Integrated analysis of nature-based water management in the Rhine

Conflicts between environment, navigation, and flood protection

Cyntha Nijmeijer
Master Thesis
August 2018

Integrated analysis of nature-based water management in the Rhine

Conflicts between environment, navigation, and flood protection

Master thesis submitted to Delft University of Technology in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE in Engineering and Policy Analysis

Faculty of Technology, Policy and Management

By

Cyntha Nijmeijer

Student number: 4157974

To be defended in public on August 20 2018, 15:00

Location: Faculty of Technology, Policy and Management – Room B

Graduation committee

Chairperson	Prof. Dr. J.H. Slinger	Policy Analysis, Faculty of TPM & Visiting professor, Rhodes University
First Supervisor	Prof. Dr. J.H. Slinger	Policy Analysis, Faculty of TPM & Visiting professor, Rhodes University
Second Supervisor	Dr. J.A. Annema	Transport and Logistics, Faculty of TPM
External Supervisor	Prof. Dr. ir. P. van der Zaag	Integrated Water Systems and Governance, IHE-Delft & Department of Water Management, TU Delft

Summary

Research problem: river use conflicts regarding nature-based water management in the Rhine

Whereas pure engineering measures have been the preferred approach for river management in the Rhine for the past centuries, nowadays nature-based water management is rising as an alternative approach. Nature-based water management makes use of ecological, hydrological, and morphological processes of natural rivers in designing river management policies. Furthermore, it helps conserving or restoring these natural processes for environmental purposes (WWAP, 2018). Next to changes in water management, changes in the earth's climate are occurring. Due to climate change, the water inflow in the Rhine will become more variable throughout the seasons; the water flow in summer and autumn is expected to decrease, while the flow in winter is expected to increase.

The changes in water management approach and water flow will affect river uses and might cause conflicts of interest between them. Environment is expected to benefit from the nature-based water management approach, while the shipping industry fears that a combination of climate change and nature-based water management will harm navigational conditions. Moreover, flood protection is the river use with highest priority and therefore needs to be secured under any circumstances. Most previous research focussed on the effects of nature-based water management on a single river use, often without considering changes in water inflows. Therefore, this research consists of an integrated analysis that shows where and when conflicts between the three river uses arise and answers the following research question: *What conflicts arise between environment, navigation, and flood protection when nature-based water management policies are implemented under different water flow scenarios and how can insights in these conflicts be used in the policy-making process?*

Research design: modelling

Since the changes in water flows are expected in the future, their effect cannot be measured yet and a modelling approach is required to analyse the effects of nature-based water management under potential future water inflow scenarios. In this research, system dynamics (SD) modelling has been used as the modelling method, because SD enables integration of physical, social and economic factors influencing water resources while addressing inter-sectoral, long-term problems (Winz, Brierley & Trowsdale, 2009). A literature review and expert interviews ensured a thorough model conceptualization process, in which the scope of the model has been set to analysing a side channel as a nature-based water management example. The model has been built up of four sub-systems that are interrelated: the river system (including a main channel, side channel, and floodplain), the environmental system, the navigation system, and the flood protection system. The river sub-model analyses how the different water inflow scenarios and side channel configurations influence water quantities and water levels in the main channel, side channel, and floodplain. The environmental sub-model analyses how water quantities influence channel habitat availability and floodplain vegetation development – which in turn affects the water level in the floodplain. The navigation sub-model determines the available cargo capacity for navigation at different water quantities. Finally, the flood protection sub-model analyses the

occurrence of flooding and of dike failure mechanisms (inward macro-instability, outward macro-instability, piping, and dike erosion).

Conflicting values with regard to side channels

The model described in the previous section has been run for eight combinations of scenarios and policy configurations. The results are summarised in *table i,* which shows that environment and flood protection or navigation and flood protection can find a solution that is beneficial (or neutral) for both. However, the environment requires a side channel that is connected on both its ends – and therefore has a year-round water flow –, while navigation prefers a side channel that is only connected on its downstream end in order to prevent lowering of the water level in the main channel. The ambiguous effect of a side channel on the environment lies in the fact that a side channel improves channel habitats, but at the same time reduces floodplain flooding which impairs floodplain habitats.

Table i: Conflicts with regard to side channels and water inflow scenarios

Water inflow scenario	Side channel configuration	Effect on environment	Effect on navigation	Effect on flood protection
High inflow	Connected on 1 side	Positive	No effect	Positive
	Connected on 2 sides	Positive	No effect	Positive
Low inflow	Connected on 1 side	Ambiguous	No effect	No effect
	Connected on 2 sides	Ambiguous	Negative	No effect

Insights for policy-makers

Insights for policy-makers are found in five ways. First, the conflicts between river uses do not necessarily arise regarding a policy – a side channel per se – but can also concern the configuration of that policy – connected on one side or on two sides. Therefore, it is important to first determine whether the conflict concerns the overall policy or its configuration when deciding about nature-based water management. Secondly, the conflicts strongly depend on the changes in water inflow due to climate change, so further evaluations of nature-based water management and its effect on river uses should consider different water inflow scenarios. Third, attention should be paid to compromises that are made in the policy-making process. The side channel that is connected on only one side can be seen as a compromise between nature and navigation and it indeed eliminates the negative effects of a side channel on navigation, but it strongly reduces the benefits for nature. Therefore, it is recommended to include representatives of each river use during the complete decision-making process and to re-evaluate the effectiveness of policies after each iteration to ensure that compromises do not reduce the effectiveness of the policy. Fourth, for nature-based water management to be truly effective for environmental purposes, integration of several measures is required, construction of a side channel should for example be combined with summer dike removal. Finally, the model showed that system behaviour is strongly dependent on fixed standards (e.g. maximum amounts of vegetation and presence of summer dikes), while changing these standards could have beneficial results for nature, and do not harm the other river uses when combined with other measures (such as floodplain widening).

Discussion and further research

The model that was developed in this research is not only suitable for analysis of side channels, it can also be used to study the effects of river channel widening, floodplain widening, summer dike removal, and changes in floodplain vegetation management. During the modelling process, several numerical issues arose. These issues had two main causes; the principle of conservation of mass – which is required for detailed hydrological analyses – and differences of time scales between sub-systems. Both issues did not limit the usability of the model for the purpose of analysing conflicts on a high level. Besides, the numerical issues indicate the difficulty of developing such an integrated model and that the model operates right at the edge of what is (numerically) possible. For further research, four steps are recommended. First, expert validation of the model is required to increase confidence in the model results. Secondly, the model settings can be changed so that the sub-models are run at different time steps to investigate whether this solves some of the numerical issues. A next proposal for further research is extending the model by including summer dike removal, different processes of human vegetation removal, river channel widening, and floodplain widening in the model. Finally, it is recommended to further study the longitudinal training dam (LTD) as a possible alternative for side channels.

Contents

Summary 5
Contents 8
List of figures 10
List of tables 11

Part 1 The research problem: conflicts regarding nature-based water management policies in the Rhine 12
1. Introduction to the research problem 13
1.1 Nature-based water management 13
1.2 Influence of climate change 15
1.3 Effects on river uses 15
1.4 Research question 16
1.5 Report structure 16
2. Further specification of the research problem 17
2.1 Previous research and its focus 17
2.2 Knowledge gap 19
2.3 Link with EPA programme 19
3. Methodology 20
3.1 The research approach; modelling 20
3.2 Research methods 20

Part 2 Understanding the Rhine, conflicting interests, and nature-based water management policies 27
4. Hydrology, morphology and flow variation in the Rhine 28
4.1 Hydrology and morphology in the Rhine 28
4.2 Future water flow variation in the Rhine 36
5. Criteria for environment, navigation, and flood protection 38
5.1 Environmental criteria 38
5.2 Criteria for navigation 39
5.3 Criteria for flood protection 40
6. Nature-based water management policies 42
6.1 Literature on policies 42
6.2 Findings on policies from interviews 42
6.3 Reflection on policies 43

Part 3 An integrated model on side channels and resulting conflicts 44
7. Model conceptualization 45
7.1 Model choices 45
7.2 High-level model conceptualization 47

7.3 Detailed model conceptualization 49
8. Model description 58
8.1 Criteria – from measurable to comparable 58
8.2 Model equations and assumptions 59
8.3 Model parameters 66
8.4 Model settings 66
9. Model verification and validation 67
9.1 Model verification 67
9.2 Model validation 69
10. Design of experiments 72
10.1 Policy options 72
10.2 Scenario variables 73
10.3 Experiments 75
11. Model results 77
11.1 Comparison BAU, EXP1, EXP2, and EXP3 77
11.2 Comparison BAU, EXP4, EXP5 80
11.3 Comparison BAU, EXP6, EXP7 82
11.4 Decision analysis 84

Part 4 Conclusion and discussion 89
12. Conclusion 90
12.1 Conflicts regarding nature-based water management 90
12.2 Insights for policy-makers 91
13. Discussion 93
13.1 Results 93
13.2 Methods 93
13.3 Applicability of the model 95
13.4 Recommendations 96

Bibliography 97

Appendices 102
Appendix A: Interviews 103
Appendix B: Background on the Rhine River system 140
Appendix C: International agreements on environmental issues in the Rhine 150
Appendix D: Model description 152
Appendix E: Model verification 172
Appendix F: Model validation 184
Appendix G: Policy and scenario implementation 230

List of figures

FIGURE 1: STATE OF THE RHINE RIVER (ICPR, 2015B) 14
FIGURE 2: HIERARCHY FOR WATER INFRASTRUCTURE (RIJCKEN, 2017) 15
FIGURE 3: RESEARCH FLOW DIAGRAM 21
FIGURE 4: ABSTRACT STANDARD SYSTEM DIAGRAM 24
FIGURE 5: ABSTRACT SYSTEM DIAGRAM FOR THIS RESEARCH 24
FIGURE 6: CAUSAL DIAGRAM OF RHINE RIVER PROCESSES – DERIVED FROM LITERATURE AND INTERVIEWS 33
FIGURE 7: CONFLICTING INTERESTS IN THE RHINE – DERIVED FROM LITERATURE AND INTERVIEWS 36
FIGURE 8: RELATION BETWEEN LOW WATER LEVELS AND CARGO CAPACITY OF SHIPS 39
FIGURE 9: CAUSAL DIAGRAM – MODEL CHOICES BASED ON CHAPTER 4 46
FIGURE 10: HIGH-LEVEL CONCEPTUALIZATION - SYSTEM DIAGRAM 48
FIGURE 11: RIVER SYSTEM SKETCH – NO SIDE CHANNEL 49
FIGURE 12: RIVER SYSTEM SKETCH – SIDE CHANNEL 50
FIGURE 13: DETAILED CONCEPTUALIZATION – SYSTEM DIAGRAM RIVER SUB-MODEL 51
FIGURE 14: DETAILED CONCEPTUALIZATION – SYSTEM DIAGRAM ENVIRONMENT SUB-MODEL 53
FIGURE 15: DETAILED CONCEPTUALIZATION – SYSTEM DIAGRAM NAVIGATION SUB-MODEL 55
FIGURE 16: DETAILED CONCEPTUALIZATION – SYSTEM DIAGRAM FLOOD PROTECTION SUB-MODEL 57
FIGURE 17: WATER DISCHARGE EFFECT ON CURRENT SPEED MAIN CHANNEL 60
FIGURE 18: WATER LEVEL DIFFERENCE EFFECT ON SIDE CHANNEL INFLOW 60
FIGURE 19: WIDTH EFFECT ON CURRENT SPEED SIDE CHANNEL 61
FIGURE 20: WATER VOLUME EFFECT ON CURRENT SPEED FLOODPLAIN 62
FIGURE 21: VEGETATION EFFECT ON CURRENT SPEED FLOODPLAIN 62
FIGURE 22: WATER LEVEL FLOODPLAIN ABOVE NAP 63
FIGURE 23: EROSION SEDIMENTATION MULTIPLIER 63
FIGURE 24: FITTING UNDER BRIDGE EFFECT BULK 64
FIGURE 25: FITTING UNDER BRIDGE EFFECT CONTAINER 64
FIGURE 26: LOW WATER LEVEL EFFECT 64
FIGURE 27: WATER LEVEL EFFECT ON INWARD MACRO-INSTABILITY 65
FIGURE 28: DURATION EFFECT ON INWARD MACRO-INSTABILITY 65
FIGURE 29: WATER LEVEL DIFFERENCE EFFECT ON OUTWARD MACRO-INSTABILITY 65
FIGURE 30: DURATION EFFECT ON OUTWARD MACRO-INSTABILITY 65
FIGURE 31: WATER LEVEL EFFECT ON PIPING 65
FIGURE 32: DURATION EFFECT ON PIPING 65
FIGURE 33: FLOODING PER M DIKE EFFECT ON DIKE EROSION 66
FIGURE 34: DURATION EFFECT ON DIKE EROSIO 66
FIGURE 35: RIVER SUB-MODEL OUTPUT WITH TIME STEP 0.001389 AND TIME STEP 0.00104167 69
FIGURE 36: WATER INFLOW SCENARIOS 74
FIGURE 37: RIVER BED LEVEL ABOVE NAP SCENARIOS 75
FIGURE 38: EFFECT OF BAU, EXP1, EXP2, AND EXP3 ON THE RIVER SYSTEM. 78
FIGURE 39: EFFECT OF BAU, EXP4, AND EXP5 ON THE RIVER SYSTEM. 81
FIGURE 40: EFFECT OF BAU, EXP6 AND EXP7 ON THE RIVER SYSTEM. 83

List of tables

TABLE i: CONFLICTS WITH REGARD TO SIDE CHANNELS AND WATER INFLOW SCENARIOS..6
TABLE 1: OVERVIEW OF PREVIOUS RESEARCH..18
TABLE 2: TOPICS COVERED BY EXPERTS..23
TABLE 3: CRITERIA ENVIRONMENT..58
TABLE 4: CRITERIA NAVIGATION..59
TABLE 5: CRITERIA FLOOD PROTECTION..59
TABLE 6: POLICY CONFIGURATION OPTIONS..73
TABLE 7: WATER INFLOW SCENARIOS..74
TABLE 8: SIMULATION EXPERIMENTS..76
TABLE 9: COMPARABLE CRITERIA OUTPUT BAU, EXP1, EXP2, AND EXP3..79
TABLE 10: EXPERIMENT DESIGNS BAU, EXP4, AND EXP5..80
TABLE 11: COMPARABLE CRITERIA OUTPUT BAU, EXP4, AND EXP5..81
TABLE 12: EXPERIMENT DESIGNS BAU, EXP6, AND EXP7..82
TABLE 13: COMPARABLE CRITERIA OUTPUT BAU, EXP6, AND EXP7..84
TABLE 14: EXPERIMENT DESIGNS..85
TABLE 15: SCORECARD EXPERIMENTS..86
TABLE 16: EFFECTS OF DIFFERENT SIDE CHANNEL CONFIGURATIONS AND WATER INFLOW SCENARIOS ON RIVER USES 88

Part 1

The research problem; conflicts regarding nature-based water management policies in the Rhine

1. Introduction to the research problem

This section introduces the research in section 1.1 to 1.3, the research question in section 1.4, and the report structure in section 1.5.

1.1 Nature-based water management

Human influences in the Dutch Rhine branches first started around the year 1100 AD (Berendsen & Stouthamer, 2000). In order to protect ourselves from floods during high water discharges and to increase water levels for navigation during low water discharges, many engineering structures have been built on and along the Rhine, especially over the past two centuries. Examples of these structures are canals, dikes, sluices, and groynes. The purpose of these measures was to increase the depth of the river channel and straighten the waterway for navigation, and to reduce flooding. After centuries of human influence, the Rhine River has become an engineered river, as the map in *figure 1* shows. For each stretch of the Rhine, it is indicated whether it is natural (blue), artificial (pink), or heavily modified (yellow). Only upstream of Basel does the Rhine exhibit natural stretches.

The engineering structures in the Rhine perform relatively well for flood control and navigation purposes, but not if we look at it from an environmental perspective; the river ecosystem has been degraded (Gilvear, Spray & Casas-Mulet, 2013; Loucks & Van Beek, 2017). Besides, unexpected side effects, such as erosion of the river bed, are occurring. That is why different types of river policies are now being developed, based on the concept of nature-based water management. Nature-based water management uses nature as a source of inspiration and information to design water management policies. In addition, it makes use of ecological, hydrological, and morphological river processes (WWAP, 2018). Since natural systems and processes adapt to changes in their surroundings, using natural processes for water management purposes increases the resilience of the system (Demmers, 2018). Furthermore, nature-based water management can focus on restoring or conserving natural river processes and ecosystems to improve environmental aspects of rivers (WWAP, 2018).

1.1.1 Nature-based water management policies

Examples of nature-based water management policies are (i) reducing the extent of engineering on riverbanks, (ii) improving fish migration, and (iii) improving lateral river continuity such as floodplains and backwaters, amongst others (ICPR, 2015a). Other examples are counteracting river bed erosion, preserving freely flowing sections of the Rhine and reactivating inundation areas along the Rhine (ICPR, 2015c). The construction of a side channel, which increases habitat availability for aquatic species while at the same time acting as a natural discharge channel for high water flows, is an example of a nature-based water management policy as well.

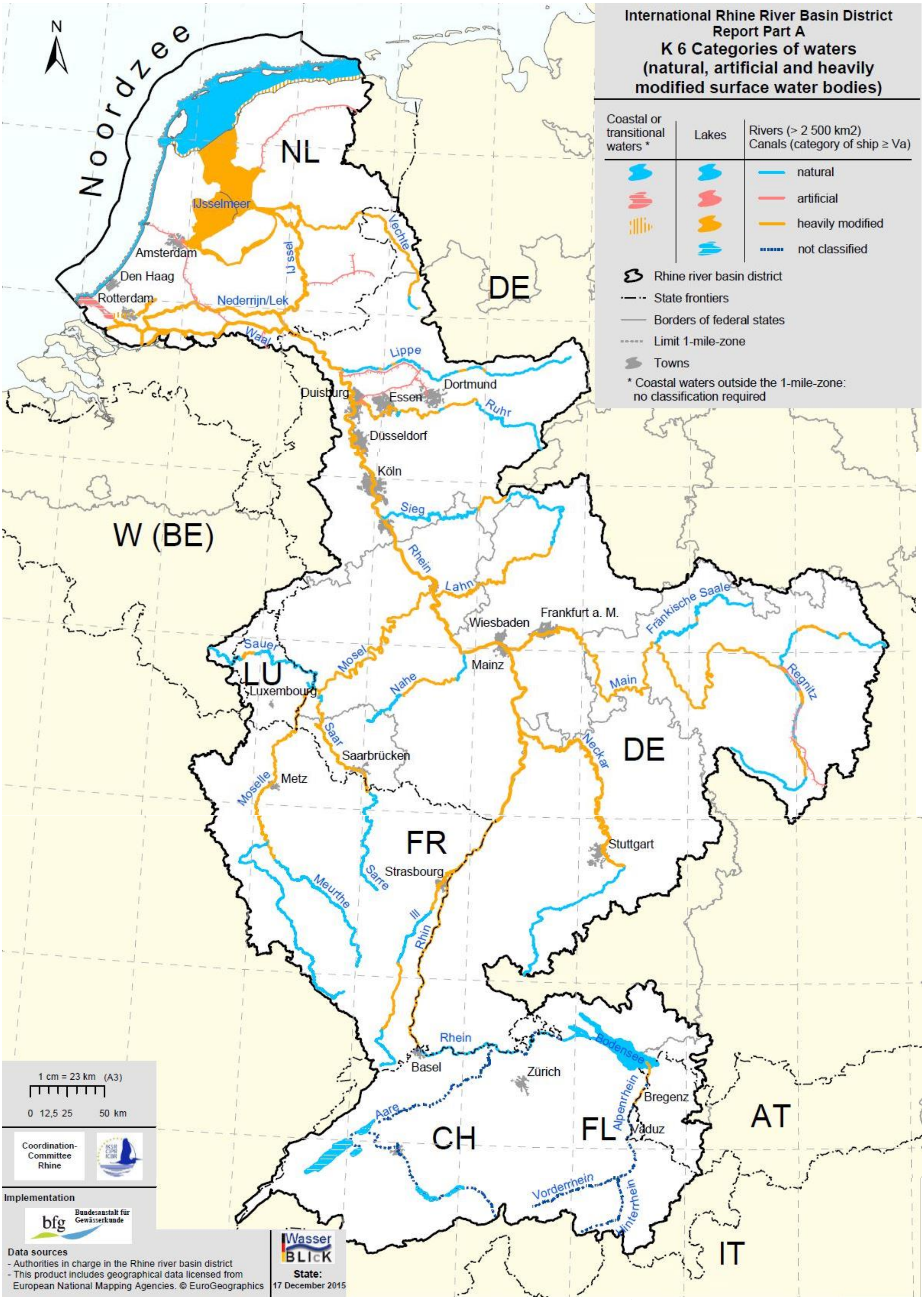


Figure 1: State of the Rhine River (ICPR, 2015b)

1.2 Influence of climate change

Not only the type of river policies is changing, our climate changes as well. This has an effect on the water flows in the Rhine (and other rivers). The water discharge (in m^3/s) in the Rhine has a natural variability within seasons and years and even between years. This actually enhances and steers natural processes such as fish spawning. However, this seasonal variability is expected to become more extreme. Nowadays, the Rhine is snow-driven in its upper reaches and rain-driven in its lower reaches (Bormann & Pinter, 2017), but it is expected that the river will become more rain-driven due to climate change (Jonkeren, Jourquin & Rietveld, 2011; Van Slobbe, Werners, Riquelme-Solar, Bölscher & van Vliet, 2016). Van Slobbe et al. (2016) indicate that this will result in a decreased flow in summer and autumn and an increased flow in winter, because less precipitation will be stored as snow in the Alps. This will result in more risk of flooding in winter, and more water scarcity in summer.

1.3 Effects on river uses

Both nature-based water management policies and changes in the water flow will affect river use. Rijcken (2017) altered Maslow's hierarchy of needs to show how priorities in river management are assigned at this moment. He argues that nature and landscape quality only become important when the basic needs (flood protection, freshwater conveyance, and navigation) are met (see *figure 2*). If the history of the Rhine is analysed, this indeed shows that flood protection and navigation were given a higher priority than the environment. In an ideal situation, one which nature-based water management tries to achieve, multiple objectives in *figure 2* would be attained simultaneously. However, whether this is possible has not been thoroughly analysed yet. Therefore, this research studies the effect of nature-based water management under different water inflow scenarios on multiple river uses to identify conflicts that might arise. The river uses that are included in the research are the environment, navigation, and flood protection. The environment is included because it is expected to benefit significantly from the nature-based water management approach. Navigation is included because the Rhine is one of the largest shipping waterways in Europe and of great importance for the economies of riparian countries. Policies should therefore not have negative effects on navigation. Flood protection is included because it is of highest priority in river management. River policies that negatively influence flood protection are generally rejected.

