural grassland and pioneer vegetation.

Herbaceous vegetation (3,11%) and *reed* (0,67%) are two relatively small classes in the winter bed of the River Vecht. Based on these percentages, it would make sense to add them to other classes or combine them. On the other hand, the roughness curves for *herbaceous vegetation* and *reed* are totally different from other classes, including each other (Figure 41). Locally, this can strongly influence the water depth. For this reason, the classes *herbaceous vegetation* and *reed* will remain as separate classes.

Shrubs are not very common in the winter bed of the River Vecht as well, however its roughness curve (**Fout! Verwijzingsbron niet gevonden.**) is not similar to other vegetation classes. Of all vegetation classes, the class *shrubs* has the highest roughness. Where there is vegetation of this class present, it can strongly influence the water level. This class will therefore not be combined with other classes and remain separate.

In the winter bed of the River Vecht, 14,76% of the total area belongs to the vegetation classes with a certain type of trees. The largest of these classes is the *hardwood riparian forest* class, with 13,46% of the total area (Figure 36). The roughness curve of *hardwood riparian forest* shows a peak between a water depth of 0,5 to 1 meter, with a Chézy value of 18,5 $m^{1/2}/s$ (Figure 42). The classes *softwood riparian forest, production forest* and *standard tree orchard* have similar roughness curves, with different peak values. The Chézy values at different water depths for *softwood riparian forest* are lower, while for *production forest* and *standard tree orchard* the Chézy values are higher (Figure 42). For all three classes, it holds that they are very uncommon in the area of the River Vecht. Considering the rarity of these classes and the similar roughness curves, it has been decided to add *softwood riparian forest*, *production forest* and *standard tree orchard* to the *hardwood riparian forest* class. The last class with trees, *low trunk tree orchard*, is very uncommon (0,01% of the total area). The roughness curve (Figure 42) of this class is different for larger water depths (>3 meter), for smaller water depths it is similar to the other classes with trees. However, in the floodplains, larger water depths will not often occur. Therefore, the *low trunk tree orchard* class will be added to the *hardwood riparian forest* class, resulting in one class for all types of trees: *forest* (Figure 42). The roughness curve is calculated based on the roughness curves of the different types of forest and the percentage of occurrence in the winter bed of the River Vecht.

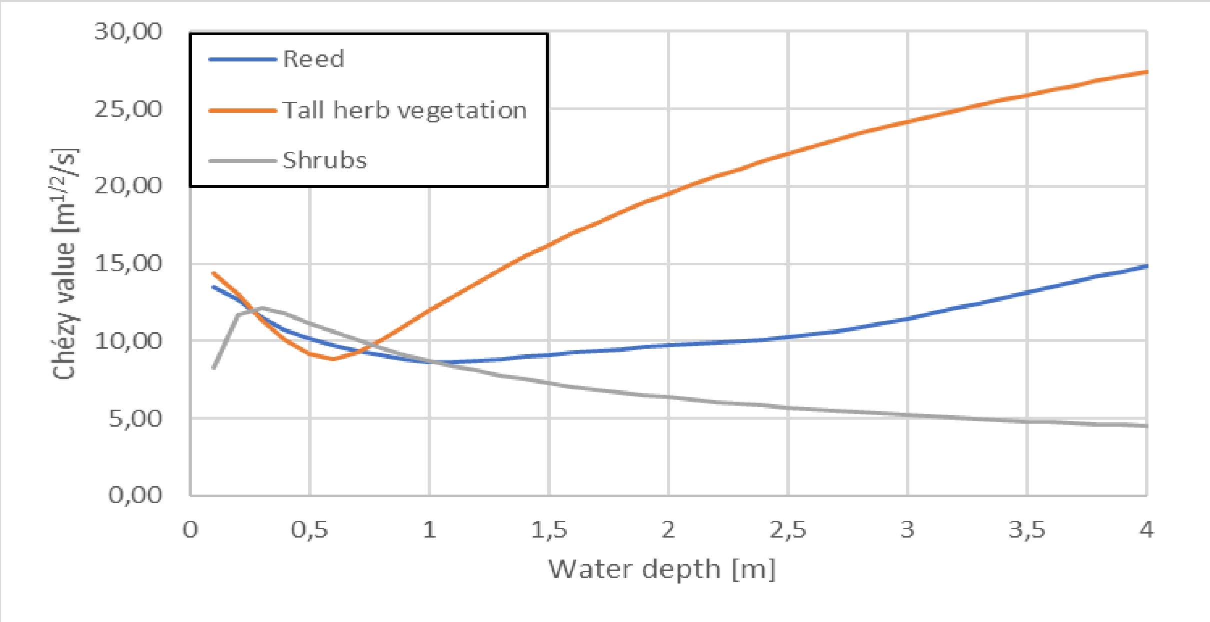

Figure 41. The Chézy values at different water depths for herbaceous vegetation, reed and shrubs.

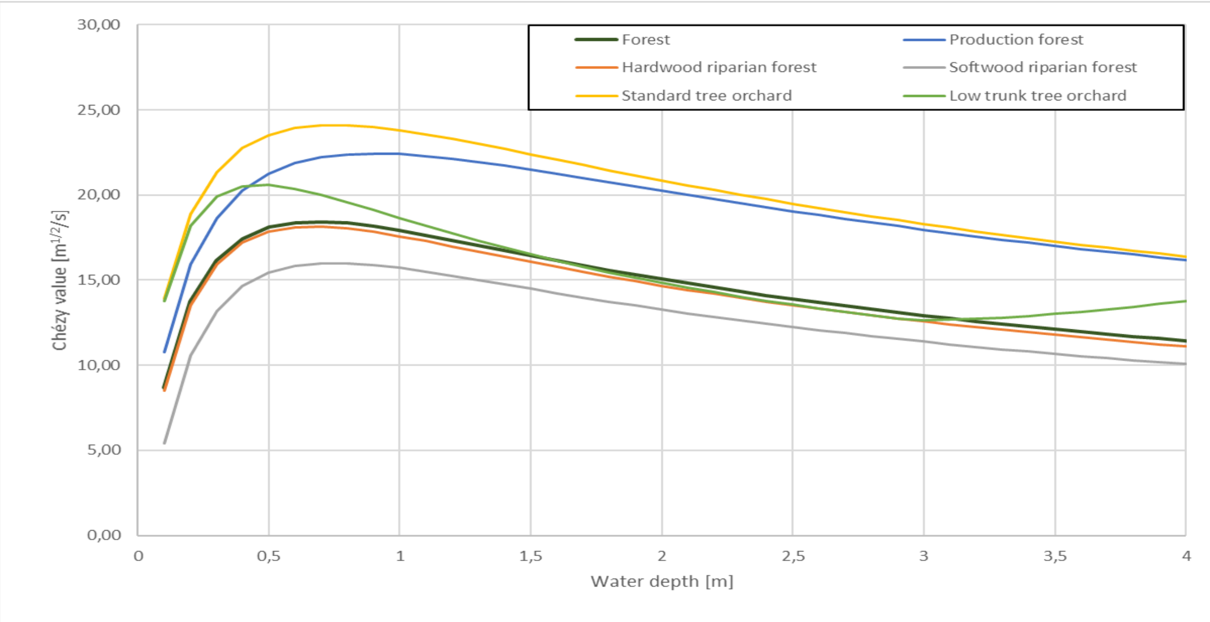

Figure 42. The Chézy values at different water depths for different types of forest.

Altogether this results in seven homogenous vegetation classes: *production grass, natural grass, agricultural land, herbaceous vegetation, reed, shrubs* and *forest.*

Mixing classes

When an area is assigned a homogeneous vegetation class, only this type of vegetation can occur in the area. However, in practice, it will regularly occur that more than one vegetation species occurs in a certain management area. The roughness-value of an area is then a combination of the roughness-values that belong to the occurring vegetation species in the area. A solution for this is the so-called mixing classes. Mixing classes are vegetation classes with several vegetation species and a corresponding roughness-vales based on these vegetation species. This means that managers of an area are free to set up the area themselves, within the margins of the mixing class assigned to an area, and for the hydraulic model, the combined roughness-value can be used.

Cadastral lots

Within the winter bed of the Overijsselse Vecht are 868 cadastral lots, varying in size. In order to determine which mixing classes are suitable for the Overijsselse Vecht, the vegetation on these lots was analysed. For each (homogenous) vegetation species, the frequency with which this species occurs on cadastral lots was examined; this can be seen in Table 9.

Table 9. Per vegetation species the number of times that this species occurs in a certain percentage on cadastral lots.

Vegetatiesoort	<10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%	70-80%	80-90%	>90%
Akker	*98*	13	7	0	9	3	7	6	10	36
Bos	*250*	73	37	28	21	17	16	11	18	103
Natuurlijk grasland	*76*	6	7	5	6	8	12	12	19	35
Productiegrasland	*138*	36	23	31	25	29	44	35	43	276
Riet	*37*	2	1	1	0	1	0	0	0	0
Ruigte	*133*	11	4	3	2	0	2	0	1	2
Struweel	*185*	14	6	2	0	0	0	1	1	1

In order to obtain this table, a shapefile with polygons had to be converted into a raster-dataset. The grid was then compared with the cadastral lots, which is a shapefile with polygons. It often happens that at the edge of a cadastral lot a small percentage of a certain type of vegetation occurs. This is an inaccuracy due to the conversion of the polygons into a grid. The numbers in the column '<10%' will in reality be much lower.

The vegetation classes *agricultural land*, *forest* and *production grassland* occur relatively often with high percentages. The classes *herbaceous vegetation*, *reed* and *shrubs*, on the other hand, often occur with lower percentages, while these vegetation species above 30% rarely occur. It therefore seems logical to use these classes in mixing classes.

SNL types

In the winter bed of the Overijsselse Vecht there are many nature reserves. In addition to the cadastral lots, the SNL types that occur in the winter bed of the River Vecht have also been studied. By mapping how often the SNL types occur, logical combinations of vegetation species for mixed classes can be determined. Figure 43 shows the distribution of the SNL types over the winter bed of the Overijsselse Vecht. The SNL dataset contains data for 93.2% of the total area of the winter bed of the Overijsselse Vecht, for the remaining 6.8% no data is available.

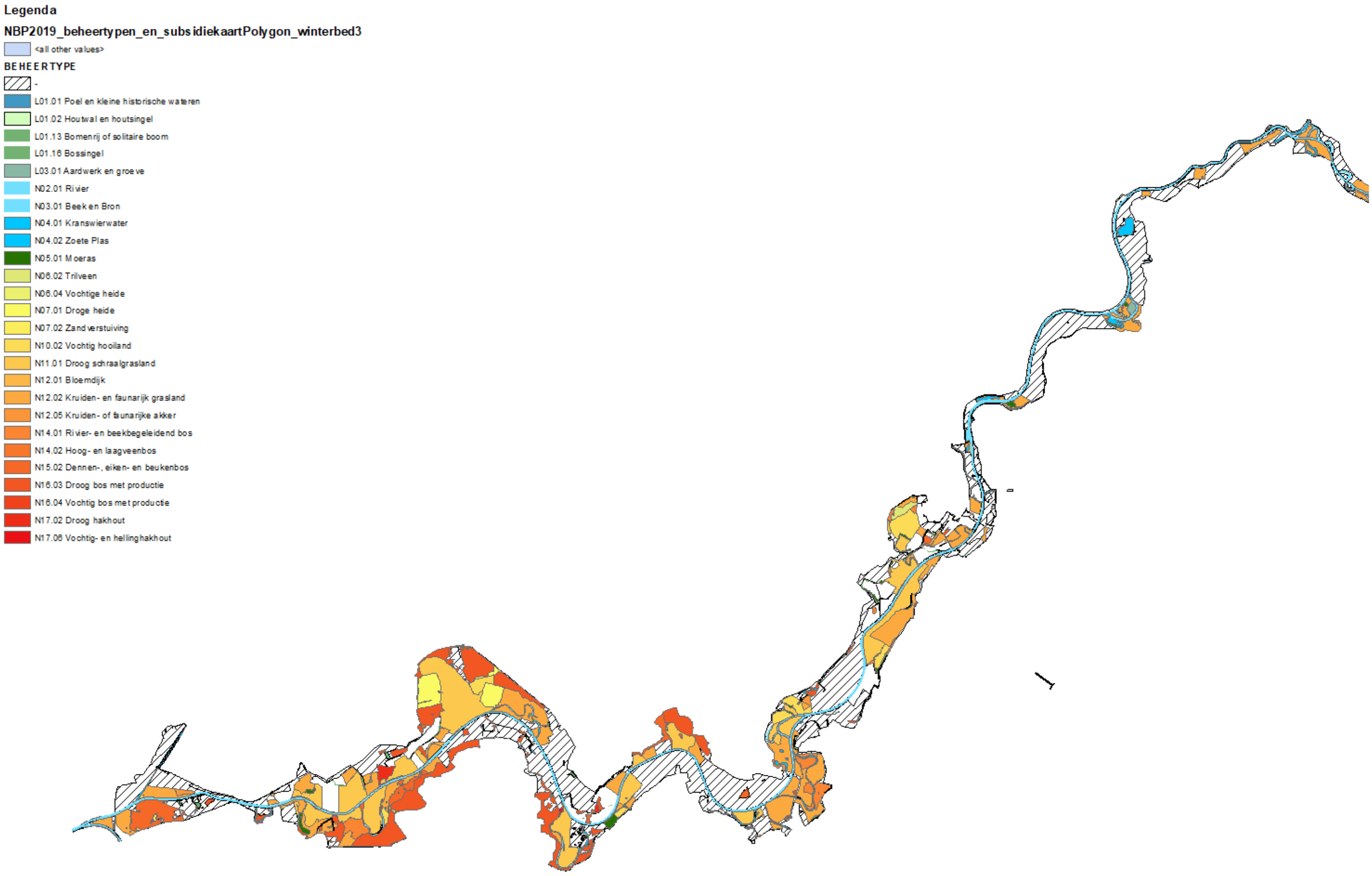

Figure 43. SNL types in the winter bed of the River Vecht.

The striped areas in Figure 43 indicate search areas. These are areas for which a subsidy can be applied for, but to which no management type is linked yet. Figure 2 shows the percentage of the total area of the winter bed per SNL management type. The search areas represent the remaining 42.3% of the total surface area of the Overijsselse Vecht (omitted in Figure 2).

