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The mutual relation between vegetation and inundation characteristics in floodplains

A case study of the Duursche Waarden

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SUMMARY

This report describes the investigation of the mutual relation between vegetation and environmental conditions (flood duration, frequency, dry periods, flow velocity). In the Netherlands water management is an ongoing challenge, of which the idea behind the solution has changed several times. This lead in recent times to giving the rivers more room to flow during high water ("Ruimte voor de rivier"), however the effect on the vegetation growth in the floodplains has not been studied very well. It is known that vegetation growth leads to an increase in the flood risks for that area, as the vegetation increases hydraulic roughness and therefore causes increased water levels (project "Stroomlijn"). It is therefore important to know how vegetation evolves in an area, to be able to manage it better and maintain water safety. In this report we will look at the link between environmental conditions and vegetation of the Duursche Waarden, which is a floodplain along the IJssel. Understanding this relation will help water managers to better manage the floodplains and possibly predict where vegetation might lead to problems for the water safety.

To investigate the relation between vegetation and environmental conditions, firstly the environmental conditions are mapped for the Duursche Waarden. For this, a model (WAQUA) is used to simulate flood waves to determine a Q-h relation and calculate the flow velocities in the Duursche Waarden. The Q-h relation is used to calculate inundations frequency, maximum inundation duration and a maximum dry period. These mapped environmental conditions are linked to vegetation classes of the ecotope map (grass, shrubs and forest) which remain the same over the years of 1998, 2005 and 2012. Areas which experience changes in the vegetation classes from those ecotope maps will also be linked to the environmental conditions, to see if this can be explained by environmental conditions. Comparing the different vegetation classes and under which environmental conditions these vegetation classes are found most, it can be concluded that there is a difference between grass and shrubs and under what environmental conditions they are present. Interestingly, the areas where the vegetation changes between they years show to be contained to areas which experience environmental conditions more similar to what vegetation they change into.

Secondly, the relation of vegetation on the flood characteristics is investigated. To do that, the Duursche Waarden is simulated as completely covered by paved surface, grass, shrubs or forest. The results from the simulations show how much different types of vegetation affect the flood characteristics and with that the water safety. The resulting information is compared to the current situation, which leads to the conclusion that not all vegetation has necessarily a bad influence on a flood. While a large forest does slow down the water flow and increase the water levels in an area, there are still locations within the Duursche Waarden which do not seem little to not affected.

To conclude, vegetation affects floods and floods affect vegetation. Linking vegetation to environmental characteristics can help predict where certain vegetation is likely to change into another type of vegetation. Furthermore, not all vegetation forms a risk for the water safety. Depending on the amount and where it is located the effect could almost be neglectable. Knowing this mutual relation between vegetation and environmental conditions could help water managers manage floodplains, while still reserving space for nature.

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1 INTRODUCTION

1.1 BACKGROUND

Providing water safety against flooding is a major management challenge in the Netherlands. This management challenge is not only caused by water quantity, but also by the interaction of water with environmental and socio-economic sectors such as health, agriculture, industry, navigation and tourism (Zevenbergen, et al., 2013). Over the years, the way on how to combine water safety with other riverine functions has changed. Plan “Ooivaar” (1986) and project “Ruimte voor de Rivier’ (2007) adopted the view that water safety and other riverine functions could be combined when working with nature instead of seeing it as a threat (Zevenbergen, et al., 2013). Project “Ooievaar” aimed at bringing nature back to the river areas to, among other things, attract species not seen in several years (de Bruin, et al., 1987). Project “Ruimte voor de Rivier” expanded the floodplain areas (Zevenbergen, et al., 2013). However, a more recent project, “Stroomlijn”, stressed that nature may jeopardize water safety if nature is allowed to develop freely into floodplain forests (Rijkswaterstaat, 2009).

The interaction between floods and vegetation has been demonstrated by several studies. On the one hand, flooding affects floodplain vegetation by flow velocity, erosion, sedimentation, inundation depth, inundation frequency and duration (Blanch, et al., 1999, van Eck, et al., 2004, Jackson & Colmer, 2005, Miao & Zou, 2012, Riveas, et al., 2014). On the other hand, vegetation affects water flow and level as well, potentially causing water safety issues. As vegetation increases the roughness of an area, flow velocities decrease and water levels increase (Baptist, et al., 2007).

In the Netherlands the ecotope class system is used to relate vegetation to roughness. These ecotopes are georeferenced and contain information about abiotic, biotic and anthropogenic conditions of an area (Wolfert,1996). Because ecotope classes have detailed information about the vegetation found in an area which, they can be used to make a translation to roughness of that area. The translation of ecotope class to roughness has been done by van Velzen, et al (2002), they published what roughness coefficient and formulas should be used for each ecotope class. The ecotopes are found in ecotope maps published in 1998, 2005 and 2012, giving access to information about the changes in vegetation over the last 2 decades.

Having access to several time periods of vegetation is important to see what changes in this vegetation could lead to safety risks, which is the thought behind project “Stroomlijn”. Makaske, et al (2011) has done simulations to see what effect management can have on the roughness of floodplains. In which it is concluded that vegetation development can lead to a relatively large hydraulic impact. To investigate how current vegetation is linked to environmental conditions and what these environmental conditions can say about the potential development of vegetation in the future. Using this relation to predict the likely development of vegetation and roughness changes in floodplains to support management of the floodplains to increase water safety and other ecosystem services. Therefore, this study will look at the linking of ecotope classes to flood characteristics and how these flood characteristics are affected by differences in vegetation, on the Duursche Waarden. Which is a floodplain in the river IJssel, where there have been few management influences. This is important as to understand how floodplain vegetation evolves over time based on what happens in these floodplains. Knowing where certain vegetation will grow and what its influences on the safety are, can be used to making predictions of how a floodplain will look like in the future. This study will contribute to the PhD work of V. Harezlak, within the "Rivercare" programme.

1.2 OBJECTIVE

The objective of this research is to determine and the map various environmental conditions and linking them to ecotope classes, to get a better understanding of the mutual relation between vegetation and environmental conditions.

In this study, the following environmental conditions will be considered: inundation frequency, inundation duration, ground water levels and flow velocities. To link these to vegetation the ecotope maps of 1998, 2005 and 2012 will be used. The objective leads to the following research questions and will be focused on the Duursche Waarden.

1. How can the environmental conditions of the study area over the last 25 years be characterized?
2. How do these environmental conditions correlate with the vegetation in this area?
3. To what extent does the vegetation affect the environmental conditions?
4. How does the vegetation affect the flow capacity and water levels in the floodplain?

1.3 METHODS AND REPORT OUTLINE

The first research question is answered by using a 2D-model of the Dutch Rhine river system in WAQUA. The model uses roughness based on ecotope maps. Simulations in the model will be done with available discharge data from Lobith. The resulting data will be used to create maps for each considered environmental characteristic (inundation frequency, maximum duration of inundation, maximum flow velocities and ground water level). The tools and methods will be described in more detail in chapter 2 and the results in chapter 3.

For the second research question, the maps from research question 1 will be used together with the available ecotope maps. Points will be selected, using the model's grid, which will be filtered on vegetation classes found in all 3 ecotope maps (grass, shrubs, forest and changing vegetation between the 3 time-periods). These points will be compared with the environmental conditions simulated. The aim is to find if specific environmental conditions are present in an area with the same vegetation classification. This will be described in chapter 3.

The third and fourth research questions will be answered by doing new simulations will be done with different vegetation classes dominating the case area. From the results of these simulations, maps will be created with the different environmental condition and compared to the original situation. From the results an estimate will be made on how much vegetation can affect flood characteristics in this area. This will be described in chapter 4.

2 METHOD

This chapter describes the study area, the model, the data and the data preparation.

2.1 STUDY AREA

The case that will be studied is the Duursche Waarden, a floodplain along the IJssel. This is a nature area which functions as floodplain during extreme discharges. The Duursche Waarden was one of the first nature development plans of the Dutch Rhine from the “plan Ooievaar” (Dirks, et al., 2014). This area was altered in 1989 to be more dynamic, letting the area be controlled by the river rather than men. Cattle was introduced to graze the area to control the vegetation growth in a natural way. Shown in figure 1 is the location of the Duursche Waarden and its layout. The study area has been divided into 3 areas for this research. Area 1 contains the nature area of the Duursche Waarden, area 2 is a higher laying area, containing a forest, area 3 is dominated by agriculture and this area floods in times of high water creating a by-pass of the river together with area 1. These locations are based on the height and vegetation types found.

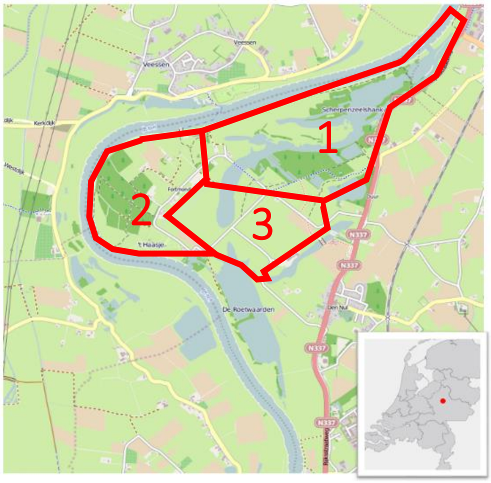

Figure 1: Duursche Waarden (Openstreetmap), divided into 3 areas: area 1: natural area, area 2: high laying area and area 3: agricultural area.

While the original plan was to keep nature the main drive behind this area, there have been a few interferences. Because of safety reasons there were a few measures taken in the projects of “Ruimte voor de rivier” and “Stroomlijn” (Dirks, et al. 2014). This consists of a new channel north of the Duursche Waarden (2014, this measure is not visible in figure 1), extending a channel in the Duursche Waarden themselves (2007, the channel extending from section 1 into area 3 in figure 1) and the removal of rough vegetation within the Duursche Waarden (2013, focussed in area 1 in figure 1).

This area has been redeveloped in the last 25 years, where it used to be an agricultural and industrial area (clay mining and a brick factory) it has been redeveloped to be more natural. This area is now being dominated by the river and natural processes rather than by human influences, so most relevant changes due to inundations of the floodplain should be observable (Dirks, et al., 2014). While there is little human interference since the redevelopment except for the projects mentioned, it makes a good study area for this research. The area consists mostly out of grassland, shrubs (herbaceous vegetation) and forest, which will be the three vegetation types most focused on in this study.

2.2 MODEL

The model used for this study is a complete schematization of the Dutch Rhine in WAQUA. This model contains:

- Roughness based on ecotope maps
- Constructions within this area including dams and locks
- The height profile of the river Rhine and surrounding land

The model solves the shallow water equations, assuming incompressibility and shallow flow. See the WAQUA manual for the exact equations and derivatives used (Rijkswaterstaat, 2015).

The schematization used is the 1995 situation. It should be noted that several alterations have been made in the Dutch Rhine in the last decades, like the Room for the River projects. To limit the influence of these alterations this older model was chosen to have more correct comparison with the ecotope maps as 2 were created before the Room for the River projects. Note that the ecotope classification of 2012 was made after some alterations to the study area, these alterations will be ignored in this study. Ignoring these alterations can lead to some inaccuracies for the results for the 2012 ecotope map. However, by using 1 model for the whole study other changes between model schematics are avoided. The grid for the model is shown in figure 2.

The input used in the model is the discharge at Lobith and several secondary lateral discharges. For this a dynamic flood wave will be used based on the available data (see section 2.3.1). To lower the simulation time, every simulation will be started with an initial water level based on a 1600 m^3/s discharge at Lobith. Using an initial water level rather than set global values to remove spin up time of the model.

The model will do 7 simulations. Every simulation with a flood wave of different magnitude, see section 2.3.1. The results from the simulations are used to estimate a Q-h relation (see section 2.4), which will be used as baseline for the maps to translate the discharge data available to water levels in the Duursche Waarden (will be described in section 2.5).

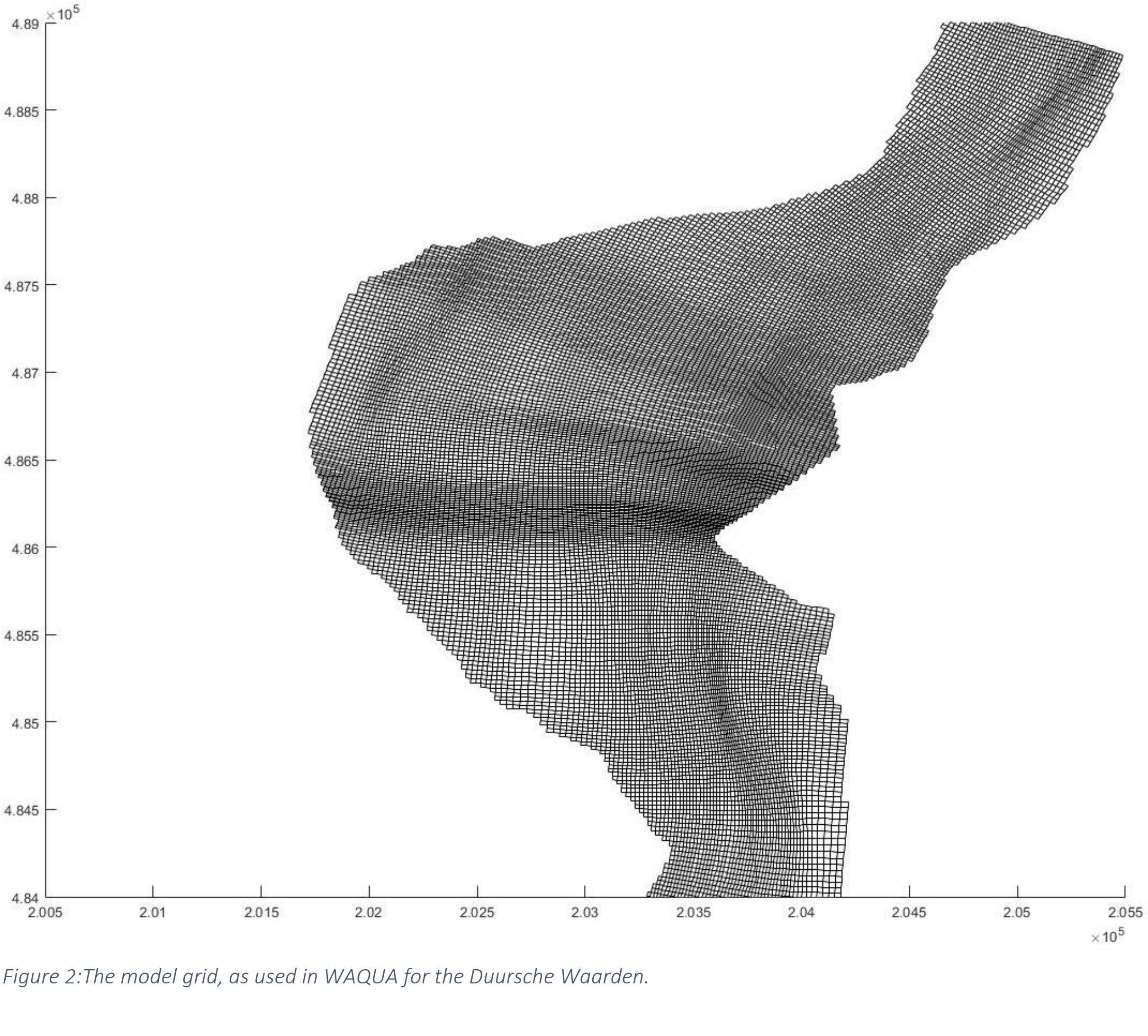

Figure 2:The model grid, as used in WAQUA for the Duursche Waarden.

2.3 DATA

2.3.1 DISCHARGE DATA

The different discharges that will be used for the simulations will be estimated based on return periods and an extreme value distribution. The discharge data at Lobith is shown in figure 3. This discharge data is freely available through live.waterbase.nl. The available time-series contains daily values for the Rhine at several locations in the Netherlands. The available data for discharges (in m^3/s) at Lobith starts at 1989 and continues to November 2016 (as off 12 May 2017). While longer time-series exist for the water levels at Lobith, discharges are only available from 1989 onwards, therefore that time period is used for this research.

From the discharge data, the yearly maxima are taken and sorted in ascending order. These yearly maxima are fitted to an extreme value distribution (Gumbel). From the extreme value distribution, different peak values for the simulations can be found based on return periods. These peak discharges are used to scale the flood waves to, which are used in the model. Both the extreme value distribution and the flood wave used within the model are shown in figure 4.

The lateral discharges will not be scaled according to the used maxima. This because these lateral discharges are relatively small compared to the discharges at Lobith. Therefore, any changes happening to the water in the model are caused by the discharge data at Lobith.

2.3.2 ECOTOPES

The vegetation in an area must be mapped and classified to be able to use it in models and simulation. In the Netherlands, this is done through ecotopes. An ecotope is a spatial confined ecological unit, of which the composition and development is determined by abiotic, biotic and anthropogenic conditions at that location. An ecotope is a recognizable, approximately homogeneous scenic unit (Wolfert, 1996). These ecotopes represent the vegetational state in an area which, among other things, can be used to estimate the roughness of these areas.