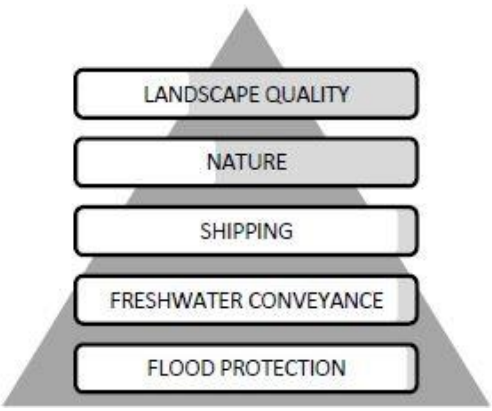


Figure 2: Hierarchy for water infrastructure (Rijcken, 2017)

1.4 Research question

From the previous sections it has become clear that new nature-based water management policies should not compromise navigation or flood protection. Therefore, an integrated analysis that shows where and when conflicts between the three river uses arise is required. Most research evaluating river policies is very detailed and focusses on a single river use or even a single aspect of this river use (e.g. sediment flows impacting navigation) – this is elaborated further in chapter 2. Higher level, integrated policy evaluations are rare. Moreover, most evaluations do not consider different water flow scenarios, while flow variability is expected to increase in the Rhine and measures are likely to perform differently under high-flow and low-flow scenarios. Therefore, this thesis aims to support the ongoing policy-making process by taking all three aspects into account, seeking a balance between them for society. This is done by answering the following research question;

What conflicts arise between environment, navigation, and flood protection when nature-based water management policies are implemented under different water flow scenarios and how can insights in these conflicts be used in the policy-making process?

1.5 Report structure

This report is divided into four main parts; the first part introduces the research problem and consists of chapters 1, 2, and 3. Chapter 2 further specifies the research problem by analysing previous studies. In chapter 3 the research approach to answer the main question, the sub-questions, and the methods to answer these are discussed. The second part of this report describes the Rhine River system in detail and consists of chapter 4, 5, and 6. Chapter 4 deals with hydromorphological processes and water flow variations in the Rhine and how these influence environment, navigation, and flood protection. In chapter 5, the criteria for environment, navigation, and flood protection are elaborated. Chapter 6 discusses nature-based water management policies that have been developed. Part 3 concerns the system dynamics model that is developed for evaluating a specific nature-based water management option in chapters 7 through 11. In chapter 7 the research problem and the information from chapter 4 through 6 is used in focussing and conceptualizing the model; the relations between components of the issue are identified. Chapter 8 describes how the conceptualized system is implemented in the model. Next, chapter 9 discusses whether the model sufficiently represents the real-world system and is fit for purpose. Chapter 10 presents the water flow scenarios for which the policies will be tested. Then, in chapter 11 the model results are discussed. Part 4 of this report presents the conclusion and discussion of the thesis. A series of five appendices present specific details of the work.

2. Further specification of the research problem

This chapter reviews existing literature about the research topic to provide background information about previous research and to indicate the area where new research is required; the knowledge gap. The research question as stated in chapter 1 lies in this knowledge gap which indicates the scientific relevance of the thesis.

2.1 Previous research and its focus

Multiple evaluations of nature-based water management policies have been performed; some of the benefits of nature-based water management policies in general, some on the governance of the cooperation in the Rhine basin and others on specific measures in the Rhine. *Table 1* provides an overview of these studies. An example of the first type is a research by Vermaat et al. (2016), who monetize river services and conclude that environmental river restoration enhances societal benefit. Gilvear et al. (2013) also measure the societal benefit of river restoration, but they analyse the effect of individual measures (e.g. re-meandering). Both researches aim to include all societal costs and benefits, but they neglect the potentially negative effects on navigation. Plum & Schulte-Wülwer-Leidig (2014) evaluate the effectiveness of different programmes of the International Commission for the Protection of the Rhine (ICPR) and provide lessons-learned for future international cooperation. They compare the effects with the targets that were set by the ICPR, but do not analyse the effects on other criteria.

Examples of evaluations of specific measures can be found for each involved country; Arnaud, Piégay, Schmitt, Rollet, Ferrier & Béal (2015) analyse the effect of adding gravel downstream of the Kembs dam on the border between Germany and France and conclude that aquatic habitats are possibly enhanced. They also indicate that a temporary sand bar is formed, but do not elaborate on its effect on navigability. Collas et al. (2018) and Kurstjens (2016) evaluate the effect of the replacement of groynes with longitudinal training dams (LTD's) in the Waal (a Dutch distributary of the Rhine). This measure is supposed to enhance environmental aspects, navigation, and flood protection at the same time (Eerden, 2013). According to Collas et al. (2018), the LTD's indeed have a positive effect on fish habitat and increased the number of fish in the area. Ongoing research of De Ruijsscher, Naqshband & Hoitink (2018) indicates that erosion is expected in the fairway side of the LTD, so this may be an interesting study to follow. Le, Crosato, Mosselman & Uijttewaal (2018) found that it is likely that one of the channels (i.e. either the main channel or the shore channel) of an LTD will gradually silt-up, depending on the starting location of the LTD. Another policy recently implemented in the Netherlands is the 'Room for the River' programme that restores the river's natural floodplains, lowers groynes, and introduces high-water side-channels (Room for the River, 2018). A related measure is Cyclic Floodplain Rejuvenation (CFR), first applied in the floodplains of Beuningen, which re-initiates natural ecological and morphological processes in floodplains (Vreugdenhil, 2010). This was designed to be achieved without negatively influencing flood protection and navigation conditions (Vreugdenhil, 2010). The major concern of the shipping industry relating to CFR is the unknown effects this measure might have on sedimentation in the navigation channel (Vreugdenhil, Slinger & Kater, 2008). Baptist et al. (2004) study CFR and conclude that it is a successful measure for maintaining safe flood levels while at the same time increasing floodplain vegetation diversity. In the latter research, the navigability of the Rhine has not been studied. Van Vuren, Paarlberg & Havinga (2015) do analyse the effect of room for the river interventions on navigation. They conclude that these interventions increase riverbed dynamics and therefore erosion and sedimentation, which hinders the navigability of the Rhine. This results in an increased need for dredging and higher navigational costs. Geerling & Van Kouwen (2011) evaluate the benefits of a side channel for nature development and provide guidelines for side channel construction by studying several existing side channels. They do mention navigation as a factor that should be taken into account when determining the side channel dimensions, but they do not study this further. Most of the evaluations described above focus on one or two aspect of the measures. Vreugdenhil et al. (2008) have a broader focus and include the possible negative effects of CFR on navigation through changes in sedimentation processes, but they do not regard issues related to water quantity. Rijkswaterstaat (2004) and Ruimte voor Levende Rivieren (2018) provide detailed information about side channels and how this influences the river system as a whole. However, their main focus is on the issues with sedimentation in the main channel that is caused by side channels and that hinders navigation, not on changes in water levels (so related to water quantity).

Another important note is that the variability in river flow, as discussed above, is disregarded by most evaluations while a nature-based water management measures will perform differently in a high-flow period compared to a low-flow period. As discussed before, the flow of the Rhine is changing due to climate change, and high-flow and low-flow periods might occur more often, at a different moment in the hydrological year or become more extreme. Beijk, Coonen, van den Heuvel & Treurniet (2017) have researched the performance of several barrages in the Nederrijn-Lek (again a Dutch distributary of the Rhine) during low-flow events. They conclude that during these events, there was insufficient water to meet the demands for navigation, agriculture and the prevention of salt intrusion. However, they do not discuss other environmental implications.

Table 1: Overview of previous research

Research	Nature-based water management	Rhine	Environment	Navigation	Flood protection	Changing water flows
Arnaud et al. (2015)	X	X				
Baptist et al. (2004)	X	X	X		X	
Beijk et al. (2017)	X	X		X		X
Collas et al. (2018)	X	X	X			
Geerling & Van Kouwen (2011)	X	X	X			
Gilvaer et al. (2013)	X		X		X	
Kurstjens (2016)	X	X	X			
Plum & Schulte-Wülwer-Leidig (2014)	X	X	X		X	
Rijkswaterstaat (2004)	X	X	X	X	X	
Ruimte voor Levende Rivieren (2018)	X	X	X	X	X	X
Van Vuren et al. (2015)	X	X		X	X	
Vermaat et al. (2016)	X		X		X	
Vreugdenhil et al. (2008)	X	X	X	X	X	
Vreugdenhil (2010)	X	X	X	X	X	

2.2 Knowledge gap

As *table 1* indicates, little integrated research on the effects of nature-based water management policies on environment, navigation, and flood protection exists. Ruimte voor Levende Rivieren (2018) did discuss many issues related to water management, nature, and conflicting river uses, but this report did not study the effects related to water quantities in-depth. Therefore, the objective of this thesis is to develop an integrated model that provides insight in the effect of nature-based water management policies in the Rhine river under different flow conditions on socio-economic and environmental criteria; navigability, flood protection and environment. This integrated model enables making a connection between different fields of study. The result will be policy insights on the multi-actor and multi-functional nature-based management of river basins, which can be used for future policy-making in the Rhine or for similar cases elsewhere.

2.3 Link with EPA programme

The EPA master programme deals with international grand challenges. An international grand challenge has the following characteristics: an urgent decision is needed; there is a lot of data, information and expertise involved; there are many possible problem definitions and solutions; there are many parties involved; and there is no single problem owner or responsible authority (Broekhans, 2017). Obviously, the Rhine is an international river, making it an international issue by definition. But the environmental issues in the Rhine have other characteristics of an international grand challenge as well. First of all, environmental river conservation is much cheaper than environmental river restoration, and yet the Rhine is suffering ongoing degradation, making the problem urgent. Secondly, many parties are involved in the problem; not only the countries in the Rhine basin, but also shipping companies, users of floodplains, nature conservation organisations et cetera. None of these parties is solely responsible for the problem or its solutions; the problem is owned by no-one but is felt by the societies of all of the Rhine countries.

3. Methodology

The research question that is answered with this thesis is *What conflicts arise between environment, navigation, and flood protection when nature-based water management policies are implemented under different water flow scenarios and how can insights in these conflicts be used in the policy-making process?*. This chapter describes how the objective of this thesis (section 2.2) will be achieved. First, in section 3.1 the research approach and sub-questions will be presented. Section 3.2 then describes the methods to answer each sub-question.

3.1 The research approach; modelling

Since the objective of this research is to explore which conflicts arise under possible future water flow scenarios – that are not yet present today – a modelling approach is required to provide insight in possible futures with regard to the system behaviour and the effectiveness of policies. Moreover, the modelling approach is suitable when interactions between different components of a system are to be captured, which is an important part of this research.

In order to answer the research question following the modelling approach, five sub-questions have been formulated;

1. What are the hydrological and morphological processes and water flow variations in the Rhine and how do they interact with environment, navigation, and flood protection?
2. What are the criteria for environment, navigation, and flood protection in the Rhine?
3. What nature-based water management policies have resulted from the international agreements on the Rhine and which are most relevant to study further?
4. What are the possibilities for modelling the system described in sub-questions 1, 2, and 3 using the system dynamics approach?
5. What does the model show regarding the performance of nature-based water management policy configurations and the resulting conflicts between the three river uses?

3.2 Research methods

This section presents the specific methods that are used in this thesis and explains why these have been chosen. *Figure 3* visualises the phases of the research, and the steps within each phase. The steps and their method(s) are shown in white boxes. The lines between the research parts indicate that a certain part needs the output of a previous part as input. The blue boxes indicate which question – sub-question (SQ) or research question (RQ) – is answered. Below the figure, each method is discussed in more detail.

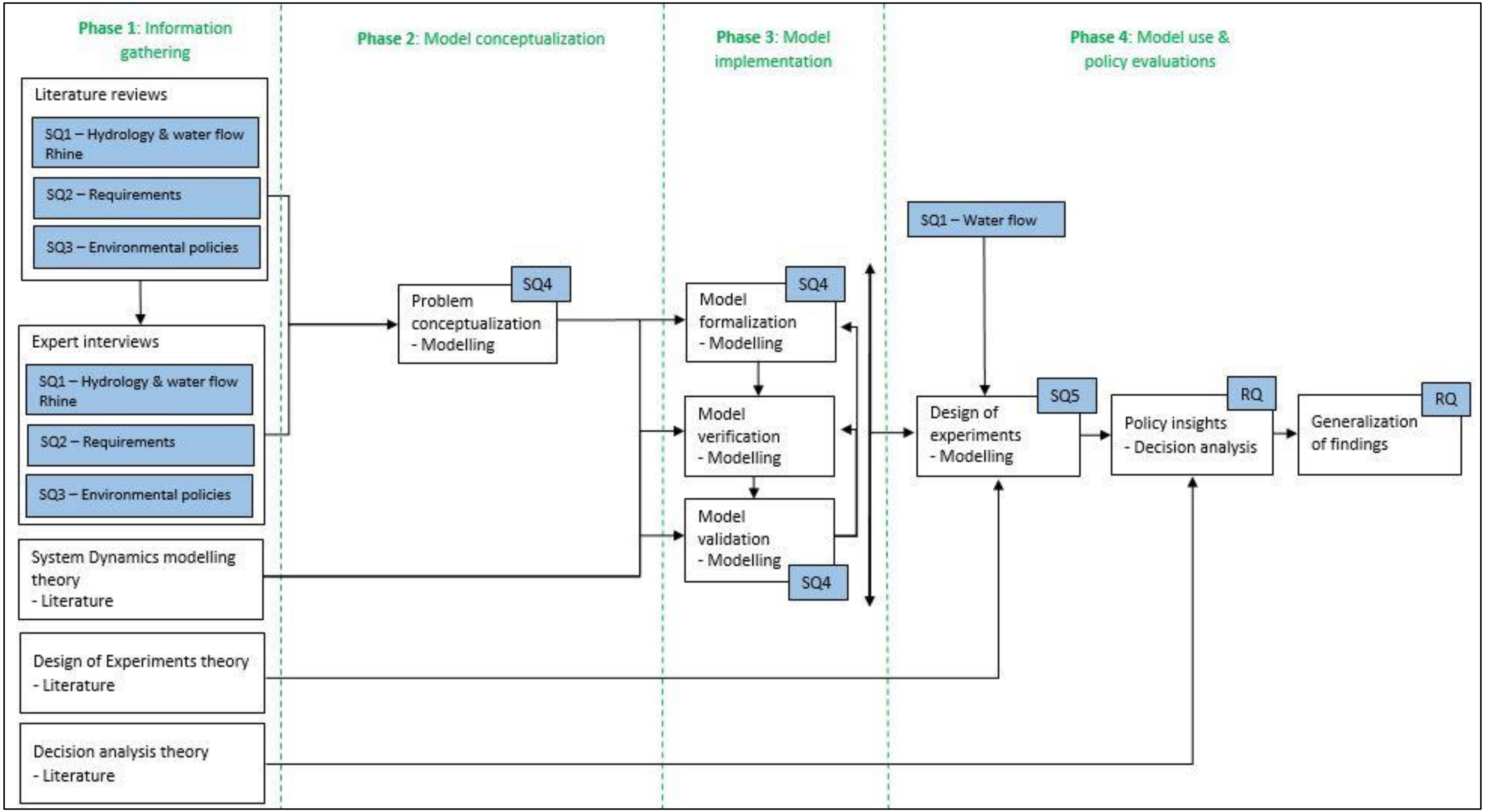


Figure 3: Research flow diagram

3.2.1 Literature review

A literature review is chosen as the first research step, because it enables obtaining thorough knowledge on the Rhine river system and its components which is required to model the system adequately. Limitations of a literature review are that keeping it focused can be difficult and using the appropriate search queries is essential to retrieve relevant information (TUlib, 2018). The literature review is performed to obtain answers to sub-question 1, 2, and 3 (together with the expert interviews, section 3.2.2). Search terms that are used are: 'river dynamics', 'river morphology', 'Rhine morphology', 'Rhine hydrology', 'Rhine normalisation', 'Rhine water flow', 'Rhine hydrograph', 'river ecosystems', 'Rhine ecosystems', 'Rhine nature', 'navigation Rhine', 'flood protection Rhine', 'Rhine flooding', 'river flooding', 'nature-based water management', 'nature-based water management Rhine', 'environmental policies Rhine', and 'water management Rhine'. Of all these search terms, similar terms are derived. Besides, combinations of the search terms are used to find extra information.

3.2.2 Expert interviews

Expert interviews are chosen as a second research step, because it allows for in-depth information gathering for each component of the river system. Also, experts are aware of the issues that are currently being studied and enable focussing the research and the model on the issues that currently important. Moreover, the expert interviews serve as a check on the literature review. The interviews are conducted using an open or non-standardized approach. This type of interviewing allows for in-depth questions that are focussed on the respondent. The questions are predetermined, but the order can be changed during the interview and questions can be omitted or added (Van Teijlingen, 2014). Since the interviewees are experts with knowledge of a particular topic pertaining to the research, this is a suitable method, because it enables fitting the questions to the expertise of the interviewee. The most important limitations of the method are that it is relatively time consuming and that it leaves room for bias since the interviewee can give their views on the topic instead of the facts. However, for this thesis a limited number of interviews with established experts in the field of river research and policy is conducted. The interviewees are chosen by consulting a member of the Netherlands NCR Programme Committee. The interviewees are also informed that other experts will be consulted, as a bias control measure.

The interviews are conducted to answer sub-question 1, 2, and 3 (together with the literature review), so the following list of topics has been established:

1. Topic 1: River hydrology and morphology
2. Topic 2: History of Rhine normalisation
3. Topic 3: River ecosystems
4. Topic 4: Navigation
5. Topic 5: Flood protection
6. Topic 6: Nature-based water management policies

Six experts are interviewed in this phase of the research, and each of them needs to have knowledge on at least one of the topics listed above. *Table 2* shows the interviewees and the topic(s) they are interviewed about, the bold X indicates their main area of expertise. For a more elaborate explanation of the interview method, see Appendix A.

Table 2: Topics covered by experts

Expert	**Topic 1**	**Topic 2**	**Topic 3**	**Topic 4**	**Topic 5**	**Topic 6**
Dr. ir. Cornelis van Dorsser				**X**		
Prof. dr. Frans Klijn	X	X			**X**	X
Drs. Daphne Willems			**X**			X
Dr. Gertjan Geerling			**X**			X
Dr. ir. Erik Mostert						**X**
Dr. ir. Astrid Blom	**X**	X				

By combining literature and interviews, some limitations of both methods are avoided. By performing the literature review first, background knowledge is acquired which is useful when preparing the interviews. Also, the expert interview acts as a check whether all information is found and the focus is appropriate. Following the interviews, new facts, additional insights or contradictory information are checked by a second literature study. This way, triangulation – a combination of multiple methods or data sources in order to increase system understanding and data validity (Denzin, 2012) – is achieved. The results of the literature review and expert interviews can be found in chapters 4, 5, and 6 of this report.

3.2.3 System dynamics modelling and water balance

With system dynamics (SD) modelling, dynamic, complex systems can be described, modelled, simulated and analysed in terms of processes, information, organizational boundaries and strategies (Pruyt, 2013). SD is especially useful for capturing non-linear behaviour, something that human beings are usually unable to do (Forrester, 2009). This method is chosen, because it enables a holistic analysis of the issue, where multiple (socio-economic) aspects can be evaluated in one model. SD is not a predictive approach giving exact values for future system states, but it improves understanding of the system and its behaviour (Ford, 1999). Winz, Brierley & Trowsdale (2009) argue that SD is suitable for water management, because the dynamic simulation of changes in water systems over time enables scientifically informed decision-making and because SD aims to integrate physical, social and economic factors influencing water resources while addressing inter-sectoral, long-term problems. Also Mirchi, Madani, Watkins & Ahmad (2012) emphasise the advantage of the multi-sectoral approach of SD for strategic water management analyses. Clifford-Holmes, Slinger, de Wet & Palmer (2017) emphasise that SD enables the analysis of secondary, long term consequences of short-term actions, that it contains many social dimensions and that it allows for studying actual practices. Ford (1999) also indicates the usability of SD for water (resources) management. Winz et al. (2009) mention several limitations of using SD for water management. First of all, models are often made too complex and focussed. Secondly, the problem, purpose and deliverables are often insufficiently defined. A third common mistake is that stakeholders are insufficiently involved in the process, so they do not 'believe' in the model or conflicts are inadequately addressed. In this research, the first two limitations were addressed by an extensive literature review and expert interviews phase, which allowed for a strong definition of model scope and deliverables. The third limitation was addressed by performing expert interviews to define the important processes and model components.

A simplified water balance is incorporated into the SD model (à la Slinger, 1986 and Slinger, 1997). The water balance of a river basin describes the change in water storage in the area as the inflow minus the outflow of surface water and groundwater. It is important to incorporate this in the model for this research, because the water balance influences environmental processes, the water level for navigation and occurrence of flooding. Several examples of research that includes the water balance in SD exist, but they mostly use water quantities to analyse water allocation to the different uses (hydropower generation, drinking water supply, irrigation, et cetera). A first example is Ford (1996) who made a model with hydrological details (evaporation, percolation, groundwater flow, et cetera) to simulate the annual flow in a river. A second example is the research of Clifford-Holmes, Slinger, Musango, Brent & Palmer (2014) that analyses municipal water demand and supply in the Sundays River Valley Municipality. Ahmad & Prashar (2010) have made a model that analyses water supply and demand in a river and lake, and have included environmental requirements. For this thesis, hydrological processes such as evaporation and groundwater flow will be disregarded for simplification purposes. Only the surface water flows between a river's main channel, a side channel and the floodplain are included.

A first step in modelling is to conceptualise a problem by a system diagram of which an abstract version is shown in *figure 4* (based on Van der Lei, Enserink, Thissen & Bekebrede, 2011).

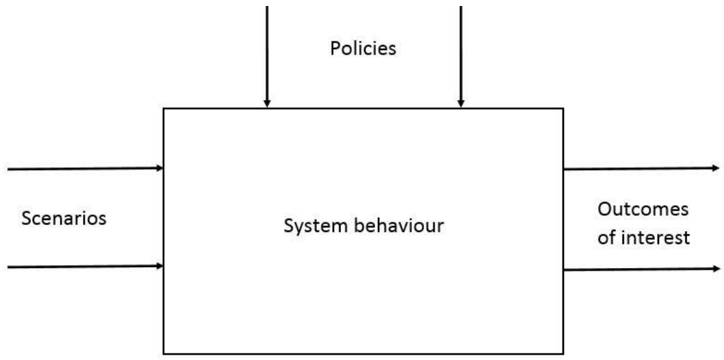


Figure 4: Abstract standard system diagram

The components of the system diagram of this research are partly constructed by the information obtained in sub-questions 1, 2, and 3, as can be seen in *figure 5*. The system diagram still needs to be elaborated to show the processes within each component, which is done in the conceptualization phase of the modelling approach (chapter 7). Starting from the system diagram, an actual policy model is formalized by implementing (differential) equations for each variable in the model (chapter 8).