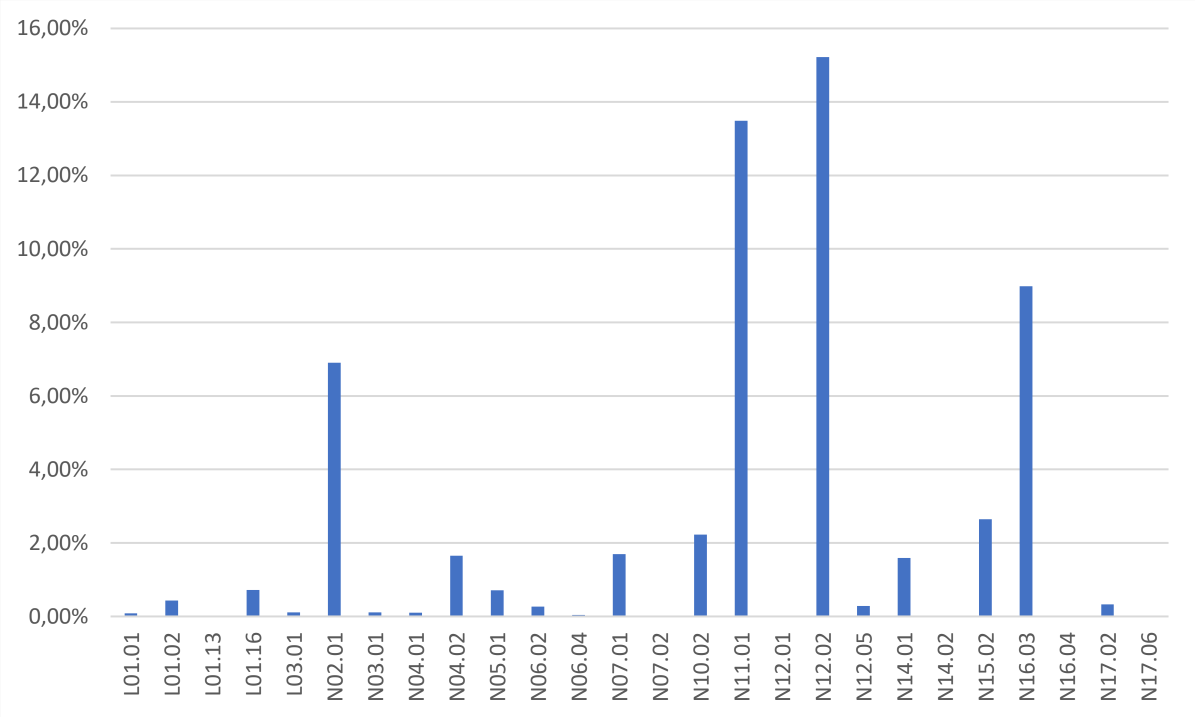

Figure 44. Percentage of the total winter bed per SNL-type.

For each type of management there is a guideline for maintenance, these guidelines differ greatly from one type of management to another. For eleven of the management types occurring in the winter bed there are guidelines for the occurring vegetation. These guidelines are defined based on structural elements.

Example: For the class Droog Schraalland (N11.01), 60% of the area must consist of low grasses and herbs. In addition, the manager can choose from the following structural elements:

Table 10. Structure elements Droog Schraalland (N11.01).

Structure element	Min %	Max %
Bare soil and/or pioneer vegetation	5	20
Heather	5	20
Herbaceous vegetation	5	20
Shrubs	5	20
Solitaire trees and small bushes	5	20

The quality of the area is then assessed on the basis of the following criteria:

"High”: if 4 qualifying structure elements are present.

"Intermediate”: if 3 qualifying structure elements are present.

"Low”: if 0-2 qualifying structure elements are present.

This gives the owner freedom to choose the structure elements. The freedom within the SNL management types ensures that the vegetation can vary greatly, which makes it difficult to link a roughness to a management type. In order to obtain an indication of possible vegetation combinations, an average and a rough scenario (quality: "high") have been determined for each SNL management type, which are then expressed in the homogeneous classes. The three common classes are briefly discussed here.

Droog Schraalland

Within the 'droog schraalland' management type, in addition to 60% grassland, *herbaceous vegetation*, *Forest* and *shrubs* can occur. The management type is the second most common management type and, in terms of vegetation, resembles other, less common, management types.

Table 11. Scenarios SNL type N11.01.

N11.01 Droog schraalland		**13,49%**
	Average	*Rough*
Grassland	67,5	60
Herbaceous vegetation	15	10
Forest	7,5	10
Shrubs	10	20

Kruiden- en faunarijk grassland

The management type 'kruiden- en faunarijk grasland' consists for a large part of grassland. In addition, *Shrubs* and a small amount of *Forest* can occur. The management type is the most common management type.

Table 12. Scenarios SNL type N12.02.

N12.02 Kruiden- en faunarijk grasland		**15,22%**
	Aveage	Rough
Grassland	85	75
Forest	3	5
Shrubs	12	20

SNL types with Forest

The three SNL types that consist mainly of *forest*, have the same structur elements and are therefore dealt with together. This class may also include *shrubs*.

Table 13. Scenarios SNL types N15.02 + N16.03 + N16.04.

N15.02 + N16.03 + N16.04		**11,65%**
	Average	Rough
Forest	90	80
Shrubs	80	20

Initial proposal for mixing classes

Below, the mixing classes for the Overijsselse Vecht are presented, in Table 14, an overview of all proposed mixing classes is shown.

- Based on Table 9, three vegetation classes are proposed with 90% grassland and 10% of one of the following vegetation species: *herbaceous vegetation, reed* and *shrubs*. The same applies to 80% grassland and 70% grassland.
- Management type N12.02 (due to the small amount of forest allowed) is very similar to the above mentioned classes. No additional mixing class is proposed for this.

- Based on management type N11.01 (and less common, comparable classes), two additional classes are proposed: 60-20-20 (*natural grassland-herbaceous vegetation-shrubs*) and 60-10-10-20 (*natural grassland-herbaceous vegetation-forest-shrubs)*.
- Within the management types with *forest*, *shrubs* can occur, which has a higher roughness than *forest*. For this reason, an 80-20 *forest-shrubs* class is proposed, in which 20% *shrubs* is permitted.
- In order to be able to allow a lot of rough vegetation, a mixing class with a lot of rough vegetation is also proposed. This class corresponds to the mixing classes 50/50 of Rijkswaterstaat, but is mentioned here as 10/90 (the first number refers to the minimum percentage of grassland).

Table 14. Initial proposed mixing classes for the River Vecht.

Mixing classes	Natural grassland	Herbaceous vegetation	Reed	Forest	Shrubs
90/10a	>90%	<10%			
90/10b	>90%		<10%		
90/10c	>90%				<10%
80/20a	>80%	<20%			
80/20b	>80%		<20%		
80/20c	>80%				<20%
70/30a	>70%	<30%			
70/30b	>70%		<30%		
70/30c	>70%				<30%
N11.01a	>60%	<20%			<20%
N11.01b	>60%	<10%	<10%		<20%
10/90	>10%	Undefined		<60%	
Forest-shrubs				>80%	<20%

Second proposal for mixing classes

After the determination of the mixing classes described in the previous section, the lots were assigned a mixing class. It appeared to be very difficult to assign a mixing class to a lot, because often more than one of the rough classes were present. Therefore, the distinction between the classes with *herbaceous vegetation, reed,* and *shrubs* was needles. It was thereafter decided to create the following mixing classes: *90/10, 80/20, 70/30, 60/40, 50/50, 40/60, 30/70, 20/80* and *10/90.* For this mixing classes, the first number indicates the amount of *natural grassland* and the second number the amount of rough vegetation, so *herbaceous vegetation, reed, forest* and *shrubs.* The class *forest-shrubs* is remained.

Appendix 3: Effects of the vegetation distribution scenarios on the maximum water levels and maximum flow velocities

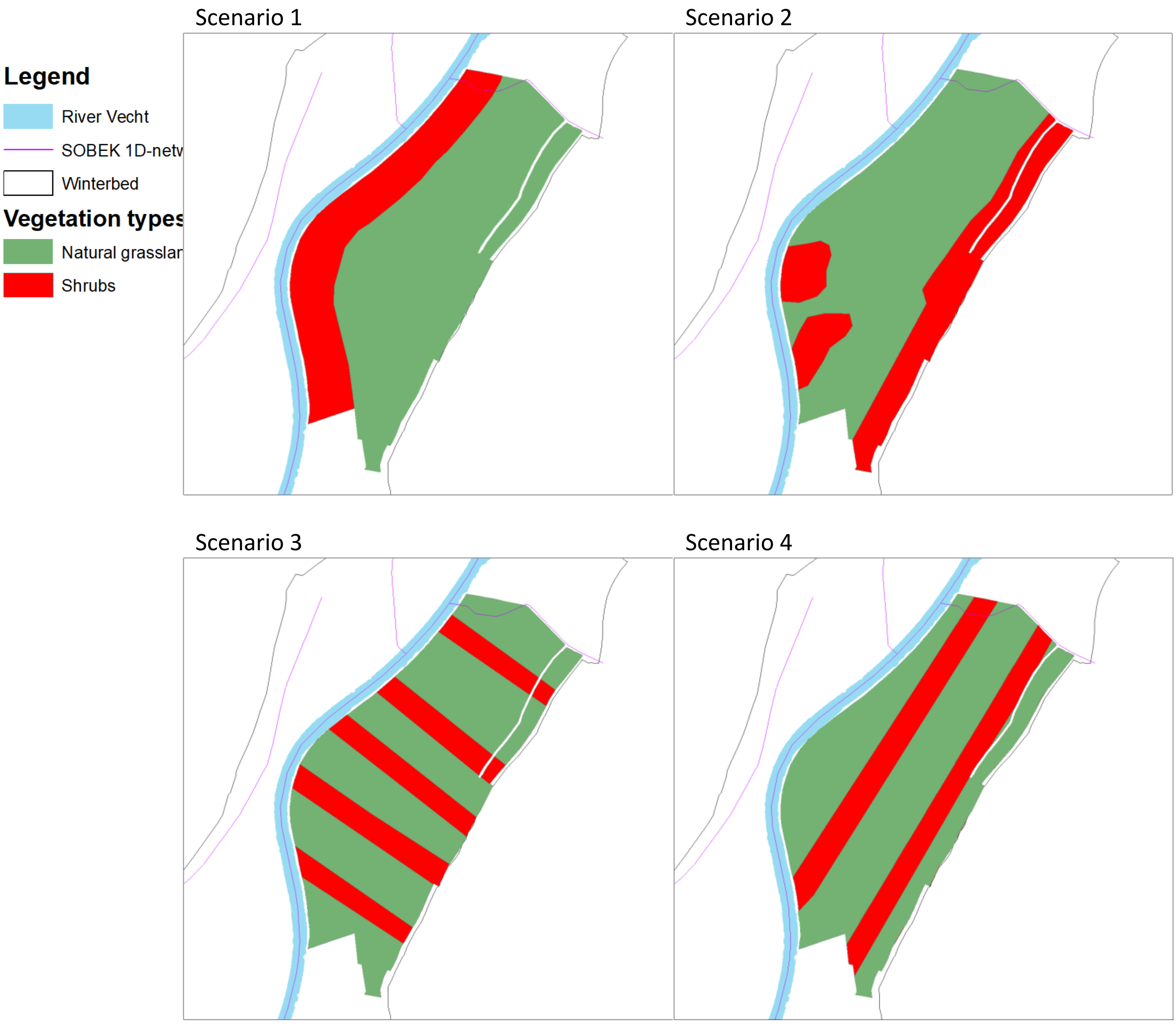

Figure 45. Different scenarios of vegetation distribution on the lot with mixing class 70/30.

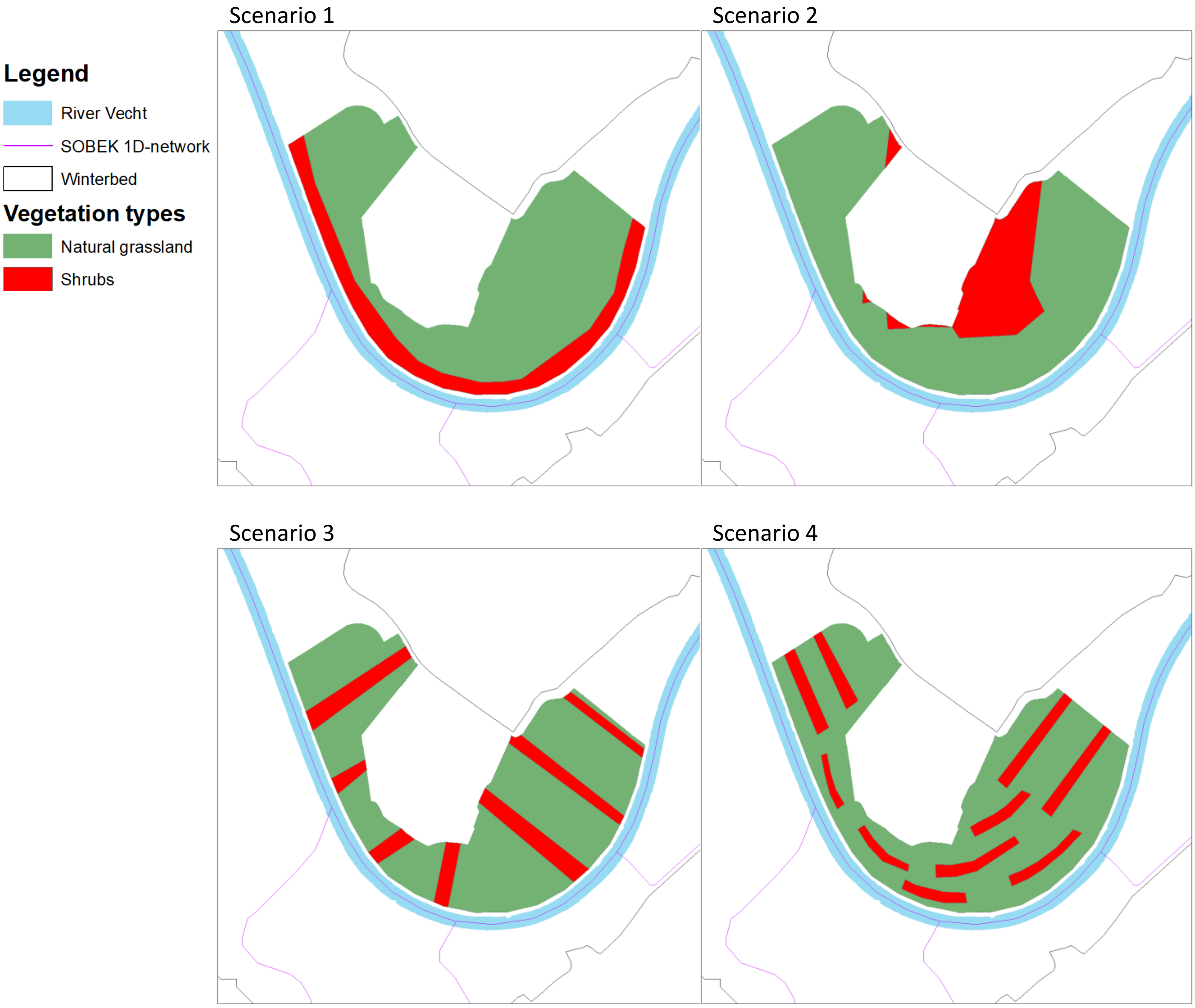

Figure 46. Different scenarios of vegetation distribution on the lot with mixing class 80/20.