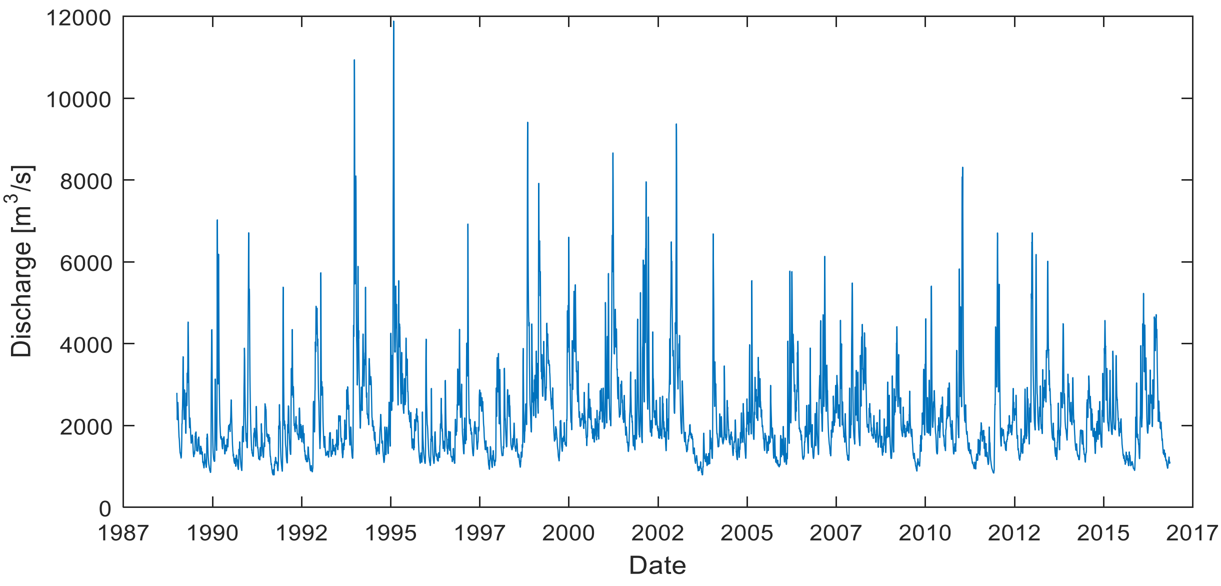

Figure 3: Discharges Rhine at Lobith (live.waterdatabase.nl)

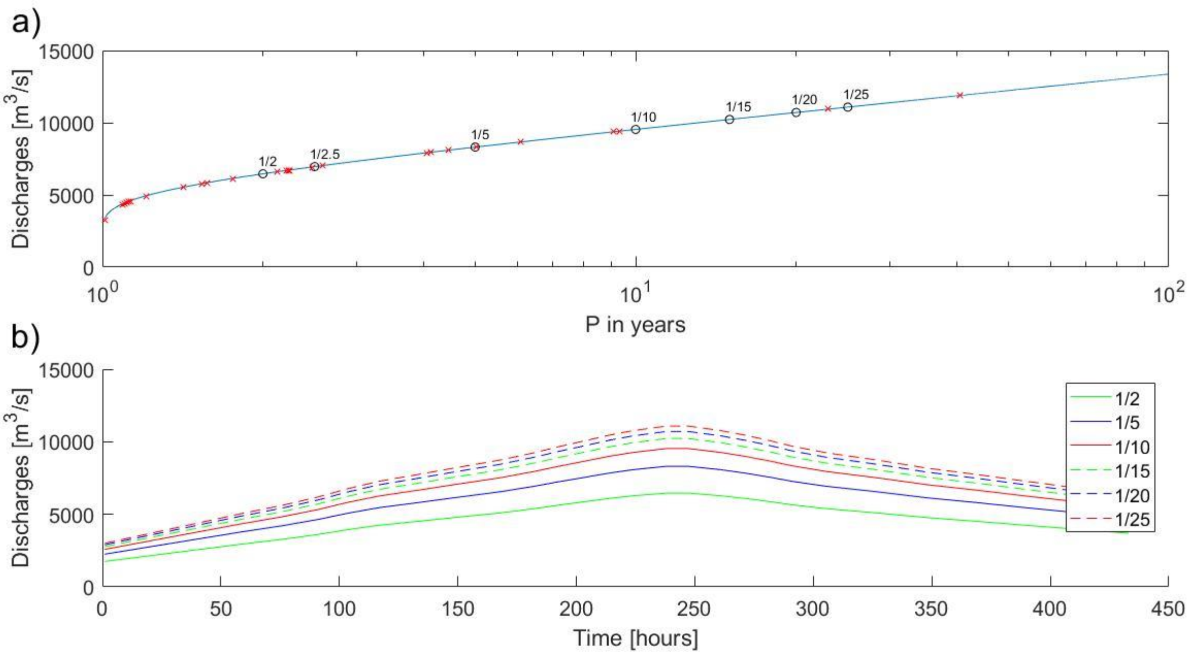

Figure 4: a) Extreme value distribution (blue line), black circles are the peak discharge used for the flood waves in the simulation, the red markers indicate the yearly maxima in the data set which are used for the fit of the extreme value distribution. b) the used flood wave for the model which will be up or downscaled based on the found values in the extreme value distribution.

These ecotopes are described in Van Velzen, et al. (2002), which includes the factors that determine the flow resistance of this area, i.e. include the average height of the vegetation, the number of stems per square metre, the stem diameter and the drag coefficient. These factors are all based on a winter situation. If needed different situations for the grazing of these areas are enlisted, using no grazing, extensive grazing and intensive grazing scenarios. As stated in section 2.1, the Duursche Waarden are grazed by cattle, which means that most vegetation types will have a lower height which makes it smoother in terms of hydraulic resistance.

These ecotopes are georeferenced into maps. These maps are available through PDOK (public services on the map) or Rijkswaterstaat. Figure 5 shows the ecotope maps for the Duursche Waarden, showing all three different cycles made over the years (1997/1998, 2005 and 2012). Notable however is the difference in classifications over these years. For example, the forest in the bend of the river has been

Change in vegetation in the Duursche Waarden	**Area in ha**			**change in area in percentage**	
Vegetation Type	**1998**	**2005**	**2012**	**1998 to 2005**	**2005 to 2012**
Crop field	60	38	42	0	0
Urban	24	25	25	3.44%	-0.66%
Forest	**82**	**85**	**81**	**4.22%**	**-4.26%**
Grass	**369**	**358**	**363**	**-2.86%**	**1.45%**
Natural grassland	124	0	125	-100.00%	
Production/natural grassland	0	66	37		-44.22%
Production grassland	245	292	201	19.02%	-31.14%
Shrubs	**45**	**74**	**42**	**62.87%**	**-43.47%**
Reed	9	9	11	5.34%	23.96%
Tall Herbaceous vegetation	28	53	19	92.80%	-63.72%
Brushwood	9	11	11	25.13%	-1.02%
Barren	0	0	20		
Shallow water	0	0	17		
River-guided water	84	84	74	0.00%	-11.73%
River	91	91	91	0.00%	0.09%
else	1	0	0		
total	755	754	755		

Table 1: Changes between the different ecotope maps for the Duursche Waarden.

classified as forest in 1998 and 2005, while it is classed as hardwood forest in 2012. Table 1 shows the changes in ecotope classes over the years.

Comparing these maps shows the differences between vegetation over the years. The first thing to note is the increased area with shrub vegetation from 1998 to 2005 and a strong decrease of this in 2012. Here it seems to be mainly a change from natural grassland to shrubs and from shrubs back to natural grassland again.

Secondly there is grassland that turned into shrubs from 1998 to 2005 and then in to bare soil in 2012 in the middle southern area (near the lake). This could possibly due to erosion or manmade influences.

Lastly there seems to be a change in the usage of farm land in this area, whereas it was first used as crop field, which has later been turned into production grassland. Possibly a result of floods in the past which changed the agricultural focus from crops to production grassland.

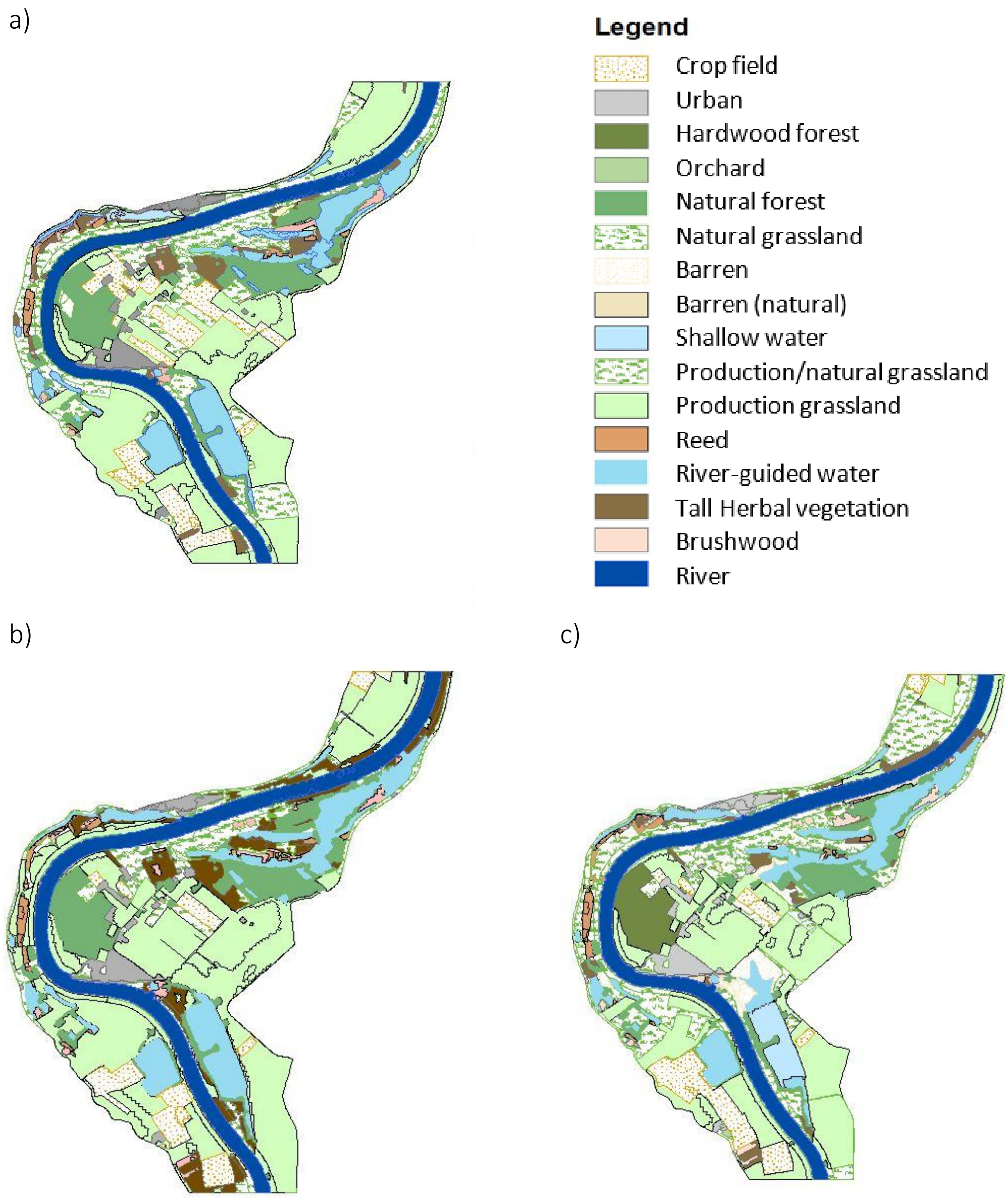

Figure 5: Ecotope maps Duursche Waarden from Rijkswaterstaat a) year 1998 b) year 2005 c) year 2012 (Geodata Rijkswaterstaat)

2.4 Q-H RELATION DUURSCHE WAARDEN

As stated in section 2.2, a Q-h relation will be derived for the Duursche Waarden using WAQUA and the discharges at Lobith as input. This relation will be used to calculate how often an area experiences certain inundation characteristics. For this the water level in location B, see figure 6, will be used. This area lays relatively in the middle of the research area which limits the over or under estimation of the water level when another location would be used, as upstream areas would have a higher water level and more downstream areas a lower water level. The maximum water level on this location is taken and linked to the maximum discharge at Lobith for the flood wave used in the simulation.

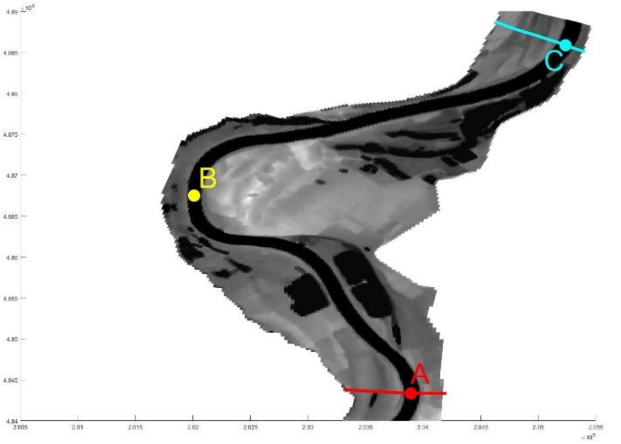

Figure 6: Locations q-h relations, location A in red, location B in yellow and location C in blue.

To derive the Q-h relation the results of the simulations of the peak discharges in section 2.3.1 are used together with 3 lower discharge flood waves to also get information for lower discharges. The lower discharges used are 3278 m^3/s (the lowest yearly peak in the data set), 1600 m^3/s (half the maximum yearly peak) and a situation with no discharge. The Q-h relation derived from this is shown in figure 7, added here are location A and C which are upstream and downstream of the area. These extra locations show the possible over and underestimation in the Q-h relation, this is the potential inaccuracy in the mapped characteristics in chapter 3.

For location A and C, the discharges over the cross-section, shown in figure 6, are estimated by taking the maximum water depth and flow velocities, based on only the 6 peak discharges from section 2.3.1. The Q-h relation found is shown in figure 8, which shows that this floodplain lowers the peak discharge with a small bit. This means that the floodplain lowers the peak discharge with roughly 50 m^3/s.

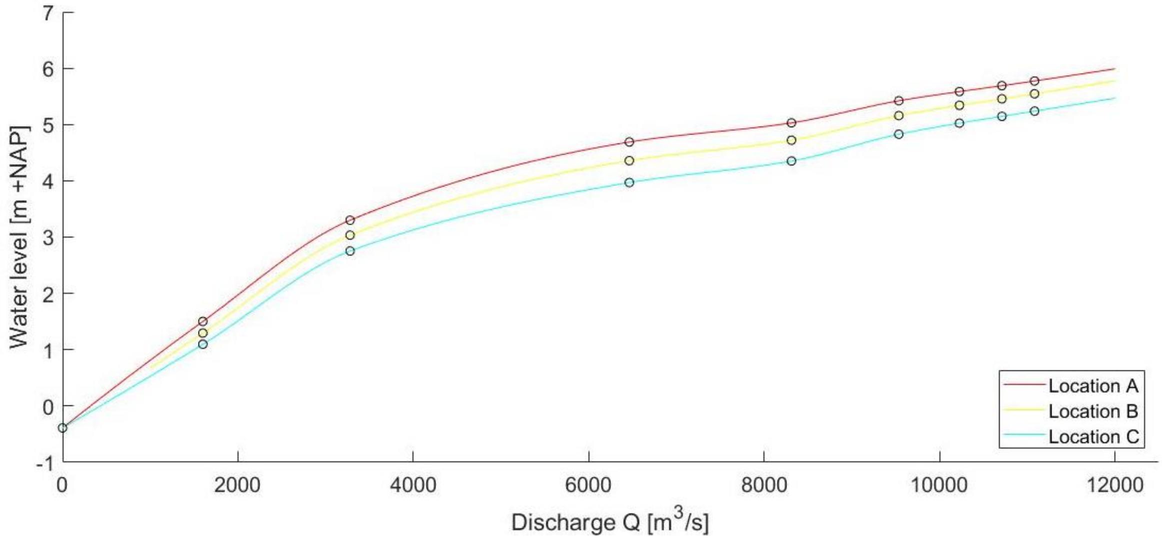

Figure 7:Q-h relation Duursche Waarden with the discharges at Lobith and the water level at the Duursche Waarden.

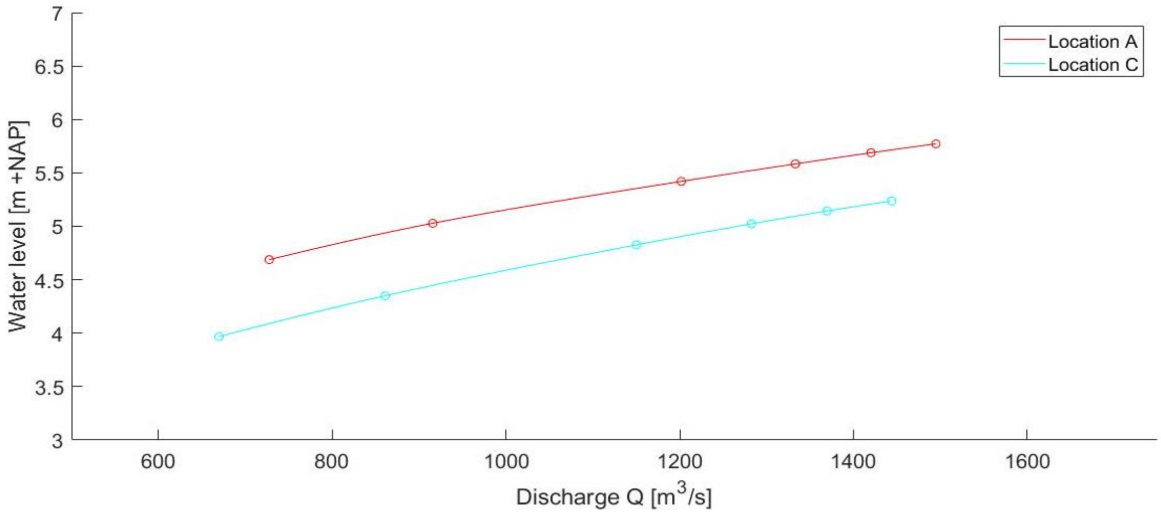

Figure 8: Q-h relation Duursche Waarden with the discharges at Duursche Waarden and the water level at the Duursche Waarden.