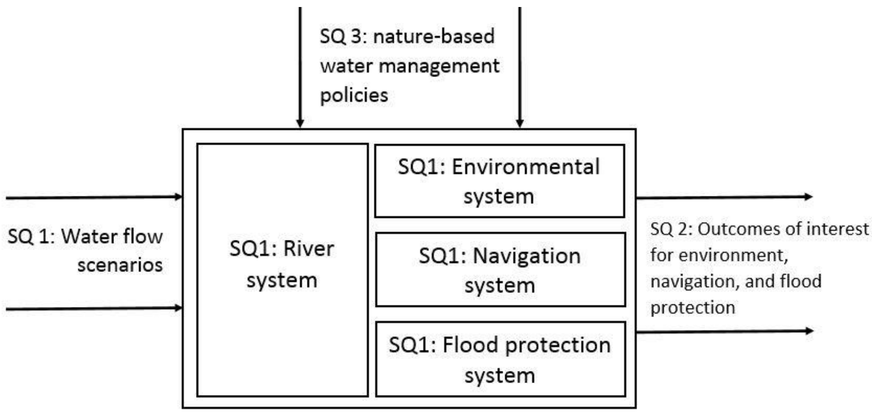


Figure 5: Abstract system diagram for this research

A critical step when using a modelling approach is model verification and validation. Model verification tests whether the model is coded correctly, if units are consistent and whether the numerical simulation is accurate (Slinger, personal communication, June 11, 2018). The Vensim software has some built-in functions for this, and several manual checks can be performed. For a more detailed description of model verification, see chapter 9 and appendix E. Model validation checks if the model is fit for purpose (Pruyt, 2013), while keeping in mind that all models are actually wrong (Sterman, 2002). There are many validation tests and Sterman (2002) advises to perform multiple of these. In this research, qualitative comparison of the model with real-world system behaviour, extreme conditions behaviour tests and sensitivity analysis will be used. The first test checks whether the model includes all important processes of real-world river systems, which is necessary because the model effects would be different if key processes were missing. The second test tests the plausibility of the model under extreme conditions through simulation (Pruyt, 2013). This test is chosen for this research, since in sub-question 5 policy configurations will be evaluated for different (extreme) water flow scenarios. Sensitivity analysis studies changes in model outputs caused by small changes in model input (Tank-Nielsen, 1980, p. 187). During model validation by sensitivity analysis, the modeller should ask two questions: "Would the real system exhibit the same sensitivity?" and "Does the model fail behaviour tests previously passed?" (Eker, Slinger, Van Daalen & Yücel, 2014). Sensitivity analysis is chosen because it helps the modeller to identify parameters that require accurate measurement, to locate errors in the model, to identify inputs that have little effect on the output or on the other hand have a large effect, and to improve their understanding of the model (Pruyt, 2013). For more detail on validation and the methods used in this research, see chapter 9 and appendix F. The conceptualization, formalization, and verification and validation steps together answer sub-question 4.

An important note is that modelling always consists of an iterative process. After every version of the model, short verification and validation tests are performed, resulting in a new model version. In this report, only the last verification and validation steps are included, because they are the ones that indicate the level of trust that can be put in the model.

3.2.4 Design of experiments

When the model is validated and is considered adequate enough for policy analysis purposes, it is time to use it. Several experiments – model runs under different scenario and policy combinations – are performed with the model, and the results are stored and analysed. Many experiments could be performed, but the purpose of this thesis is not to perform all these possible model runs. A well-argued choice is made which experiments are relevant for this thesis and might have interesting effects. Park (2007) identifies four steps in the process of performing experiments. First, the objective of the experiments needs to be defined. Then, the output variables that are used to evaluate the experiments (outcomes of interest) and the input variables that form the experiment (scenario and policy variables) need to be determined. Subsequently, the experiment is performed and finally the results of different experiments are analysed. In chapter 10, the choice of experiments is discussed, and their implementation is explained.

3.2.5 Decision analysis

Finally, to answer the research question, the performance of the different experiments in terms of the criteria (in the categories environment, navigation, and flooding) are analysed and compared. It is expected that not all criteria can be optimized and compromises need to be made, since environmental, navigational, and flooding criteria are different in nature and they have potentially negative effects on each other. Therefore, decision analysis is used to compare the effects of different experiments on the criteria. Decision analysis is a systematic, quantitative approach aimed at improving decision-making (Keefer, Kirkwood & Corner, 2004). The result can be visualised in a scorecard, which is a table that shows the effect of each experiment on the criteria, relative to the business as usual scenario (De Haan, Willemse, de Heer, Vos & Bots, 2009). The effects are classified in positive and negative and are coloured accordingly (red for negative effects, green for positive effects). This results in policy insights that can be used in policy-advice for decision-makers. In chapter 11, the results of the different experiments are discussed and compared.

Part 2

Understanding the Rhine, conflicting interests, and nature-based water management policies

4. Hydrology, morphology and flow variation in the Rhine

This chapter answers the first sub-question *'What are the hydrological and morphological processes and water flow variations in the Rhine and how do they interact with environment, navigation, and flood protection?'* by performing a literature study and conducting expert interviews. The chapter is divided into two sections. In the first section the hydrology and morphology in the Rhine and its effect on the environment, navigation, and flood protection are elaborated. In section 4.2 the expected future changes in the Rhine water flow variations are discussed. Each section is divided into three sub-sections; the first one describes findings from literature, the second one adds findings from expert interviews, and the third sub-section summarises these findings and reflects on them.

4.1 Hydrology and morphology in the Rhine

The characteristics that the Rhine currently exhibits, are defined by both natural river processes (Appendix B1) and normalisation measures (Appendix B2). In this section the characteristics of the Rhine river system, its influence on the environment, navigation, and flood protection, and the conflicts between river uses will be discussed.

4.1.1 Literature on contemporary characteristics

The characteristics of the Rhine are extensively discussed in the literature. Of course, differences between the Rhine stretches exist, but from Basel downstream – the part of the Rhine that is navigable – most processes and normalisation measures are similar, and will be discussed collectively.

4.1.1.1 Hydrology and morphology

Although the Rhine's main channel is now strictly defined and maintained by groynes, levees, and other engineering structures, the river bed is still changing. As described in appendix B1, the natural river had four ways to respond to an increase in discharge. Of these, meandering and river widening cannot occur anymore due to the normalisation measures, but the river can still use bed degradation, which is now occurring more strongly. The bed degradation of the Dutch Rhine branches happens at a rate of up to 2 centimetres a year (Niesten & Becker, 2018). However, this is not only caused by the higher current speeds, but also by barrages and dams acting as a sediment trap upstream, and bank protection that halts bank erosion (Deltares, 2017). Bed degradation of the main channel does not only affect the main channel itself, but also the floodplains. Bed degradation has caused the floodplains to be situated relatively higher than they used to be. This has lowered the groundwater level and decreased the frequency of floodplain flooding, causing dehydration of the floodplains. Moreover, the decreased flood frequency hampers erosion and sedimentation in the floodplains and obstructs floodplain rejuvenation, together with the lack of bank erosion due to protection measures (Deltares, 2017). Only during very high discharges will the floodplains be inundated, allowing the erosion and sedimentation process in the floodplains to take place.

Bed degradation could be stopped by allowing the river to widen again, but according to Frings (2017) this will not be feasible as long as the Rhine is an important transportation route between the Netherlands and Germany. Another measure to counteract the bed degradation process is sediment nourishment, which happens downstream of the Iffezheim dam at a rate of 330000 tonnes per year (Wasserstraßen- und Schifffahrtsamt Freiburg, 2018).

4.1.1.2 Environment

In a natural river, hydrological and morphological processes and variations create different types of habitat in the river system. Because of the hydrological and morphological changes due to river normalisation (see appendix B2), however, river ecosystems have degraded and habitat availability and diversity has decreased (Cron, Quick & Vollmer, 2015). Several processes play a role here. First of all, the decrease in erosion and sedimentation of the floodplains has disturbed the balance between progression and regression of vegetation in favour of progression (Diaz-Redondo, Egger, Marchamalo, Hohensinner & Dister, 2017), and has decreased the rejuvenation of the floodplains (Deltares, 2017). At the same time, there are strict vegetation norms that determine the roughness of vegetation on floodplains to maintain water safety (Rijkswaterstaat, 2014a), so vegetation is cut down if it becomes too rough. Secondly, barrages form physical obstructions for migratory fish, therefore restricting ecological continuity (ICPR, 2015a). Waves and current caused by navigation have increased the dynamics in the main channel of the river to an extent harmful for nature (ICPR, 2015a).

4.1.1.3 Navigation

Navigation was one of the main reasons why river normalisation measures were implemented; a deep main channel is exactly what the shipping sector needs. However, bed degradation has a negative effect on shipping, because it decreases the connection between constructed shipping canals and rivers, it can undermine groynes, and it increases the relative height of solid structures (either natural or man-made) in the river bed that may therefore act as obstructions (Deltares, 2017).

4.1.1.4 Flood protection

The process of river narrowing has increased the water levels in the main channel and the floodplains have decreased in size. This has led to too little room for rivers in case of high water levels (Deltares, 2017). Narrow rivers also decrease dampening and flattening of flood waves (Deltares, 2017). Furthermore, the difference between river water levels and groundwater levels inside the dike increases the risk of piping, a process where water flows under the dike, eventually causing erosion and weakening of the dike (Dirkx, Winkels, Van Beek & Bierkens, 2018). Other influences on the strength of a dike are the water level it needs to withstand (Gensen, Warmink & Hulscher, 2018), and the number of time units it needs to withstand this water level (Curran, De Bruijn & Kok, 2017). If the water level is too high for too long, dikes become saturated and might collapse inward ('t Hart, De Bruijn & De Vries, 2016). On the other hand, low water flows are also important for the strength of dikes, because they can cause dikes to collapse towards the river if the water level drops too fast or in case of extreme rainfall events ('t Hart et al., 2016), and because they can cause peat dikes to dry out and crack (Van Baars, 2004). Vegetation in the floodplain should not have a too high roughness, because it hinders water discharge during high water periods (Rijkswaterstaat, 2014a). Therefore, vegetation removal takes place regularly (Harezlak, Hulscher, Augustijn, Leuven & Geerling, 2016; Vreugdenhil et al., 2008).

Although the historic trend used to be focused on controlling rivers and bending them to our will (see appendix B2), a paradigm shift has occurred at the end of the twentieth century. The flood events in 1993 and 1995 started this shift regarding flood protection measures; a change was observed from infrastructural flood protection towards flood risk management, where water should no longer just be kept out but should be accommodated (Hartmann & Spit, 2016). An example of this new approach is the Dutch Room for the River programme, where the river literally received more space by the construction of retention areas and bypasses, enlargement of the floodplain, lowering of the floodplain, et cetera.

4.1.1.5 Conflict between river uses

A conflict between environment and navigation is mainly found in the engineering structures such as groynes, sluices, and bank protections that have been constructed for navigational purposes, but that have a negative effect on the environment (Loucks & Van Beek, 2017). However, conflicts between river uses are not always directly caused by differences in demands on the river system, but they can also be caused by differences in the way of thinking. Water managers can approach floodplains from a fixed viewpoint; a measure is implemented and from that point onward the situation should not change. On the other hand, nature managers can approach floodplains from a development point of view; after a certain measure is implemented, nature can develop itself further and the situation will change (Den Haan, Arevalo, Van der Voort & Hulscher, 2018). Besides, for nature it is beneficial to regard the river system on a larger scale, while water managers usually prefer smaller scales (Vreugdenhil et al., 2008).

4.1.2 Findings on contemporary characteristics from interviews

In this section, the information concerning hydrology and morphology is mostly based on the interview with Astrid Blom, the information related to the environment is obtained from Daphne Willems and Gertjan Geerling, the navigation section is based on information from Cornelis van Dorsser, and the interview with Frans Klijn provided information for the section on flood protection.

4.1.2.1 Hydrology and morphology

The most important finding about the hydrology and morphology of the Rhine is that the river has only two ways left (out of 4, see appendix B1) to adapt itself to changing circumstances:

1. Changing its slope by upstream erosion
2. Coarsening of its river bed

One effect of the changes in hydrological and morphological processes is incision of the river bed due to erosion, with a rate of 1 to 5 cm per year (depending on the location of measurement). At the same time, the floodplains are rising due to sedimentation with a rate of 0.1 to 1 cm per year (which is at a lower rate than would happen in a natural river system). The interviews confirmed that this decreases the frequency of floodplain flooding. Another cause of less frequent flooding in the floodplains are the summer dikes protecting agriculture land.

4.1.2.2 Environment

The decrease in flooding frequency of the floodplain causes the floodplains to dry out. Another reason for this is that the groundwater level has decreased to accommodate for the lower river bed level. Also, the man-made shores are very steep, which results in an abrupt change from not flooded to flooded, instead of a gradual transition as happens with a natural, smooth shore. A smoother shore would increase the habitat diversity. The strict vegetation norms in floodplains are mentioned by both interviewees as well, but they added that vegetation can sometimes improve flood protection (for example trees that protect dikes against wave action), and that the norms could be less strict if the floodplains were made bigger.

Basically, all river processes are now restricted to the main channel. Therefore, the dynamics in the main channel have become too strong for nature, and the dynamics in other parts of the system have become too low. If the river could be allowed to be wider, the stronger dynamics in the navigation channel would be less of a problem, because there would be a broader shore-channel where the dynamics would be less and species could seek shelter.

4.1.2.3 Navigation

Navigation is not directly negatively influenced by the changes in hydrological and morphological processes, but the solid structures in the river bed that do not erode and therefore become obstacles in the waterway do harm the shipping industry. Navigation is expected to be strongly affected by climate change and the resulting longer periods of low water flow.

4.1.2.4 Flood protection

Although there is indeed more attention for Room for the River types of measures in the Netherlands, technical flood protection measures are a necessity, because otherwise the country would not exist. We should find a balance between technical flood protection and other types of measures. In Room for the River attention is paid to the natural river processes. Dike diversion, bypassing, floodplain clearance, and floodplain excavation are examples of these types of measures. When a river is given more space, the water level upstream will be lowered, but the water downstream will remain unchanged. If you want to change the water level downstream, water should be extracted from the river.

4.1.2.5 Conflict between river uses

Frans Klijn and Daphne Willems indicated the existing order of priority within water management:

1. Flood protection
2. Economic water uses such as navigation
3. Quality of the living environment, including nature

Gertjan Geerling also indicated that nature, unless required to receive attention by law or regulations, always loses to other river uses. Besides, he indicates that if too many compromises are made, the plans for nature will not be successful.

Gertjan Geerling mentioned the different ways of thinking between engineers and ecologists (as described in section 4.1.1.5) as well. Not only do they think differently about development after finishing a project, but they also think on different time scales and physical scales. Nature needs several decades to develop, so ecologists have a long term view. Rijkswaterstaat has a yearly budget it needs to justify, so they think on a shorter term. Besides, large connected areas are necessary for nature, while other actors think more on a project basis.

An interesting note is that three interviewees – Cornelis van Dorsser, Frans Klijn, and Gertjan Geerling – suggested the same solution for river use conflicts. They indicate that constructing a canal next to the natural river would solve many problems; then the canal only needs to satisfy the navigational requirements, and the natural river the environmental and flood protection requirements.

4.1.3 Reflection on contemporary characteristics

The most important change that was made to natural rivers when they were normalised, is that their own ability to change decreased. Of the four possible ways a natural river has to adapt, the Rhine now only has two options left; changing its bed slope by upstream erosion and coarsening its bed. This results in bed degradation of the Rhine, with varying estimates of the rate of this degradation, dependent on the location of measurement. These changes in river hydrology and morphology have affected environmental issues in the Rhine through two main causes; the main channel of the river has become too dynamic for natural development, while the floodplains have lost their dynamics. Navigation does not directly suffer from the current changes in hydrology and morphology, but it might be severely impacted by climate change causing longer periods of low water flow. Furthermore, nature-based water management policies that try to improve the natural aspects of rivers do affect variables like the water level and therefore also affect navigation. Regarding flood protection, river normalisation has caused the water level in rivers to rise, and has increased the risk of several processes that might undermine dikes, such as piping. The findings from this chapter have been captured in a causal diagram (see *figure 6*), as a means to provide an overview of the important processes in the river, environment, navigation, and flood protection system. This causal diagram forms the basis for the model conceptualization that is described in chapter 7. *Box* 1 explains how to read causal diagrams.

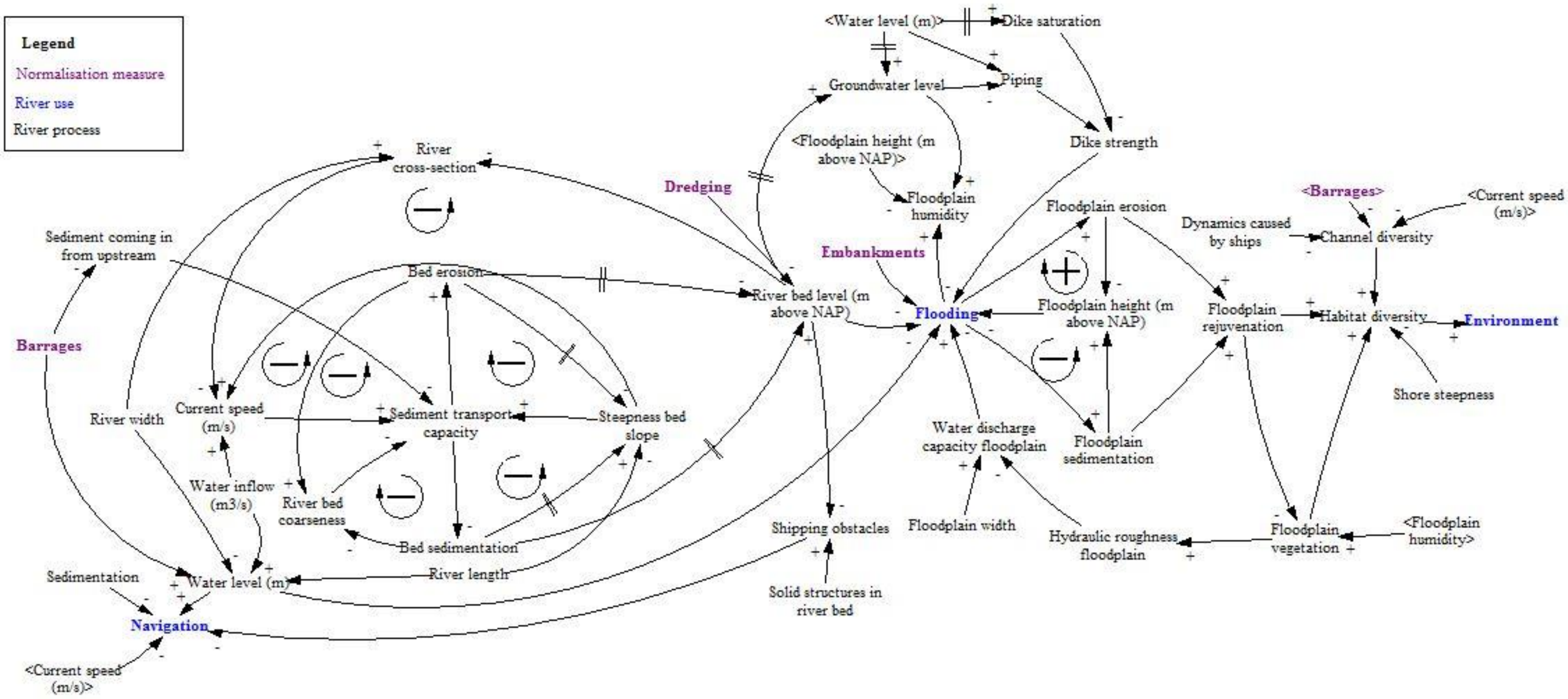


Figure 6: Causal diagram of Rhine river processes – derived from literature and interviews

Box 1 - How to read a causal diagram

A causal diagram consists of variables, arrows between them with a polarity (+ or -), feedback loop signs, and delay marks (||).The easiest way to explain what all these symbols mean is by using a population model as an example. In this model, the arrow from Births to Population with polarity + indicates that the population increases when the number of births increases. The arrow from Population to Births with polarity + indicates that the number of births increases when the population increases. This results in a positive feedback loop (self-reinforcing behaviour), which is indicated with the round arrow with a + in it. However, if the population has been increased this does not immediately result in more births, since the new population members first have to mature. This results in a delayed increase of births, as is indicated by the delay symbol (||).

In addition to positive feedback loops, negative feedback loops exist, as is indicated by a round arrow with a – in it. A negative feedback loops results in balancing behaviour, as is the case with Population and Deaths. If the population grows, the number of deaths will also grow (with a delay, because people usually die after several decades), which then leads to a decline in the population.

Now that the symbols have been explained, there remains one important issue; direct and indirect effects. The number of deaths directly influences the population size. Life expectancy also influences Population, but indirectly via Deaths instead of directly; if the life expectancy increases, people will die at an older age, and therefore the number of deaths will decrease. This increases the population size. Since Life expectancy has a negative effect on Deaths, and Deaths has a negative effect on Population, the indirect (or secondary) effect of Life expectancy on Population is positive.

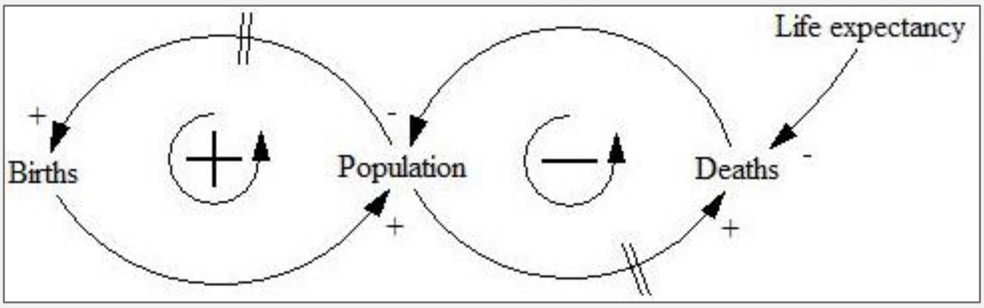


Figure 7 shows simplified versions of the causal diagram for environment, navigation, and flood protection. These diagrams indicate which processes influence the three river uses and whether such a processes needs to increase (green) or decrease (red) to be beneficial for the specific river use. The first conflict relates to the water level in the river – this should be high for navigation, but lower for flood protection (however, it should not be too low either). The second conflict relates to the floodplain height, which should be high for flood protection, but low for the environment. Next, floodplain vegetation increases habitat diversity which is positive for the environment, but at the same time it decreases the water discharge capacity of the floodplain which is negative for flood protection. Additionally, the river width should be small for navigation, because this creates a deeper channel, but it should be wider for the environment to ensure that species can seek shelter from the high dynamics in the main river channel. Furthermore, barrages are vital to ensure a sufficient water depth for navigation, but they have a devastating effect on environmental conditions. Finally, embankments (in this case the summer dikes next to the river channel) are necessary to protect the land in the floodplain from smaller floods, but this disables the floodplain inundation necessary for the environment. Luckily, not only conflicts are found in the causal diagram, but also possible aspects on which cooperation is possible or necessary; the river bed level and the floodplain width. Lowering of the river bed level is problematic for all three river uses, and can therefore form a first issue for cooperation. The floodplain width is a river aspect that does not cause conflict between the three river uses; both for flood protection and for environment it is desirable to have wider floodplains, and it has no effect on navigation.