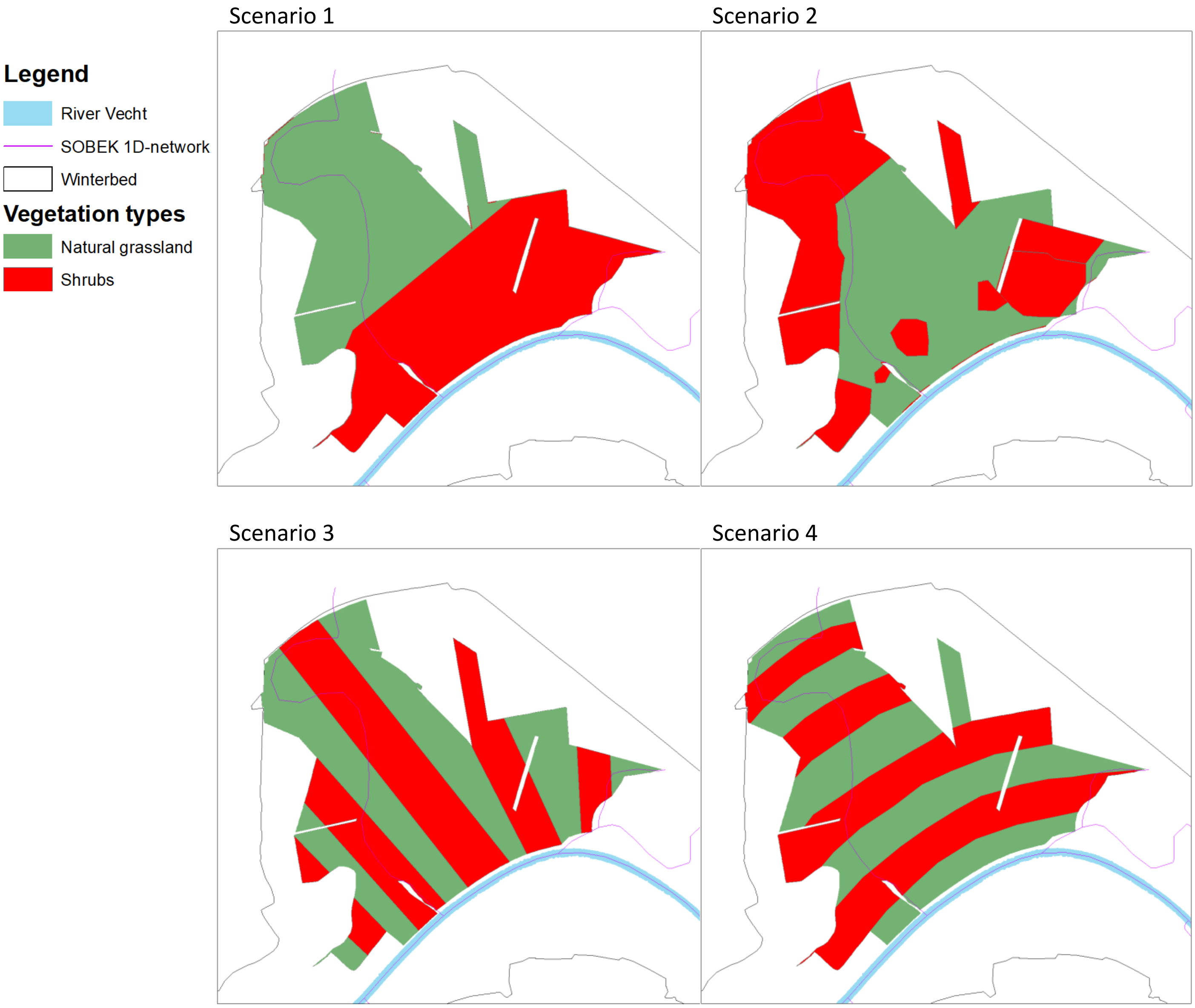

Figure 47. Different scenarios of vegetation distribution on the lot with mixing class 50/50.

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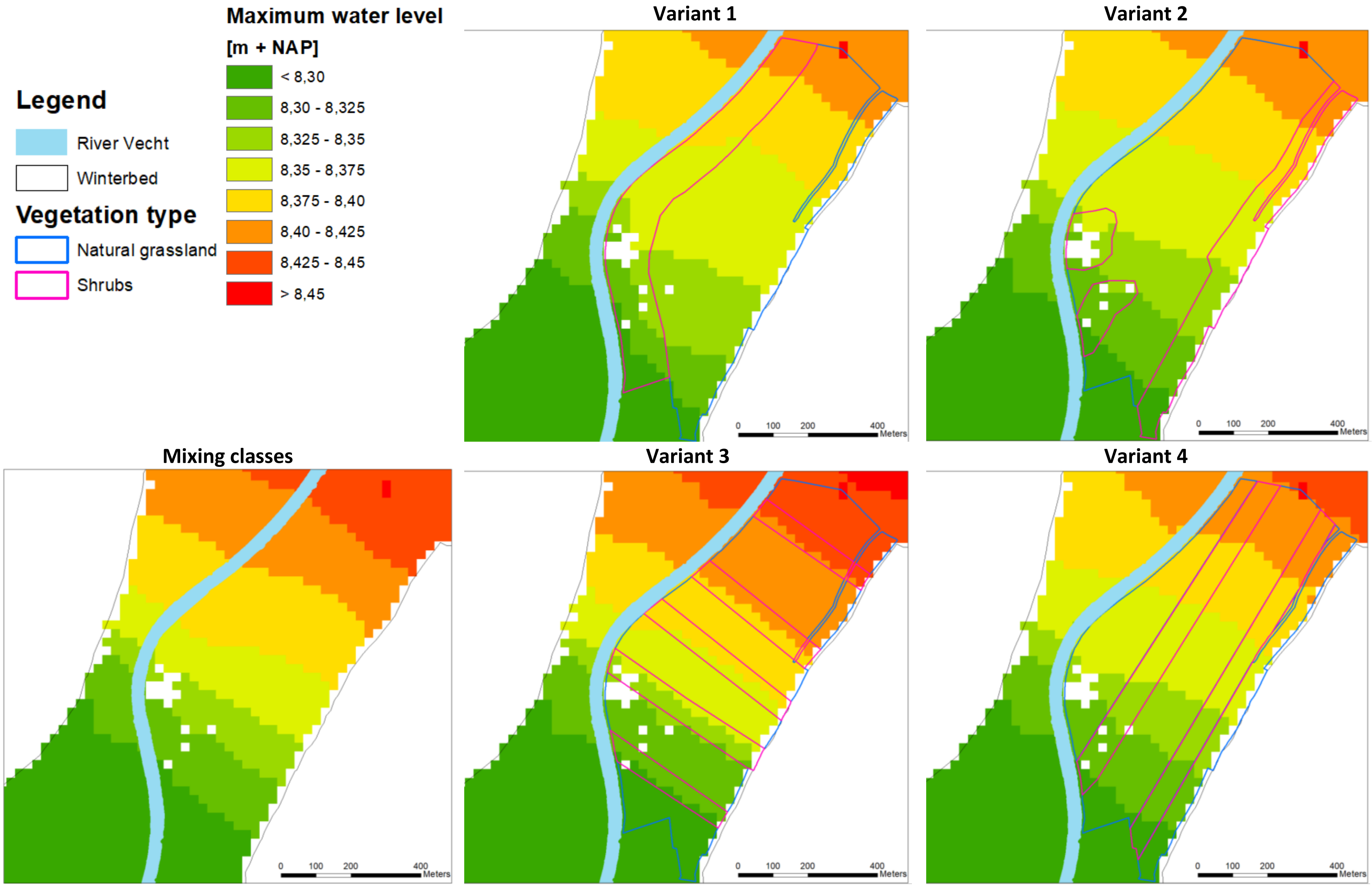

Figure 48. Maximum water levels [m + NAP] on the lot with mixing class 70/30 for the different scenarios.

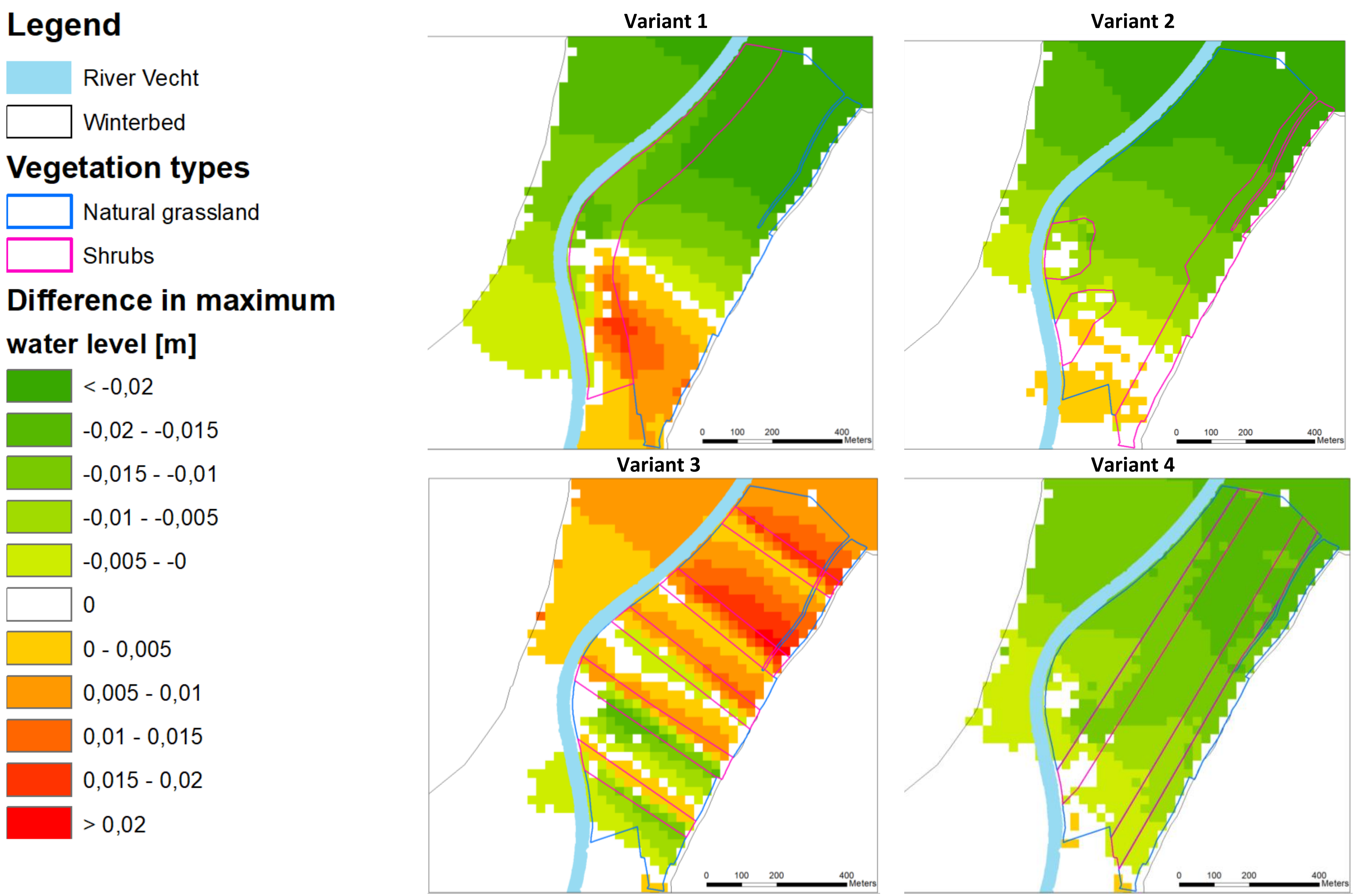

Figure 49. Difference in maximum water levels [m] for the different scenarios on the lot with mixing class 70/30 compared to the model run with the mixing classes.

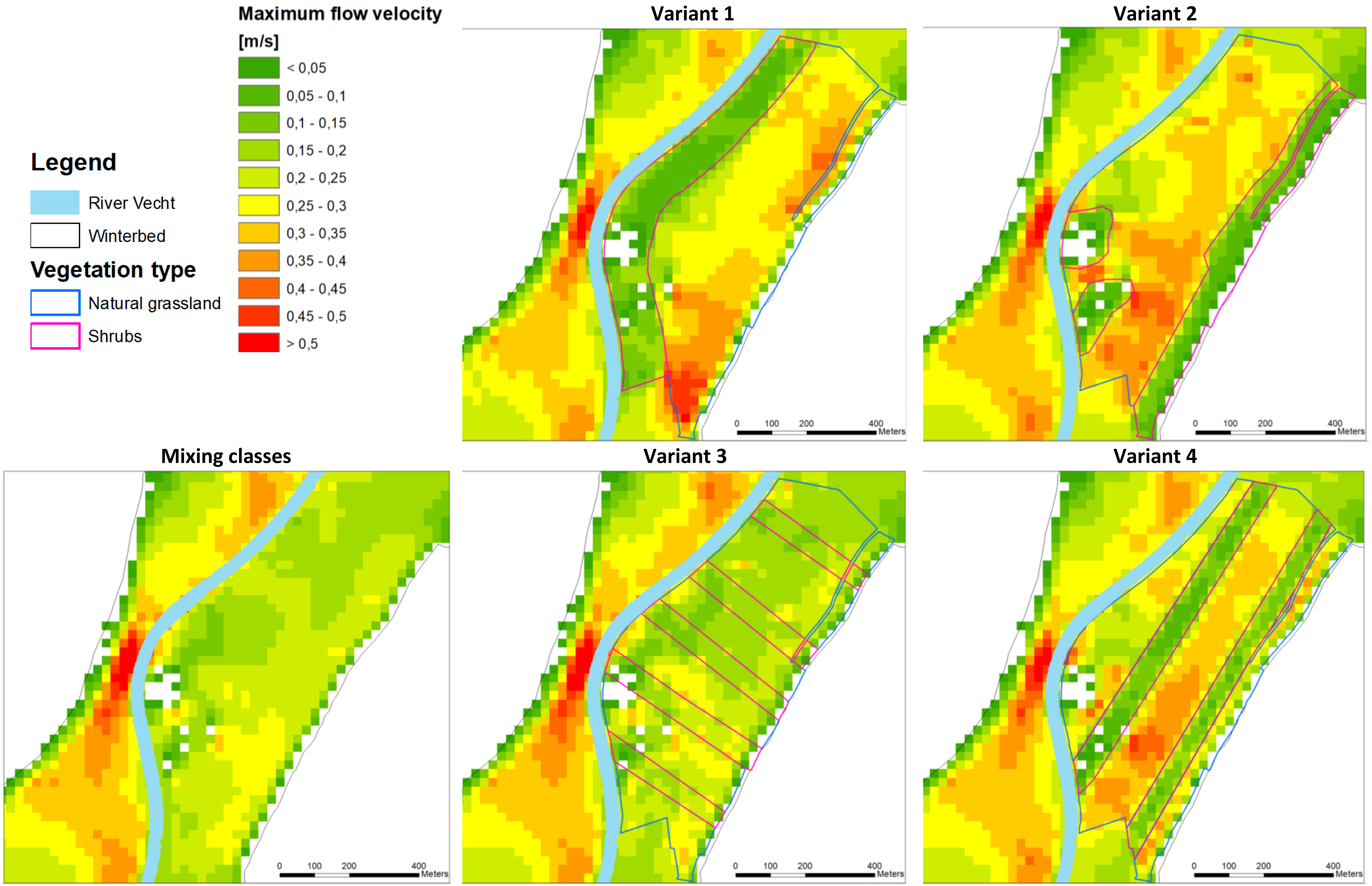

Figure 50. Maximum flow velocities [m/s] on the lot with mixing class 70/30 for the different scenarios.