2.5 DETERMINATION OF ENVIRONMENTAL CONDITIONS

To map the environmental conditions, the discharge data (figure 3) will be converted into water levels by use of the Q-h relation found in section 2.4 (figure7). This is done by taking the empty river data as a baseline for the ground level of the Duursche Waarden. For every grid cell the intensity of each environmental condition is calculated. This will be done for the time periods leading up to the creation of the different ecotope maps (1991-1998, 1998-2005 and 2005-2012) and the entire discharge data available (daily discharges). A difference map will be made which is based on the 7 years of discharge data leading up to the creation of the ecotope maps, showing the difference between those time periods (1998, 2005 and 2012).

The environmental conditions are defined as follows:

- The inundation frequency: the percentage of the time a cell is flooded. This means that a location with 10% inundation frequency on average will be flooded 36 days a year.
- The maximum inundation duration: the maximum continuing flood duration in days. This means that the longest consecutively succession of days that a cell is flooded is calculated.
- The dry period duration: the maximum continuing period in days that the groundwater is below 1 meter under ground level. For the groundwater level an estimation is made, in this report the groundwater level is considered to be the same as the water level in the river.
- The flow velocity: as the flow velocity cannot be based on the Q-h relation, the simulation results from the peak discharges found in section 2.3.1 are used. From the simulation results the maximum flow velocity per cell is used in the maps.

The maps created from this are displayed in chapter 3. Linking these environmental conditions to vegetation classes is done by comparing the vegetation classes over the 3 ecotope maps and see if the vegetation classification remains the same or if it changes. The vegetation classes taken into account are grass (nature and production), shrubs (herbaceous vegetation, brushwood) and forest (natural, production and hardwood). No initial difference will be made between different types of similar vegetation, like natural grass and production grass as over the different ecotope maps these classifications sometimes change and natural grass is suddenly classed as natural/production grass in another ecotope map. The grid cells leftover from this selection are looked up in the 1991-1998, 1998-

2005 and 2005-2012 maps for each environmental condition, except flow velocity as this environmental condition isn't based on the discharge data but rather the flood waves used for he simulations. The resulting data is displayed in a boxplot, see section 3.5.

3 Environmental conditions

This chapter answers the first two research questions as described in chapter 1. This chapter can therefore be split in 2 parts, first the mapping of the environmental characteristics (sections 3.1 -3.4) and the linking of these environmental characteristics to ecotope classes (section 3.5).

3.1 Inundation frequency

The frequency map is displayed in figure 9 and a difference map is displayed in figure 10. The individual maps per period can be found in the appendix. Areas within these maps:

1. The nature area: This low laying area close to the river, is more often inundated than surrounding areas. The time this area is inundated ranges between 25 and 100%. Variations in inundation time are caused by differences in elevation. The main part of this area shows no variation between the three 7-year periods before each ecotope map. However, the parts that are showing changes, change between all three periods. The dryer parts experience fluctuating inundation frequencies over time. The comparison of this area with the ecotope maps, shows that the changes in vegetation over the years in this area, partly correspond with the changes in inundation frequency. An increase in inundation frequency may have resulted in a shift from inundation sensitive species to species that are fit to handle frequent inundations (Jackson & Colmer, 2005). This change could occur due to vegetation being damaged by the inundations (van Eck, et al., 2004, and Blanch, et al. 1999). Which results in more inundation resistant species growing in these areas (Jackson & Colmer 2005, and van Eck et al., 2004).
2. The high ground: This area is rarely to never inundated because of its elevation. Small areas near the river are sometimes inundated for short time periods, this is less than 10% of the time within the dataset. This area changes little over the different time periods, the changes mainly occur near the river.
3. The agricultural area: This area has a variety of inundation frequencies. This area becomes inundated before the higher grounds (area 2). Therefore, this area contributes significantly to the flow in case of high discharges. Nevertheless, a large part of this area is inundated less than 1% of the time, while smaller parts vary between 1 and 10%. This area shows a lot of changes between the different time periods. Comparing this with the discharges at Lobith, it shows that after 2005 the peak discharges are slightly lower than before 2005. Which could be the reason of the change between the 1998-2005 and 2005-2012.

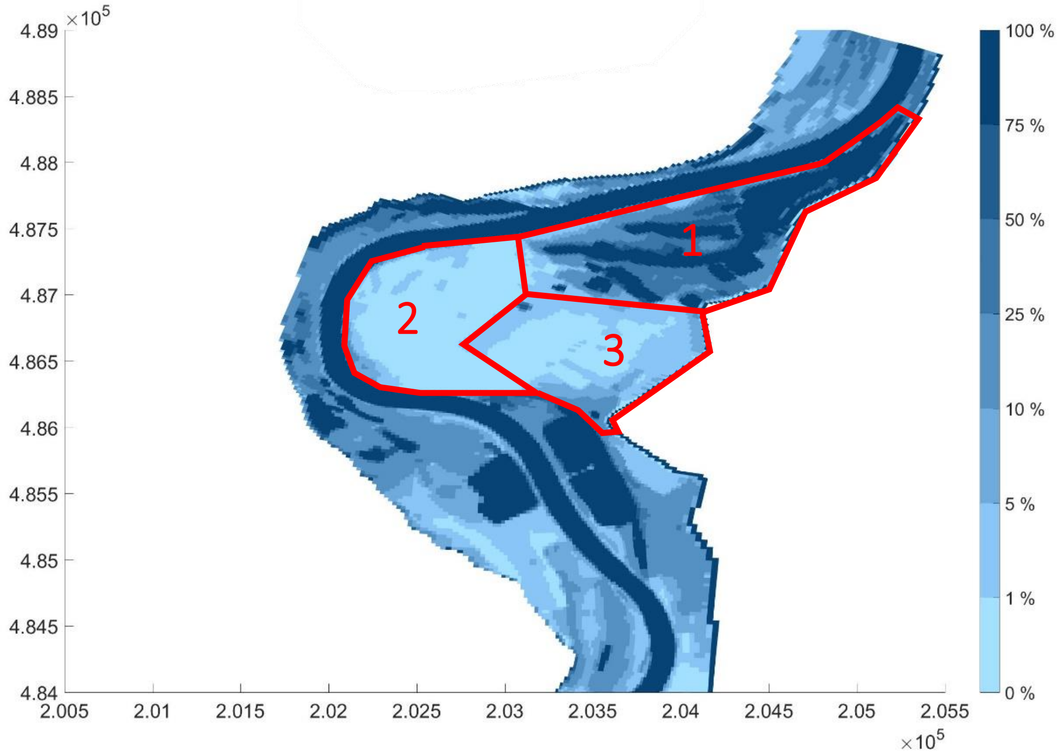

Figure 9: Inundation frequency expressed as percentage of time inundated, based on the complete available data-set (1989-2016). Coordinate system is based on the Dutch coordinates (RD) in metres.

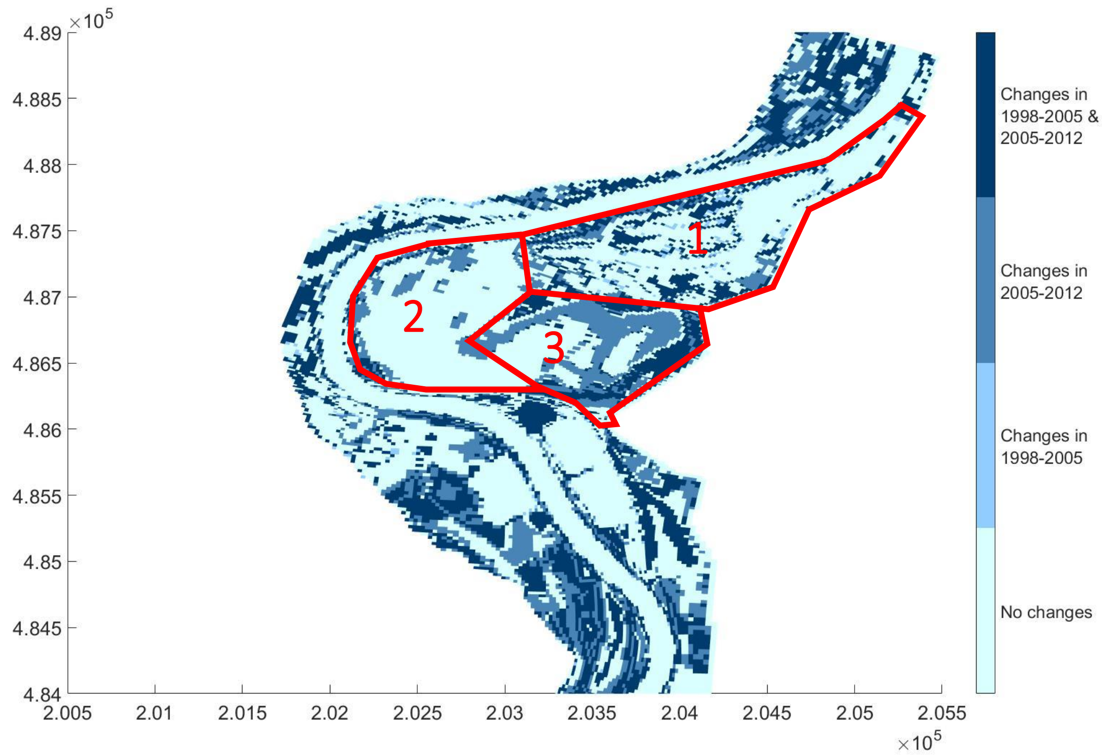

Figure 10: Differences in frequency in an area in the 7 years before the creation of the ecotope maps of 1998, 2005 and 2012. Coordinate system is based on the Dutch coordinates (RD) in metres.

3.2 INUNDATION DURATION

The inundation duration is displayed in figure 11 and a difference map is displayed in figure 12. The individual maps per period can be found in the appendix. Areas within these maps:

1. The nature area: This being a lower laying area close to the river, shows that it is longer inundated then the other areas. Varying between 50 days to 250 days in some locations. Looking at the differences map, there are a lot of changes between the different time periods. This is to be expected as this characteristic looks at the most extreme situation in the available data. This could lead to various kinds of vegetation which are more or lesser resilient towards longer inundations (Blanch, et al, 1999).
2. The high ground: Again, not much happens in this area due to the high location. Therefore, there are nearly no changes over the time periods in this area. This could suggest that the area is stable allowing for the vegetation to remain the same. Looking at the ecotope map, it shows that there are little to no changes in the vegetation here.
3. The agricultural area: This area has a very consistent inundation duration over the entire section, varying between 0 to 75 days and is concentrated between 25 and 50 days. The difference map shows mostly no changes, except for the middle area where it shows changes for all time periods.

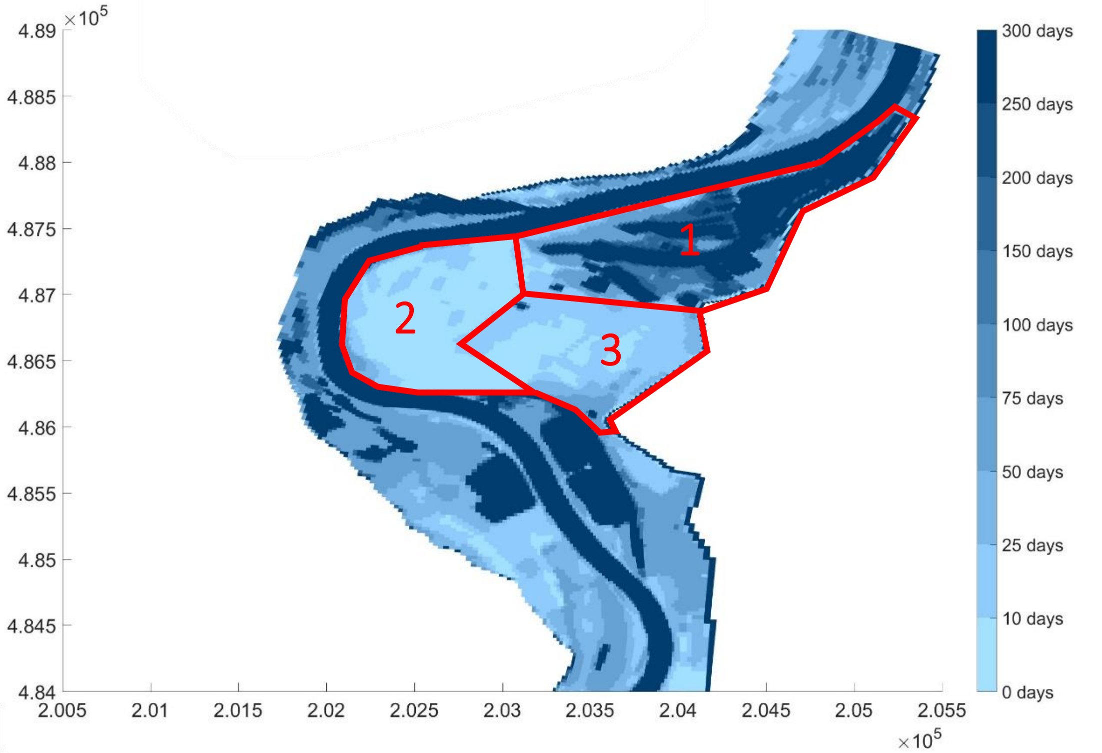

Figure 11: Maximum flood duration expressed in days, based on the complete available data-set (1989-2016). Coordinate system is based on the Dutch coordinates (RD) in metres.

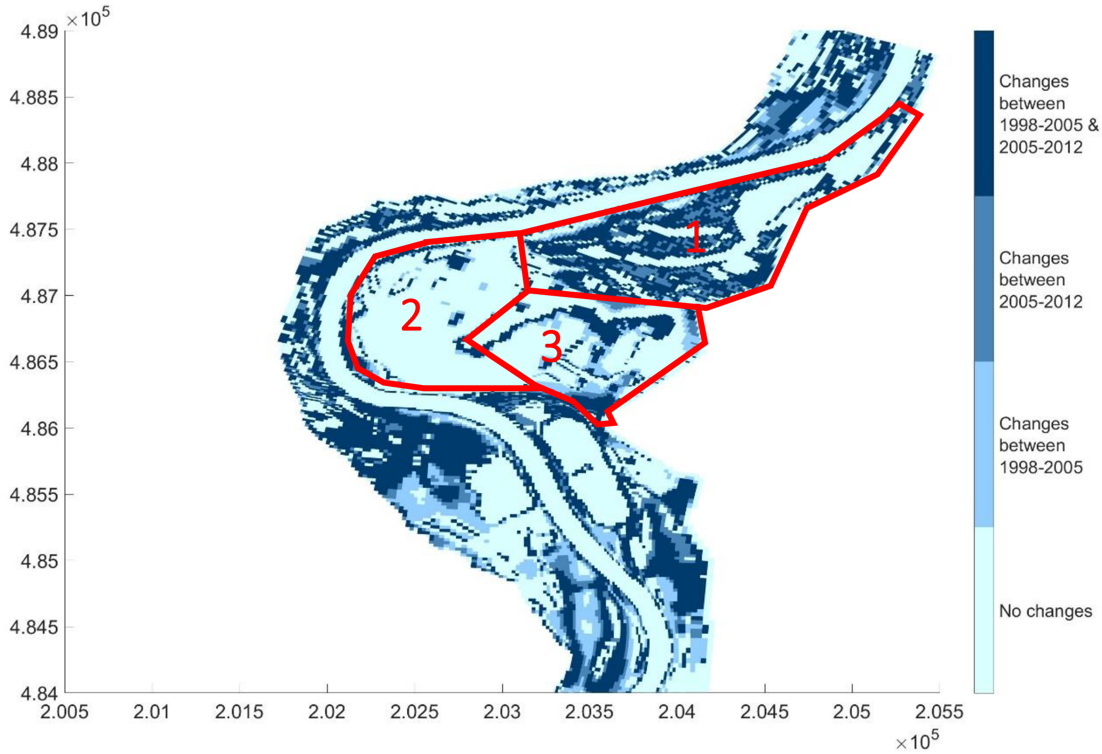

Figure 12: Differences in inundation duration per area in the 7 years before the creation of the ecotope maps of 1998, 2005 and 2012. Coordinate system is based on the Dutch coordinates (RD) in metres.

3.3 Dry period duration

This is displayed in figure 13 and a difference map is displayed in figure 14. The individual maps per period can be found in the appendix. Areas within these maps:

1. The nature area: The map shows only a few dry areas, which are contained between the channels found in this area. This would suggest that the groundwater is rather high throughout the entire data set, keeping the vegetation wet in this area. Having longer dry periods might lead to vegetation with longer roots having a better survival chance, while the shorter rooted vegetation will possibly die due to dehydration (Jackson & Colmer, 2005).
2. The high ground: This area shows a long dry period, this is not unexpected as the area is a lot higher than the surrounding area. This might be an explanation to why there is a forest in this area as trees are able to abstract water from deeper locations compared to other vegetation types.
3. The agricultural area: It is rather unexpected to see that this area shows a long dry period. However, comparing this to the maximum flood duration, it shows that the maximum flood duration only goes up to 75 days. Considering this is an agricultural area, it is not unlikely that this area has artificial managed ground water levels. Also considering the method used to estimate the groundwater level ignores bulging, which would cause the groundwater level to be both over and underestimated depending on other environmental conditions, like rainfall.