However, the conflicts as depicted in *figure 7* are based on qualitative information only and do not provide any insights when a certain water level becomes problematic for the river uses, if overlap in fitting water levels for the three uses exists, and in potential co-operative strategies. Moreover, the simplified causal diagrams for each river use only show the issues that arise in first instance, but do not take the strong interdependence of river processes into account. Also, for each river use the water level should be within two limits, so heightening (for navigation) or lowering (for flood protection) the water level for example has positive effects until a certain limit, and then starts having negative effects as well. Therefore, in part 2 of this research a quantitative, integrated policy model is developed that identifies the conflicts of the three interests under different water flow scenarios and policies.

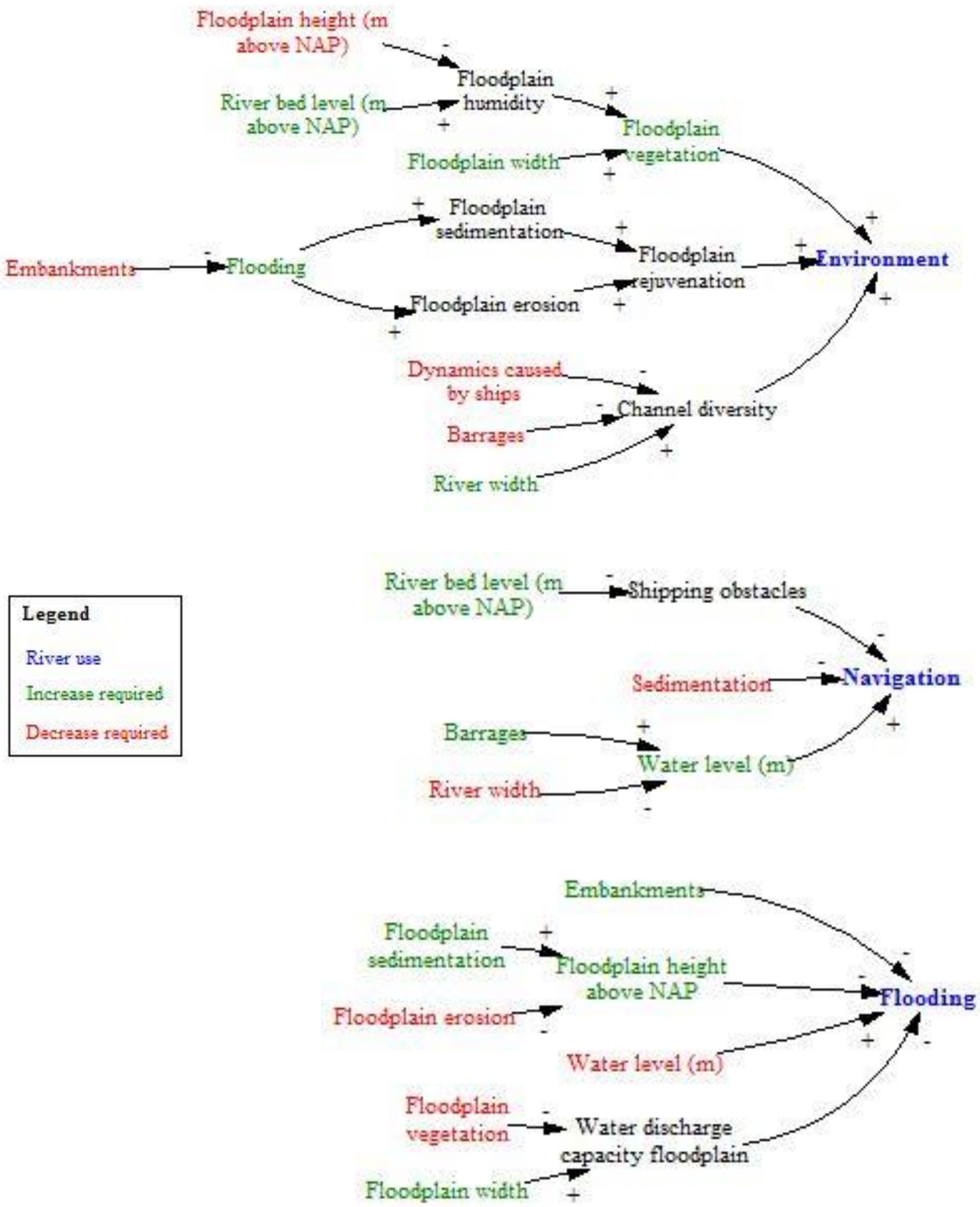


Figure 7: Conflicting interests in the Rhine – derived from literature and interviews

4.2 Future water flow variation in the Rhine

The water flow variation in the Rhine is an essential driver of the river processes and river ecosystems. It is therefore important to identify potential future changes in this water flow variation.

4.2.1 Literature on future water flow variation

Van Slobbe et al. (2016) argue that the Rhine is expected to become more rain-driven (instead of snow-driven) due to climate change. This will result in less snow storage in the Alps during winter, therefore increasing discharge in winter and decreasing it in summer. This would lead to longer periods of low flow (ICPR, 2015a). According to Van Slobbe et al. (2016) these impacts will occur in the second half of this century. However, Bormann & Pinter (2017) investigated changes in low flow since 1950 and found that climate-induced changes mostly occurred in unregulated rivers, while in regulated rivers low flow sometimes even increased due to river normalisation measures. They found an increase in the minimum flow and a decrease in low flow duration (compared to 1950) along the German part of the Rhine, but this effect was smaller for measuring stations located further downstream. They attribute the decrease in low flow to navigational measures in the Rhine and the lower effect downstream to the fact that the Rhine becomes more rain-driven in its downstream reaches. However, low flow can be defined by several indicators, which might show different results (Bormann & Pinter, 2017). Jonkeren et al. (2011), Pfeiffer and Ionita (2017), and Plum & Schulte-Wülwer-Leidig (2014) hold views similar to Van Slobbe et al. (2016); they expect more and longer periods with low water levels to occur in summer and that higher water levels will occur in winter, where Plum & Schulte-Wülwer-Leidig (2014) indicate that this will become problematic in the second half of this century.

A change in the discharge regime of rivers and in the water flow variation will result in altered hydrological and morphological processes and affect nature, navigation, and flood protection. Examples of natural consequences are that lower flows might have a negative impact on fish spawning (Forseth et al., 2014) and that they negatively influence water quality (Zwolsman & Van Bokhoven, 2007). Lower water flows harm navigation because skippers need to lower their load or cannot sail at all (Jonkeren et al., 2011; Van Slobbe et al., 2016). Finally, low water flows can have a negative impact on flood protection when they occur simultaneously with a saturated dike because of reduced dike strength (‘t Hart et al., 2016).

4.2.2 Findings on future water flow variation from interviews

Both Astrid Blom and Cornelis van Dorsser indicated that longer periods of low flow will occur in the future due to climate change. According to Cornelis van Dorsser, the effect will be small until 2050, but will become more and more significant from that time onwards. It is expected that the Rhine will become unnavigable for a few months per year. This would require radical measures, for example canalization. Already, shipping has top priority during low water levels, according to Daphne Willems; side channels are constructed in such a way that no water is directed to them during low water periods. In the future, more and stronger measures will be required.

4.2.3 Reflection on future water flow variation

Although the low flows in the Rhine are not expected to become problematically lower in the near future, they will do so in the longer term. This might result in more tension between environment, navigation, and flood protection because of the limited amount of available water. Timely planning for this might save significant costs. Therefore, it is important to analyse the effects of lower water flows on environment, navigation, and flood protection now.

5. Criteria for environment, navigation, and flood protection

In the previous chapter, the influence of the Rhine river system on environment, navigation, and flood protection in general has been discussed. However, in order to measure the effects of different scenarios and policies on the three river uses, more specific criteria need to be defined for each of the river uses. Therefore, this chapter answers sub-question 2, *'What are the criteria for environment, navigation, and flood protection in the Rhine?'*, again by using the literature review and expert interview methods. The chapter is divided into three sections; section 5.1 provides the environmental criteria, section 5.2 the criteria for navigation, and section 5.3 the criteria for flood protection. In each section the findings from literature and expert interviews are discussed in a separate sub-section, followed by a sub-section where the criteria are grouped, combined and integrated into measurable criteria.

5.1 Environmental criteria

Environmental requirements of a river are the circumstances nature needs to develop and maintain itself. Since this thesis focusses on the requirements for a river to support nature, the focus is on abiotic river requirements.

5.1.1 Literature on environmental criteria

Nature needs a dynamic river shore and side channels for habitat diversity, and erosion and sedimentation of the floodplains for floodplain rejuvenation (Deltares, 2017). In the floodplains, vegetation is most important, since it ensures habitat diversity. Floodplain vegetation can be divided into four main categories; grass and farmland, reeds, scrub, and forest (Rijkswaterstaat, 2014b). These categories are also used to determine whether vegetation needs to be removed to improve the floodplain discharge capacity. Natural succession of bare land would follow the sequence as given in the previous sentence and without human intervention, flooding, or natural disasters, it would result in a forested floodplain after several decades. In reality, however, floodplain vegetation is set-back by erosion and sedimentation processes caused by flooding, or it is removed by human intervention.

5.1.2 Findings on environmental criteria from interviews

Information for this section is mostly obtained from the interviews with Daphne Willems and Gertjan Geerling. Both of them indicate that variation is the most important criterion for nature. This covers both variability in time and in space. However, dynamic change should not be too high either – there is a lower and an upper limit. The presence of side channels is important to ensure habitat diversity in the river, and also to provide shelter from the impact of ships in the main channel. Side channels should not only be present, but water should also flow through them (as is not always the case, as further elaborated in chapter 6). The conditions in the side channel should be suitable for species that seek shelter from the dynamics in the main channel.

5.1.3 Reflection on environmental criteria

The main goal for nature can be defined as increasing biodiversity and restoring natural processes. Since water quantity is the focus of this thesis, only criteria that are influenced by this are defined. The river system can be divided into the river channel and the floodplains, and each has its own criteria. The main criterion for the floodplains is the share of each of the vegetation classes described in section 5.1.1 in the total floodplain vegetation, since vegetation diversity is assumed to determine habitat diversity. For the river channels there are two criteria. The first is whether a water flow through the side channel is present, since side channels only have value for nature if they actually flow. The second one is the suitability of the current in at least one of the river channels for nature (so a current within a lower and upper limit), to ensure that fish can always find a suitable shelter.

5.2 Criteria for navigation

Requirements for navigation can vary broadly, but the focus in this thesis is on criteria that measure the influence of water quantity on shipping.

5.2.1 Literature on navigational criteria

Shipping needs a sufficiently deep main channel, and preferably as little erosion and sedimentation as possible (Deltares, 2017). Bosschieter (2005) indicates the relation between (low) water levels and the cargo capacity of the shipping fleet. *Figure 8* shows that no shipping is possible at a water level of 60 centimetres or less, and that the full capacity of the fleet can be used at a water level of 4 metres or more.

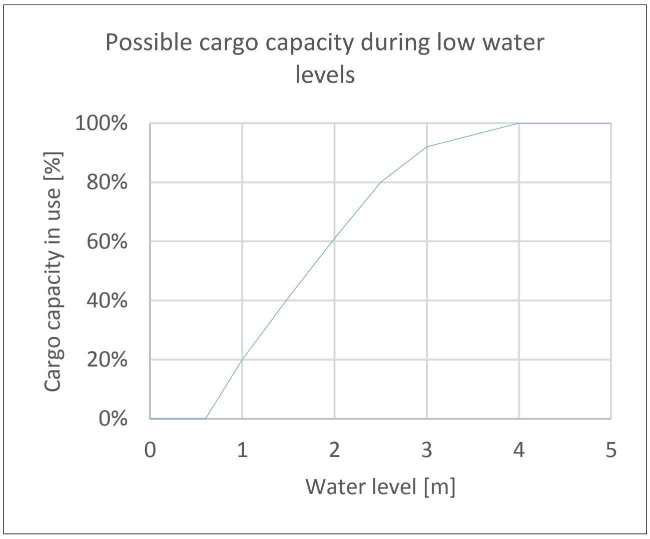


Figure 8: Relation between low water levels and cargo capacity of ships – based on Bosschieter (2005)

5.2.2 Findings on navigational criteria from interviews

Cornelis van Dorsser agrees that periods of low water are harmful for navigation and indicates that shipping becomes problematic if the water level is below 1.50m (for a large ship) or 1.20m (for a smaller ship). The reason for this is that most ships have a draught of 80-90cm when they are empty, so at this water level they can carry almost no load. Besides, their screw cannot be fully submerged, so more fuel is needed to navigate. Low water is not the only problem for navigation; during high water another issue arises, namely that of bridge height. The current norm for bridges that they should be at least 9.10m above the reference high water level. Bridge height determines the gap between the water level and the bridge and therefore the possible loading capacity of ships. The relation between high water levels and the cargo capacity of the shipping fleet differs between bulk and container ships; for container ships this relation changes in discrete steps, since a whole layer of containers needs to be removed when the gap is too small, while the relation is more gradual for bulk ships.

Two other issues mentioned by the interviewee are the current speed that limits shipping due to safety and efficiency reasons if it becomes too high, and the fact that shipping is sometimes prohibited during high water levels to prevent wave damage on dikes and quays.

5.2.3 Reflection on criteria for navigation

For shipping, the criteria mentioned in the previous two sections can be grouped into one overall criterion; the cargo capacity that can be employed. This main criterion is influenced by three main, water quantity related issues; low water levels influencing loading capacity, high water levels and the limiting height of bridges, the damaging effect of waves on dikes and quays, and current speed because of navigation safety and efficiency.

5.3 Criteria for flood protection

Of course, there are extensive and very detailed flood protection criteria in the Netherlands. However, since this thesis does not focus on the technical details of flood protection, but on the integration of flood protection requirements with the requirements for environment and navigation, less detail is required.

5.3.1 Literature on criteria for flood protection

The first and most obvious criterion for flood protection is that the water level should not exceed the maximum water level of the river and its floodplain. This is influenced by the size of the river channel, dike height, and the water discharge capacity of the floodplain (Harezlak et al., 2016). The latter is influenced by the size of the floodplain and its vegetation roughness. Vegetation roughness is determined by the roughness of each of the vegetation classes as described in section 5.1.1, and the share of each of these classes in the total floodplain vegetation. The order of roughness of vegetation is different from the order of succession; scrub is the roughest vegetation class, followed by forest, then reeds and last grass and farmland (Ruimte voor Levende Rivieren, 2018).

Another important issue for flood protection is dike strength. Dike strength is determined by many technical parameters and failure mechanisms. The most important failure mechanisms are inward macro-instability, outward macro-instability, piping, micro-instability, and dike revetment instability – dike erosion – ('t Hart et al., 2016). Inward macro-instability leads to a dike collapse towards the land, while outward macro-instability leads to a dike collapse towards the river. Each is caused by slightly different mechanisms. Inward macro-instability is caused by high water pressures in the dike (for example due to the occurrence of high water or due to heavy rainfall) that cannot be counteracted by the hinterland, and therefore leads to the collapse of the dike towards the hinterland. Since inward macro-instability often occurs during high water levels, it might cause extreme flood events ('t Hart et al., 2016). In the case of outward macro-instability, the water pressure in the dike is high as well. This will not lead to outward macro-instability if the water level is high, since the water will then act as an opposing force, but when the water level is low, the dike might collapse towards the river. Inward macro-instability usually does not lead to extreme flood events, because it happens at low water levels ('t Hart et al., 2016). Piping occurs when the water level difference between the river water level and the groundwater level is too large. Then, water seepage occurs underneath the dike followed by erosion and formation of a pipe that might undermine the dike ('t Hart et al., 2016). Micro-instability is caused by groundwater flows through the dike that for example flush dike material outwards ('t Hart et al., 2016). Since groundwater flows are not included in this research and this would require more complex modelling methods, micro-instability is further excluded. Dike erosion occurs when water flows over the dike (flooding) at a rate too high for too long and therefore erodes the dike material (Van der Meer, 2008).

5.3.2 Findings on criteria for flood protection from interviews

From the interview with Frans Klijn it is derived that a combination of technical flood protection measures and space are necessary. Therefore, dikes need to be of sufficient strength, and floodplains need to be large and smooth enough to provide fast discharge of high water levels. Furthermore, side channels and bypasses will also increase the discharge capacity of the floodplains.

5.3.3 Reflection on criteria for flood protection

For flood protection, several criteria have been identified. The first criterion is the most obvious; flooding (in m^3/s), which represents the amount of water that flows over the winter dike when there is simply too much water in the river system. The other criteria are related to dike strength, and indicate the possibility that the dike will be damaged. Of the multiple mechanisms that can harm dike strength, four have been chosen, because they are mostly related to water quantity. Since this research will not determine exact dike failure probabilities, the possibility that the mechanism occurs will be determined, without putting an exact number to this possibility. This has resulted in the following criteria; possibility of outward macro-instability, possibility of inward macro-instability, possibility of piping, and possibility of dike erosion. An extra criterion has been defined that indicates possibility of dike breach, which is considered to happen when two or more of the mechanisms above happen at the same time.

6. Nature-based water management policies

This chapter uses literature and expert interviews to answer the third sub-question, *'What nature-based water management policies have resulted from the international agreements on the Rhine and which are most relevant to study further?'*. These nature-based water management policies are meant to improve environmental aspects of river systems, but of course this should happen without harming navigation and flood protection interests. The international agreements on the Rhine are elaborated in appendix C, and this chapter identifies the resulting nature-based water management policies, and then one of the policies is chosen to be researched further in the second part of this thesis; the formulation of the integrated policy model.

6.1 Literature on policies

As indicated by Erik Mostert, specific measures resulting from the WFD have to be found with the Dutch water authorities (waterschappen). Therefore, different documents have to be consulted to determine which nature-based water management measures have been taken. Groene Ruimte indicates two measures that influence river hydrology and morphology and connectivity; giving rivers space for re-meandering and constructing fish passages (Groene Ruimte, 2018). In the programme of measures for implementation of the WFD in the Rhine of the Dutch Ministry of Infrastructure and Environment several other measures are mentioned as well (Ministerie van Infrastructuur en Milieu, 2014a); broadening the water system by connecting floodplains to the river, lowering the floodplain height, and constructing side channels. A last nature-based water management policy is the 'kierbesluit', which is a decision to slightly open the Haringvliet sluice to allow migratory fish to swim into the Rhine (and Meuse) and to enable them to migrate upstream towards Germany and France (Kierharingvliet.nl, 2018).

6.2 Findings on policies from interviews

A first example of a nature-based water management policy is a side channel. This policy is mentioned by Frans Klijn, Daphne Willems, and Gertjan Geerling. Side channels can be constructed for two purposes; flood protection and nature development. However, a side channel does not necessarily achieve both purposes, this depends on the way the side channel is constructed. A natural side channel is connected to the main channel at both its upstream and its downstream end. This ensures that river dynamics affect the side channel and that water is flowing, which is beneficial for nature, and increases flood discharge capacity. However, for shipping this is undesirable, because during low flow periods all the water is needed in the main channel. Therefore, many side channels are only connected to the main channel on their downstream end, and will therefore only experience river dynamics and water flow during high water periods. For flood protection this is fine, but for nature, this type of side channel has little value. A completely natural side channel would erode, change its course, become the main channel, or silt-up and disappear. This amount of freedom cannot yet be given to side channels of rivers where shipping is important. In order to prevent the side channel from becoming too large, which can happen by natural processes of erosion, side channels in the Netherlands are kept relatively small (2% of the discharge) according to Astrid Blom. However, a small side channel risks being silt-up by sedimentation, which increases its maintenance costs.

A second example of a nature-based river management policy, given by Daphne Willems, is using the sponge-effect of river systems. This means that the water uptake capacity of the system (not only the river and its floodplains, but the entire river basin) should be increased. During high water periods, water can be stored, to become available during low water periods. This would benefit all three river uses. The current system is focussed on discharging the inflowing water to sea as fast as possible instead of storing it in the system.

A third example is given by Gertjan Geerling, and is focused on nature; cyclic floodplain rejuvenation. This is a strategy where multiple floodplains are connected and maintenance is performed in a coordinated manner. That way, it can be ensured that there is always at least one floodplain where nature is allowed to grow, and another floodplain where vegetation is removed to achieve a high water discharge capacity. The effect of this measure on navigation is unknown, since changes in river morphology are expected when excavating floodplains and these changes can harm navigation (Vreugdenhil et al., 2008).

A last example are the longitudinal training dams (LTD's) that have recently been constructed in the Waal. These dams have replaced the groynes in that area, and are meant to improve both environment, and navigation, and flood protection. Since the dam is constructed longitudinally in the river instead of perpendicular like groynes, it does not obstruct the water flow which is important for flood protection during high water periods. At the same time, it still maintains a deep main channel for navigation. Furthermore, it should provide a sheltered shore channel that can provide habitat for aquatic species and improve environment. However, whether all these goals are reached is still to be seen, due to the very recent completion of the dams. Besides, it is unknown how the river and its sediment balance will react to this construction.

6.3 Reflection on policies

All policies discussed in the previous sections are interesting to study, but not all can at this moment be analysed by a high-level policy model. The LTD, for example, requires detailed studies on river morphology and sediment transport through the two channels. Besides, due to its recent completion, monitoring results of its effects are still limited. The sponge effect of the river system is also not suitable for further analysis in this thesis due to its technical complexity. The concept of cyclic floodplain rejuvenation is very interesting and can potentially be analysed with a high-level policy model. However, it has limited effects on navigation, through sedimentation (Vreugdenhil et al., 2008), and there is insufficient information to study this policy further within this thesis.

Side channels, on the other hand, are very interesting and suitable to study further for four reasons. First, it has already become clear from the interviews that conflicting interests surround the construction of side channels, so it would be interesting to study whether these conflicts actually arise, or that they can be avoided. Second, several side channel configurations exist, all with different effects on environment, navigation, and flood protection. Third, information is available on this topic, for example in Room for the River documentation. Finally, this measure strongly influences and is influenced by water quantities in the river channels and floodplains, but these can relatively easily be simplified.

Part 3

An integrated model on side channels and resulting conflicts

7. Model conceptualization

The fourth sub-question, *'What are the possibilities for modelling the system described in sub-questions 1, 2, and 3 using the system dynamics approach*?', will be answered by this chapter and chapter 8 and 9 combined. In this chapter, the model choices and model conceptualization will be discussed. These form the first step in the modelling processes, and define the most important relations to be included in the model. Chapter 8 will then provide details on the mathematics behind these relationships and chapter 9 will test whether the model can be trusted. In section 7.1, information and relations obtained in part 2 (the previous part) that are included in the model are discussed and choices are made regarding what not to include. Section 7.2 presents a high-level overview of the most important relationships in the full model, while more detail on each sub-model will be presented in section 7.3.

7.1 Model choices

In chapter 4, a detailed causal diagram of the contemporary characteristics of the Rhine river system and its relation with environment, navigation, and flood protection was developed (*figure 6*). The model that is constructed in this part of the thesis is a high-level policy model, aimed at defining when and where water use conflicts may arise, and is not a detailed hydrological or morphological model. Therefore, several processes that were identified in chapter 4, are not included in this model. The omitted processes are shown in grey in *figure 9*, processes that are included in the final model are shown in black (processes), blue (river uses), or purple (normalisation measures).