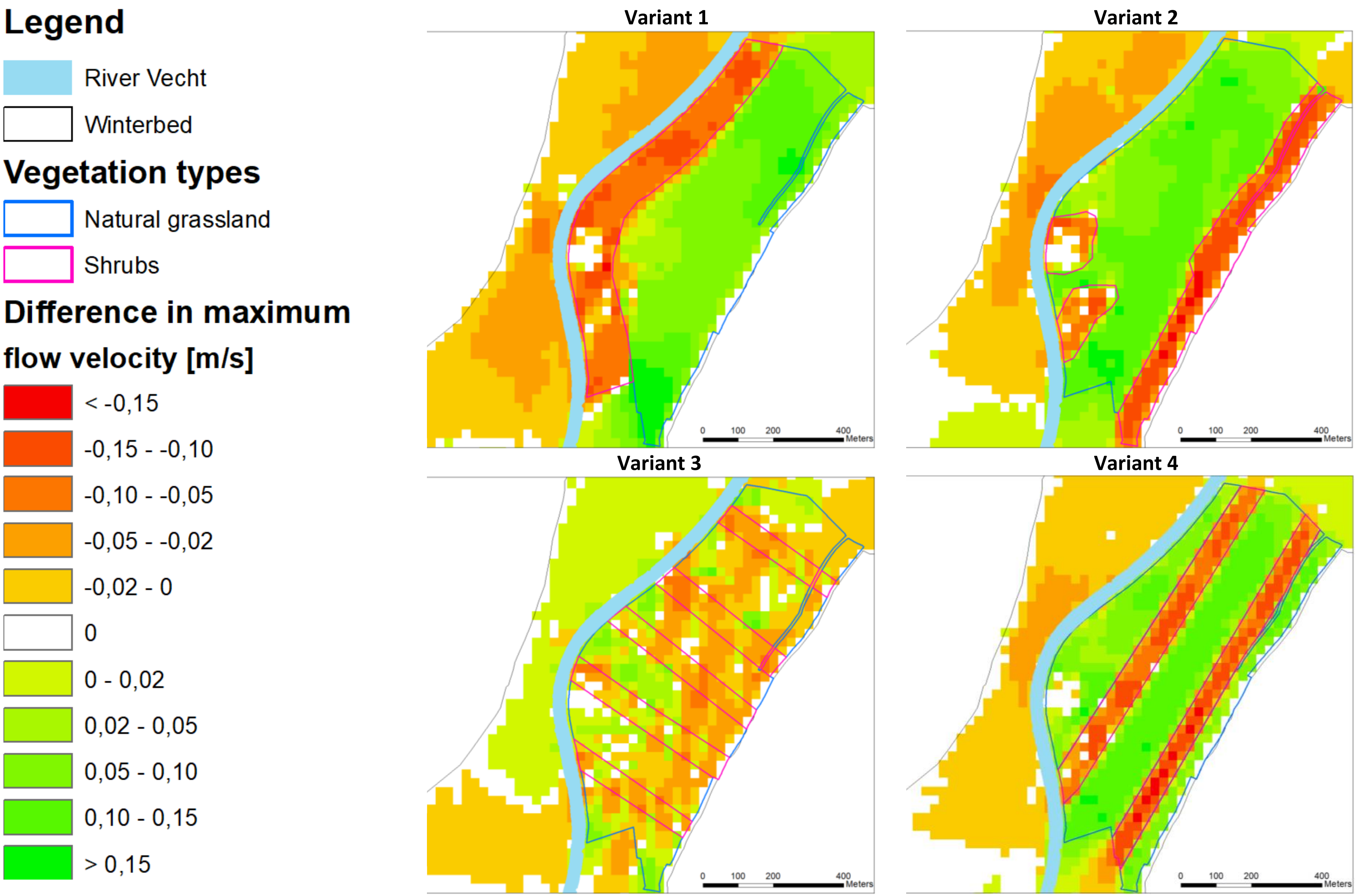

Figure 51. Difference in maximum flow velocity [m/s] for the different scenarios on the lot with mixing class 70/30 compared to the model run with the mixing classes.

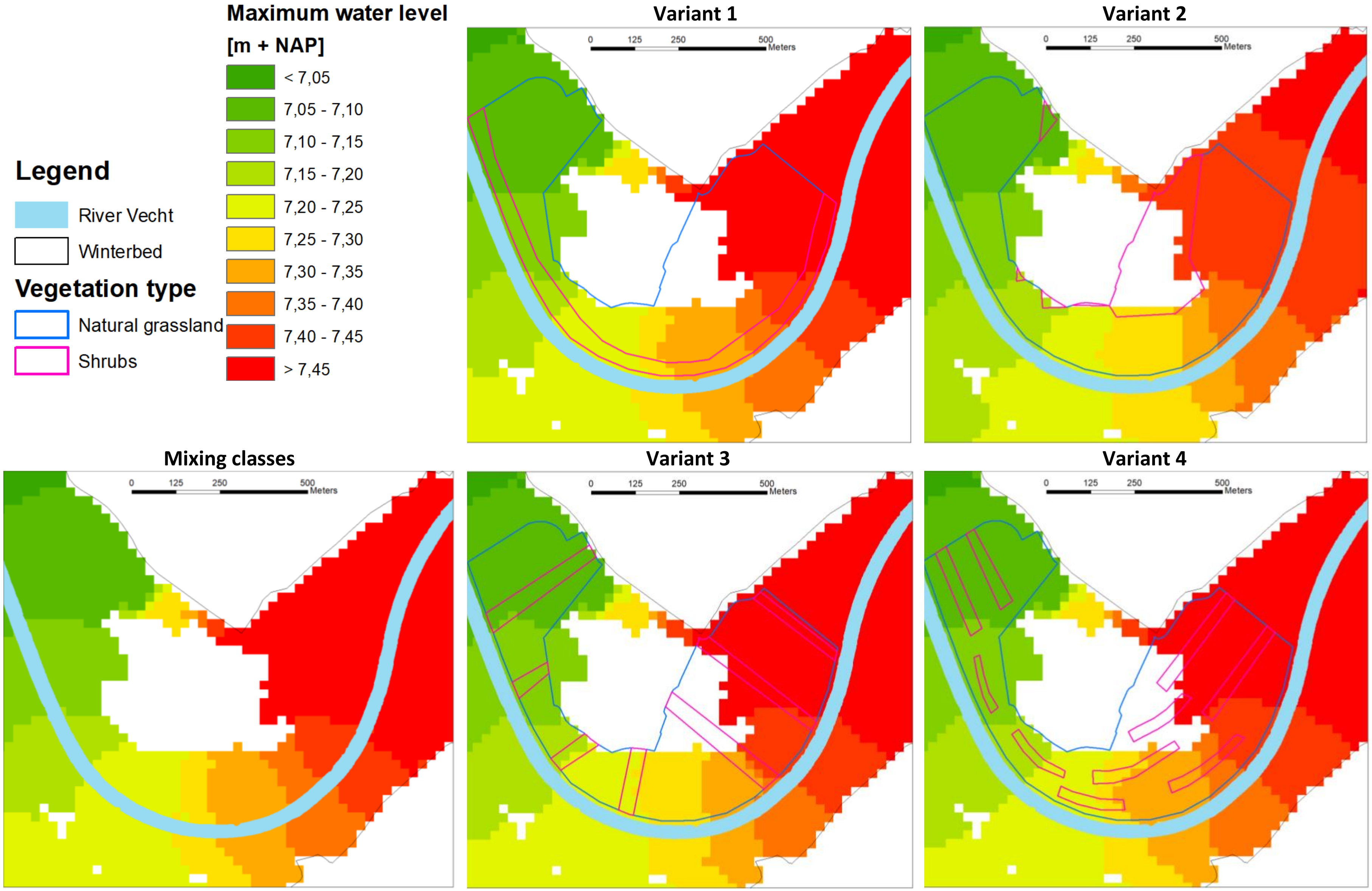

Figure 52. Maximum water levels [m + NAP] on the lot with mixing class 80/20 for the different scenarios.

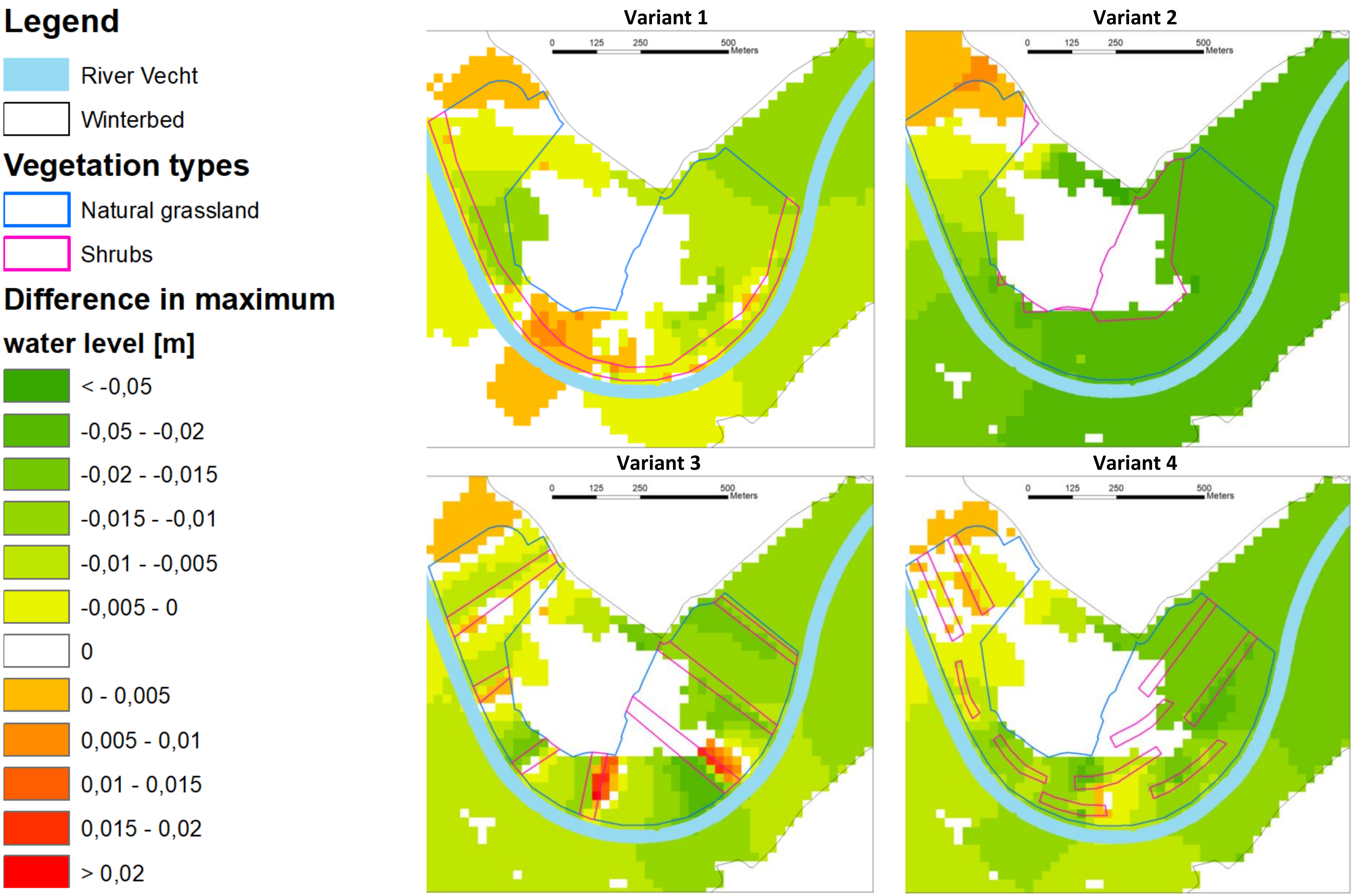

Figure 53. Difference in maximum water levels [m] for the different scenarios on the lot with mixing class 80/20 compared to the model run with the mixing classes.

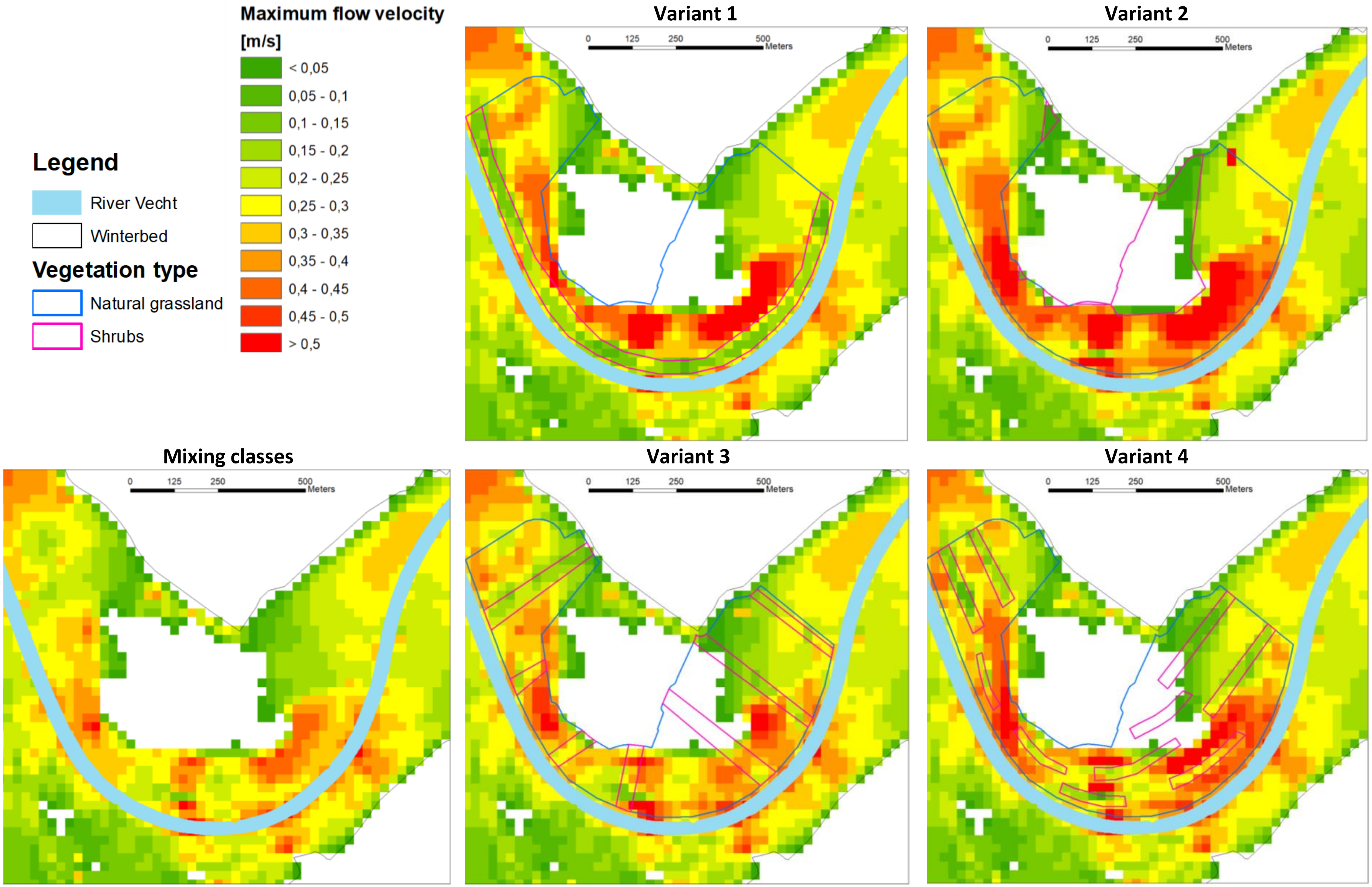

Figure 54. Maximum flow velocities [m/s] on the lot with mixing class 80/20 for the different scenarios.