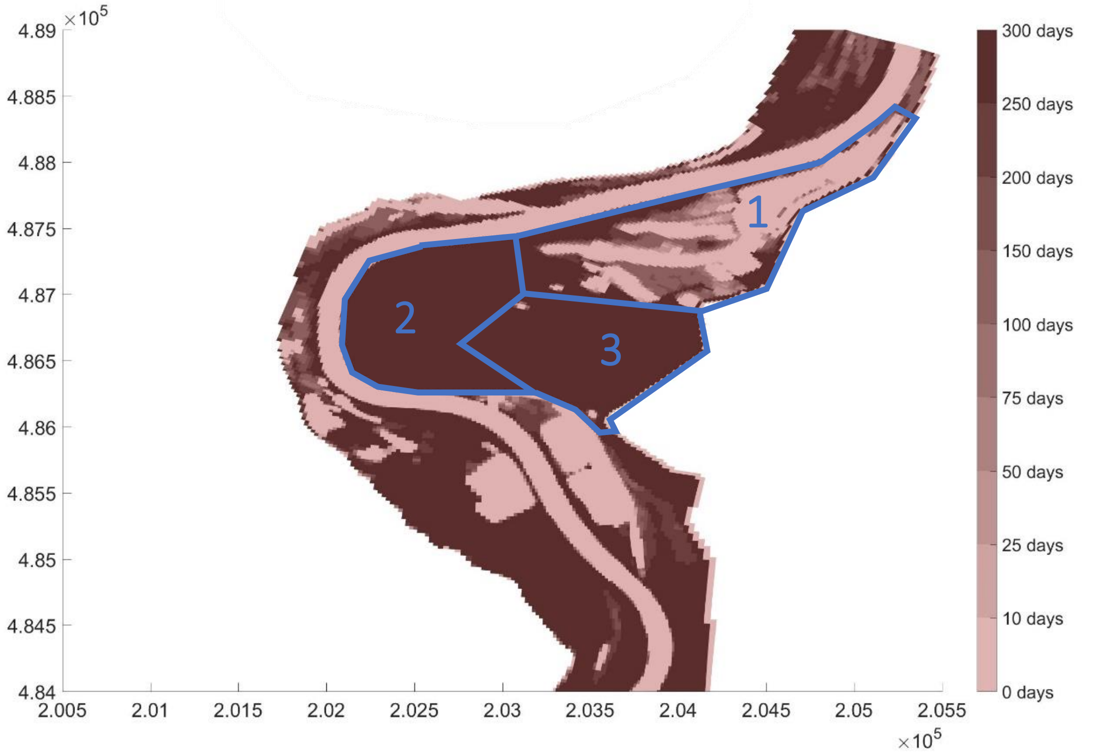

Figure 13: Maximum dry duration expressed in days, based on the complete available data-set (1989-2016). Coordinate system is based on the Dutch coordinates (RD) in metres.

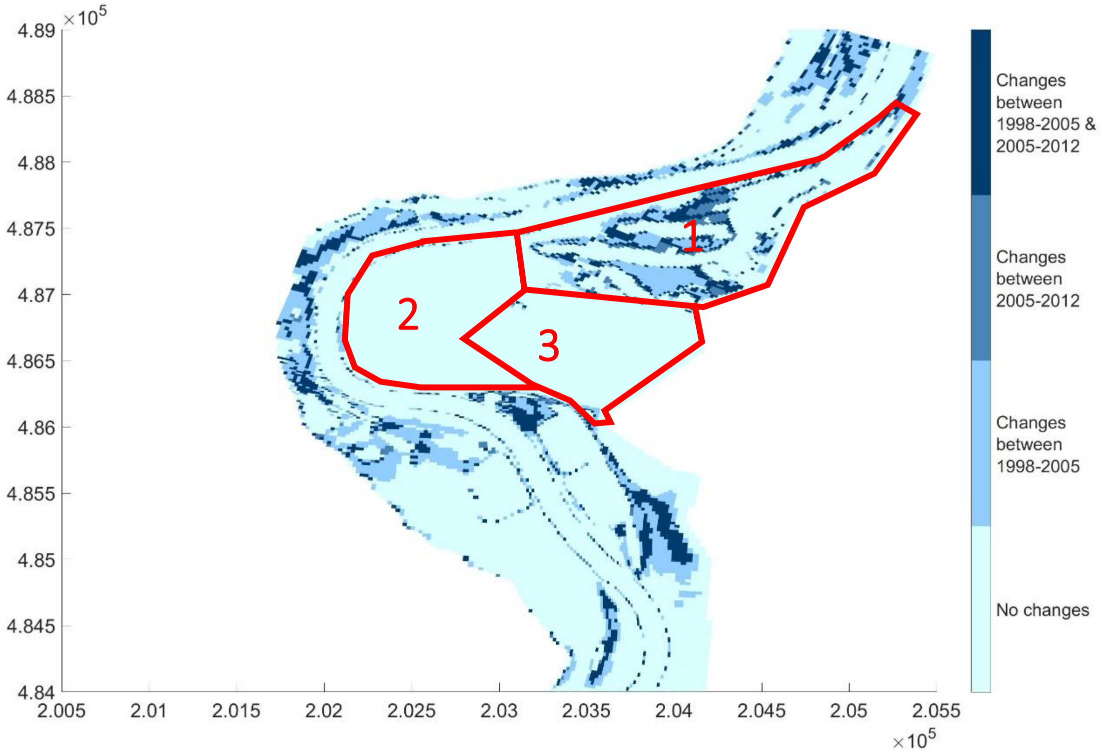

Figure 14: Differences in dry duration per area in the 7 years before the creation of the ecotope maps of 1998, 2005 and 2012. Coordinate system is based on the Dutch coordinates (RD) in metres.

3.4 Flow velocity

As stated in section 2.5, the flow velocity is based solely on the simulations, for this the flood wave of once every 2 years and once every 2.5 years is ignored as both do not show flow over the floodplain in the simulation results. The flow velocity greater than 0.3 m/s is shown in figure 15, figures for flow velocities of greater than 0.1 to greater than 0.5 m/s can be found in the appendix.

1. The nature area: The map shows only a limited area that experiences flow velocities higher than 0.3 m/s in some flood waves. This would indicate that most of the time the flow velocity in this area is rather low, causing little or no erosion and possible some sedimentation of those areas, which in turn would boost the vegetation in this area (van Eck, et al, 2004, Riveas, et al., 2014).
2. The high ground: As shown earlier, this area experiences near no inundation, which means no flow in this area.
3. The agricultural area: A large part of this area largely experiences flow velocities higher than 0.3 m/s. This relatively high flow velocity could result into erosion and/or damaging the vegetation found here. However, as this area is mainly used for agricultural purposes, this cannot be found in the ecotope maps.

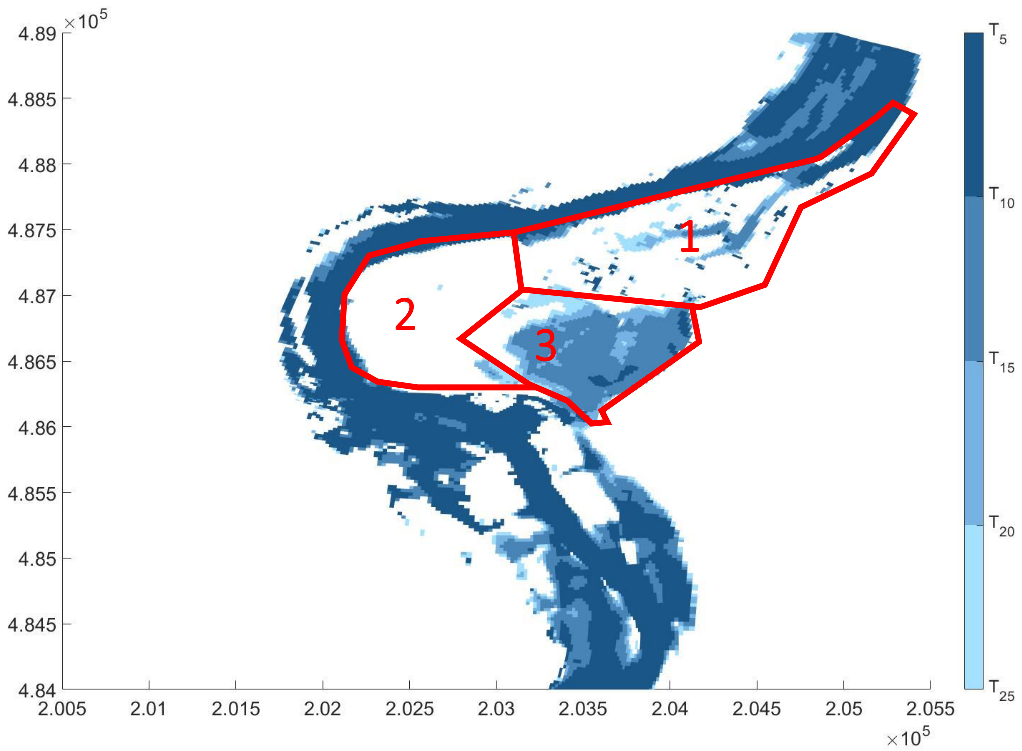

Figure 15:Maximum flow Velocity higher than 0.3 m/s, in different simulated flood waves, scale based on return period (T_5 means a once in the 5 years flood wave). Coordinate system is based on the Dutch coordinates (RD) in metres.

3.5 LINKING ECOTOPES

As described in section 2.5, grass, shrubs and forest vegetation ecotopes are linked to their environmental conditions described earlier. The points that will be compared are shown in figure 16.

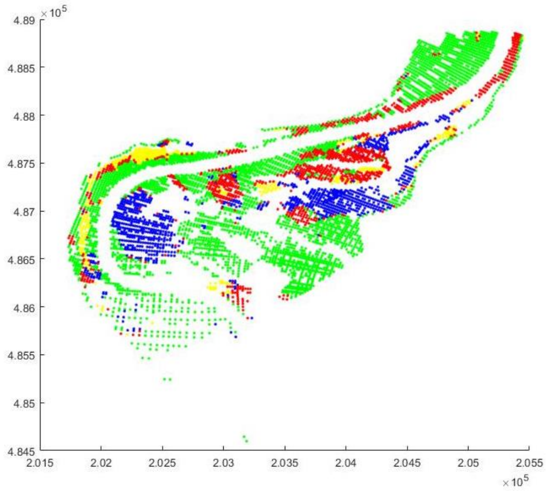

Figure 16: Location points Green = grass (3228 points), Yellow = shrubs (413 points), blue = forest (1033 points) and red = changing vegetation consisting out of grass to shrubs (591 points) and shrubs to grass (210 points).

To link these ecotopes on these locations with the environmental conditions, box plots have been made for the frequency, maximum inundation duration and maximum dry duration. The environmental conditions here are as found in the 7 years leading up to each ecotope map so possible variance in this will show in these charts. Boxplots are used to display the data as outliers are to be expected, boxplots using the median, 25th percentile and 75th percentile show where most of the results are concentrated. The boxplots are displayed in figure 17. The locations where the vegetation changes are divided by changes from grass to shrubs and to shrubs to grass.

The percentage of time flooded (frequency) on which 50% of these ecotope classes are found are for grass 2 to 19%, for shrubs 24 to 58%, for forests 1 to 39%, for grass to shrubs 18 to 35% and for shrubs to grass 0 to 32%. This shows that grass and shrubs are found under quite different flood frequencies while the forest shows some overlap with both grass and shrubs. Interestingly however, is that the changing classes (grass to shrubs and shrubs to grass) show a similarity towards the vegetation class it changes to, with some overlap between the two classes. This could mean that these changes are causes by the flood frequency, where grass is found on areas which are less likely to experience inundation and shrubs on areas which are more frequently inundated than grass. As a change in environmental conditions means the vegetation has to be able to adapt to this and if this type of vegetation cannot adapt it will die allowing new vegetation to dominate an area (Jackson & Colmer, 2005, Miao & Zou, 2012, Riveas, et al., 2014).

The same difference can be found in the inundation duration. In this case 50% of the results for grass coverage are between 12 and 55 days, for shrubs between 64 and 216 days, for forest between 3 and

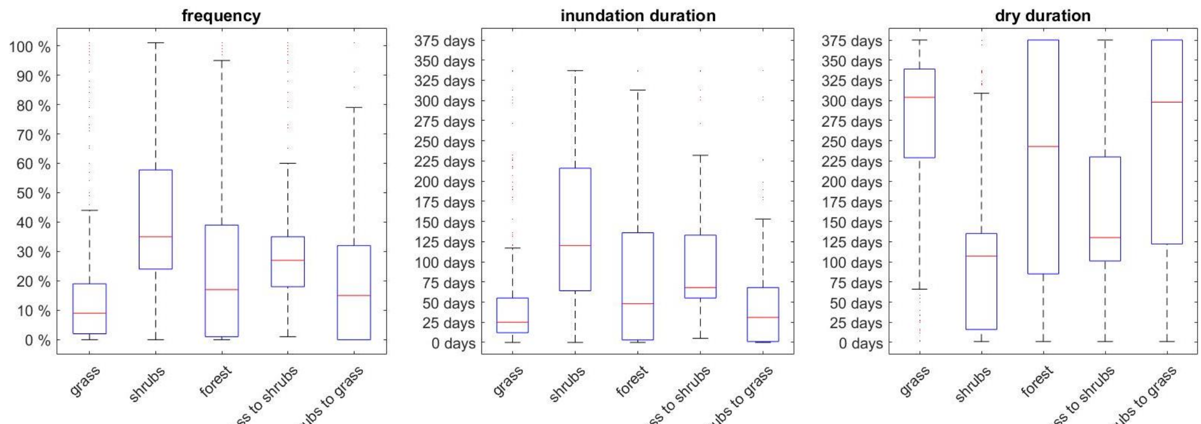

Figure 17: Comparing ecotope classification based on frequency and duration of inundation and duration of dry periods, the blue box represents the 25th and 75th percentile with the red line being the median, any outliers are marked as a small red dot.

136 days, for grass to shrubs between 55 and 133 days and for shrubs to grass between 1 and 68 days. However, the distribution of classes is different for the inundation duration. Here the grass shows less variation, while the shrubs shows more variation. The forest class shows similar variation as shrubs. The changing clases show to be in line what vegetation they change into, however the distribution is more sqewed towards the vegetation class it started out with. There being different spreads between environmental conditions could mean that the stress caused by such a condition on a type of vegetation differs (Riveas, et al., 2014), so to compare grass is less affected by changes in frequency and more by changes in the inundation duration compared to shrubs who is more affected by changes in frequency than in changes in the inundation duration.

The dry duration shows a different picture, here 50% grass coverage are between 229 and 339 days, for shrubs between 16 and 135 days, for forest between 85 and 375 days (note that only up to 375 days was tested in this analysis, it is possible that there has been a dry period longer than a year and these 375 days has occurred in the last 25 years) for grass to shrubs between 101 and 230 days and for shrubs to grass between 122 and 375 days. This would mean that grass is better suited for dry periods than shrubs. The forest class shows a larger spread than the grass and shrub classes, possibly due to there being 2 larger areas containing forest one of which is located in the higher laying area (area 3) and one being in the “wetter” nature area (area 1). The grass to shrubs and shrubs to grass classes show large variation, however note that the means for both show to be close to the classes they change into.

Vegetation is more sensitive to environmental influences in the summer half year. To see if this gives a different view than yearly data, the same boxplot is made to just show the April to October period. The boxplot is shown in figure 18. The figure shows similar differences between the different ecotope classes. The medians of each ecotope class are somewhat closer to each different ecotope for each environmental class. This is however caused by using only the summer half year, as the summer half year generally experiences less high discharges means that the water level of the river is also lower. This shows in the dry duration conditions, here both grass and forest both have a median on 183 days, meaning the entire half year the water is lower than 1 meter under ground level for those ecotope classes. This lower water level also shows in the inundation frequency being lower for grass, which is halved for the summer period compared to the full year data set.

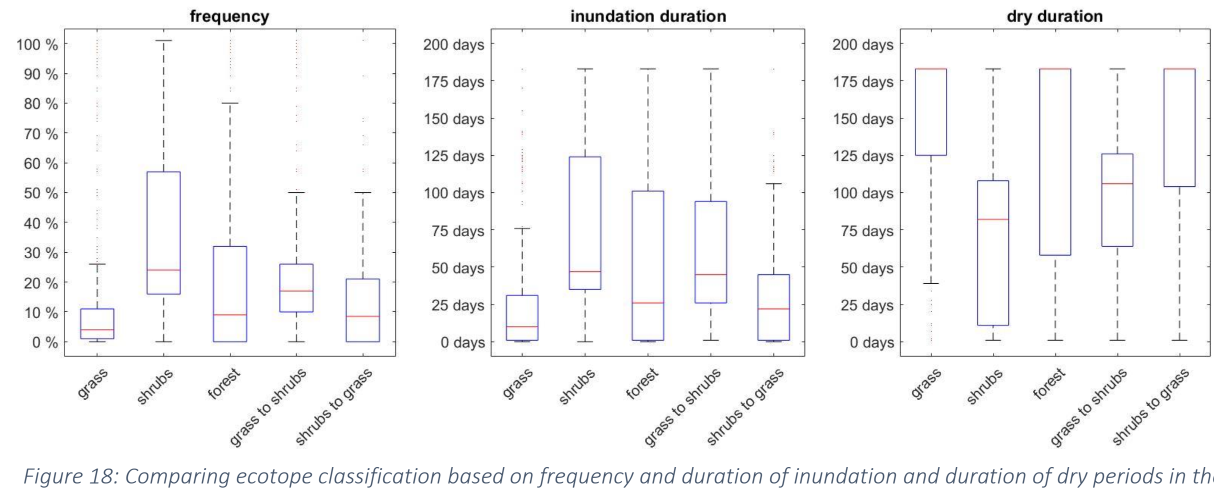

Figure 18: Comparing ecotope classification based on frequency and duration of inundation and duration of dry periods in the summer half year, the blue box represents the 25th and 75th percentile with the red line being the median, any outliers are marked as a small red dot.