First of all, the erosion and sedimentation processes in the main channel are not included explicitly in the model, because these processes are very detailed and complex and require precise modelling. Instead, the lowering of the river bed is included as an external factor to be considered in the experiments with the model, where the influence of river bed lowering is tested (see chapter 10). Related to the river bed lowering are the solid structures that are possibly present in the river bed. For this thesis, it is assumed that they are not present, because they primarily influence navigation and therefore are not highly relevant to a study about conflicting interests. However, it would be possible, and relatively easy, to add them to the model in future research. Another issue that is not modelled explicitly is the groundwater level that influences the occurrence of piping. The reason for this is that groundwater flow is a complex process as well, extending beyond the scope of this thesis. Instead, it is assumed that the groundwater level is at the level of the foot of the dike when determining the critical water level difference for piping. Also floodplain humidity and its effect on the environment are not included in the model, again because modelling the groundwater flow would be too detailed for this high-level model. Floodplain sedimentation and erosion processes are partially included in the model; the effect on floodplain vegetation is included, but the floodplain height is assumed constant. This is something that could be included in further research if this model were to be extended. The same goes for the dynamic effects of ships on flora and fauna in the main river channel.

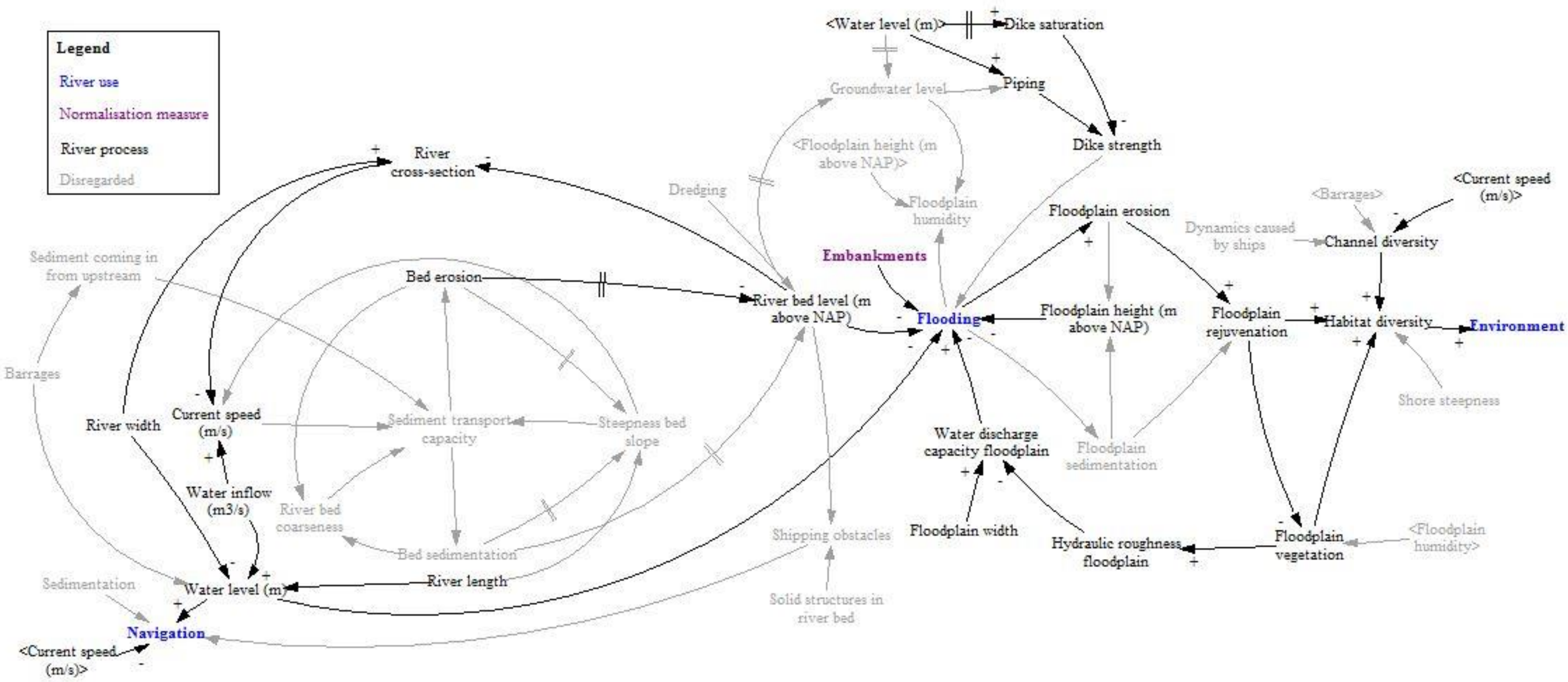


Figure 9: Causal diagram – model choices based on chapter 4

A last important issue relates to the choice between a theoretical model and a case specific model. In this thesis a theoretical model that clearly represents the trade-offs between river uses is developed. In future research, case studies could be performed to test the model under different conditions. However, some river system characteristics such as soil type, river bed level, and floodplain dimensions have been obtained by looking at a specific location: Gameren. The reason for this is that several side channels are present at that location and they have been constructed several years ago, so the information is readily available.

The focus of the model is therefore on the policy-relevant surface water flows in river systems, how the water quantity is divided over the channels and the floodplain, and how this influences environment, navigation and flood protection. The next section will provide a high-level overview of the model and its processes.

7.2 High-level model conceptualization

Figure 10 shows the high-level system diagram of the river, environment, navigation, and flood protection system. A system diagram consists of external parameters and scenario parameters (which are assumed not to be influenced by the system itself), variables (that are influenced by the system, and influence the system), and criteria (which indicate the outcomes of interest). External parameters are shown in orange, scenario parameters in pink, variables in black, and criteria in blue. The arrows with polarity (+ or -) between variables are read in the same way as in a causal diagram (see Box 2). The system diagram clearly shows the interdependencies of the four sub-systems. Mainly, the environment, navigation, and flood protection sub-system depend on the river sub-system; the water level in the main channel and floodplain, the current speed in the main and side channel, and the amount of water in the side channel influence the three other sub-systems. But the environment sub-model also influences the river sub-model; if the vegetation roughness in the floodplain increases, this reduces the discharge capacity of the floodplain, and therefore increases the water in the floodplain. This then increases the risk of flooding. In section 7.3, the relationships between variables will be explained and the model formulated.

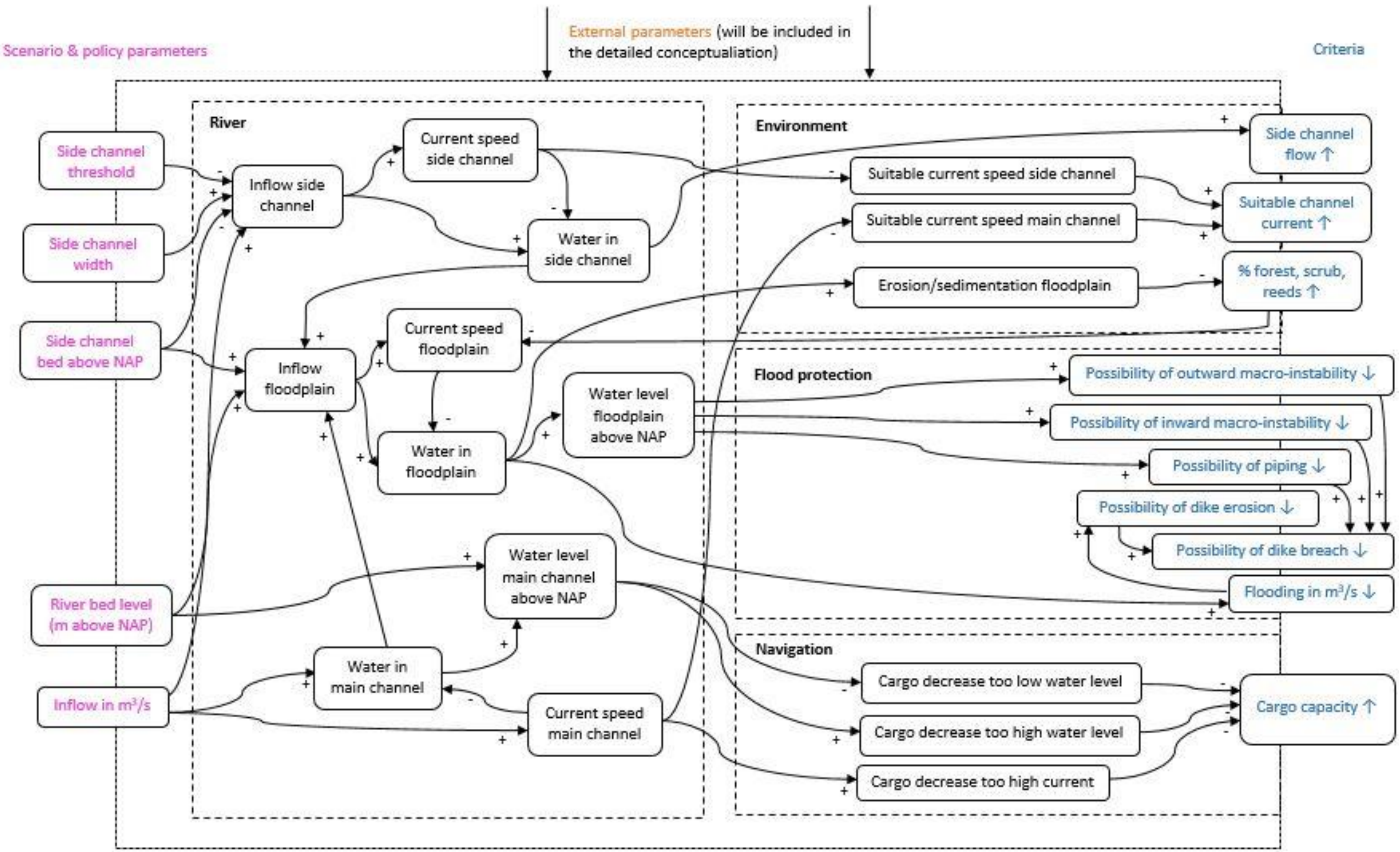


Figure 10: High-level conceptualization - system diagram

7.3 Detailed model conceptualization

The detailed model conceptualization will be discussed for each sub-model separately, because that is how the models were designed initially. For each sub-system, it has been determined how the processes work, and what information is needed from other sub-systems. Only after this step has been completed, were the models connected.

7.3.1 River sub-model

The dimensions of the river system as they are assumed in the model are shown in *figure 11*. The former figure indicates the river system without side channel; it consists of a main channel, summer dike, floodplain, and winter dike. The main channel can have a rectangular shape or be a trapezium shape. By altering the shore width of the channel, its shape can be changed. The more rectangular the shape of the main channel, the more linear the relation between the volume of water in the channel and the water level. The grey area in the picture indicates the floodplain capacity. The area above the main channel is assumed to be part of this, to simplify the modelling process. Furthermore, the floodplain consists of two zones, with slightly different characteristics. This enables the analysis of different (ecological) behaviour in the two zones.

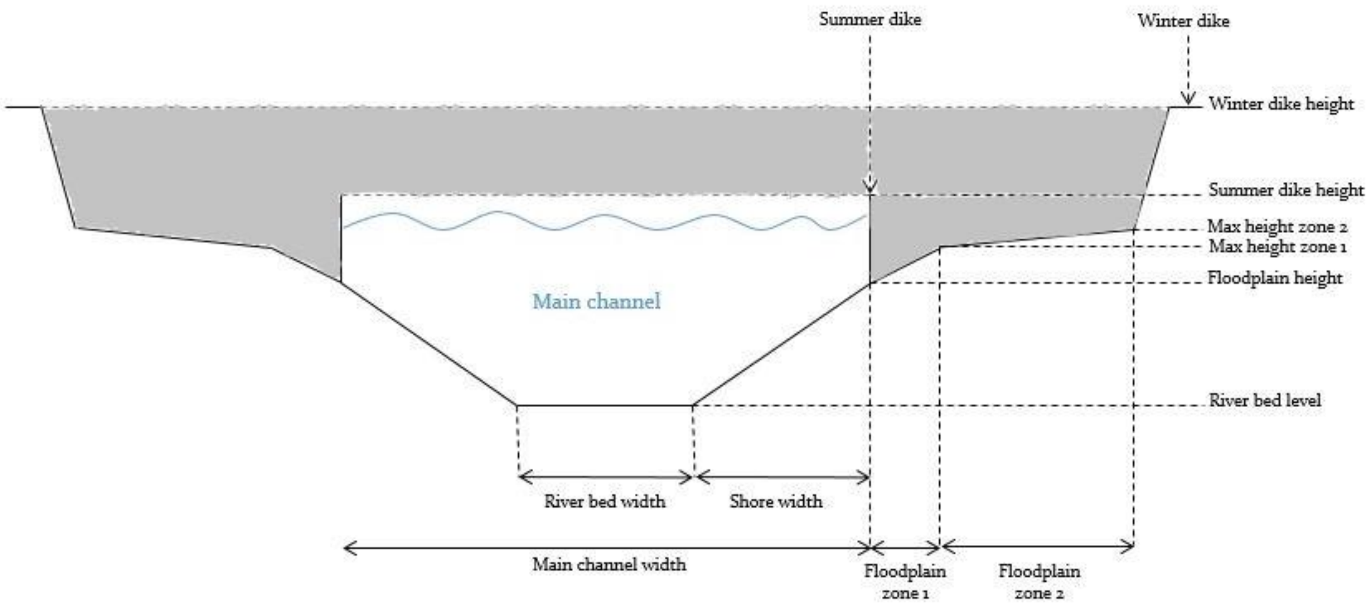


Figure 11: River system sketch – no side channel

When a side channel is added to the model, the river system dimensions change (see figure 12). Most importantly, it is assumed that the side channel is constructed right next to the main channel, and that it has a summer dike of the same height as the main channel. The side channel is constructed in the floodplain and therefore decreases the width of floodplain zone 1 (and perhaps also of floodplain zone 2). For simplification, the side channel is assumed to have a rectangular shape.

The river system can be divided into three main components; the main channel, the side channel, and the floodplain. *Figure 13* shows the maximum capacity, actual water volume, inflow and outflow, current speed, and water level for each component and how they interact.

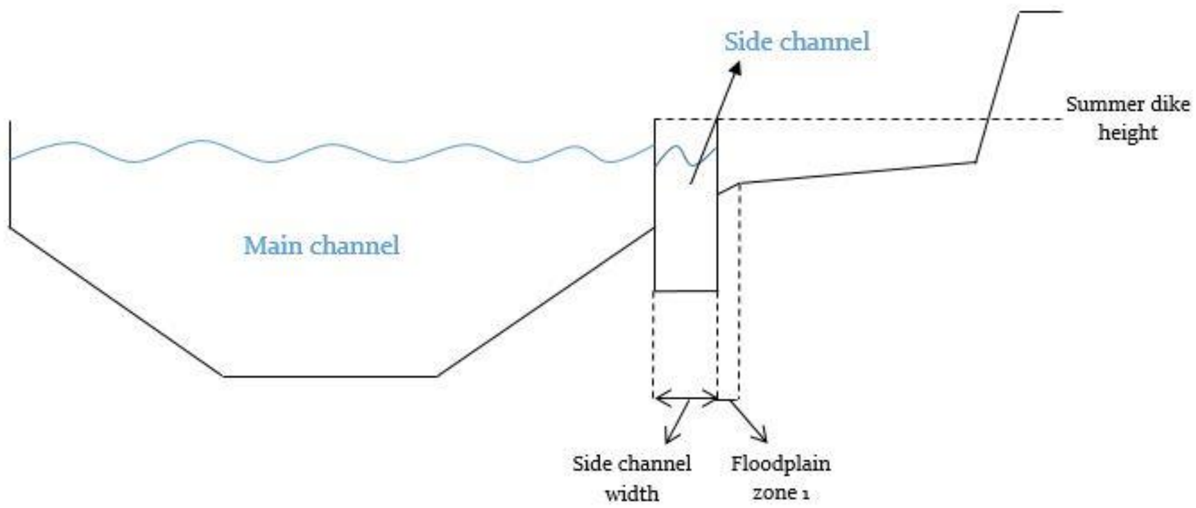


Figure 12: River system sketch – side channel

The water volume in the main channel is determined by the inflow (a scenario parameter), the outflow downstream, the water flow to the side channel, and the water flow to the floodplain. The outflow downstream is determined by the amount of water in the channel and the current speed. The current speed in turn is determined by the inflow, according to a relation as described by Rijkswaterstaat (2004). They indicate that the current in the Waal at Gameren is 0.5 m/s during low discharges, 1.1 m/s during average discharges, and 1.8 m/s during very high discharges. They also indicate that the discharge at this location is below 900 m^3/s for 10% of the time, below 1573 m^3/s for 50% of the time, and that the summer bed of the river is full at a discharge of 3000 m^3/s. With this information, the relation between inflow and current speed was derived. A water flow from the main channel to the floodplain occurs if the water volume in the main channel exceeds its maximum.

The inflow into the side channel is determined by the inflow into the main channel and the maximum capacity of the side channel; if the capacity of the side channel is larger, a larger share of the inflow will flow to the side channel. Since in reality the water level in the main channel and the water level in the side channel are at the same height, an extra control variable influences the side channel inflow; if the water level in the main channel is higher than the water level in the side channel, more water will flow into the side channel and vice versa. Furthermore, water will only flow into the side channel if the water level in the main channel is higher than the side channel threshold. By altering the threshold, side channels can be designed to flow all-year-round (no threshold), or only during high water flow periods (high threshold). The current speed in the side channel is based on the relation between water discharge and current speed that was found for the main channel, but this relation is multiplied with a correction factor since the side channel is usually less wide than the main channel, its current speed is higher for the same inflow (Geerling & Van Kouwen, 2011). Again, a water flow towards the floodplain occurs if the water in the side channel exceeds its maximum.

The water in the floodplain follows the same processes, except that an extra influence on the current speed is present in the floodplain. More or rougher vegetation decreases the current speed in the floodplain, therefore retaining more water in it and increasing the risk of flooding.

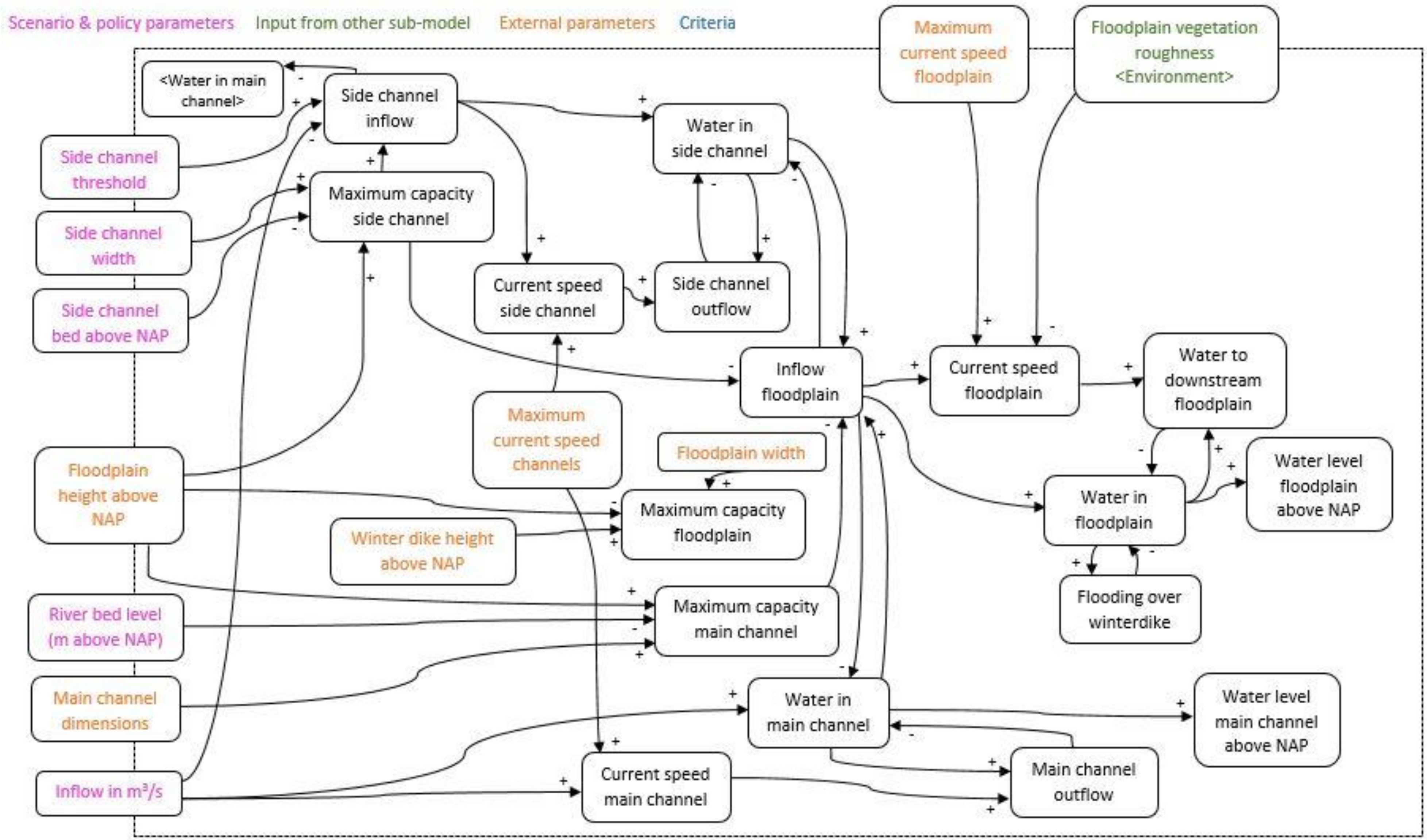


Figure 13: Detailed conceptualization – system diagram river sub-model

7.3.2 Environment sub-model

In a natural river, multiple zones of vegetation exist in the floodplain, with different characteristics based on the frequency of flooding that occurs in the zone. Presently, in normalised rivers, there are less differences between zones, because flooding occurs less frequently, and if it occurs it happens abruptly in the whole floodplain area due to its limited steepness. However, there is still a difference in flooding frequency between parts of a river floodplain, so the floodplain in the model is divided into two zones. Floodplain vegetation can be divided into four stages (classes), and if no intervention (human or natural) occurs, after several decades all vegetation has transformed towards the last stage (Rijkswaterstaat, 2014b);

1. Grass
2. Reeds
3. Scrub
4. Forest

The process of succession from one vegetation class to the next takes several years to decades, so it would take one to two hundred years for the whole floodplain to become forested. Succession from grass to reeds is determined by the amount of grass and the time it takes for grass to turn into reeds. The same goes for succession towards the next vegetation classes. The area of the floodplain that is not occupied by one of the vegetation classes, is classified as bare soil. Grass species can pioneer on this bare soil, and will eventually turn it into grassland. Initially, there will be no bare soil in the floodplain, because it is assumed that human intervention will at least have made grass or farmland of it. However, if floodplain inundation occurs, erosion and sedimentation will remove some of the vegetation, and turn the area into bare soil. Another way in which vegetation can be removed is via direct human intervention. If vegetation is removed by humans, it is assumed that the soil is not left bare, but that it is turned into grass or farmland. The reason for human vegetation removal, is that a higher vegetation roughness decreases the floodplain's discharge capacity. Therefore, less vegetation roughness is preferred from a flood protection perspective.