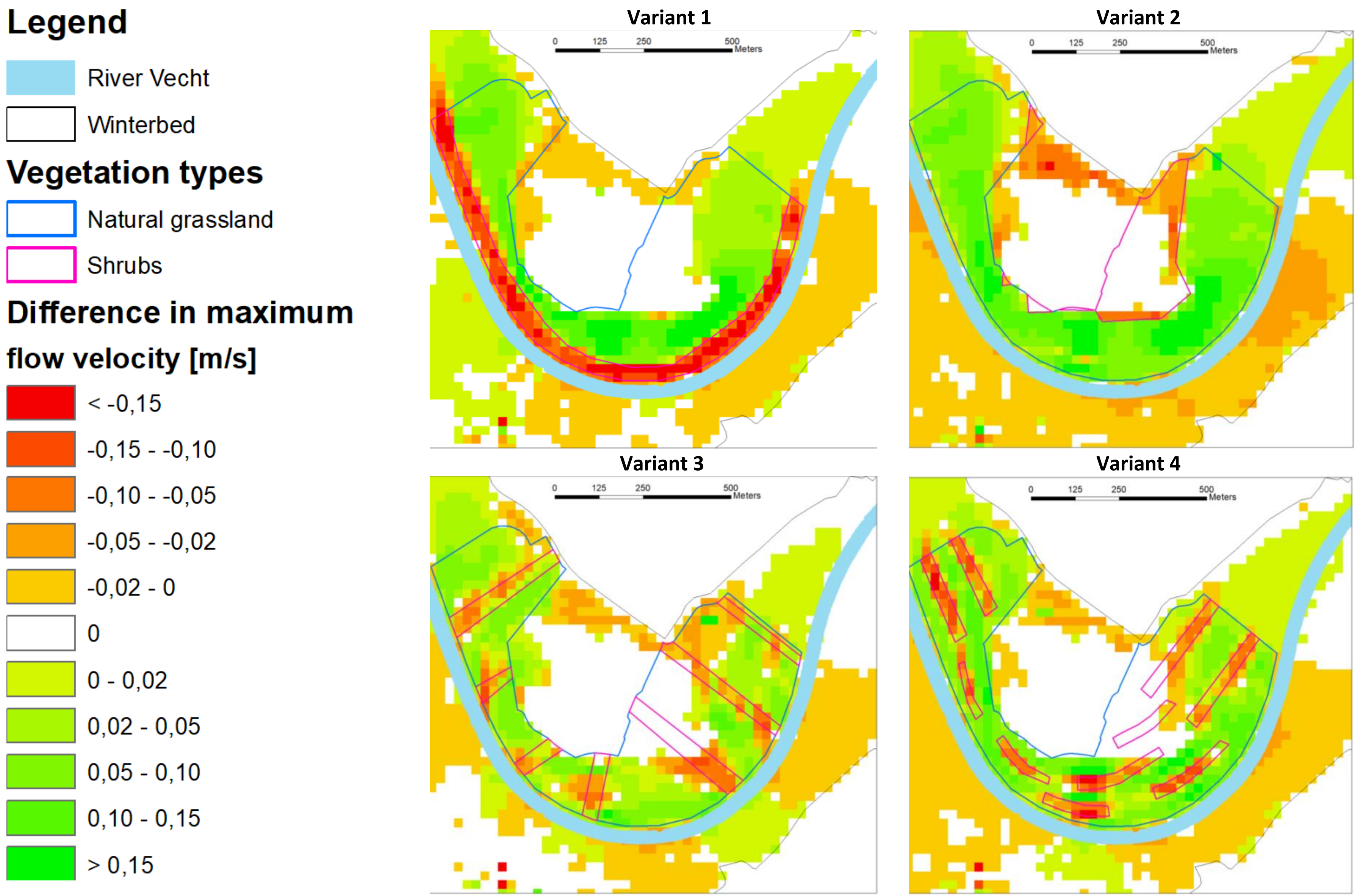

Figure 55. Difference in maximum flow velocity [m/s] for the different scenarios on the lot with mixing class 80/20 compared to the model run with the mixing classes.

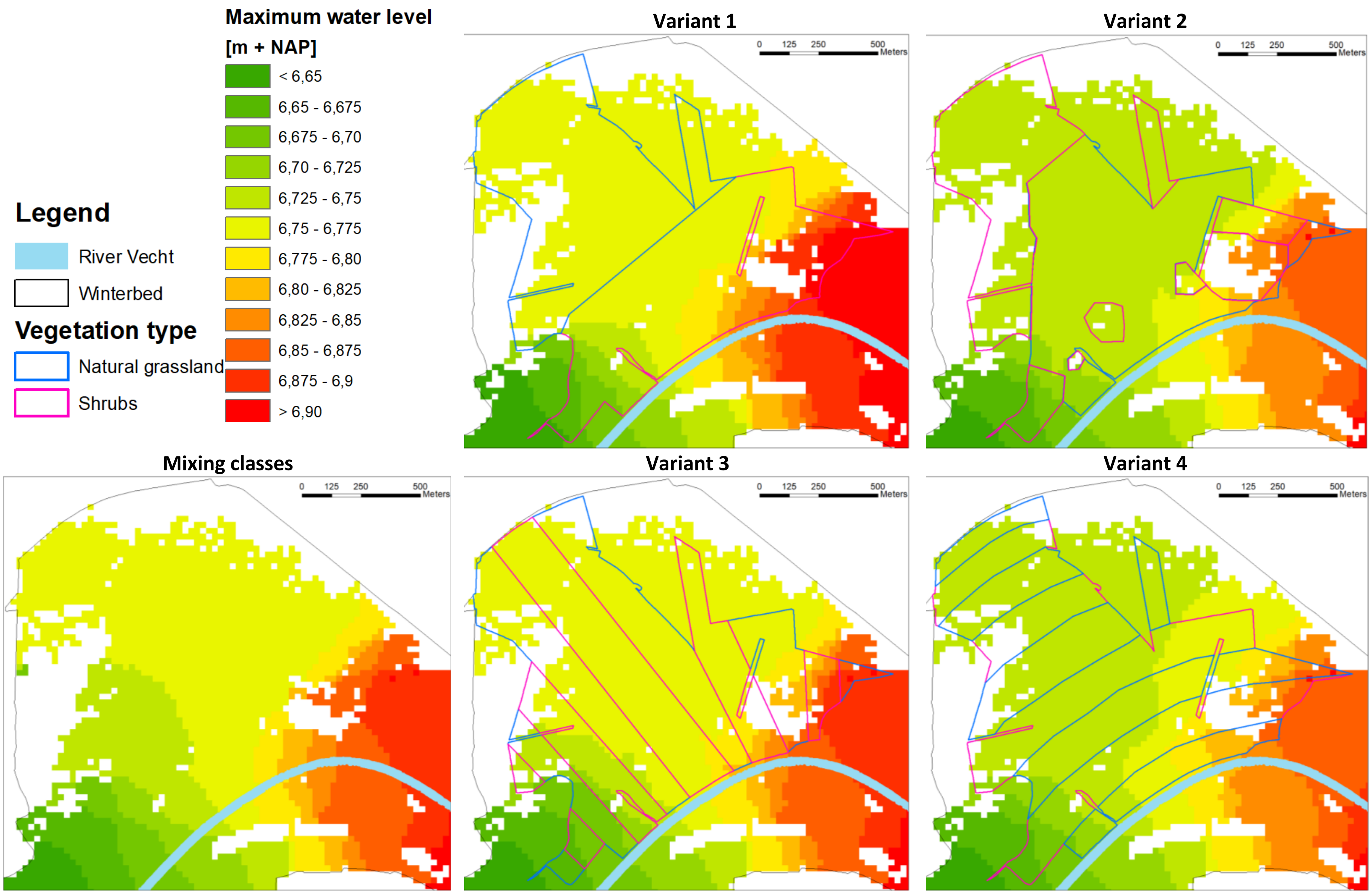

Figure 56. Maximum water levels [m + NAP] on the lot with mixing class 50/50 for the different scenarios.

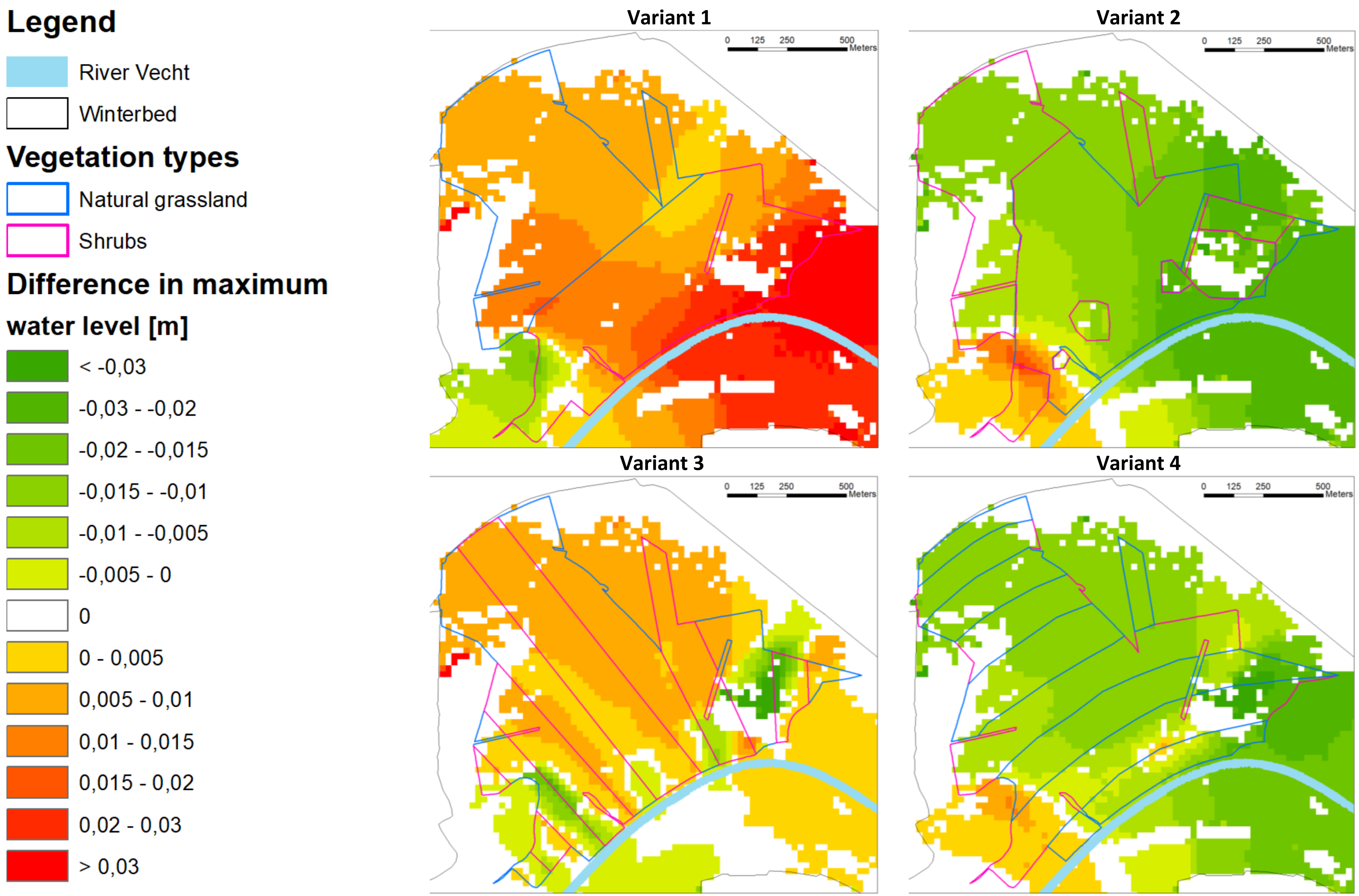

Figure 57. Difference in maximum water levels [m] for the different scenarios on the lot with mixing class 50/50 compared to the model run with the mixing classes.

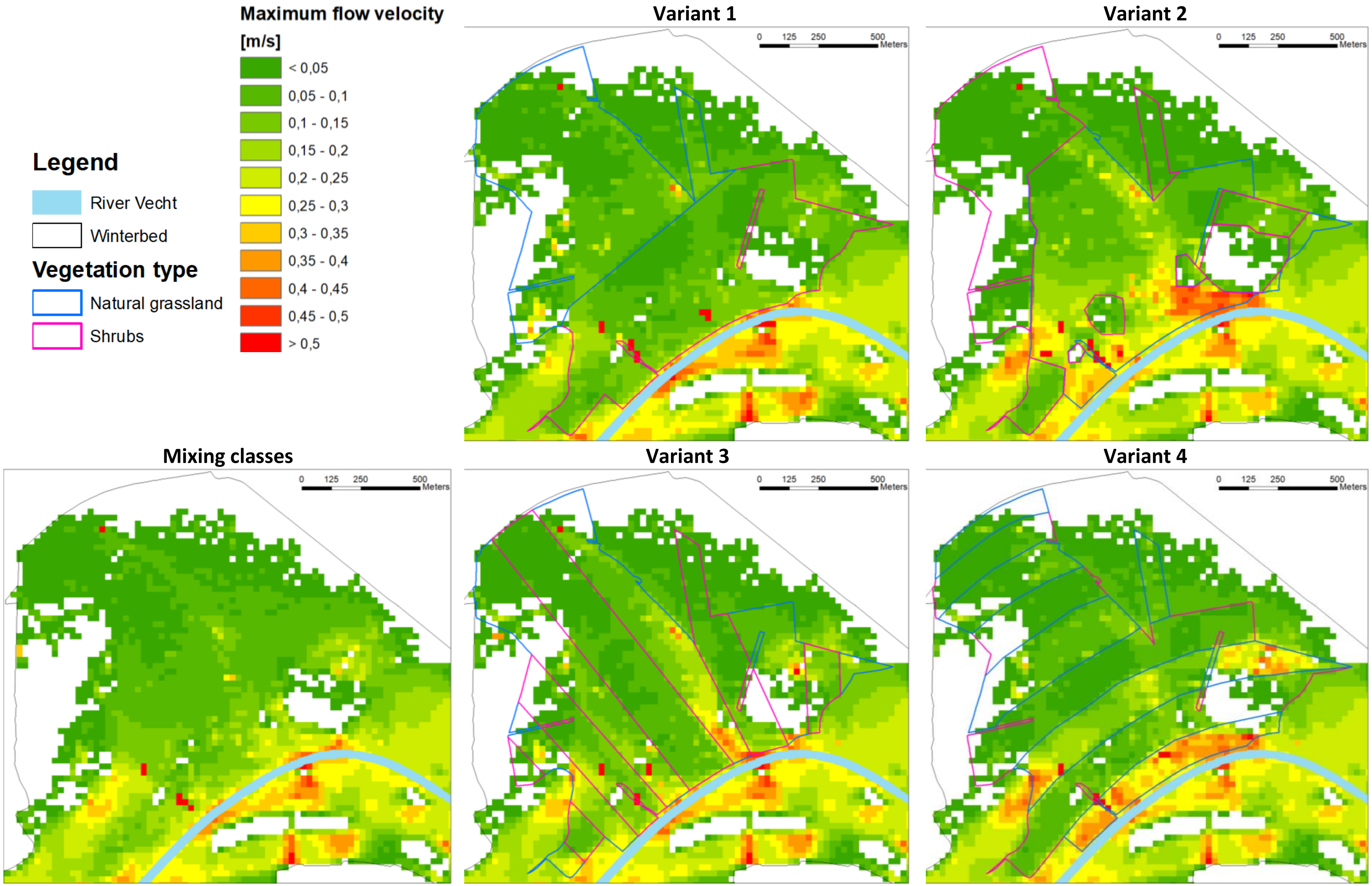

Figure 58. Maximum flow velocities [m/s] on the lot with mixing class 50/50 for the different scenarios.