4 VEGETATION AFFECTING ENVIRONMENTAL CONDITIONS

To answer the third and fourth research questions, alterations have been made in the model in the Duursche Waarden. The alterations are made to the roughness of the Duursche Waarden to simulate different types of vegetation. These alterations, from here referred as scenarios, are shown in table 2. These scenarios will be compared with the situation as used in the earlier parts of this report, here referred to as the current situation. The described scenarios are used in simulating a once in the 25 years flood wave (T_{25} flood wave) to see what effect different kinds of vegetation have on the inundation and if there is room to allow vegetation to grow, spots where there is nearly no difference between the scenarios.

Scenario	Description
Paved area	A smooth concrete area to simulate paved area in the floodplain as an extreme scenario
Grass land	Grass land, the grass type will be the natural grass ecotope class as found in the ecotope maps for the Duursche Waarden.
Shrubs	Herbal vegetation/shrubs vegetation, for this the herbaceous vegetation class is used as found in the ecotope maps for the Duursche Waarden.
Forest	A semi-dense forest in the floodplain, using the natural forest ecotope class as found in the ecotope maps for the Duursche Waarden.
Current situation	The situation as used in the earlier results, which makes use of the ecotope maps of 1995.

Table 2: Scenarios vegetation for modelling

4.1 ROUGHNESS

To see how the roughness changes by implementing the scenarios, the Chézy values per cell area are computed for the T_{25} flood wave. Because these values are depended on the water depth very low values will be found for areas with no inundation, for this reason the Chézy values will be shown for the peak discharge. Maps for this are shown in figure 19.

Comparing these figures, the first thing to notice is the similarity between the current, paved, grass and herbal vegetation scenarios and the dissimilarity of those with the forest scenario. The later showing very low Chézy values compared to the others, indicating this area is much rougher.

To compare these better the mean value of the Chézy values in this area is computed. These are shown in table 3. The averaged Chézy values show that while little difference between the paved, grass, shrubs and current scenario. It is as expected that the paved scenario is the smoothest surface with the highest Chézy value, however grass and shrubs are very close. This is likely caused by both vegetation classes being low in height, due to the vegetation in the Duursche Waarden being grazed by cattle, see section 2.1. Natural grassland and low herbaceous/shrub vegetation having a height of 0.05-0.2 for grass and 0.1 to 0.25 depending on how extensive the grazing of the cattle is (van Velzen, et al, 2002).

Scenario	Chézy in $m^{1/2}/s$	Velocity in m/s	Water depth [m]
Paved area	36.8	0.46	6.17
Grass land	35.2	0.45	6.20
Shrubs	35.3	0.45	6.20
Forest	20.2	0.33	7.13
Current situation	33.4	0.45	6.22

Table 3: Average roughness, average flow velocity and water depth in the Ijssel of the different scenarios for the study area.

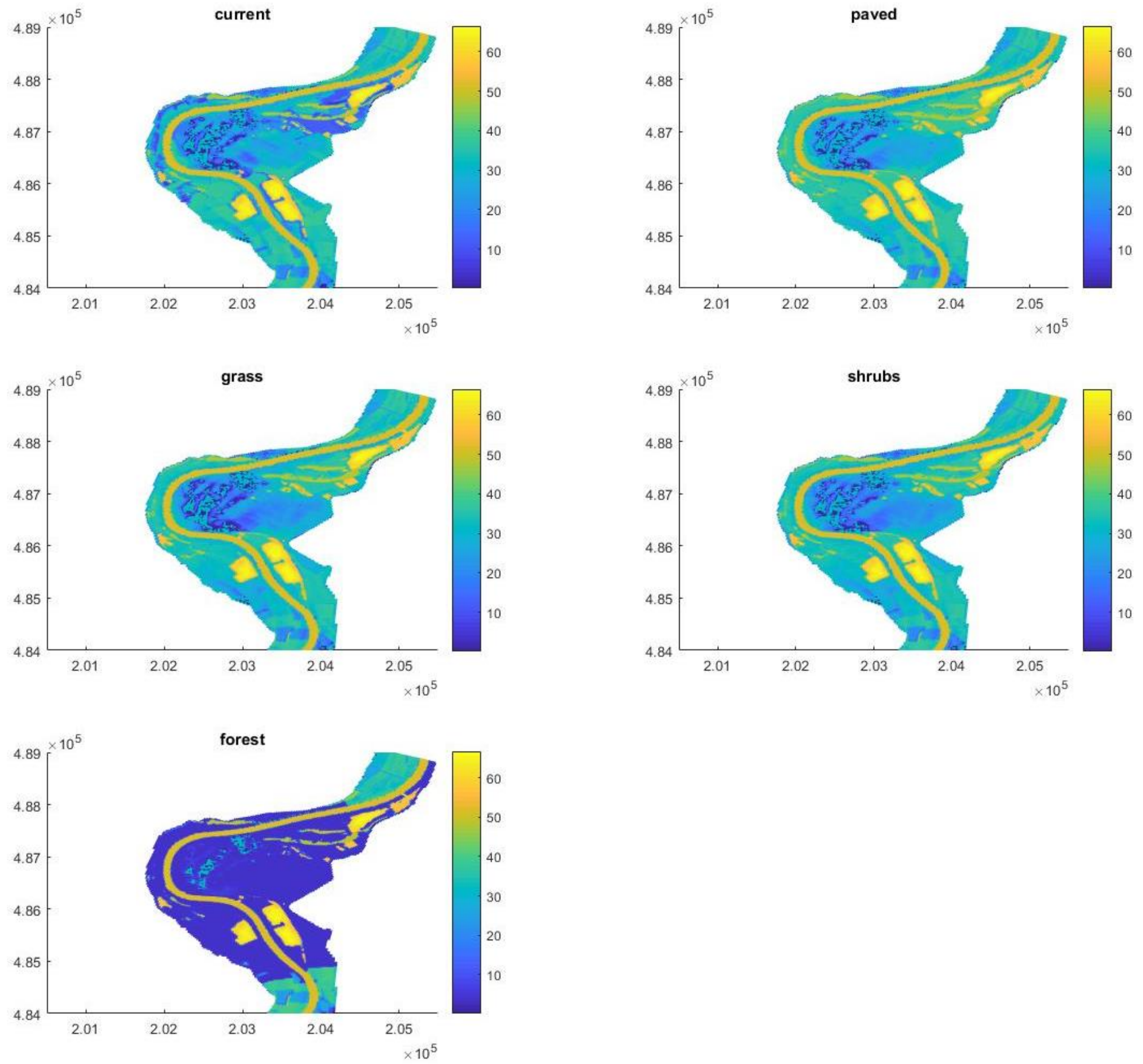

Figure 19: Chézy values for every scenario [$m^{1/2}/s$] at maximum discharge of a T_{25} flood wave.

4.2 FLOW PATTERN

Due to the scenarios being represented as a complete homogeneous area, the first comparison will be the flow pattern of one of these scenarios with the current situation, see figure 20. No comparison between the other scenarios is made as there are only changes between the current situation and any of the other scenarios as those other scenarios contain just a single vegetation type, whereas the current situation contains several types. This leads to the flow following the path of least resistance, which leads to the changes in the flow pattern between these scenarios.

The figure shows the current situation overlaid by the grass scenario, here any differences can be observed as the underlaying arrows should not be visible as long as they follow the same direction. The main changes can be found in the nature area (area 1). Here quite a few arrows have a slightly different direction, indicating that there is some obstructing vegetation in the current situation, which could possibly be altered to create a smoother flow through this area. However, any improvements that would be made my making it smoother, would likely results in insignificant improvements for the area itself as the changes in direction of the flow pattern are almost neglectable.

There are also some changes found within the agriculture area (area 2), here however they seem to be more of the magnitude of the flow rather than the direction. This being a smoother area due to it being part crop field (roughness is based on winter periods, so it is assumed to be empty land) and grassland in the current situation compared to mainly grassland which would result into less resistance for the current situation compared to the grassland scenario. More about flow velocity per scenario will be explained in the next section.

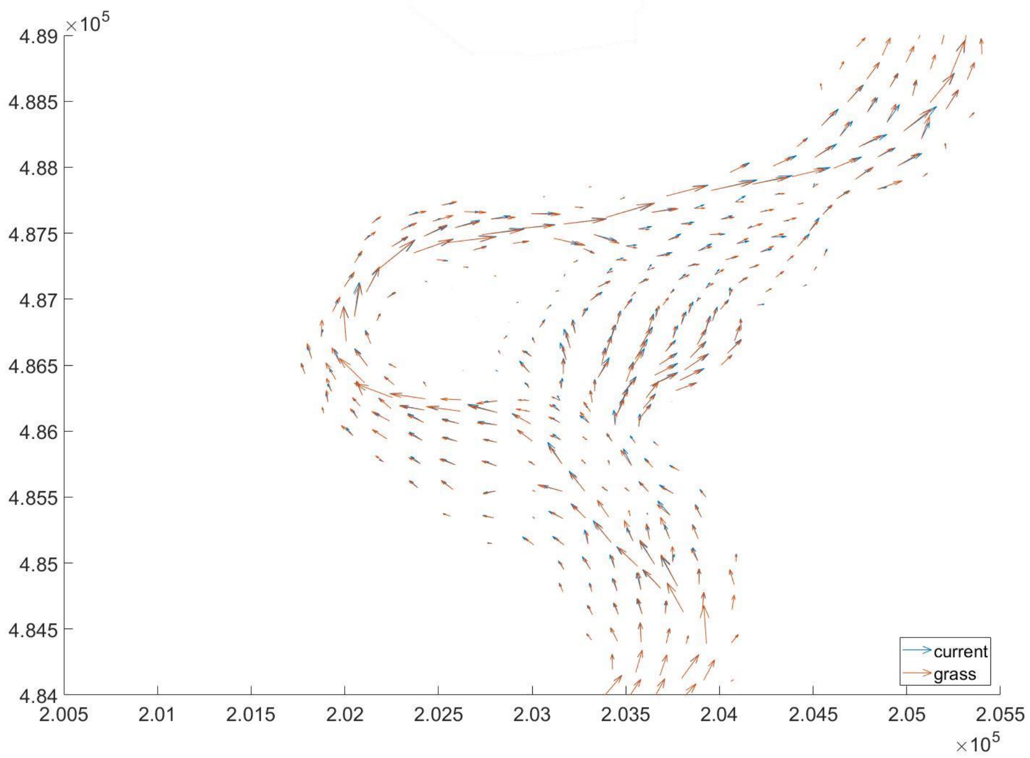

Figure 20: Velocity Vectors of the current situation compared to the grass scenario.

4.3 FLOW VELOCITY

To compare the flow velocity for the different scenarios, the maximum flow velocity of a 1/25-year flood wave has been taken. These are displayed in figure 21. The average flow velocity in this area is computed as well and shown in table 3.

1. Paved scenario: This flow velocity map looks similar to the current situation, however around the river and in the nature area (area 1 in figure 1) there are higher maximum flow velocities. It is likely that due to the homogenous land type used for the scenarios that obstructing vegetation found in the current situation is not limiting the flow anymore. Which is the case in the current situation as you see the higher flow velocities matching the channels in this area, indicating that the main flow would go through these channels instead of over land, whereas these channels are less distinguishable in the paved scenario map.
2. Grass scenario: it shows that the situation is very similar to the paved scenario of the flow not following the channels. However as to be expected the maximum flow velocity is slightly reduced compared to the paved scenario. Unexpected however is that on some location the flow velocity is lower than in the current scenario, see the centre area (area 3).
3. Shrubs scenario: the shrub and grass scenarios seem to be the same. This is due to the similarity in vegetation height as stated earlier in this chapter.
4. Forest scenario: This scenario shows a completely different picture. Being a denser type of vegetation, the map shows strongly reduced flow velocities, which in turn causes higher water levels. This can be observed in the map because now flow is present in the higher laying areas (the edge of area 2).

To conclude, there is a drastic decrease in flow velocity for the forest scenario while the other scenarios show largely similar results. This could indicate that in an extreme situation as modelled, lower types of vegetation become similar in their effect on the water flow. Furthermore, comparing the maps to each other there are areas which show the same of nearly the same flow velocity over all 5 maps. This could mean that for some location taller vegetation doesn't necessary lead to a reduction of the vegetation. As in the current situation there is a rather significant containing a forest (in area 1), this forest is likely what affects the flow to follow the channels rather than flow over land as observed in the paved, grass and shrub scenarios. To conclude, rather than removing all vegetation from floodplains to make flow over the floodplain smoother, it should be a more selective process as some areas are more important to the flow than others. This allows for vegetation to grow freely on certain locations which should have no dire effects on the safety.

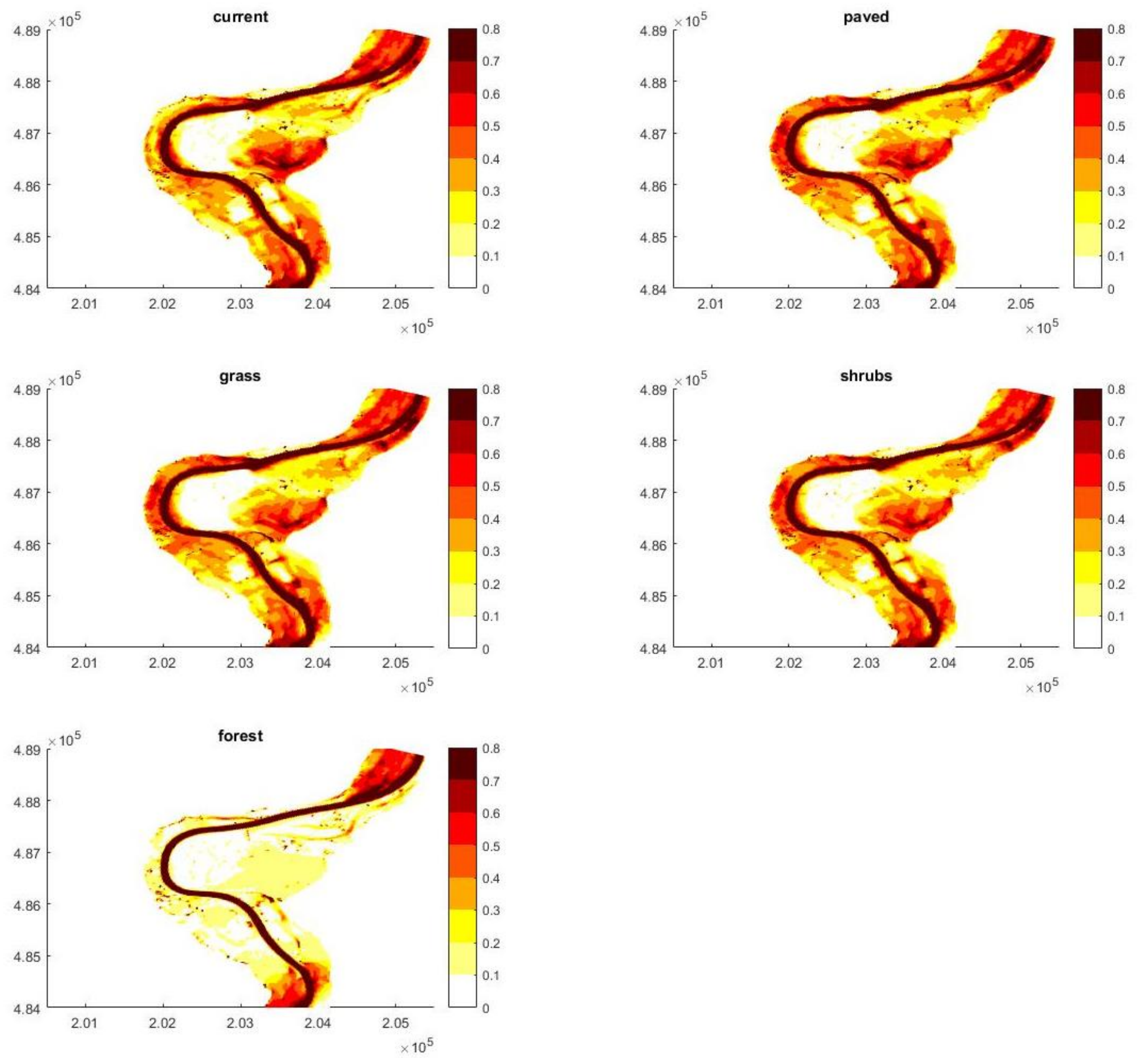

Figure 21: Maximum flow velocity in m/s per scenario.