The order of vegetation roughness is not equivalent to the order of succession, but is as follows – low to high – (Ruimte voor Levende Rivieren, 2018);

1. Grass & farmland
2. Reeds
3. Forest
4. Scrub

In the Netherlands, the 'vegetatielegger' determines how much of each vegetation class may be present in each floodplain (Rijkswaterstaat, 2018a). If the maximum for any class is exceeded, vegetation will be removed. The total vegetation roughness is in this research defined as a percentage, where low percentage values represent low roughness and percentage values near 1 represent a floodplain that is completely covered with scrub (the roughest vegetation class) and the floodplain therefore has the highest possible roughness.

Next to the floodplain, the main and side channel are important for environmental aspects of the river as well. First of all, at any time the current speed in at least one of the channels should be within appropriate limits for species to be able to seek shelter. Secondly, a higher number of days with side channel flow improves the availability of diverse habitats within the river system.

Figure 14 shows how the processes in the environment sub-system interact.

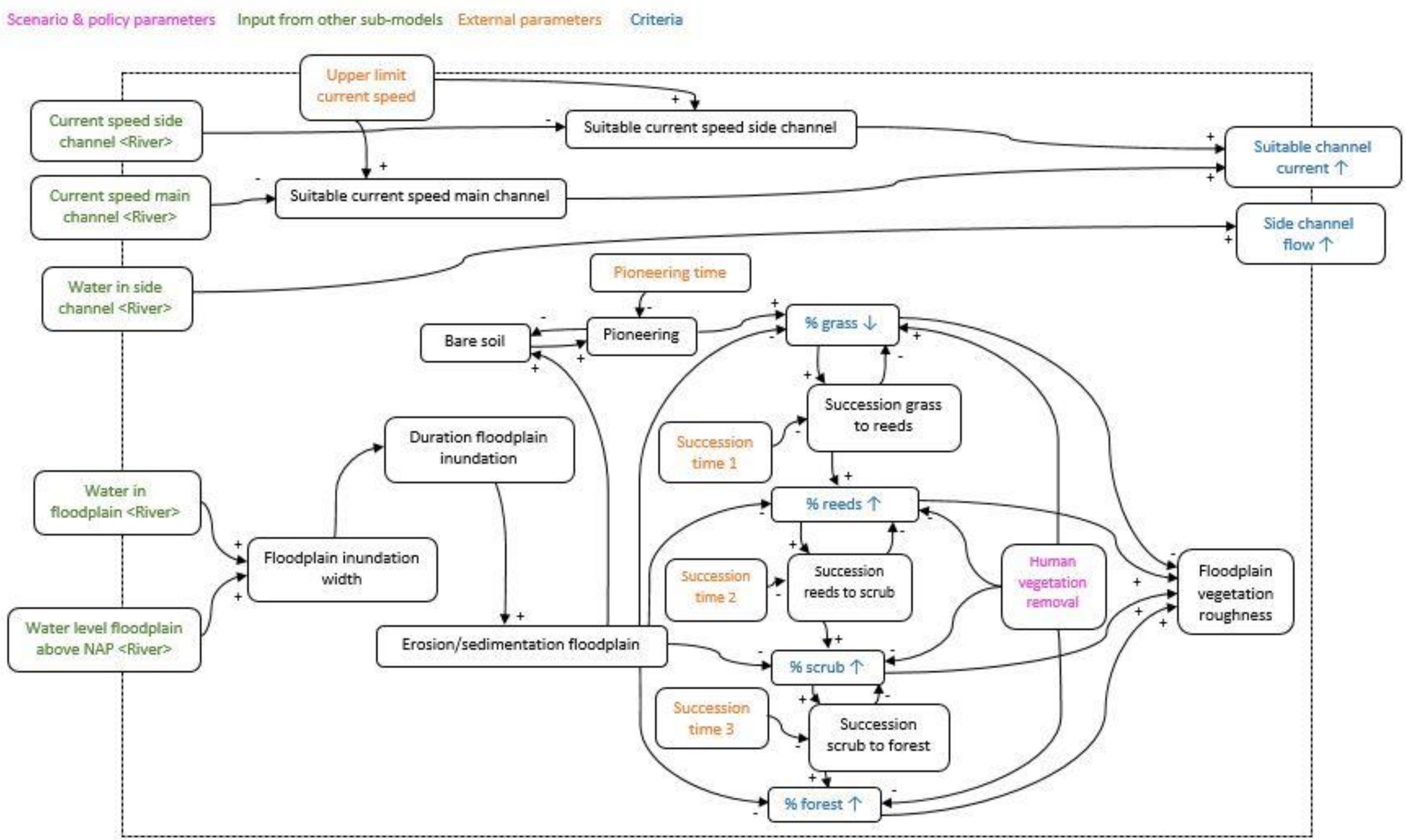


Figure 14: Detailed conceptualization – system diagram environment sub-model

7.3.3 Navigation sub-model

In chapter 5, four issues have been mentioned that can harm navigation; too high water combined with fixed bridge heights, too low water, and too high current speeds. These issues can be grouped by their cause; high water, low water, and strong currents (see *figure 15*).

At low water levels, the relation between water level and cargo capacity can be described as shown in *figure 8;* at a water level of 4m or more, the full cargo capacity can be used (Bosschieter, 2005). If the water level is below 4m, the potential cargo capacity at that specific water level is obtained from the graph in *figure 8Figure 8,* and if the cargo capacity is higher than this, it needs to decrease.

At high water levels, the relation between water level and cargo capacity is different for container ships and for bulk ships for two reasons. First of all, bulk ships are generally lower than container ships and second of all, the relation is discrete for container ships because a whole layer of containers needs to be removed if the ship could not fit under a bridge, while for bulk the relation is more gradual (Koedijk, van der Sluijs & Steijn, 2017). Again, the cargo capacity needs to be decreased if it is above the potential capacity at a certain (high) water level.

For current speed, the relation is the most simple; if the current speed is above a certain threshold, no shipping is possible and all cargo capacity is removed.

If all conditions are favourable, the cargo capacity will rise again until it reaches its maximum.

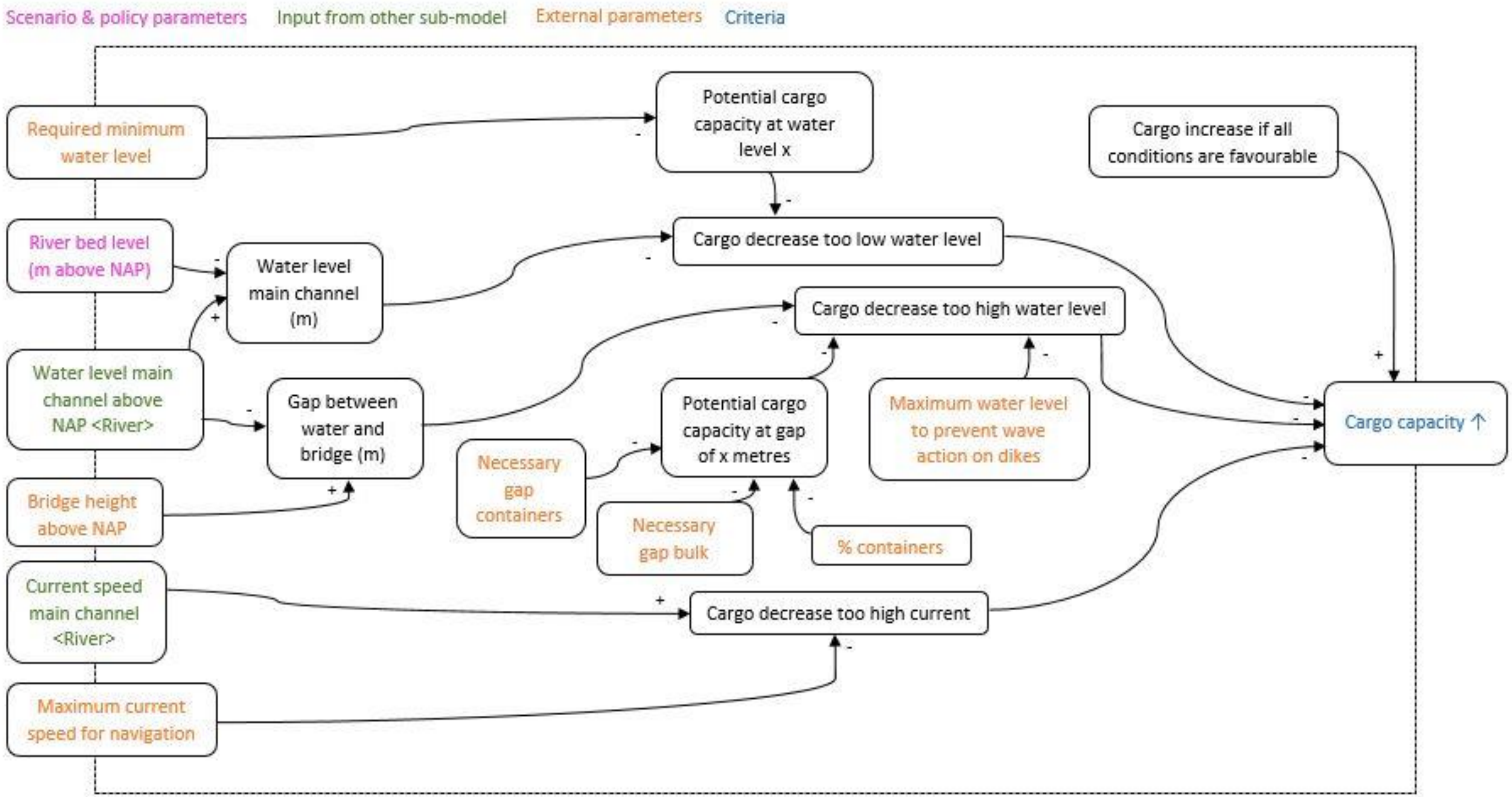


Figure 15: Detailed conceptualization – system diagram navigation sub-model

7.3.4 Flood protection sub-model

The system diagram for this sub-model is shown in *figure 16.* Information for this sub-model is highly simplified, since the concept of dike strength is very complex in reality, but this type of modelling technique (high-level policy modelling) is not fit for complex river dynamics studies. Instead, this model indicates the possibility that the processes undermining dikes strength occurs at all; no likelihood is ascribed to the occurrence. As discussed in chapters 4 and 5, four mechanisms that undermine dikes are included in this research; outward macro-instability, inward macro-instability, piping, and dike erosion. Only the dike strength of the winter dike is considered, since the winter dike is the most important for protecting the land against flooding.

The two macro-instability mechanisms included in the model are based on 't Hart et al. (2016) and Ministerie van Infrastructuur en Milieu (2014b). Outward macro-instability (collapse of the dike towards the river) is assumed to happen when the water level in the dike is higher than the water level in the river system for more than a certain time period. The high water level in the dike increases pressure, and since the low water level in the river system cannot act as a counterforce, the dike may collapse. Inward macro-instability concerns collapse of the dike towards the land, and this is assumed to happen when the water level in the dike is high and the water level in the river system is high as well. Only now, the pressure works towards the other side of the dike – landward – since the high water level in the river system requires a counterforce on the landward side of the dike and this is absent. The possibility of inward macro-instability is also influenced by both the height and the duration of the high water level in the river.

The mechanism of piping works as follows; first seepage occurs from the river side to the land side of the dike due to a difference in water level. Then, an erosion flow follows the seepage path and a pipe is formed underneath the dike. This can lead to collapse of the dike. The critical water level for piping is determined by the Bligh formula (the simplest option): $\frac{H}{L} = \frac{1}{C_{Bligh}}$

- H: critical head (assumed to be the difference between the water level and the dike foot)
- L: dike width
- C_{Bligh}: soil factor

DINOloket indicates that the soil type at Gameren is moderate fine sand (150 – 300 mu), and according to Sellmeijer (2006) this corresponds with a C_{Bligh} of 15. Not only the critical water level for piping is important, but also the time it takes for a pipe to form. This is determined by the permeability of sand, which determines the time required for seepage, and the pipe development rate, which determines the time it takes for erosion to take place. The permeability of the soil has a large uncertainty range, assumed to be between 3 and 30 m/day (grondwaterformules.nl, 2018). Vorogushyn, Merz & Apel (2009) indicate that the pipe development rate has not been studied extensively, but that they assume it to be between 0.5 and 2 m/day.

Dike erosion occurs if water flows over the dike at a high rate for too long. The model behaviour for this process is based on Van der Meer (2008), who indicates that flooding becomes problematic at a rate of 50 to 125 l/s/m, and that this water flow needs to occur at least 6 hours. If two or more of the mechanisms have a high possibility of occurrence, it is assumed that a dike breach becomes possible.

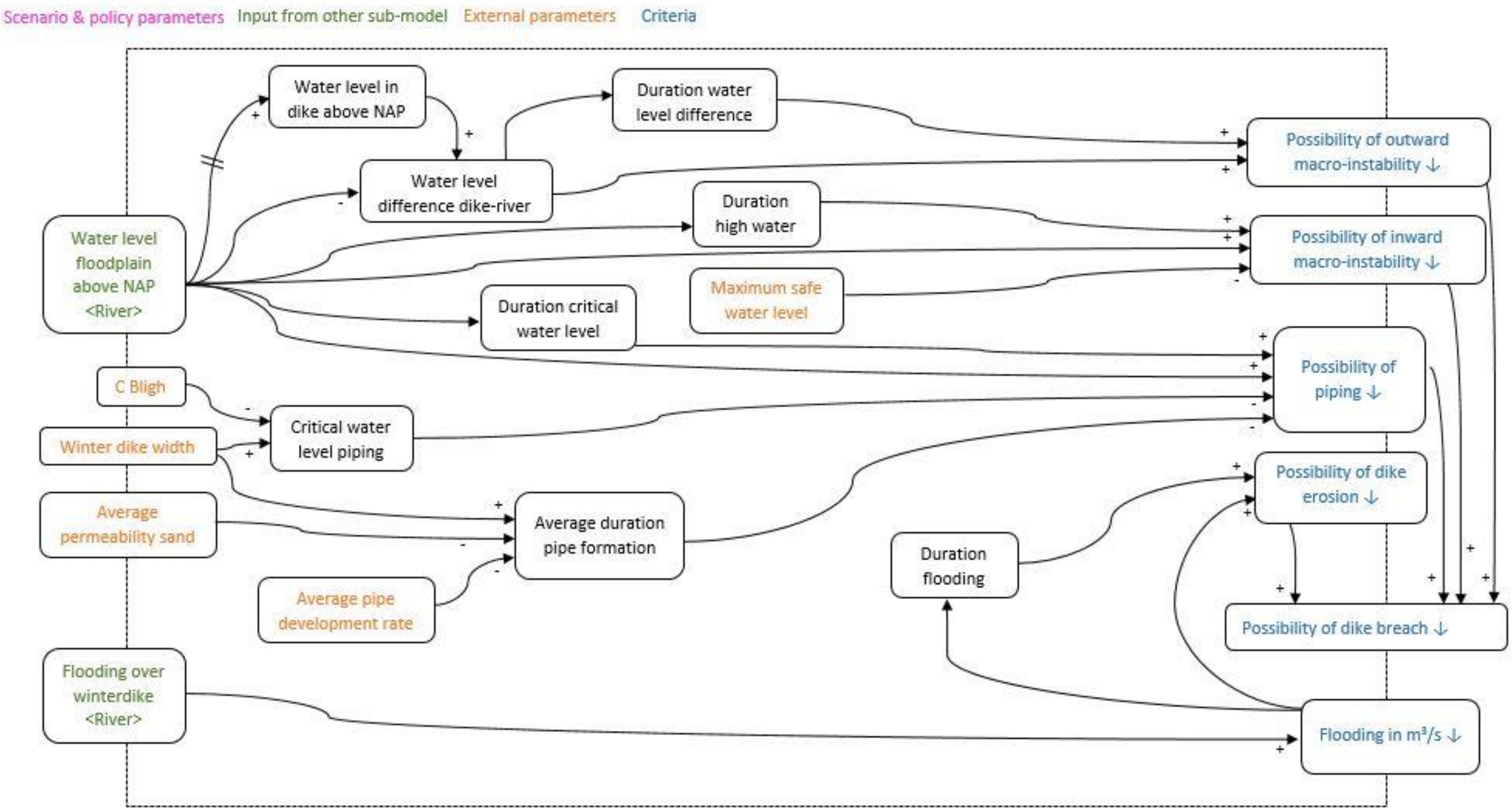


Figure 16: Detailed conceptualization – system diagram flood protection sub-model

8. Model description

This chapter further explains how the information obtained in the interviews and from literature is included in the model. Where chapter 7 discussed the most important relations between parts of the system qualitatively, this chapter will provide detail on the quantitative aspects of these relations, and on the structure of the model. Section 8.1 deals with the criteria that were defined in chapter 5, but that need more refinement. In section 8.2 the most important model equations and assumptions are explained. In section 8.3, the model parameters are introduced. And finally, in chapter 8.4, the model settings are discussed. This chapter only discusses the most important or interesting parts of the model, a full model description is included in appendix D.

8.1 Criteria – from measurable to comparable

The criteria that where defined for each river use in chapter 5 give an indication of the effects of different river system configurations on the three river uses. The criteria outputs can be visualized in a time varying graph to compare the outputs of different configurations qualitatively. However, to be able to make a quantitative comparison after the whole run between different river system configurations, the criteria need to be converted into comparable, integrative criteria. In appendix D1, the equations for each measurable criterion are given. *Table 3* shows how each environmental criteria from chapter 5 is formulated. The *Area under % grass graph* criterion is an indication of how much grass was present in the floodplain over the complete model run. *% days with suitable channel(s)* divides the number of days where the current speed in at least one of the channels was suitable by the total number of days.

Table 3: Criteria environment

Criterion	Comparable criteria
% grass	Maximum % grass Minimum % grass Area under % grass graph
% reeds	Maximum % reeds Minimum % reeds Area under % reeds graph
% scrub	Maximum % scrub Minimum % scrub Area under % scrub graph
% forest	Maximum % forest Minimum % forest Area under % forest graph
Suitable channel current	% days with suitable channel(s)
Side channel flow	% days with side channel flow

Table 4 includes the comparable criteria for navigation. These are all based on *Cargo capacity*, but represent a different aspect of it. First of all, *Total capacity* simply adds the *Cargo capacity* at each time step. Secondly, it is important to know for how many days no shipping is possible at all. The last three comparable criteria indicate by which river characteristic the cargo capacity is decreased and for how many days.

Table 4: Criteria navigation

Criterion	Comparable criteria
Cargo capacity	Total capacity [tonnes] % days with 0 cargo capacity % days with decreased capacity due to too low water % days with decreased capacity due to too high water % days with decreased capacity due to too high current

Lastly, *table 5* presents the comparable criteria for flood protection. *Flooding in m^3/s* has been split into three criteria; its maximum value over the whole run, its total value over the whole run, and the percentage of days when flooding occurred. The other 5 criteria are simply made comparable by determining the percentage of days when they occurred.

Table 5: Criteria flood protection

Criterion	Comparable criteria
Flooding in m^3/s	Maximum flooding [m^3/s] Total flooding [m^3] % days with flood
Possibility of outward macro-instability	% days with possibility of outward macro-instability
Possibility of inward macro-instability	% days with possibility of inward macro-instability
Possibility of piping	% days with possibility of piping
Possibility of dike erosion	% days with possibility of dike erosion
Possibility of dike breach	% days with possibility of dike breach

8.2 Model equations and assumptions

Appendix D1 contains a list of all variables that are present in the model and their equations. In this section, the equations of the most important variables and the equations that contain relevant assumptions are discussed. This is undertaken per river process in the following sections.

8.2.1 Current speed main channel

The current speed in the main channel is based on a relation between discharge and current speed that was found in Rijkswaterstaat (2004). This has already been discussed in section 7.3.1. *Figure 17* shows the lookup graph that was implemented in the model. The output of this lookup graph (the multiplier) is multiplied with the maximum current speed, which was set to 1.8 m/s. The unit 'Dmnl' as observed in this graph indicates that the multiplier is dimensionless. This abbreviation will be used throughout this thesis.

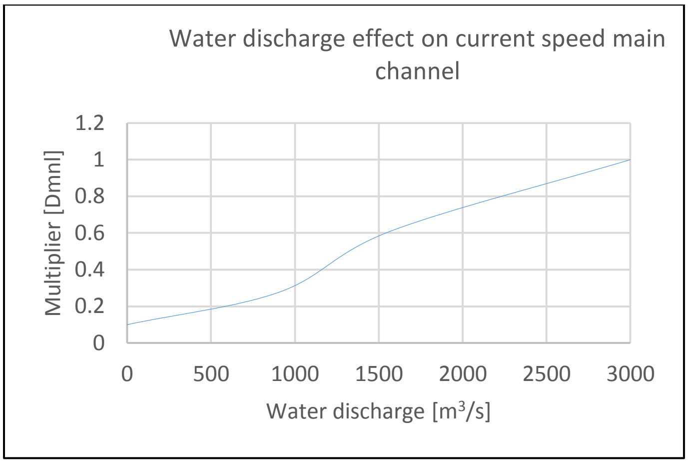


Figure 17: Water discharge effect on current speed main channel

8.2.2 Inflow side channel

The water flow into the side channel depends on many river system aspects. First of all, a side channel needs to be present. Secondly, water will only flow into the side channel when the water level in the main channel is above the side channel bed level plus the threshold (if present). Once it is established that water should flow into the side channel, its inflow rate is determined by three factors; the water inflow into the main channel, the side channel's capacity, and the water level difference between the side channel and the main channel. The inflow into the main channel is multiplied by the share of the side channel in the total river capacity and by a correction factor based on the water level difference. The water level difference is defined by substracting the water level in the main channel from the water level in the side channel. The relation between the water level difference and the correction factor is shown in *figure 18*. If the water level in the main channel is higher than the water level in the side channel, the water inflow into the side channel is increased and vice versa.