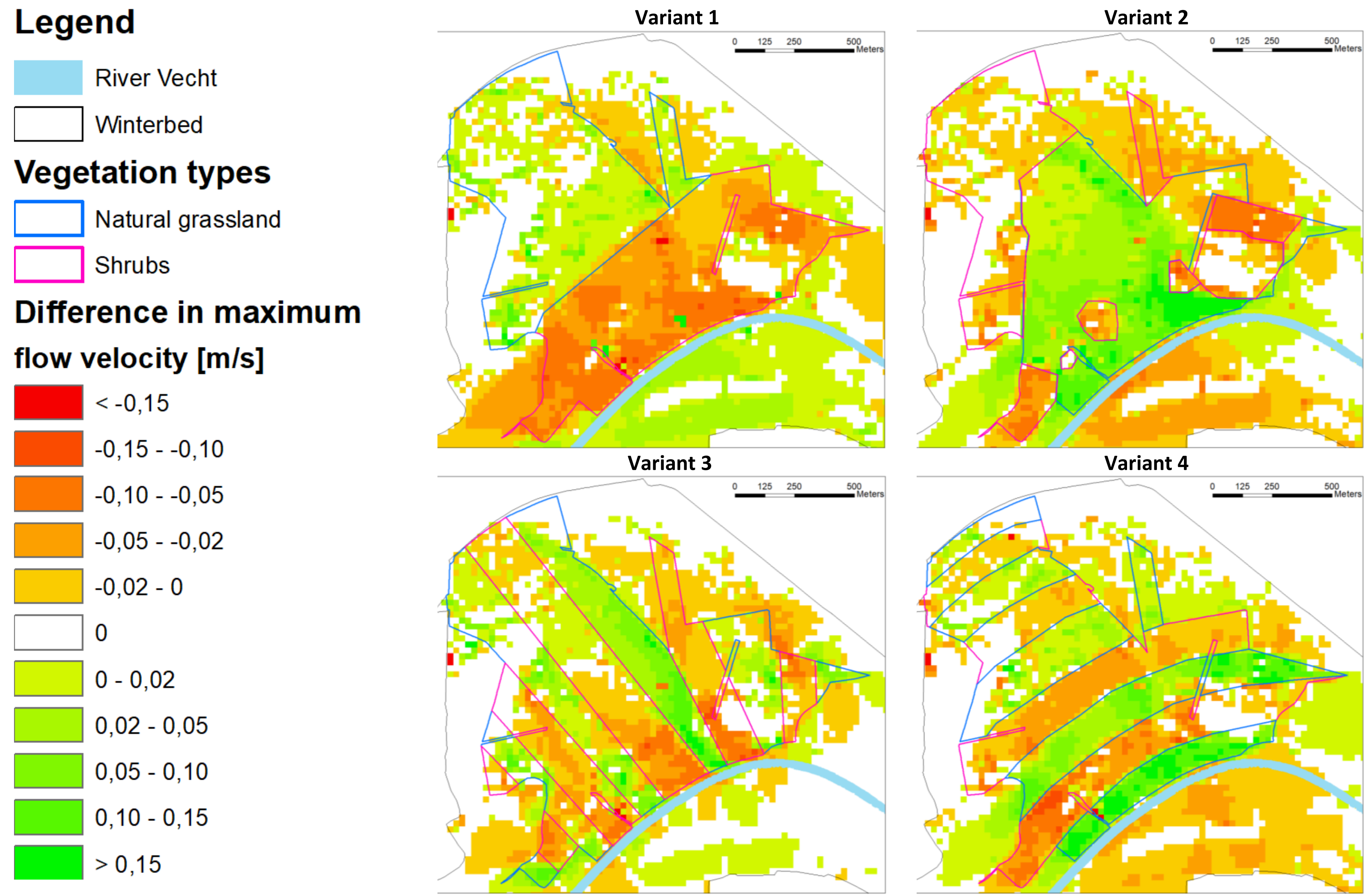

Figure 59. Difference in maximum flow velocity [m/s] for the different scenarios on the lot with mixing class 50/50 compared to the model run with the mixing classes.

Appendix 4: Effect of the planned projects along the River Vecht

Three scenarios are run: a scenario with the planned measures at Rheezermaten, a scenario with the planned measures at Karshoek-Stegeren and a scenario where all measures are combined. First, the projects are briefly described. After that, it is described how the projects are implemented in the hydraulic model and how the results contribute to this research.

Rheezermaten

The planned measures of the project at Rheezermaten are located just downstream of Hardenberg (Figure 60). The course of the River Vecht will be changed: a total of six meanders will be implemented in the river course. At several locations along the river, the vegetation will be changed into 'stroomdalgrasland' (species-rich grasslands growing on sandy soil along rivers). Somewhat further away from the main channel, there are some areas where the surface level will be heightened with 20 cm. At some small areas inside the areas where 'stroomdalgrasland' will grow, the surface level will also be heightened with 20 cm. In the most downstream new meander, the surface level will be lowered with 20 cm and the vegetation will be changed into 'plas-dras' (inundated vegetation). The last measure that will be implemented is the creation of some pools along the River Vecht. To create these pools, the surface level will be lowered to allow the pool to fill up.

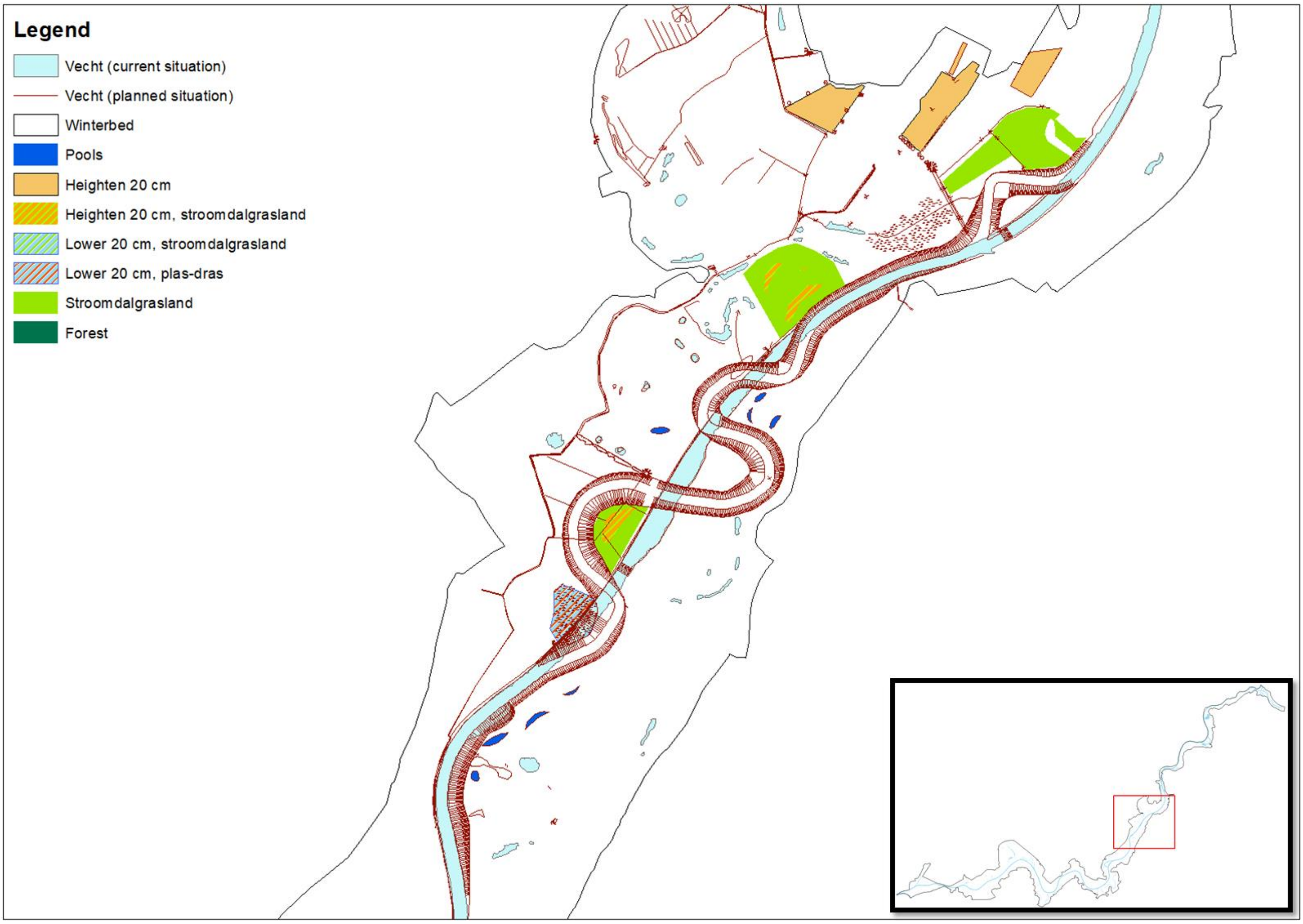

Figure 60. Overview of the planned measures at Rheezermaten.

Karshoek-Stegeren

The measures of the project at Karshoek-Stegeren take place in two bends in the middle of reach between Hardenberg and Ommen (Figure 61). In between the two existing bends, a meander will be realised. Furthermore, a side channel will be excavated and connected to an already existing side channel. At several locations, among others in the bend of the new side channel, the vegetation will be changed into 'stroomdalgrasland'. Sometimes this will be done in combination with heightening or lowering the surface level of the land. In the outer bend of the new meander, areas with forest will be realised, while in the inner bed the vegetation type will be changed into 'plas-dras' in combination with lowering the surface level with 20 centimetres. The combination of 'plas-dras' and lowering the surface level will also be realised just before the bend in the new side channel.

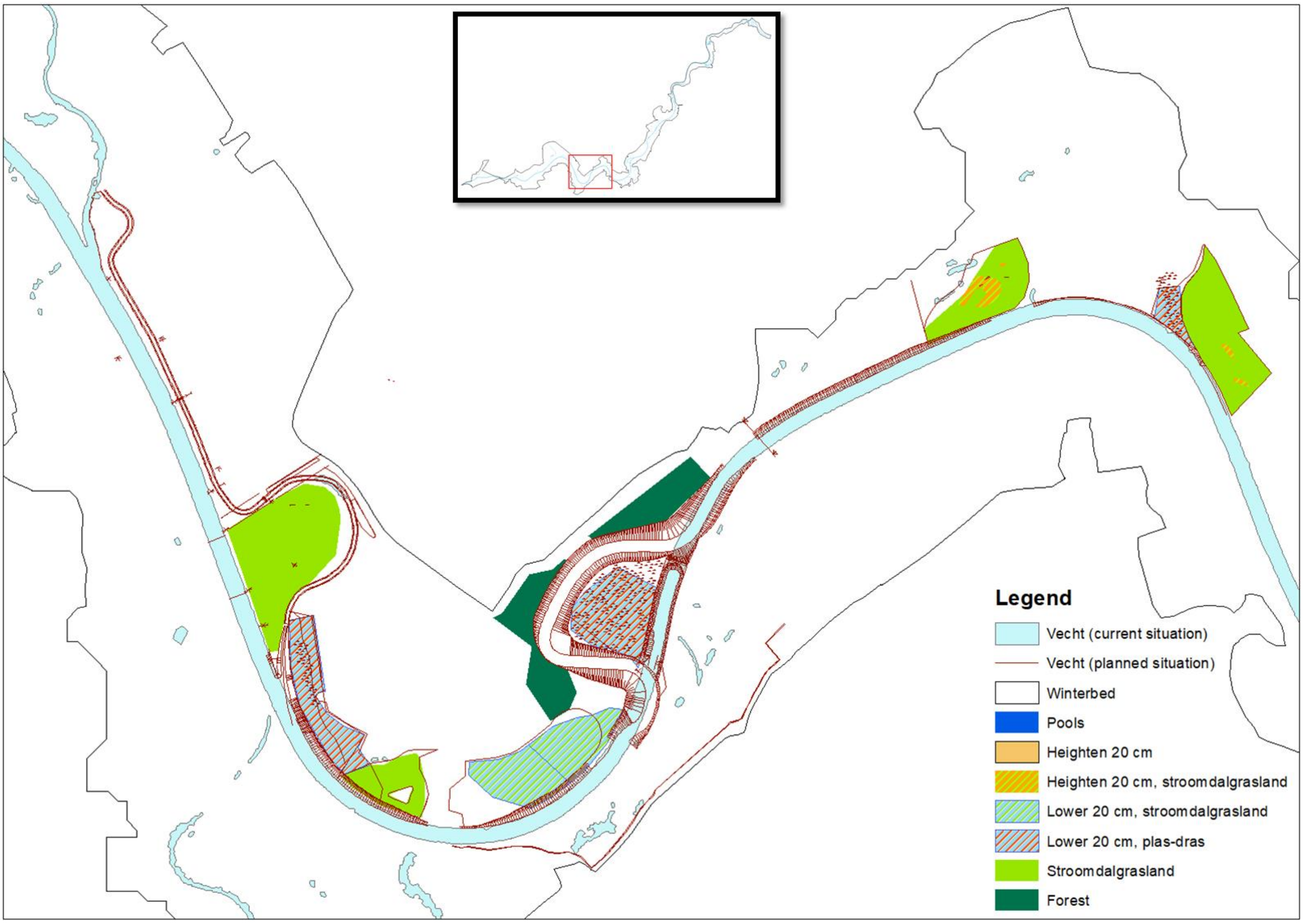

Figure 61. Overview of the planned measures at Karshoek-Stegeren.