4.4 WATER DEPTH

The water depth between the different scenarios are displayed in figure 22. The water depths in the river IJssel are displayed in table 3. The table shows slight variation between the scenarios except for the forest which is 90-95 centimetre higher than the others. Note that this is the water depth found in the river Ijssel at location B in figure 6.

This difference is shown in the maps too, here it shows that in the forest scenario even the higher laying area which is normally not affected by floods experiences inundations. The other maps show almost no differences in inundations, which is expected as the maximum water depths in the river shown in table 3 show little difference for these scenarios. Notice that there are only slight differences between the paved, grass, shrub and current situation scenarios, which are partly observable in the nature (area 1) and the agricultural area (area 3).

4.5 DISCHARGES

To see what effect the different scenarios cause, the peak discharge of the river system just before and just after the Duursche Waarden is calculated for the different scenarios (location A and C in figure 6). This is based on the maximum water depth per grid cell with the flow velocity magnitude at the same time step as the maximum water depth. These peak discharges are shown in figure 23. The figure shows that there is only a small difference between the current situation the paved, grass and shrub scenario. Which is to be expected when looking at the average roughness coefficient found earlier. The forest scenario however shows a decrease of 80 m^3s.

This indicates that the potential of this area to slow down a flood wave with about 80 m^3/s by increasing the roughness of the vegetation in this area. However, too much increase in the roughness of the area, would lead to see upstream parts of the river experiencing higher water levels due to the backwater effect as shown in the forest scenario. This could be helpful if the downstream parts are under more risk of flooding compared to upstream parts, this would move the problem upstream instead of downstream.

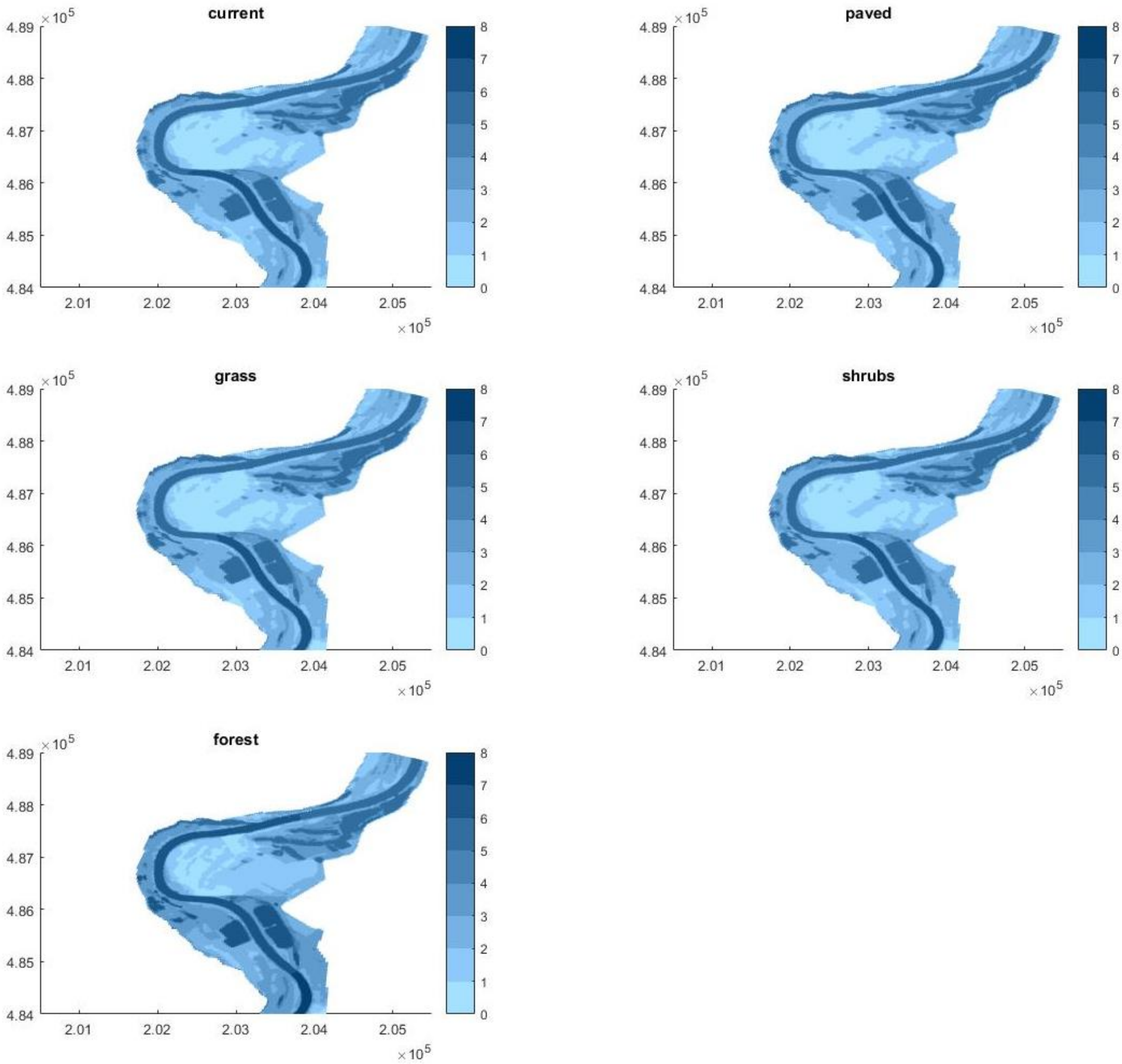

Figure 22: Water depth in meters per scenario.

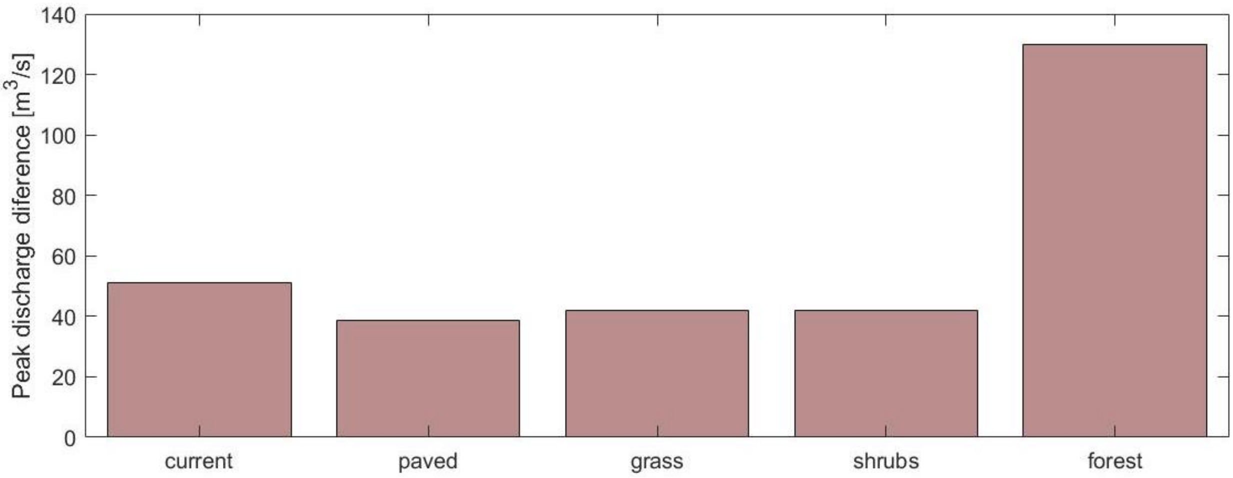

Figure 23: the difference in the two peak discharges, between location A and C see figure 6.

5 DISCUSSION

This chapter will describe several discussions points. These are divided into the model, the ecotopes, hysteresis and groundwater.

Model

The model used in this study is a 2D schematization based on the river system in 1995, with the vegetation from the ecotope maps of 1997. This means that any alterations in the Rhine system after this time period that could have affected the inundation characteristics in the Duursche Waarden are not included in this study.

Secondly the way the velocity profile is approximated in WAQUA for different types of vegetation, causes some inaccuracies in comparison to the real velocity profile. This error causes the flow velocity through the vegetation layer being underestimated and the flow velocity above the vegetation being overestimated. This error however is dependent on the land/vegetation types and are severely tested in research for Rijkswaterstaat to reduce this (Stolker, et al., 1999).

Ecotopes

There are several uncertainties involved in the ecotope classes as used in the roughness calculations by van Velzen, et al. (2003). Straatma & Huthoff (2010) identify three of them. Firstly, there is an uncertainty in the classification of ecotopes, secondly an uncertainty in translating these ecotopes to a hydraulic roughness and thirdly an uncertainty in the spatial differentiation of ecotope units.

Because the vegetation roughness calculation relies strongly on the ecotope maps, several studies have been carried out on the accuracy of these maps and all find different accuracies. Knotters, et al. (2008) find an overall accuracy of 27.8% to 47.8%, assuming that no errors were made in the field. Furthermore, Knotters, et al. (2008) find a 4.2 to 8.0% spatial error, this is however considered biased in a positive way due to the method used to estimate this spatial error. Straatma & Huthoff (2010) indicate that the validation of ecotopes are still a matter of debate, because there is lot of uncertainty in terms of the accuracy of the ecotope maps which can be between 69-92%.

In the second part of this study, the whole area of the Duursche Waarden was changed into a predetermined vegetation type, except for the water bodies. The roughness for the model is based on this, however for each vegetation type there are several different stages. Like Van Velzen, et al (2003) show that vegetation types exist in different quantities and are classed that way. The vegetation types and classes chosen were based on what is currently found in the Duursche Waarden. This means that shrubs or forest could be different from shrubs or forest elsewhere, as aspects like vegetation height and number of stems are included into this ecotope classification. This means that forest as used in this study is a specific forest and results could be different if another type of forest with different vegetation heights, vegetation density, etc. is used.

Hysteresis

Due to using a dynamic flood wave in the model, there will be some form of hysteresis in the results. Using the Q-h relation based on the highest water levels in the different simulations leads to overestimation in the water levels used for the discharge. This makes the maps the worst situation (as in an upcoming flood wave where the water level is higher for the same discharge compared to the decreasing of the flood wave where the water level is lower for the same discharge. This would affect all the maps created, except the flow velocity, giving higher frequencies and durations.

Groundwater

The groundwater level in this study was assumed equal to the water level in the river. This is not accurate as groundwater experiences bulging. This means that the groundwater level is a bit higher in reality in wet periods (winter) and overestimated in dry periods (summer) when the groundwater level is fed by the river. The difference between the reality and the groundwater level used, is smallest near the river itself. For this study it gave an easy rough estimate. Another point on the groundwater level is that its only based on the river, as there is a lot of farm land in this area, it is likely that the groundwater level is artificial managed by use of ditches (area 3). Besides this, rainfall could also reduce drought effects and possibly cause upwelling in the groundwater level.

6 CONCLUSIONS & RECOMMENDATIONS

This chapter is divided into conclusions and recommendations. The conclusions are presented as answer to by the research questions as described in section 1.2.

6.1 CONCLUSIONS

How can the environmental conditions of the study area over the last 25 years be characterized?

By running simulations with a model of the Dutch Rhine system, a Q-h relation has been derived for the Duursche Waarden (figure 7). Using this Q-h relation maps of the inundation frequency (figure 9), maximum inundation duration (figure 11) and maximum dry periods (figure 13) have been made. Using the results from the model simulations the flow velocity (figure 15) could be mapped as well. These maps are a quantification of the environmental conditions described.

How do these environmental conditions correlate with the vegetation in this area?

Using the spatial distribution of the characterisation of the environmental conditions and linking these to the ecotope classes, shows which vegetation types are found under which environmental conditions. This has been displayed in figure 17. From this it can be concluded that grass is less resilient to these characteristics than shrubs. Grass is found in less frequently inundated areas, with shorter inundation periods and longer dry periods, whereas shrubs are found in areas with more frequent inundations, longer inundations periods and shorter dry periods. Interestingly here is that the areas which show changes in vegetation over time between these two classes shows to be found under similar conditions as the class they change into. This could mean that some changes in vegetation can be predicted based on the changes in environmental conditions, as shrubs changes to grass on locations where the environmental conditions aim more towards the grass class and vice versa.

To what extent does the vegetation affect the environmental conditions?

Vegetation influences the hydraulic roughness of an area, the taller and "rougher" the vegetation the more the vegetation will slow down or restrict water flow. In this report this was especially observable when simulating the Duursche Waarden as a forest, this more than halved the maximum flow velocity in certain locations, while also increasing the water depths on those locations, see table 3 and figures 19, 21 and 22. Figure 19, clearly shows the increased roughness of the floodplain due to the vegetation changes, which is what affects the waterflow over the floodplain of which the resulting changes in water depths and flow velocity can be observed in figures 21 and 22.

How does the vegetation affect the flow capacity and water levels in the floodplain?

The peak discharge upstream and downstream of the Duursche Waarden is different due to the flow over the floodplain. This is caused by diffusion caused by the slowing down of the flood wave by the vegetation in the floodplain. Naturally this effect is a lot larger when the floodplain is covered by a forest. However, the decrease in peak discharge creates a problem upstream, due to the backwater effect. Notable is that there is not much difference between the current situation and having only grass in the Duursche Waarden. This shows that taller vegetation on certain locations doesn't have to cause big problems for the water safety. Looking further at the figures 21 and 22, shows that there are areas which are affected by a lesser extent than others, this could be an indication that taller types of vegetation could be allowed in floodplains and not decreasing the water safety, the higher laying areas and the nature area of the Duursche Waarden most likely due to it containing channels. This could for example be done by leaving enough room between the vegetation for water to flow or use areas which are not a part of the main flow in times of inundations.

The objective of this research was to determine and the map various environmental conditions and linking them to ecotope classes, to get a better understanding of the mutual relation between vegetation and environmental conditions. The mentioned environmental conditions have been determined for the Duursche Waarden and mapped in chapter 3, which are then linked to the ecotope classes in section 3.5. From this it can be concluded that grass changes into shrubs when the environmental conditions found on a location lean more towards the environmental conditions shrubs are found under and vice versa. To get a better understanding of the effect of vegetation on the environmental conditions, simulations have been done to see the effect of each individual vegetation class. This shows that vegetation does not necessary cause big effects on the environmental conditions and is largely depending on where the vegetation is found in a floodplain rather than how rough it is.

6.2 Recommendations

Based on the conclusions it is recommended to test where vegetation growth could lead to decreasing the water safety and which areas where it is safe to let vegetation grow. Rather than simply removing all vegetation to improve the flow through the floodplains to maintain water safety. Being selective about which areas form more of a risk of the water safety would allow floodplain managers to both maintain a level of nature within these areas and maintain the water safety.

Furthermore, in this study flow velocity was not linked to ecotope classes, as the available data would not be able to be translated to a map and mere shows the general areas which have higher flow velocity than others. In a future study this should be taken into account as well as possible other environmental conditions not considered in this study, to see what else contributes to vegetation changes in a floodplain. And taking a better look at the groundwater level, possibly by using ground water measurements in an area to get a better understanding of real dry periods rather than an estimation based on the water level in the river as used in this report.

7 REFERENCES

Baptist, M., Babovic, V., Rodríguez Uthurburu, J., Keijzer, M., Uittenbogaard, R., Mynett, A., & Verwey, A. (2007). On inducing equations for vegetation resistance. *Journal of Hydraulic Research vol.4*, 435–450.

Blanch, S., Ganf, G., & Walker, K. (1999). Tolerance of riverine plants to flooding and exposure indicated by water regime. *Regulated Rivers: Research & Management vol. 15*, 43-62.

de Bruin, D., Hamhuis, D., van Nieuwenhuijze, L., Overmars, W., Sijmons, D., & Vera, F. (1987). *Ooievaar de toekomst van het rivierengebied.* Arnhem: Stichting Gelderse Milieufederatie.

Dirks, P., Kooijman, G., Hottinga, A., & Gerritse, W. (2014). 25 jaar natuurontwikkeling in de Duursche Waarden. *De Levende Natuur - 115 - 5*, 198-204.

Jackson, M., & Colmer, T. (2005). Response and Adaptation by Plants to Flooding Stress. *Annals of Botany 96* , 501-505.

Knotters, M., Brus, D., & Heidema, A. (2008). *Validatie van ecotopenkaarten van de rijkswateren.* Wageningen: Alterra.

Makaske, B., Maas, G., & van den Brink, C. (2011). The Influence of Floodplain Vegetation Succession on Hydraulic Roughness: Is Ecosystem Rehabilitation in Dutch Embanked Floodplains Compatible with Flood Safety Standards? *AMBIO*, 40:370–376.

Miao, S., & Zou, C. (2012). Effects of inundation on growth and nutrient allocation of six major macrophytes in the Florida Everglades. *Ecological Engineering 42*, 10-18.

Rijkswaterstaat. (2009). *Beheer- en Ontwikkelplan voor de Rijkswateren 2010-2015.* Rijkswaterstaat.

Rijkswaterstaat. (2015). *SIMONA documentatie.* Retrieved from Manual WAQUA: http://simona.deltares.nl/release/doc/index.html

Riveas, R., Rodríguez-González, P., Ferreira, M., Pinheiro, A., Politti, E., Egger, G., . . . Francés, F. (2014). Modeling the Evolution of Riparian Woodlands Facing Climate Change in Three European Rivers with Contrasting Flow Regimes. *PLOS ONE 9 (10)*, n.a.

Robert, A. (2003). *River Processes an introduction to fluvial dynamics.* London: Hodder Education.