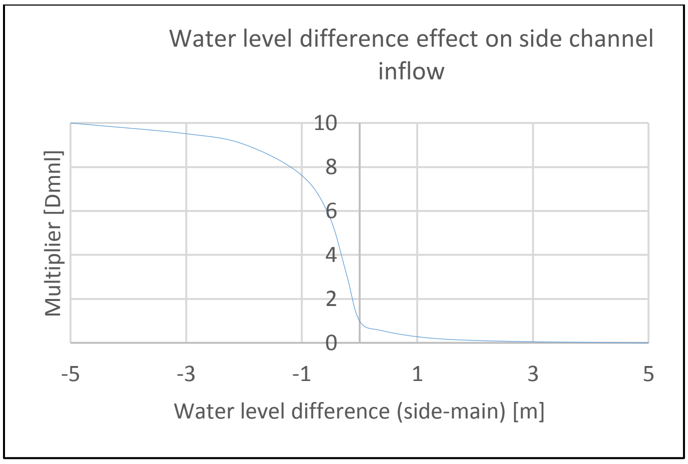


Figure 18: Water level difference effect on side channel inflow

8.2.3 Current speed side channel

The current speed in the side channel is based on the same relation as used for the current speed in the main channel. However, the side channel is narrower than the main channel, which increases its current speed for the same water inflow (Geerling & Van Kouwen, 2011). Therefore, the current speed found with the original relation is multiplied with a correction factor based on channel width. The relation between the channel width and the correction factor is shown in *figure 19*. The width ratio on the x-axis is calculated by the following formula:

$$\frac{Width\ main\ channel}{Height\ main\ channel} \Big/ \frac{Width\ side\ channel}{Height\ side\ channel}$$

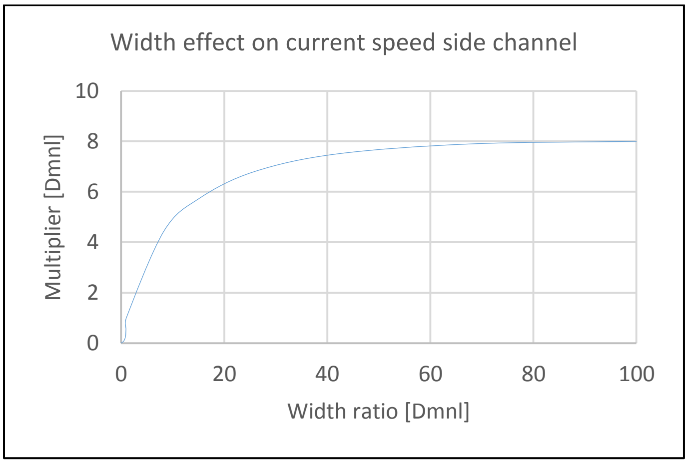


Figure 19: Width effect on current speed side channel

8.2.4 Water from channels to floodplain

Water will only flow from the river channels to the floodplain if the water volume in the channels exceed their capacity. Water can also flow back from the floodplain into the channels, but this can only occur if three conditions are met; there should be water in the floodplain, the water volume in the channel should be lower than its capacity, and the water level in the floodplain should be higher than the summer dike height.

8.2.5 Current speed floodplain

The current speed in the floodplain cannot be determined in the same manner as the current speed in the main channel, since a channel has very different characteristics than a floodplain. Therefore, the current speed in the floodplain is based on the water volume that is present. An extra effect on the current speed in the floodplain is caused by vegetation roughness; if the vegetation in the floodplain is rougher, its current speed will be lower. The current speed is calculated by multiplying its maximum value 0.25 m/s according to Ruimte voor Levende Rivieren (2018) – with a water volume multiplier (*figure 20*) and a vegetation multiplier (*figure 21*). An important assumption is that the current speed will never be 0 due to the floodplain vegetation roughness; even if the roughness is at its maximum, the current speed is multiplied by a factor of 0.25.

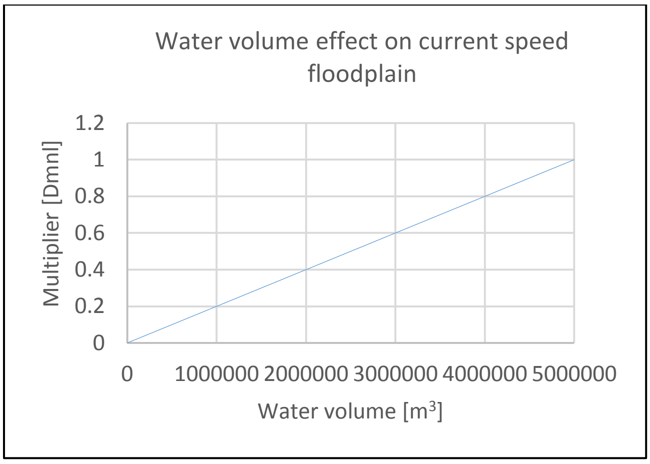


Figure 20: Water volume effect on current speed floodplain

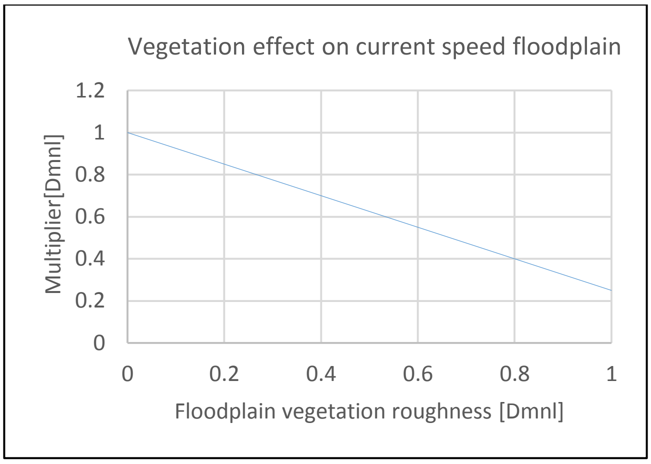


Figure 21: Vegetation effect on current speed floodplain

8.2.6 Water to downstream floodplain

The amount of water that flows out of the floodplain into the downstream floodplain is determined by the water volume in the floodplain and the current speed. An important note is that it is assumed that the water volume above the main channel (so if the water level is higher than the summer dike height) is assumed to be part of the floodplain (recall *figure 11*). However, it does have the same current speed as the main channel. Therefore, the water volume in the floodplain is divided into three parts; the water volume above the main channel, the water volume above the side channel, and the water volume above the floodplain. Each volume has its own current speed at which it moves towards the downstream floodplain.

8.2.7 Water level floodplain

The water level in the floodplain is determined by a graphical function (lookup graph) based on the water volume, since its relatively complex dimensions impede direct calculation of the water level based on the water volume. This lookup graph needs to be redesigned if the dimensions of the floodplain are altered (for example if a side channel is constructed). *Figure 22* shows the lookup graph for a side channel with the following dimensions (the standard dimensions for the model):

- Width zone 1: 50m
- Width zone 2: 150m
- Summer dike height: 5m above NAP
- Winter dike height: 9m above NAP
- Floodplain height at summer dike foot: 3m above NAP
- Floodplain height at winter dike foot: 4m above NAP
- Floodplain height at edge between zone 1 and zone 2: 3.5 m above NAP

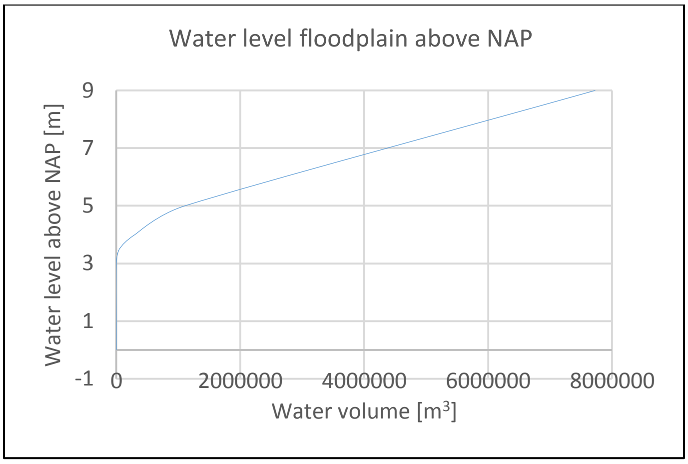


Figure 22: Water level floodplain above NAP

8.2.8 Floodplain erosion

The rate of floodplain erosion is assumed to depend on the duration of floodplain flooding; if the duration of water in the floodplain is shorter than 15 days, the normal erosion rate is multiplied with a value between 0 and 1, as indicated in *figure 23*. For all durations longer than 15 days, the normal erosion rate is multiplied by 1.

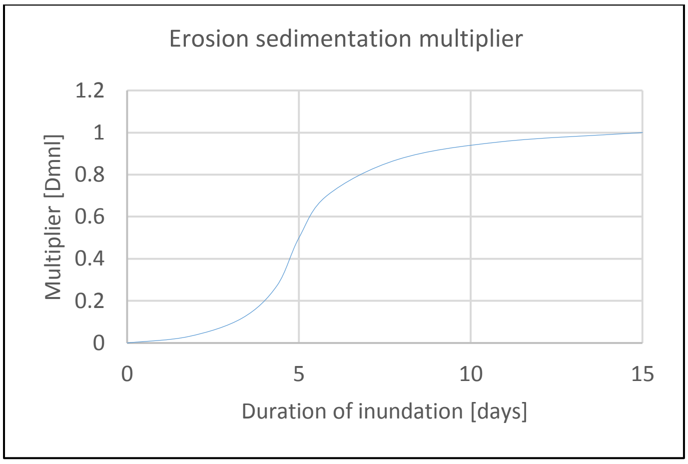


Figure 23: Erosion sedimentation multiplier

8.2.9 Human vegetation removal

In the 'vegetatielegger' determined by Rijkswaterstaat (2018a), the maximum allowed amount of each of the four vegetation classes (grass, reeds, scrub, forest) is stated. If the vegetation in the floodplain exceeds this maximum level, it will be removed by human intervention. Not only are maximum values for each vegetation class defined separately, but maximum values for the combinations 'reeds, scrub, and forest' and 'scrub and forest' are also defined. If the amount of scrub and forest is above its maximum, the rate of forest removal determined as follows; the difference between the amount of scrub and forest and its maximum is multiplied by the share of forest in the total scrub and forest vegetation, and then this amount is divided by the vegetation removal time.

8.2.10 Water level and navigation

The cargo capacity that is available for shipping depends on the water level in the main channel. If this level is too high or too low, the capacity decreases. The reason that less cargo capacity is available at higher water levels, is that the gap between the water level and the bridges becomes too small. *Figure 24* and *25* indicate the relation between the gap and the share of the cargo capacity that can be used. The relation is different for bulk ships than for container ships, because bulk ships are generally lower. Besides, the relation is discrete for container ships and more gradual for bulk, because a whole layer of containers needs to be removed at once when the gap is too small.

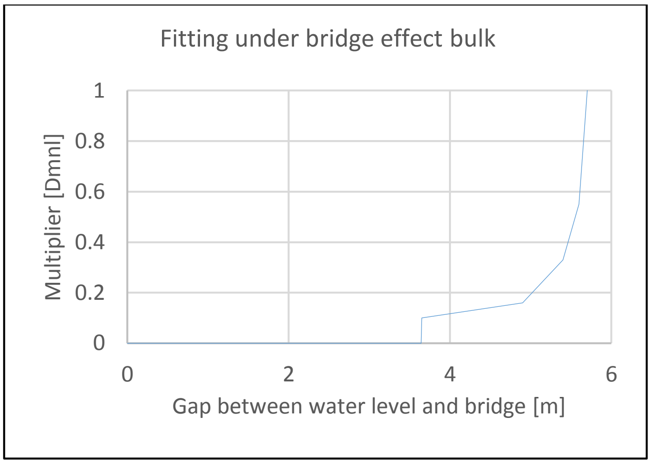


Figure 24: Fitting under bridge effect bulk

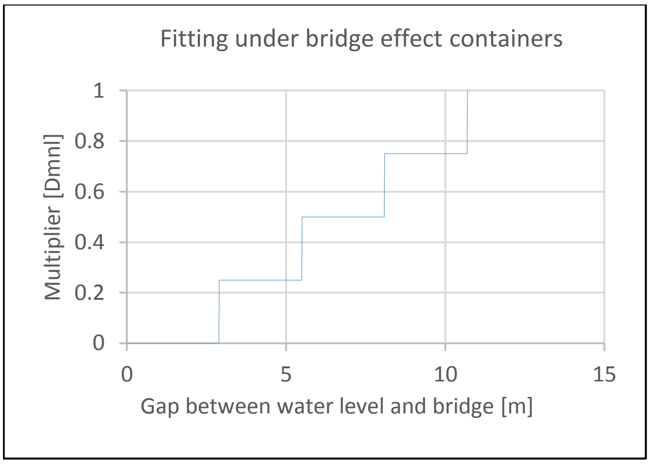


Figure 25: Fitting under bridge effect container

During low water levels, the cargo capacity decreases because ships cannot be fully loaded, or even cannot navigate at all. This relation is based on Bosschieter (2005) and is shown in *figure 26*.

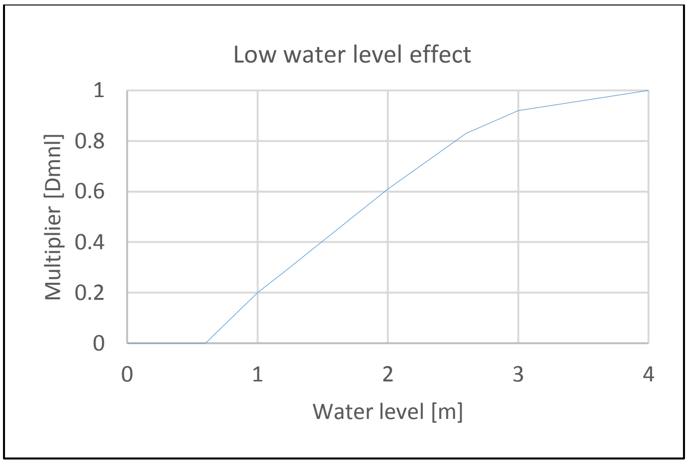


Figure 26: Low water level effect

8.2.11 Dike failure mechanisms

The possibility of occurrence of the four dike failure mechanisms included in this research is influenced by two aspects. First of all, the higher the water level (in case of piping and macro-instability) or the bigger the flooding volume (in case of dike erosion), the higher the possibility of occurrence. Secondly, the possibility of occurrence will be higher if a certain water level or level of flooding occurs for a longer period of time. For each dike failure mechanism, lookup graphs for both aspects have been developed. *Figure 27* and *28* show them for inward macro-instability, *figure 29* and 30 for outward macro-instability, *figure 31* and *32* for piping, and *figure 33* and *34* for dike erosion.

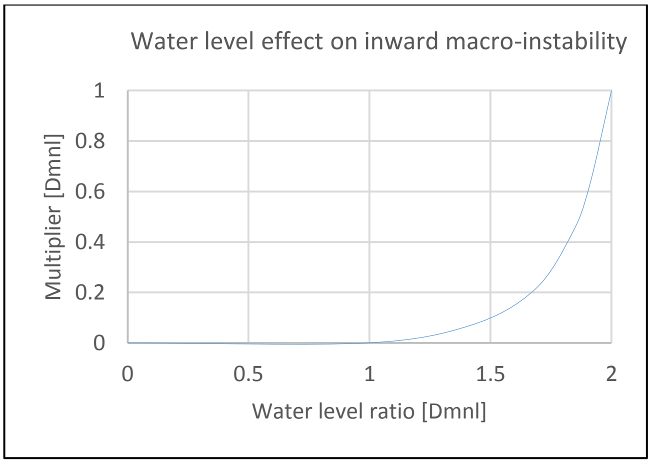


Figure 27: Water level effect on inward macro-instability

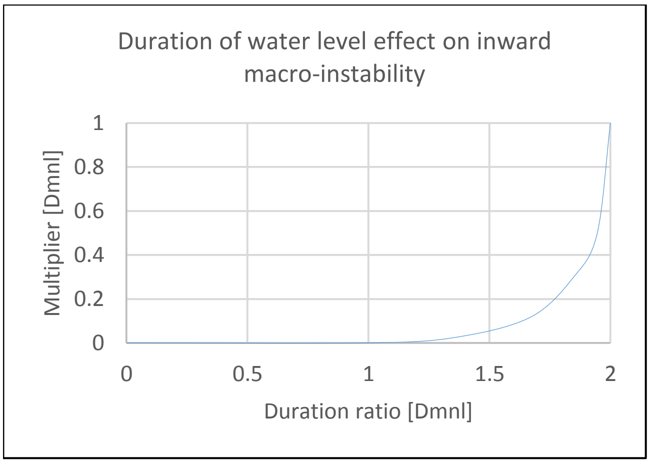


Figure 28: Duration effect on inward macro-instability

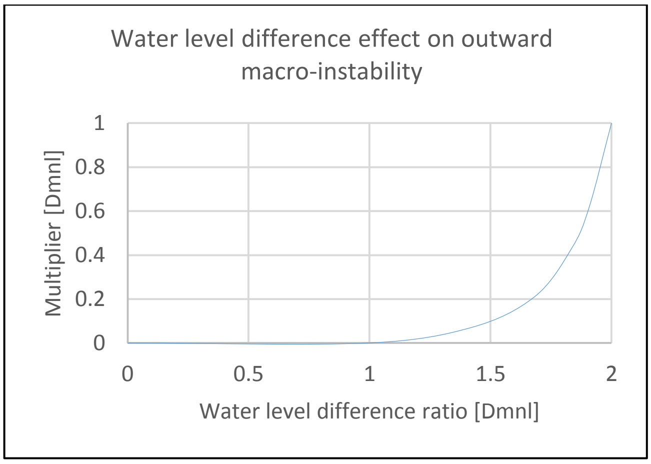


Figure 29: Water level difference effect on outward macro-instability

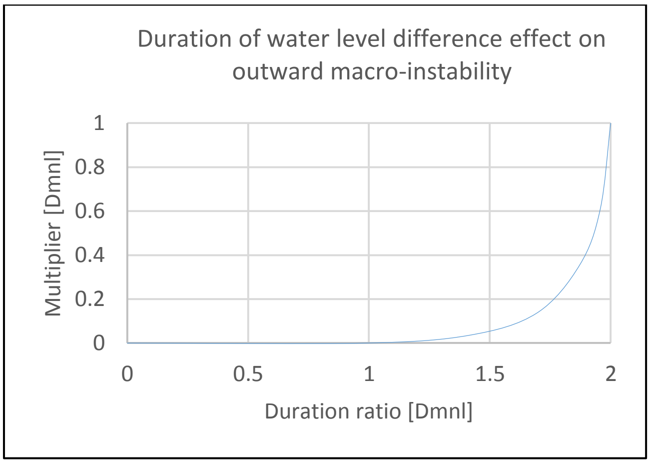


Figure 30: Duration effect on outward macro-instability

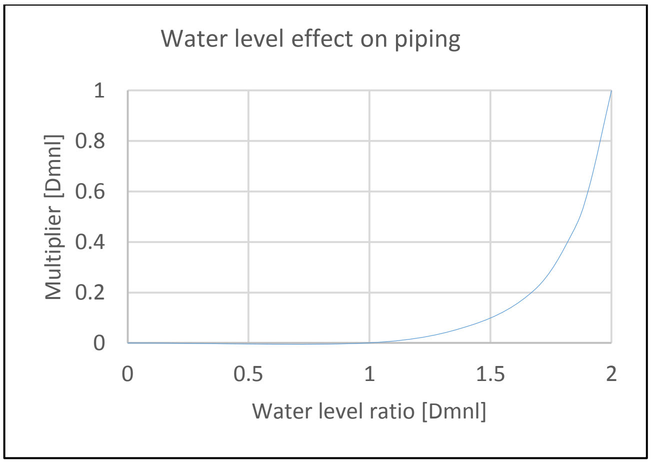


Figure 31: Water level effect on piping

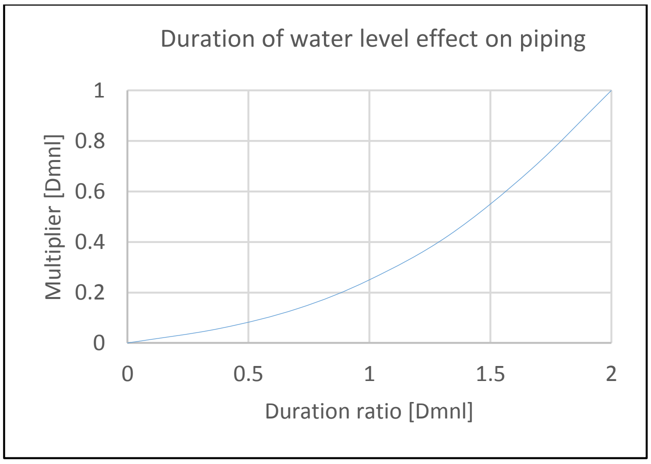


Figure 32: Duration effect on piping

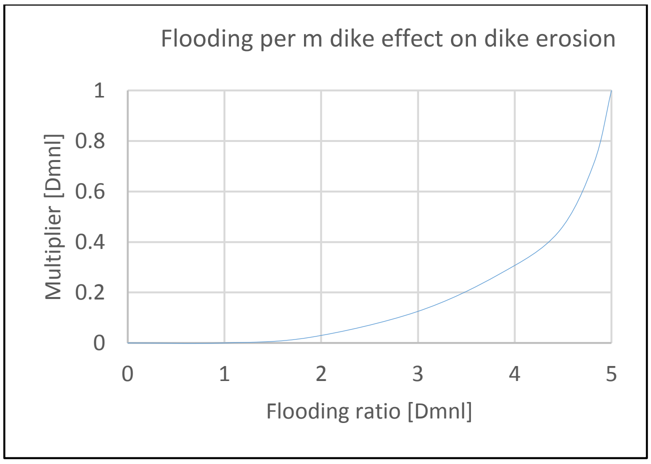


Figure 33: Flooding per m dike effect on dike erosion

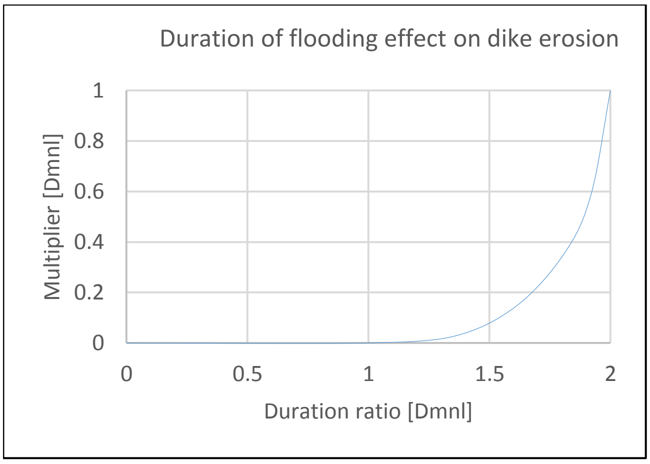


Figure 34: Duration effect on dike erosio

8.3 Model parameters

A table of all parameters and their values is included in appendix D2. For each parameter, the uncertainty range for its value has been determined. The most important or most uncertain parameters have been tested in the validation process that is described in chapter 9. Parameters that are part of an external scenario or policy configurations are elaborated in chapter 10, where the design of the experiments is discussed.

8.4 Model settings

The time unit chosen for the model is day, since river, flood protection, and navigation aspects of the system vary significantly on a daily timescale. In addition, the river sub-model requires a very small time step of 0.00104167 days to maintain an acceptable level of continuity between the main channel, the side channel, and the floodplain (for the reasoning behind this, see section 9.1.3). However, the environmental issues take place over a longer timescale, since processes such as succession take several decades. Therefore, the model is simulated for 50 years (18250 days).

9. Model verification and validation

In this chapter, the verification and validation of the model formulated in chapters 7 and 8 is discussed. This contributes to answering sub-question 4: *'What are the possibilities for modelling the system described in sub-questions 1, 2, and 3 using the system dynamics approach?'*. In section 9.1 the model verification is explained and in section 9.2 the model validation is elaborated.