Implementation in hydraulic model

The measures of the planned projects along the River Vecht can be subdivided in three types of changes in the hydraulic model: changes in the network of the hydraulic model (change of the river course, addition of the side channel), changes in the elevation grid (heightening or lowering the surface level) and changes in the roughness grid (new vegetation type). The necessary changes in the network are not implemented. It is expected that these changes have an impact on the water level. On the other hand they ask for a considerable amount of changes in the network of model. Since the focus of this research is on the effect of vegetation patterns, these changes in the network are not implemented and the course of the river is kept the same. However, it should be taken into account that the results of these scenarios are not the complete measures, but only the effect of the changes in vegetation and height. The different measures of the planned projects are implemented as follows:

- Pools: the values of the elevation raster within the polygons of the pools are changed to a specific value (5.1 or 5.2 m + NAP).
- Heighten 20 cm: the values of the elevation raster within the polygons are raised with 20 cm.
- Heighten 20 cm, stroomdalgrasland: Within the polygons, the values of the elevation raster are raised with 20 cm and the vegetation type in the ecotopes map is changed into mixing class 80/20. This mixing class is chosen, because two other areas in the winter bed of the River Vecht where there is 'stroomdalgrasland' have a ratio of natural grassland and rougher vegetation that is around 80/20.
- Lower 20 cm, stroomdalgrasland: The values in the elevation grid are lowered with 20 cm, vegetation type is changed into mixing class 80/20.
- Lower 20 cm, plas-dras: The vales of the elevation grid are lowered with 20 cm. The vegetation type is changed into reed.
- Stroomdalgrasland: The vegetation type in the ecotopes map is changed into mixing class 80/20.
- Forest: The vegetation type in the ecotopes map is changed into forest.

Results

Both the planned measures at Karshoek-Stegeren and Rheezermaten occur higher water levels (Figure 62). The difference in water level from around 16 kilometres from the German border is the same for the scenario where both projects are implemented and the scenario where only the measures at Karshoek-Stegeren are implemented. This is because Karshoek-Stegeren is located downstream from Rheezermaten and the latter therefore has no effect on the water level at Karshoek-Stegeren. The other way around, this is not the case. The effect on the water level at Rheezermaten is larger when both projects are implemented than when only the measures at Rheezermaten are implemented, since the measures at Karshoek-Stegeren do influence the water level at Rheezermaten as well.

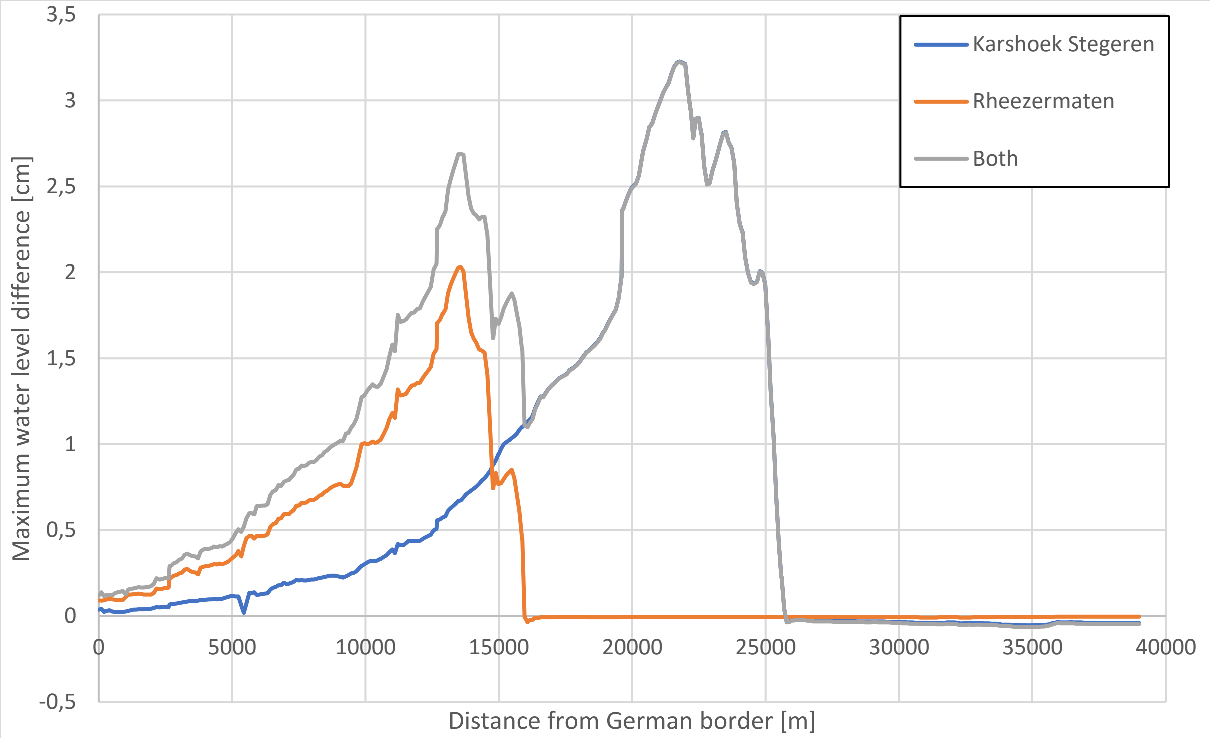

Figure 62. The difference in water level as result of the implementation of the measures of the planned measures compared to the current situation.

At Karshoek-Stegeren, the difference in water level compared with the current situation is the largest with a difference of 3,2 cm. The maximum difference at Rheezermaten is around 2 cm, which increases to 2,7 cm when both projects are implemented. More and larger areas with rougher vegetation will be realised at Karshoek-Stegeren, which explains the fact that the differences in maximum water level are larger at Karshoek-Stegeren.

The effect of the projects is noticeable up to the German border, although the difference in water level is small. In the upstream section (first 5 km from the German border) the difference in maximum water level is less than 0,5 cm for all scenarios. A difference of more than 1 cm is noticeable from 15 km, 10 km and 8.8 km for respectively the scenarios with only Karshoek-Stegeren, only Rheezermaten and both projects. Downstream of Karshoek-Stegeren, the difference with the current situation quickly decreases to 0, as the projects hardly have any effect on the water levels downstream of the projects.

It can be seen that at Karshoek-Stegeren, the highest local differences in maximum water level occur at the upstream end of the measures (Figure 63). The difference in water level here can be larger than 3 cm. The difference in maximum water level increases the fastest in the last bend where the vegetation will be changed into reed in the inner bend of the river. The area where water can flow is relatively small here, because there is a natural height present. Seen from downstream to upstream, there is not a continuous increases in difference in maximum water level. This difference decreases at the start of the last bend where 'stroomdalgrasland' will be realised and after that point increases again. The areas with forest that will be realised do not really occur any difference in maximum level, because they are located in areas where there is not so much flow present.

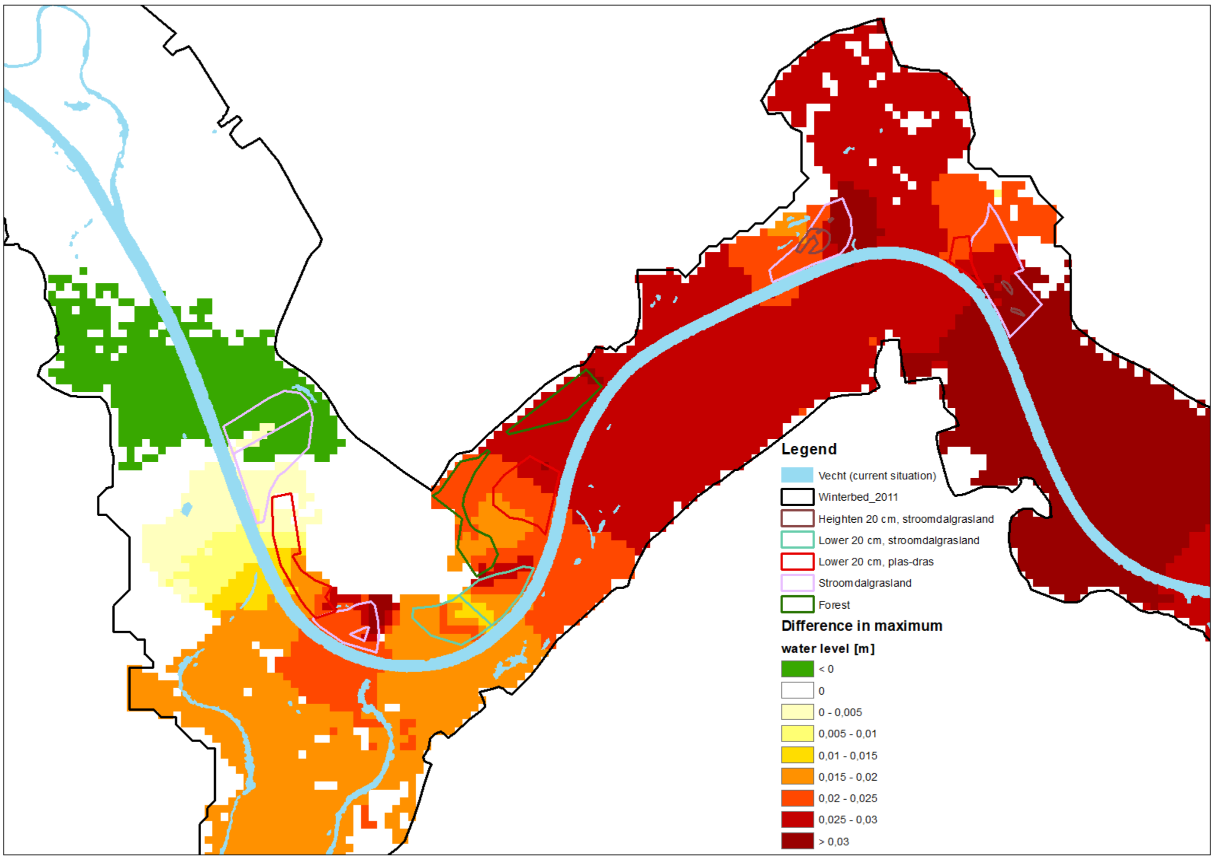

Figure 63. Difference in maximum water level [m] at Karshoek-Stegeren. A positive value indicates a higher maximum water level when the measures at Karshoek-Stegeren are implemented, while a negative value indicates a lower maximum water depth.

Also at Rheezermaten, the impoundment of water starts at the location where the vegetation is changed into reed (Figure 64). The difference in maximum water level increases here relatively fast. Somewhat more upstream, a relatively fast increase in this differences is noticeable at the location where ‘stroomdalgrasland’ will be realised. In between, there is an area where the is barely increasing over a relatively long distance, which is the case because there is only one small measure that will be realised.

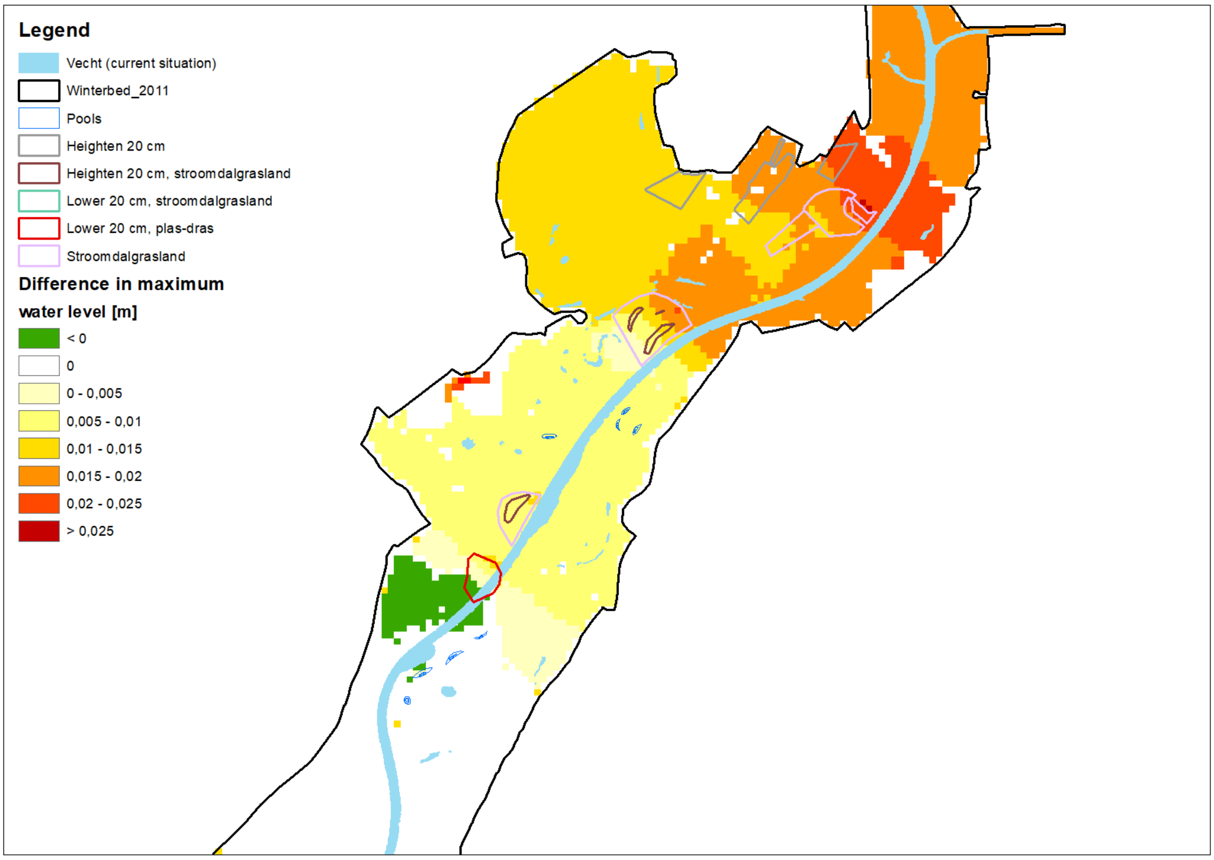

Figure 64. Difference in maximum water level [m] at Rheezermaten (only measures at Rheezermaten implemented). A positive value indicates a higher maximum water level, while a negative value indicates a lower maximum water depth.

Looking at Rheezermaten, when both projects are implemented (Figure 65), it can be seen that the impoundment of water from Karshoek-Stegeren is still noticeable just downstream of the measures at Rheezermaten. Compared to the situation without the measures at Karshoek-Stegeren, the difference in maximum water level is larger (white areas in Figure 64 become yellow in Figure 65). The combined effect of the measures of both projects occur that the order of magnitude of maximum differences in water level changes from 0-2 cm to 2-3 cm in the most upstream part of the River Vecht at Rheezermaten (upper part in Figure 65).