Stolker, C., van Velzen, E., & Klaassen, G. (1999). *Nauwkeurigheidsanalyse stromingsweerstand vegetatie.* RIZA.

Straatsma, M., & Huthoff, F. (2010). The effect of uncertain floodplain roughness in hydrodynamic flood simulations. *Proceedings of the 10th International Symposium on Stochastic Hydraulics (Water 2010)*, 1-8.

van Eck, W., van de Steeg, H., Blom, C., & de Kroon, H. (2004). Is tolerance to summer flooding correlated with distribution patterns in river floodplains? A comparative study of 20 terrestrial grassland species. *Oikos 107*, 393-405.

van Velzen, E., Jesse, P., Cornelissen, P., & Coops, H. (2002). *Stromingsweerstand vegetatie in uiterwaarden: deel 1 handboek versie 1.0.* Lelystad: RIZA.

van Velzen, E., Jesse, P., Cornelissen, P., & Coops, H. (2003). *Stromingsweerstand vegetatie in uiterwaarden Deel 2 achtergronddocument.* Arnhem: RIZA.

Wolfert, H. (1996). *Rijkswateren-Ecotopen-Stelsels: uitgangspunten en plan van aanpak.* Lelystad: RIZA.

Zevenbergen, C., Rijke, J., Ludy, J., & Ashley, R. (2013). Room for the river: international relevance. *Water Governance*, Februari 24-31.

APPENDIX: ADDITIONAL FIGURES

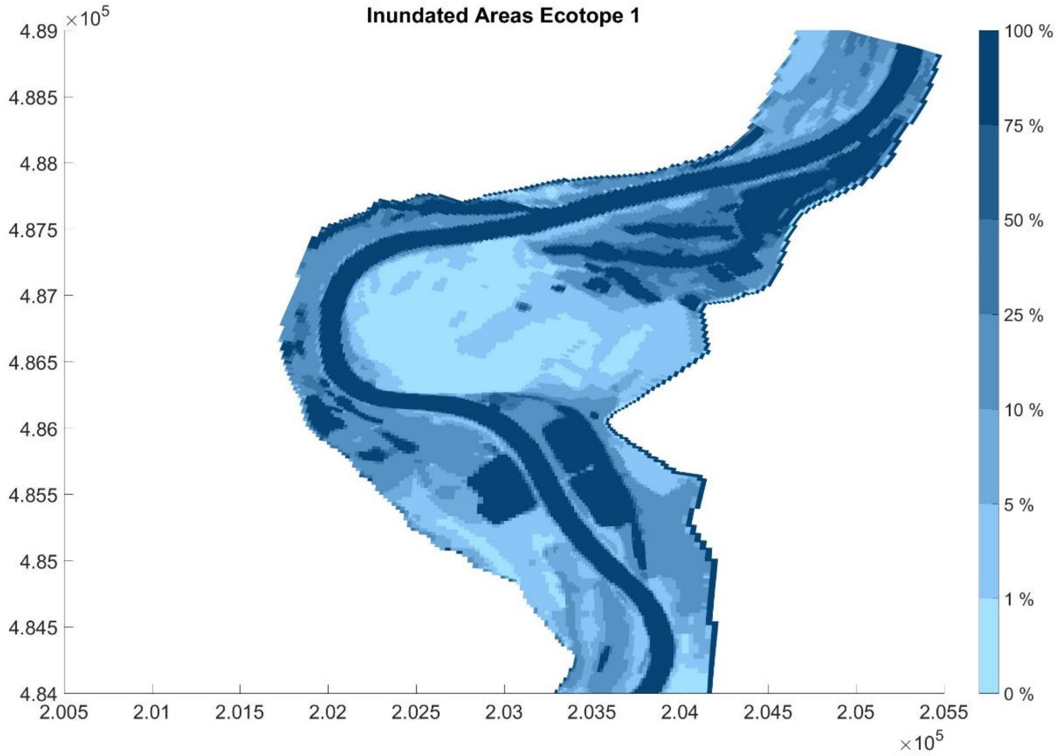

Figure 24: Frequency of inundated areas, based on discharge data from year 1991-1998

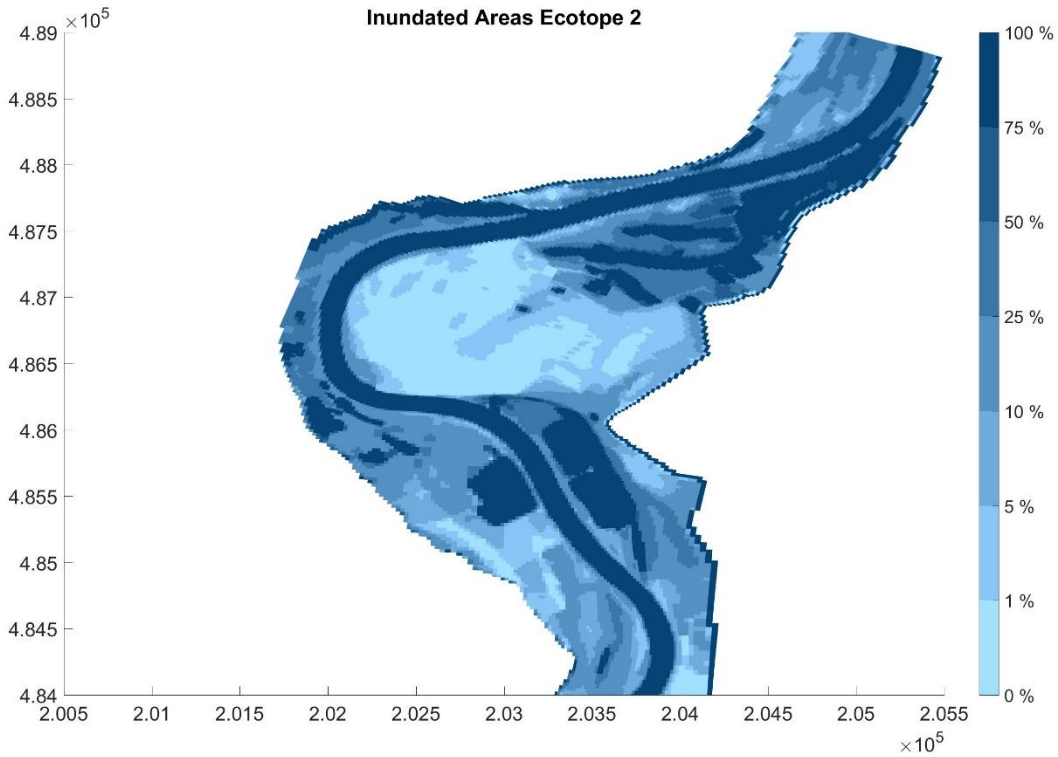

Figure 25: Frequency of inundated areas, based on discharge data from year 1998-2005

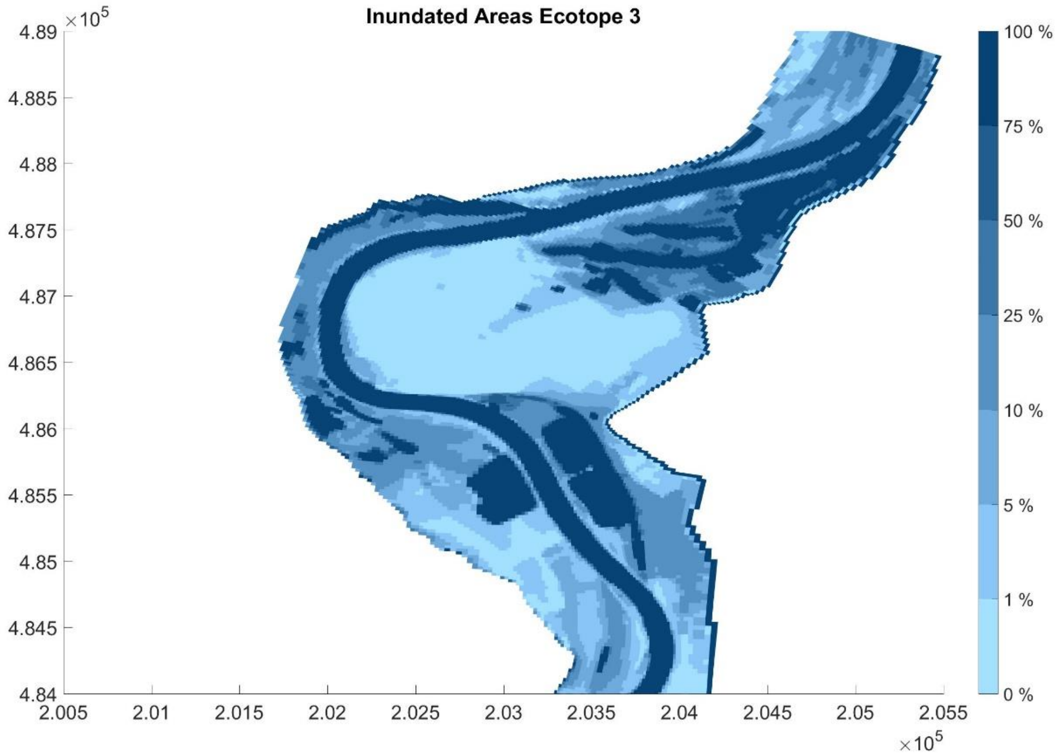

Figure 26: Frequency of inundated areas, based on discharge data from 2005-2012

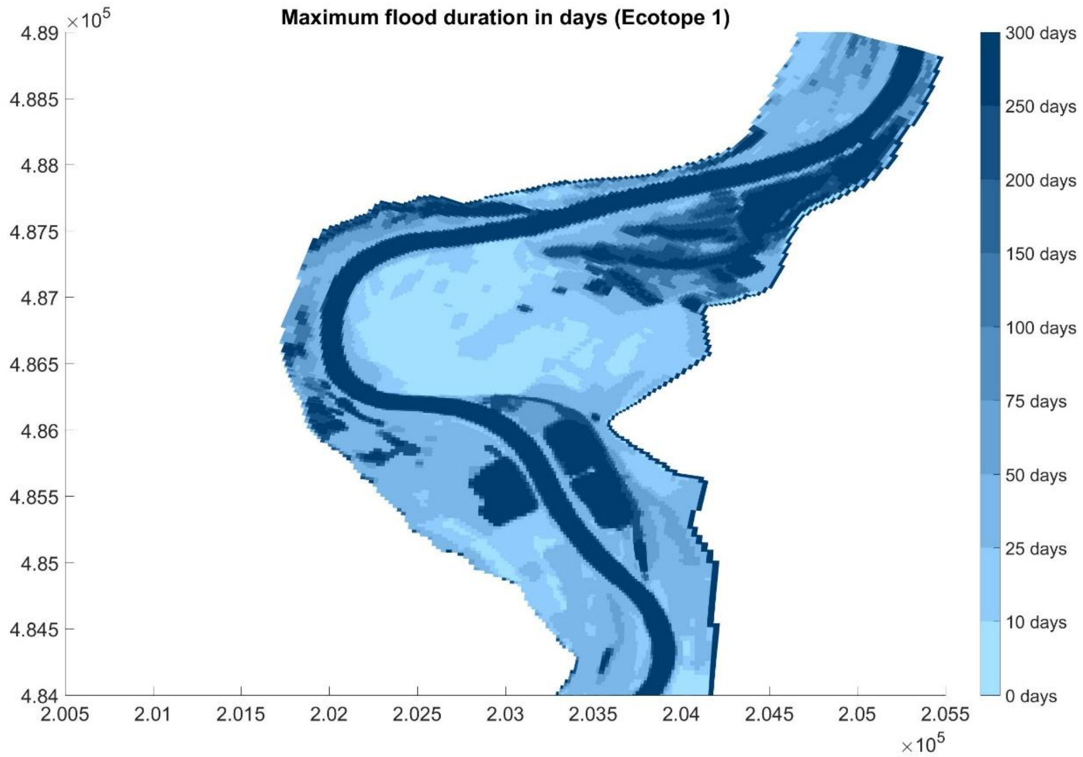

Figure 27: Maximum duration of floods, based on discharge data from year 1991-1998

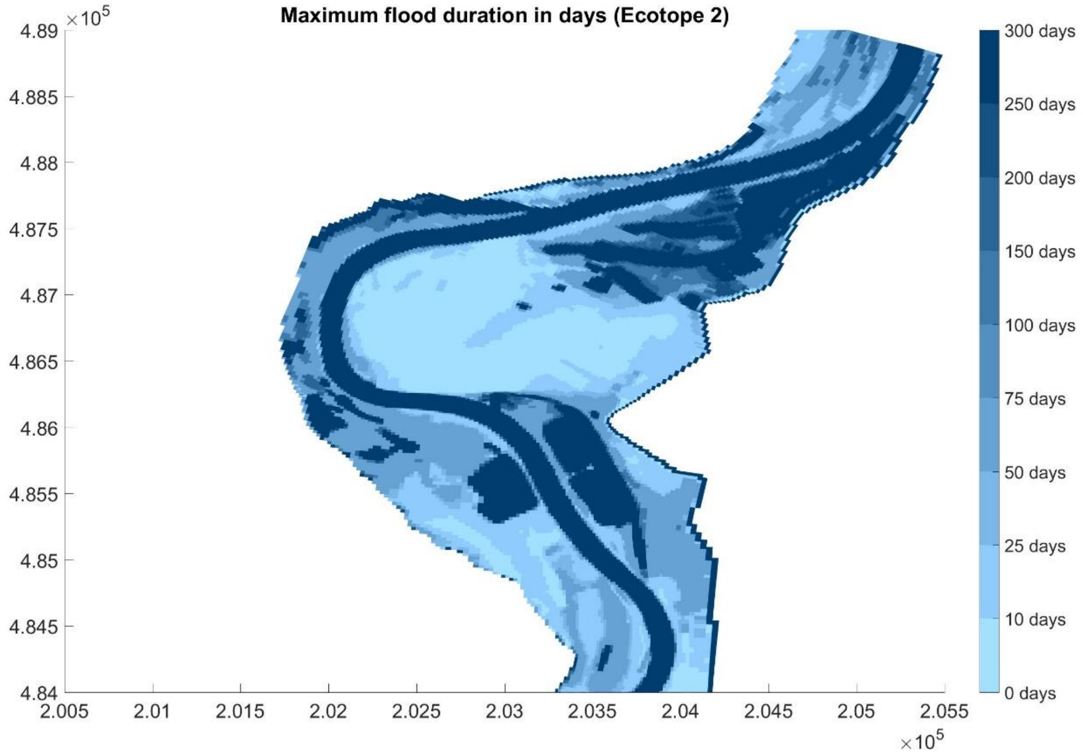

Figure 28: Maximum duration of floods, based on discharge data from year 1998-2005

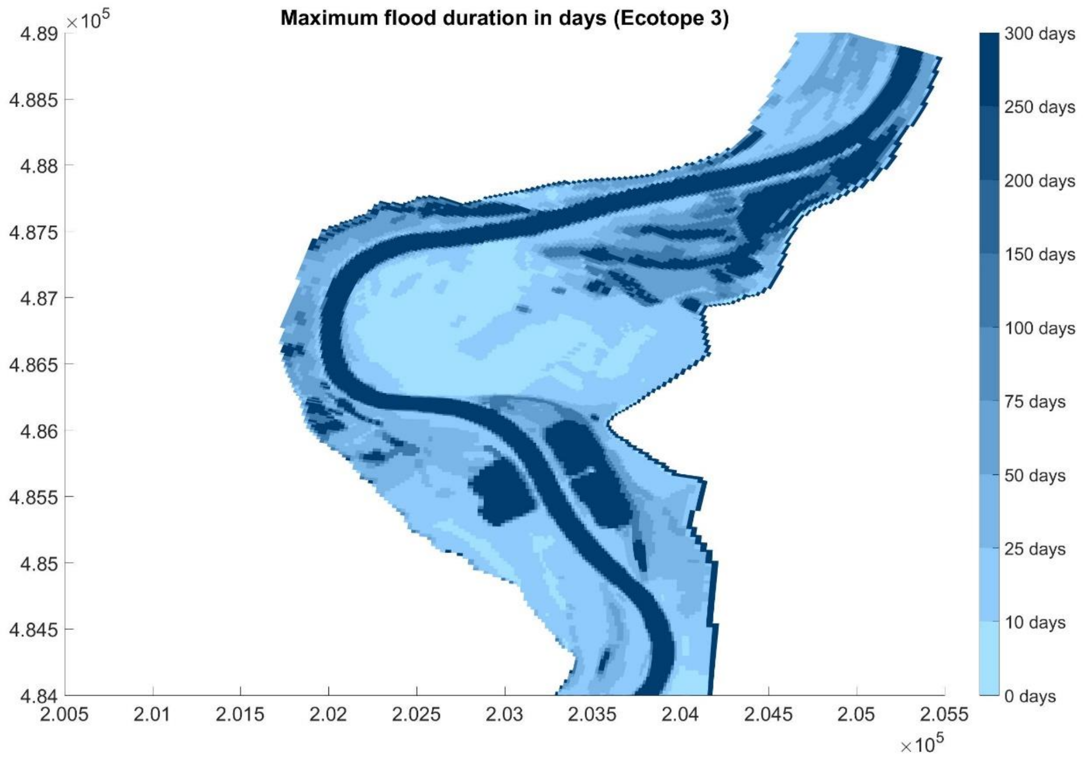

Figure 29: Maximum duration of floods, based on discharge data from year 2005-2012