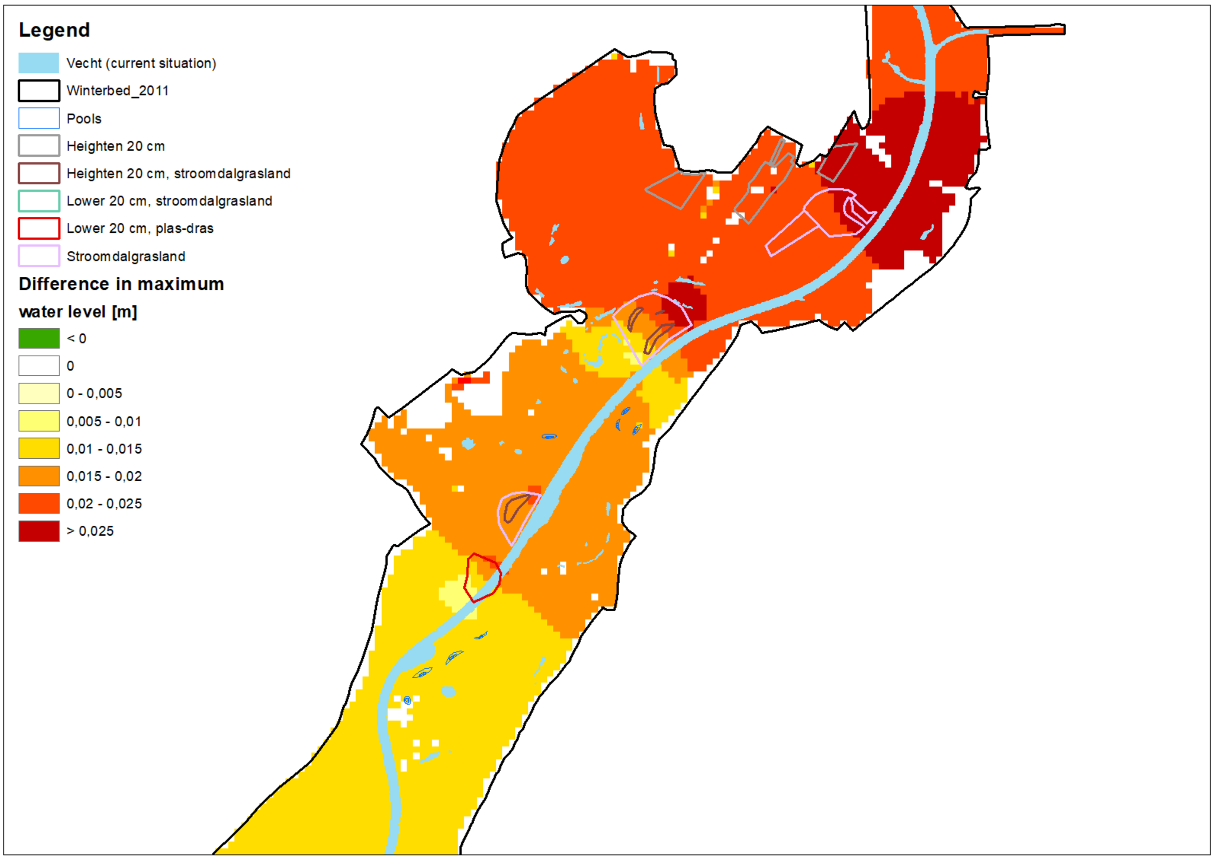

Figure 65. Difference in maximum water level [m] at Rheezermaten (both the measures at Rheezermaten and Karshoek-Stegeren implemented). A positive value indicates a higher maximum water level, while a negative value indicates a lower maximum water depth.

The change of vegetation clearly influences the flow velocity at Karshoek-Stegeren (Figure 66). The impact of reed on the flow velocity is larger than the impact of 'stroomdalgrasland' and forest. This can be easily explained by the roughness of those vegetation types. It can also be seen that one of the two areas where the vegetation will be changed into forest, the effects on the difference in maximum flow velocity is relatively low. This can be explained by the fact that this area is located in front of an area where there is no flow. Therefore, the flow velocity in the current situation is already relatively low.

When there is rougher vegetation on one side of the river, the flow velocity increases on the other side of the river. This can be seen in both bends at Karshoek-Stegeren. The same pattern can be seen at Rheezermaten (Figure 67). The rougher the vegetation type (and thus decrease in flow velocity), the higher the flow velocity on the other side of the River.

At the created pools, the difference in maximum flow velocity is the largest. This might be explained by the process of filling up the pools. Looking at Rheezermaten, when both projects are implemented (Figure 68), the flow velocity does not increase that much.

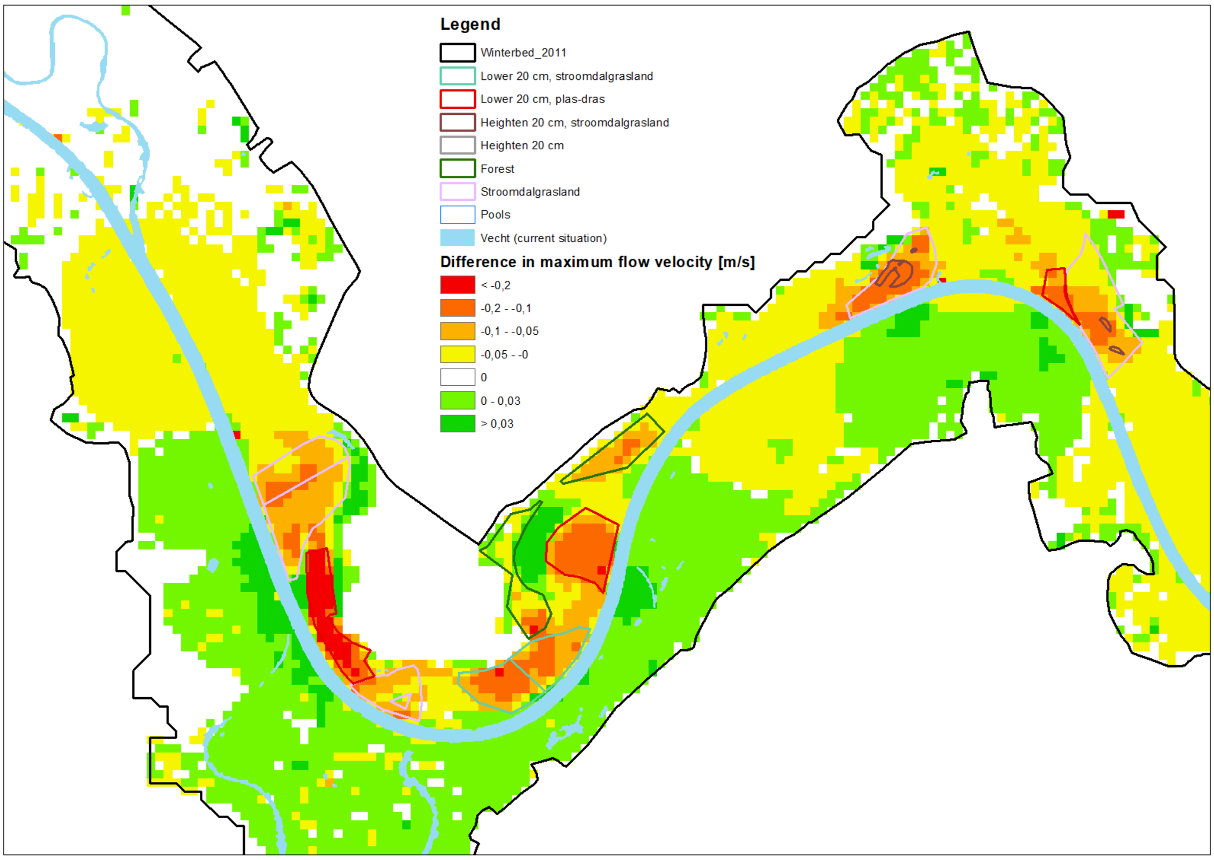

Figure 66. The differences in maximum flow velocity at Karshoek-Stegeren. A negative value indicates a lower flow velocity after the implementation of the measures, a positive value indicates a higher flow velocity.

Altogether, the impact of the measures of the projects at Karshoek-Stegeren and Rheezermaten is relatively small compared with the bandwidth (rough and smooth scenario), which is in order of magnitude of 1 metre. This is because the areas where vegetation is changed are relatively small. This shows that nature development, which is the goal of these projects, does not have to have an extreme influence on the water level. However, it must be stated that the effect of the change of the river course is not taken into account here. Alternative calculations in which the change of the river course has been taken into account, carried out by the R.W.A. Vechtstromen, show higher changes in the maximum water levels (5-10 cm).

Conclusion

There are two clear aspects of the location of rough vegetation that have a clear influence on the maximum water level: the blockage effect and the amount of space that is left for flow paths. When rough vegetation blocks the flow a lot, the maximum water level rises rapidly. The maximum water level can be lowered by creating wide flow paths. Vegetation in the river banks does not cause the maximum water level to rise very much, as long as there is room for flow behind the river bank vegetation. If this is not the case and the vegetation on the banks blocks the flow, the maximum water level will rise. Lastly, it must be taken into account that the combined effect of several changes is a different effect than when the changes are calculated separately from each other.

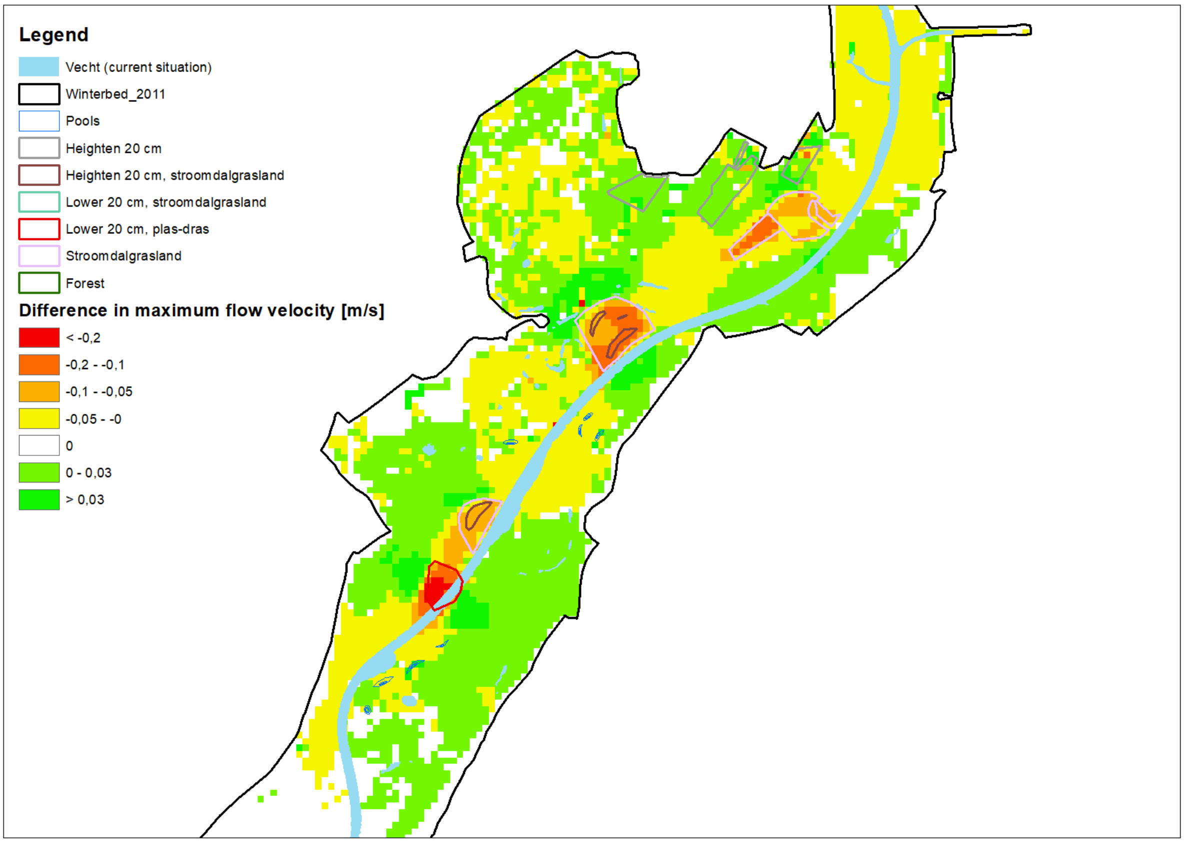

Figure 67. The differences in maximum flow velocity at Rheezermaten (measures at Rheezermaten only). A negative value indicates a lower flow velocity after the implementation of the measures, a positive value indicates a higher flow velocity.

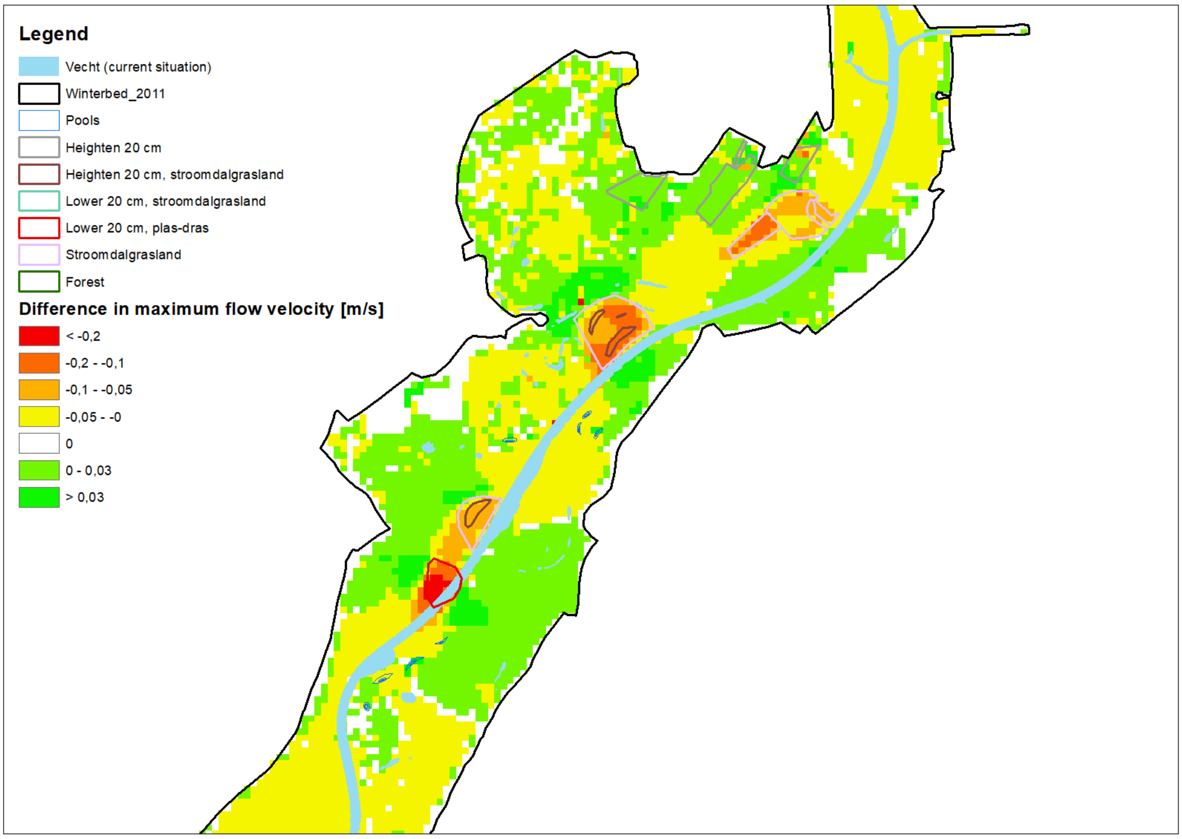

Figure 68. The differences in maximum flow velocity at Rheezermaten (both projects implemented). A negative value indicates a lower flow velocity after the implementation of the measures, a positive value indicates a higher flow velocity.