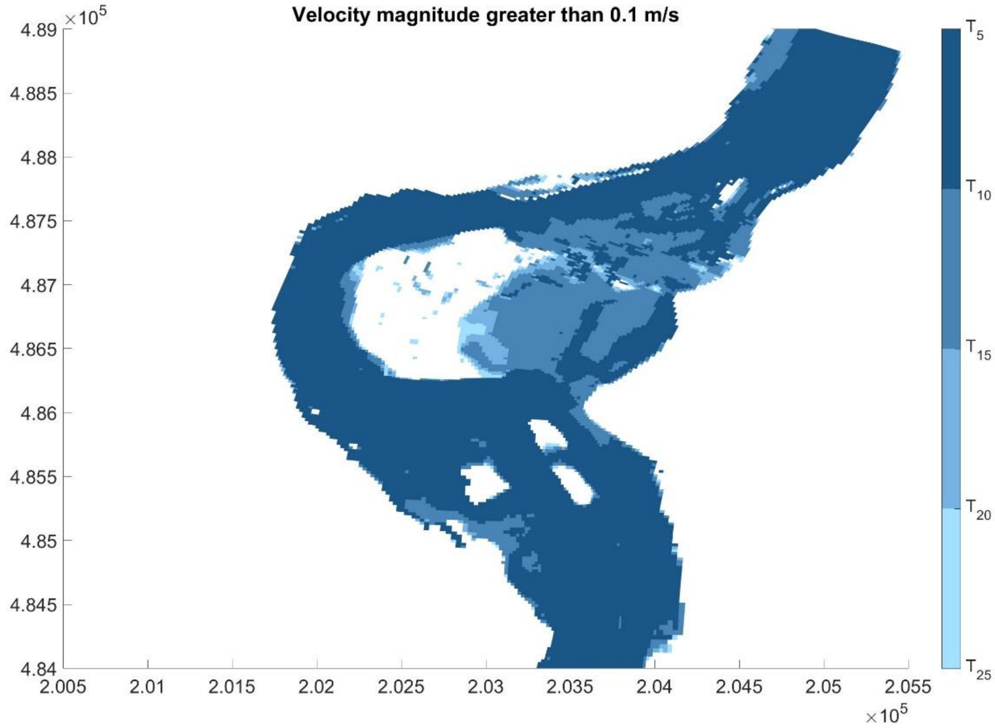

Figure 30: Velocity greater than 0.1 m/s

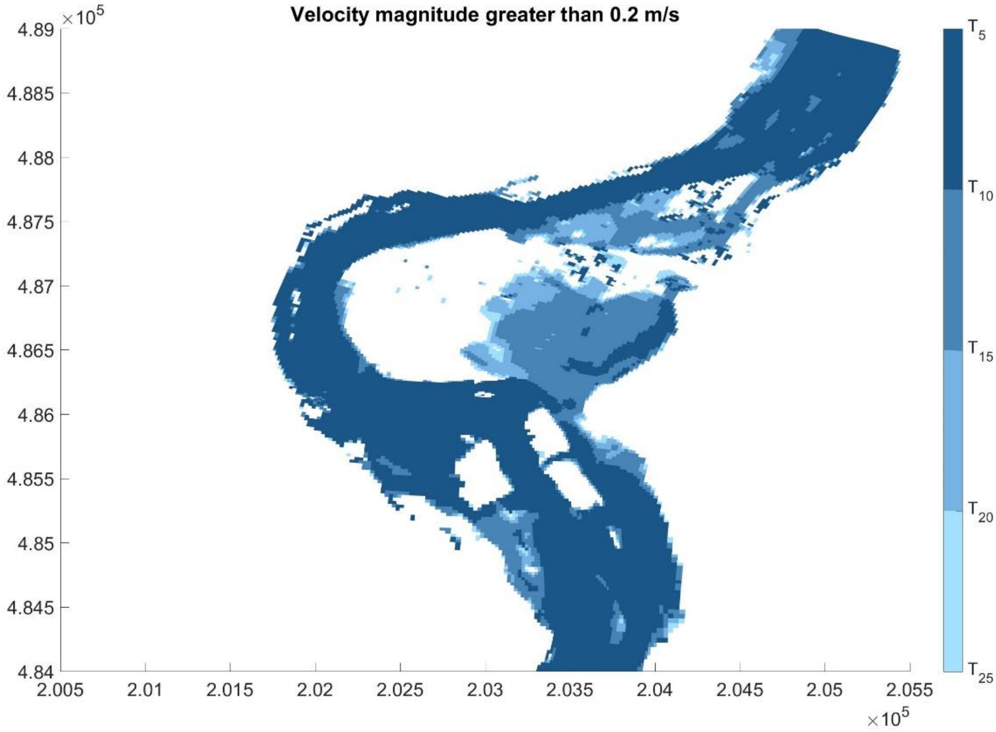

Figure 31: Velocity greater than 0.2 m/s

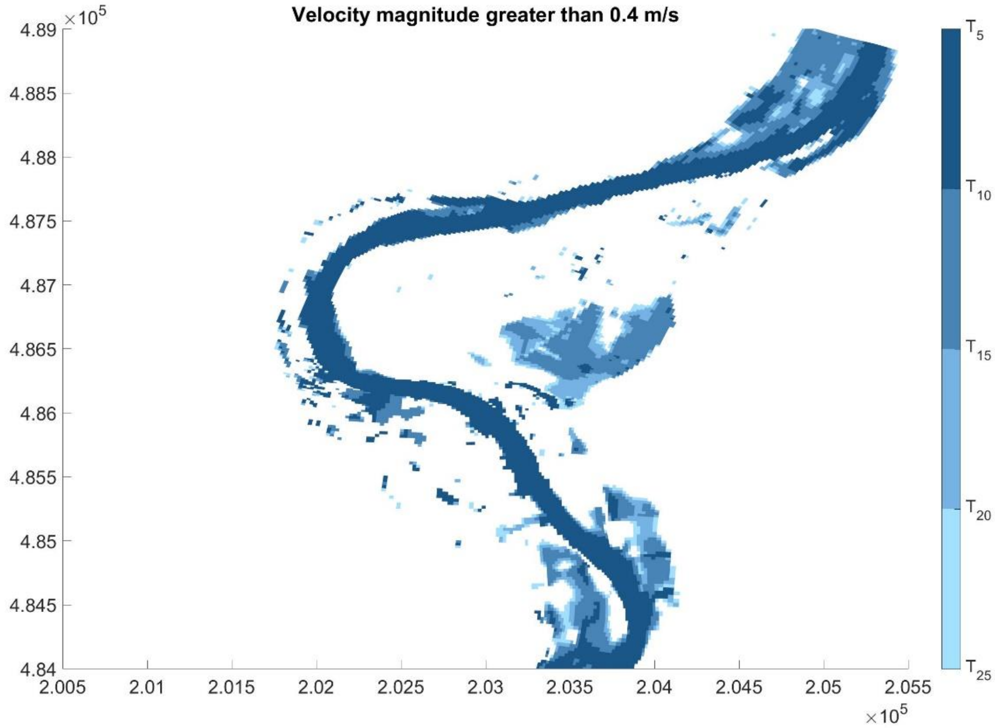

Figure 32: Velocity greater than 0.4 m/s

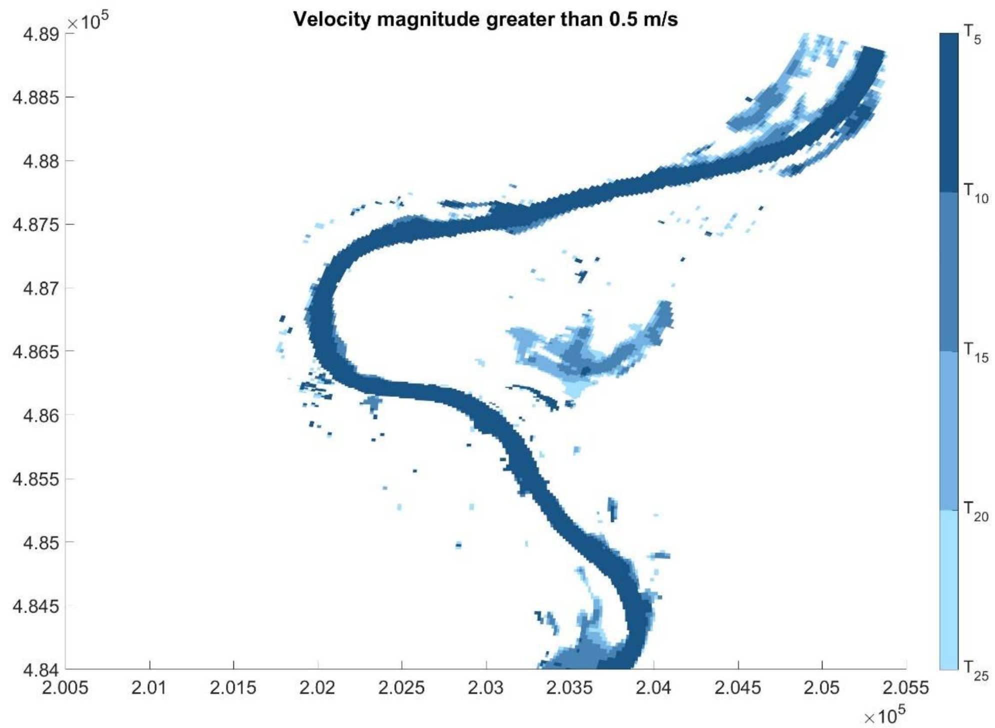

Figure 33: Velocity greater than 0.5 m/s

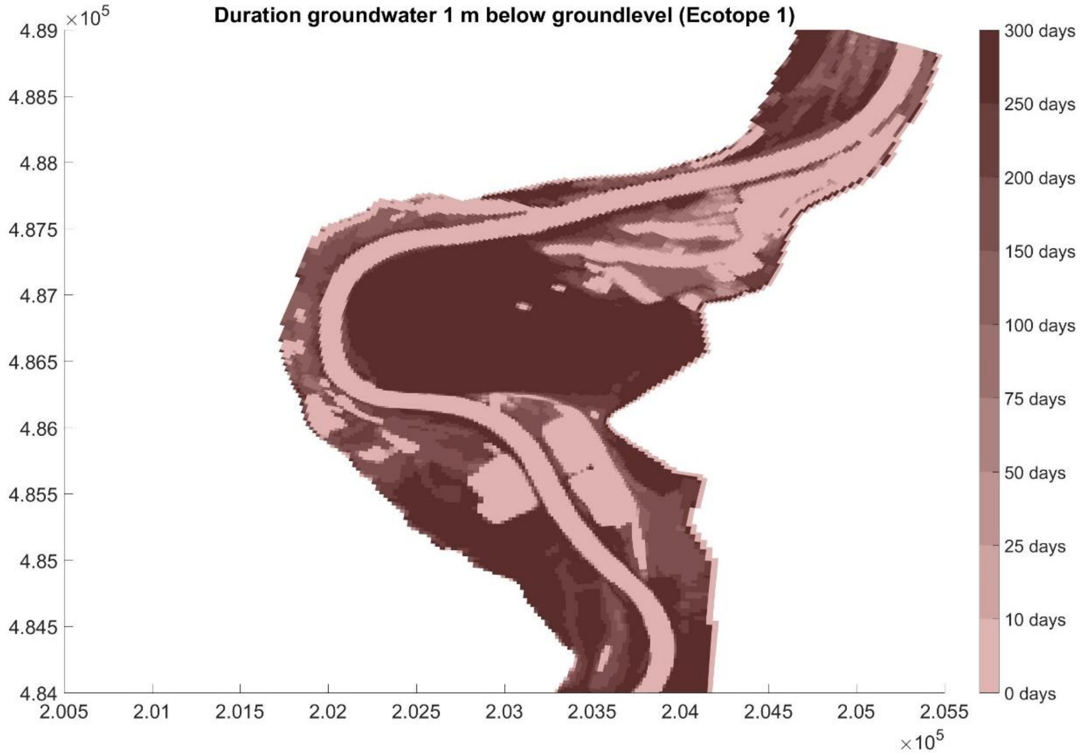

Figure 34: Maximum dry period, based on discharge data from year 1991-1998

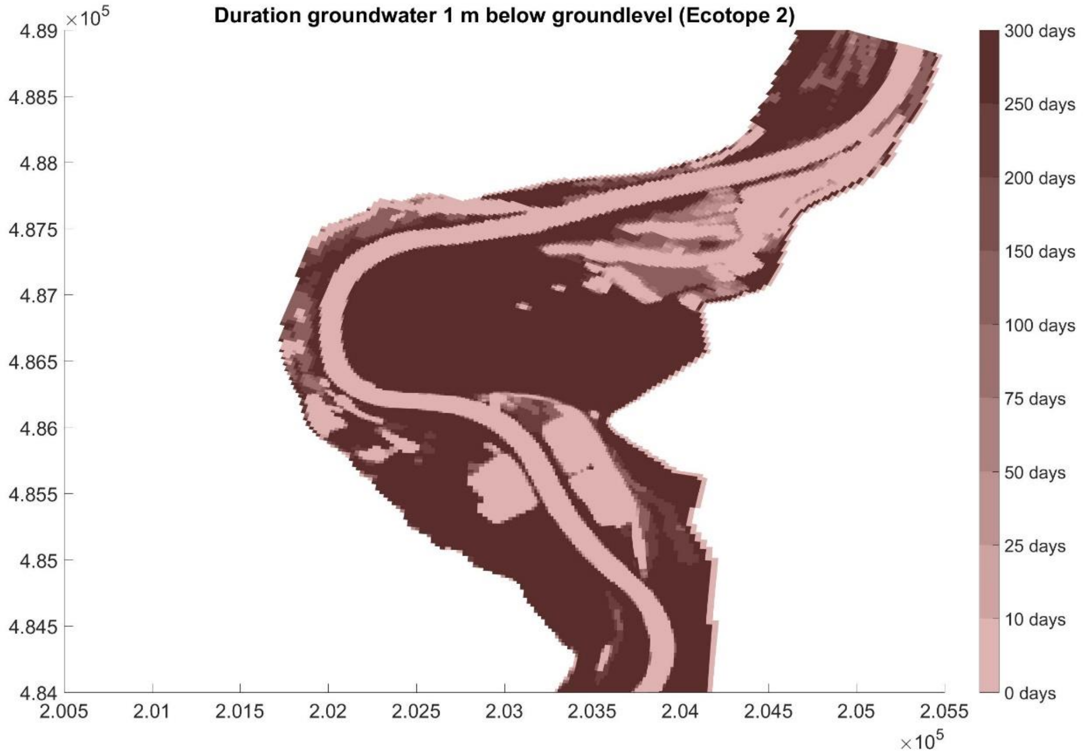

Figure 35: Maximum dry period, based on discharge data from year 1998-2005

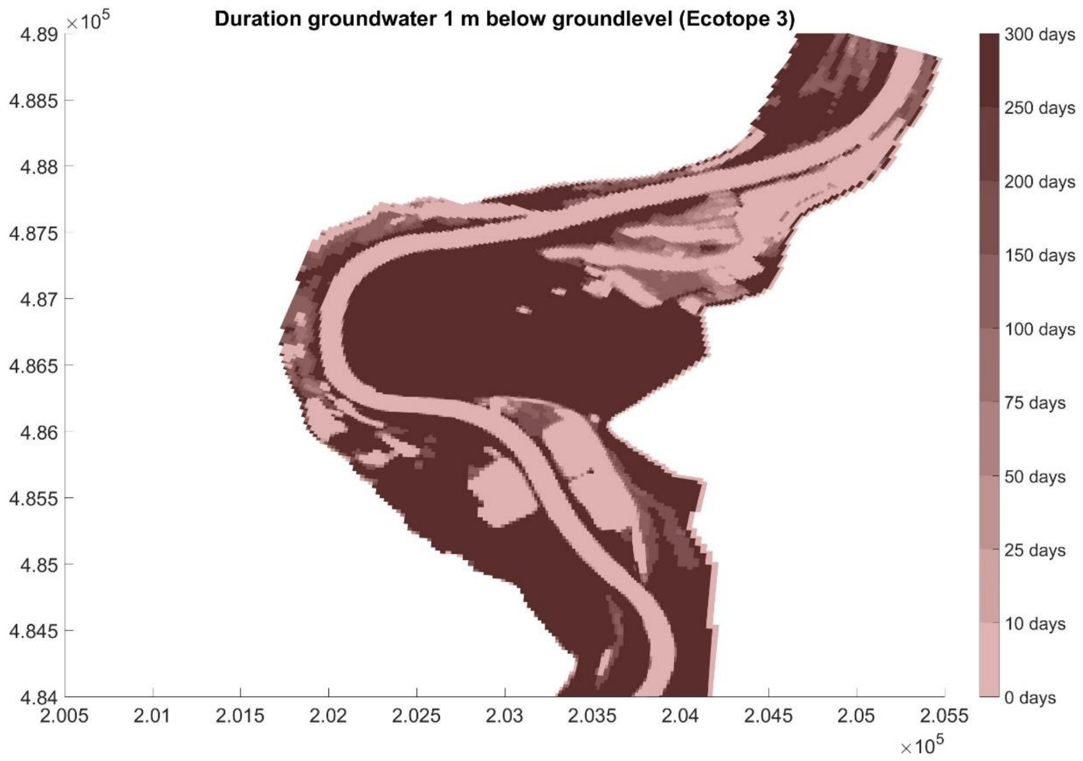

Figure 36: Maximum dry period, based on discharge data from year 2005-2012