9.1 Model verification

This section contains the main findings from the model verification process. In appendix E, this process is discussed in more detail. Model verification has the purpose of checking whether the model has been coded correctly, whether the units are consistent with the real world and within the model, and whether the numerical simulation is accurate (Slinger, personal communication, June 11, 2018). Verification is important, because even when the model is finished and apparently runs without errors, this does not automatically mean that the model is correct. Therefore, several checks need to be performed. The first is the causal relations check, the second is the unit check, and the third is the numerical simulation check.

9.1.1 Causal relations check

In the model conceptualization phase, the relations between real-world river aspects have been simplified into causal diagrams. This resulted in causal relations (either positive or negative) from one variable to another. If the causal relation is positive in reality (so an increase in the first variable results in an increase of the second variable), it should be positive in the causal diagram and in the actual model as well. The causal relations check compares the causal diagrams of each sub-model with the actual implementation in a stock-flow diagram in Vensim (Slinger, personal communication, June 11, 2018) to determine whether the direction of the causal relations has been modelled correctly.

The full test, as described in appendix E1, indicated that all causal relations were translated into the correct model relations and equations.

9.1.2 Units check

Two steps need to be taken within the unit check; the consistency of model units with real-world units needs to be determined and the consistency of units within the model should be inspected. The former is done by comparing variables and their units with real world river processes. The latter can be done within Vensim, where it is checked whether the unit on the left hand side of the equation (the variable that is calculated) is equal to the unit on the right hand side (the variables in the formula).

The complete tests, see appendix E2, showed three important issues related to unit consistency with the real world, but these were all explained and acceptable. First of all, the model uses m^3/day instead of m^3/s to indicate water flow quantities. This is due to the fact that the model is assigned a daily time step, and therefore, rate variables (such as water flow from the main channel to the side channel) are returned in units of x/day. To make the water flow variables easier to understand when analysing model results, they are all converted into m^3/s as well.

Another unit that is not similar to the real-world, is the Dimensionless unit of *Floodplain vegetation roughness*. The hydraulic roughness of a channel or floodplain can for example be indicated by a Manning's n-value, which is not necessarily between 0 and 1 and is also not dimensionless. However, since this thesis tries to simplify the river system, and the exact floodplain vegetation is not an outcome of interest, making this variable dimensionless (and between 0 and 1) is considered a satisfactory solution. A third important issue relates to the occurrence of the four dike failure mechanisms. In reality, a likelihood of failure is given to these mechanisms, and a combined likelihood of failure is calculated for the whole dike. In this model, the possibility of each failure mechanism does not give any value to the likelihood that it will happen, it only implies that it could happen. Since this thesis aims to indicate the possible conflicts that could arise between flood protection and the other river uses, less detail is tolerated here.

Issues with units within the model are also present. These can be divided into two types; dimensioned lookups and mismatches of equation and variable units. The former type of unit error indicates that the input of a lookup function is not dimensionless as it should be, but has an input in, for example, m^3. For the lookups, this dimensioned input is necessary and therefore the unit error generated by Vensim was ignored. An example is *Water level floodplain above NAP*, which takes the water volume in the floodplain (in m^3) as input, and returns the water level above NAP (in m). The latter type of unit error is caused by Vensim's inability to calculate with units; if the variable unit is set to m^3 and the equation variables are m*m*m, this is regarded as an error. Therefore, these latter errors are ignored as inaccurate as well.

9.1.3 Numerical simulation

The last model verification step relates to the model settings that determine the numerical model integration. System dynamics modelling simulates continuous behaviour of complex systems by calculating values for each variable over small time intervals. Therefore it is very important that the choice of the time step for each calculation and the choice of the numerical integration method are correct.

The choice of integration method for this model is Runge-Kutta4 (RK4), which is more accurate than Euler (for the same time step), but does not compromise the computational capacity of the computer too much. The fixed version of RK4 uses the user-defined time step, while the automatic version decreases the time step if this is necessary for sufficient accuracy. In this research it is decided to choose RK4 fixed, because the time step is already so small that a further decrease might increase the model run time and the size of the output files too much.

For the choice of the time step, a guideline exists; first, the time step is set to $\frac{1}{10}$ of the smallest time variable or delay time in the model. The model is run for this time step, and then the time step is halved and the model is run again. If the two runs produce the same system behaviour, the largest time step was sufficiently small. If not, the time step should be halved again and the same test needs to be performed. For each sub-model, the necessary time step was determined, and the smallest of these time steps was chosen as the time step for the combined model. It resulted in a necessary time step of 0.00104167 days, which was required for the river sub-model.

However, the smallest time variable in the river sub-model is *Time channel to floodplain*, which should have a value that is very small (< 1 minute) to make sure that the water in the river channels does not exceed its maximum. However, this would result in an even smaller time step, which caused computational and storage issues for the computer. Therefore, it was chosen to set this variable to 6 minutes, and to allow the time step to be less than 10 times as small as this variable (but at least 4 times as small). The model should therefore be tested with a time step of 1.5 minutes, which is 0.00104167 days, and a time step of 0.75 minutes. The latter time step, however, led to computational problems, so instead the model was tested with a time step of 2 minutes (0.001389 days) to check whether the model behaviour changed when changing the time step. *Figure 35* shows that there was no difference between the two model runs, and therefore it was concluded that a time step of 1.5 minutes is sufficiently small. An important note is that with a value of 6 minutes for *Time channel to floodplain*, the water in the main channel will exceed its maximum, which means that the amount of water in the floodplain is potentially larger than the model reports at the peak of a flood event.

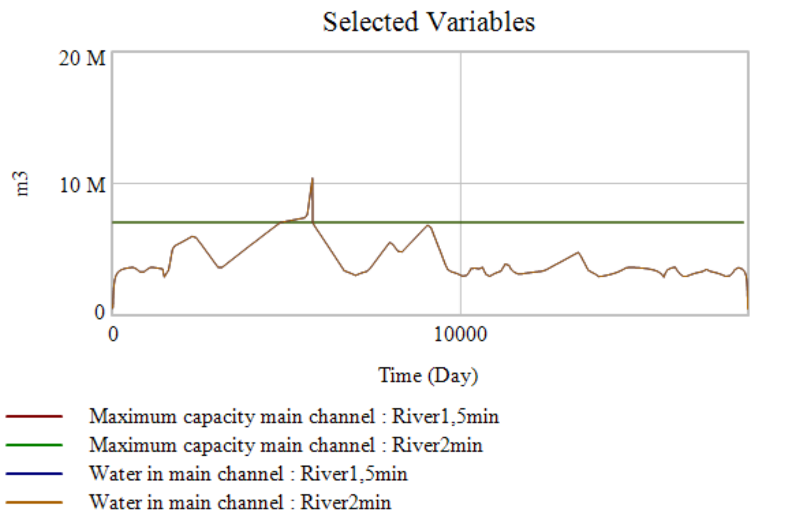


Figure 35: River sub-model output with time step 0.001389 and time step 0.00104167

9.2 Model validation

Validation of a system dynamics model is about testing whether the model is useful for its purpose (Pruyt, 2013). Validation tests should be used to show how assumptions, the model structure, and the choice of parameter values influence the model behaviour and to evaluate whether this behaviour approaches reality (Sterman, 2000). Validation tests can be divided into three categories which all contain several test options; (i) direct structure tests, (ii) structure-oriented behaviour tests, and (iii) behaviour reproduction tests. Direct structure tests analyse the model structure without simulation, structure-oriented behaviour tests require the model to run and then compare model behaviour with real or anticipated behaviour, and behaviour reproduction tests statistically compare model behaviour with real behaviour (Pruyt, 2013). Since this model does not represent an actual case with real-world data, the latter validation test category could not be used. Instead, the model structure and behaviour were qualitatively compared with real-world river systems and their behaviour. This was done for each sub-model separately. Next, an extreme conditions test and sensitivity analysis (both structure-oriented behaviour tests) were performed. When using the extreme conditions test, the model is simulated under extreme conditions of particular parameters and it is analysed whether the model behaviour is still plausible under these conditions. This test is extremely important in this research because future scenarios of extreme (both high and low) water discharge were tested. Sensitivity analysis tests whether relatively small changes in parameters, initial values, functions, and model structures lead to a change in model output behaviour. Of the direct structure tests, face validation was also considered appropriate for this research. When performing face validation, experts are asked to explain whether they consider the model structure, equations and behaviour adequate and plausible. The sub-models in this research represent strongly simplified behaviour of very detailed and complex behaviour in the real world. Experts can determine whether this simplification was done correctly. Due to time constraints, the face validation could not be performed for this research, but it is strongly recommended to undertake this in further research. Appendix F contains a more elaborate explanation of each of the validation methods, and an extensive discussion of the validation results. In the next section the most important conclusions from the model validation process are discussed.

9.2.1 Validation conclusions

Based on the three validation tests, it is concluded that the model is fit for purpose. It can be used to perform a high level, integrated analysis of the river system and the conflicts that arise between the river uses of environment, navigation, and flood protection. The qualitative validation test indicated that important river processes – such as water level continuity between the main and side channel, water level limits for cargo capacity, and the influence of water discharge and channel width on the current speed – are included in the model. The extreme conditions tests and sensitivity analysis showed that the model responds plausibly to changes in its input and that expected behaviour was obtained.

Of course, there are several issues that need to be taken into account before using the model for policy and conflict analysis. Most importantly, this model cannot reproduce natural succession in the floodplain without human interventions also being present. The time step required to simulate river processes fully is too small in relation to the delay time for succession. When human intervention and erosion and sedimentation processes are present, this problem disappears, so the model is suited to its purpose. Furthermore, the current speed in the model is constant for each river component (main channel, side channel or floodplain), while in reality the current speed differs within each component. Another issue is that the model does not allow for a choice in the type of vegetation that is removed when the floodplain vegetation reaches its maximum; all three rough vegetation classes (reeds, scrub, and forest) are simply cut back, while in reality a choice can be made. The next issue is also related to the floodplain vegetation; maximum limits for the rough vegetation classes are given as a percentage of the floodplain area, while actually they are determined by the floodplain's discharge capacity and therefore should attain higher values if the floodplain is enlarged. This can be solved by altering the vegetation limits manually when floodplain enlargement is studied. The last issue relates to the limit of model applicability. The model cannot be used for purposes that require very detailed and accurate information regarding the water flows in the river system, since this accuracy cannot be achieved using an approach with ordinary differential equations such as System Dynamics. Other (modelling) methods such as process-based hydrodynamic modelling exist for these purposes.

Another validation result is that several model variables were found to have a large influence on the model behaviour. First of all, the roughness values for the vegetation classes have a large influence on the total vegetation roughness, and their values should therefore be correctly ascertained. Most importantly the order of increasing roughness should be as defined in Ruimte voor Levende Rivieren (2018): grass, reeds, forest, and scrub. Secondly, the time needed for pioneering and the three succession rates can cause significant changes in the model behaviour, both directly and via secondary or higher order effects. Finally, the erosion sedimentation multiplier did not have a large effect on the test runs, but it could have a large effect on the model behaviour if many short periods of floodplain inundation occur. The reason for this is that it only influences the model during the first 15 days of a floodplain inundation period.

Finally, the validation tests showed the importance of correctly defining some lookup graphs. Especially the lookup for *Water level effect on side channel inflow* should be defined correctly; this effect should not be too strong, since that results in high interdependency between the water levels that cannot be solved validly by System Dynamics. On the other hand, the effect should not be too weak, since that results in large water differences between the main and side channel which is unrealistic. In addition, *Vegetation effect on current speed floodplain* and *Water volume effect on current speed floodplain* are important lookup graphs, since they strongly affect the current speed.

Despite simplification choices, the model does contain the essential river, environment, navigation, and flood-related processes. The model is sufficiently detailed and shows plausible behaviour for the purpose of comparing several policy and scenario combinations to determine changes in conflicting values between river uses.

10. Design of experiments

In this chapter the experiments that will be executed using the model are identified, in order to be able to answer sub-question 5: '*What does the model show regarding the performance of nature-based water management policy configurations and the resulting conflicts between the three river uses?*'. The question will be answered in chapter 11, in this chapter only the combinations of policy configurations and water flow scenarios (the experiments) will be discussed. In chapter 3 it was explained that there are four steps in the Design of Experiments method. The first step is to define the objective of the experiments. This has already been done in formulating sub-question 5; the objective is to analyse conflicting interests under different scenarios and policy configurations. The second step is to determine the criteria on which experiments are compared – this has been described in chapter 5 and section 8.2 – and the input variables that form the experiment – which are discussed in section 10.1 and 10.2. Then, in section 10.3 the different experiments – combinations of scenario and policy variables – are elaborated. The last two steps – the performance of the experiments and the analysis of their results – will be discussed in chapter 11.

10.1 Policy options

As described in section 6.3, the model focusses on side channel configurations and their effect on the three river uses. However, there are several other nature-based water management measures that can easily be tested with the model and that are interesting when studying river use conflicts. In this section, all policy options are discussed. Appendix G includes a detailed overview of all model components that need to be altered when implementing a certain policy and their range of plausible values.

The first and most important policy option is the construction of a side channel. Several choices need to be made when this is done; its size and its connectivity need to be determined. The size of a side channel is determined by its bed level and its width. The connectivity is determined by designing a threshold at the upstream end of the channel or not. If a threshold is present, the side channel will only discharge water during high water levels, and will be empty during low water levels. Another option is to heighten the winter dike, which increases the capacity of the floodplain and reduces flooding. Actually, this is not a nature-based water management policy, but a technical solution that has often been used in the past. It is included in the policy options, because it is interesting to compare this policy with the nature-based options. A third policy option is a nature-based option again; increasing the floodplain width would increase the floodplain capacity and therefore the amount of allowed vegetation. The last policy option is removing the summer dike, which increases floodplain flooding and lowers the maximum water level in the main channel.

Some of these policies have several configurations, others only two. *Table 6* indicates possible configurations for the policy options and which are relevant for this research.

Table 6: Policy configuration options

Policy	**Possible values**
Side channel construction	No side channel Side channel without threshold (connected on both sides) Side channel with threshold (connected on downside)
Increase winter dike height	Normal height Increased height
Increase floodplain width	Normal width Increased width
Summer dike removal	Summer dike present No summer dike present

10.2 Scenario variables

In the research question of this study, it was already indicated that it would be interesting to study the influence of different water inflow (in m^3/s) scenarios on the conflicting values of environment, navigation, and flood protection. There are four possible scenarios related to the water inflow; a normal water inflow, a year-round high water inflow, a year-round low water inflow, and an inflow with extreme high water inflows and extreme low water inflows. The normal inflow is calculated from water discharge data obtained from Rijkswaterstaat (2018b), who provide this data for Lobith at a 10 minute interval over the years 2016 to 2018. These data were multiplied by 2/3 since the Waal – on which the river stretch near Gameren is located – draws 2/3 of the discharge at Lobith. Next, the average daily discharge is calculated. By using the average, extreme values that might have occurred in one of the years are moderated. It would have been better to use the average discharge over a longer period of time, but unfortunately data for previous years were not obtained. The water inflow scenario with a year-round high water discharge is determined by multiplying the average daily discharge values with 250%, and the water inflow scenario with a year-round low water discharge is determined by multiplying the average daily discharge values with 30%. The reasoning behind this is based on information obtained from Rijkswaterstaat (2004); nowadays, the discharge of the Waal at this location is below 900 m^3/s for 10% of the time and the summer bed of the river is full at a discharge of 3000 m^3/s. Therefore, the low inflow scenario is designed so that the discharge hardly exceeds 900 m^3/s (see *figure 36 top right*), and the high inflow scenario is designed so that the discharge is below 3000 m^3/s for approximately 3 months each year (see *figure 36 top left*). The scenario with extremely high and extremely low discharges is determined by calculating the average discharge over the whole year and then multiplying the average daily discharge values above the average with 250% and the average daily discharge values below the average with 30%. *Table 7* and *figure 36* summarise the water inflow scenarios. The year is considered to start at the 1st of January, so calendar years are considered rather than hydrological years.

Table 7: Water inflow scenarios

Water inflow scenarios	Values
Normal inflow	Daily average of 2016 until 2018
High inflow	Daily average * 250%
Low inflow	Daily average * 30%
Extreme inflow	Daily average < yearly average * 30% Daily average > yearly average * 250%

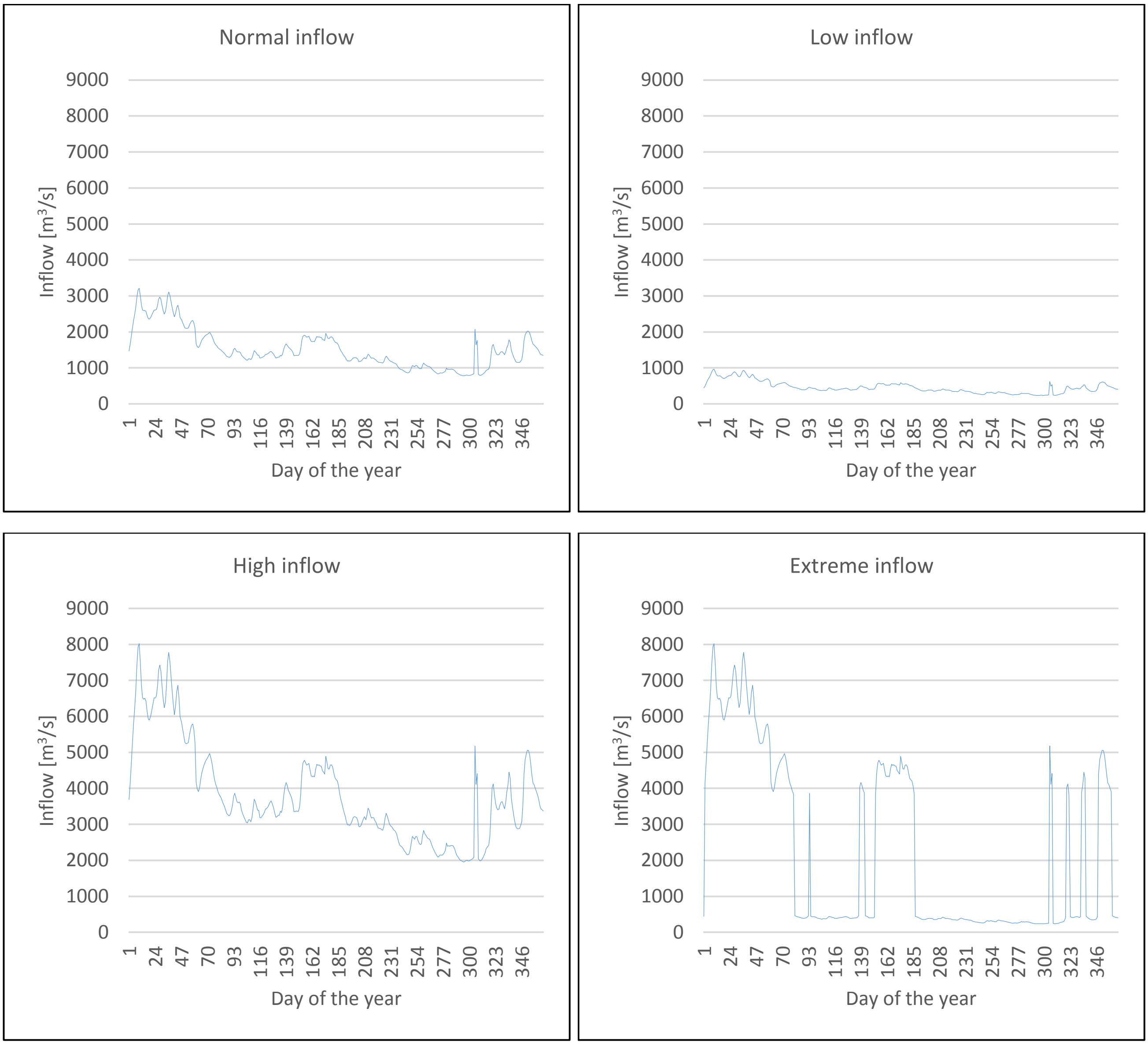


Figure 36: Water inflow scenarios

Next to the water inflow, which is the main scenario variable, the rate of river bed lowering has also been identified as a scenario variable in the conceptualization phase, because it turned out to be too difficult to model this accurately and it is an important issue in river management. The rate of river bed lowering is different for different locations along the Rhine and the Waal. At some locations, it does not even occur at all. In the expert interviews, rates of 1 cm/year and 5 cm/year have been mentioned. For this thesis, the most extreme value is taken to study the effect on conflicting river uses. Therefore, the rate of river bed lowering can adopt two values; 0 m/day, and $\frac{0.05}{365}$ m/day. This scenario variable is implemented in the model by a lookup graph with time on the x-axis and river bed level above NAP on the y-axis (see *figure 37*).

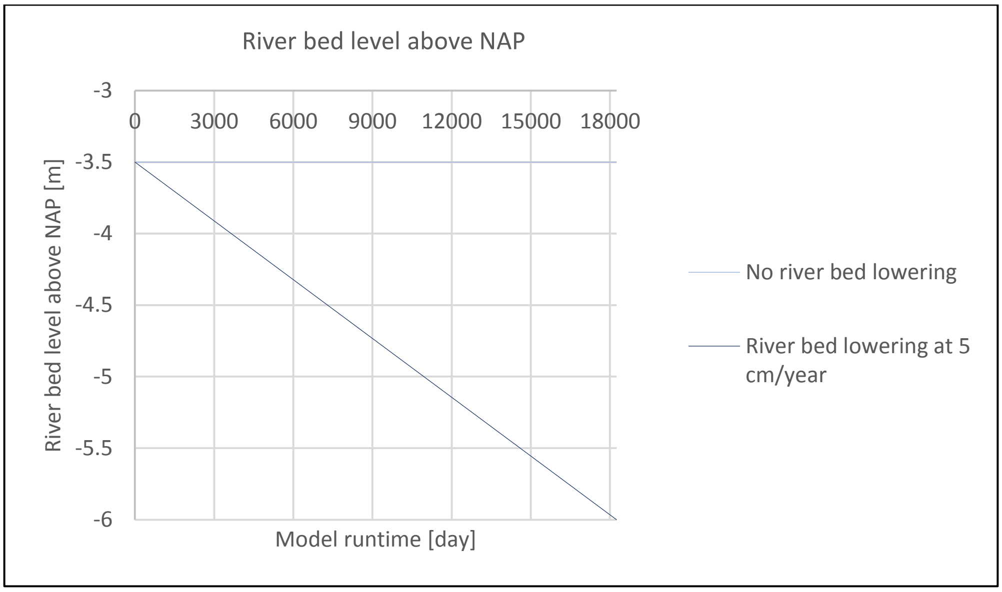


Figure 37: River bed level above NAP scenarios

10.3 Experiments

After the scenarios and policy options have been identified, interesting combinations need to be made. In total, 384 options are possible (2 river bed level scenarios, 4 water inflow scenarios, 3 side channel policy options, and 2 policy options for each of the other 4 policies). For now, the 4 other policies are disregarded, which leads to 24 remaining options for the experiments. The other 4 policies could be included in experiments in further research. 24 experiments was still too much to be included in this research. Therefore, a selection was made based on the expert interviews and literature review, where issues for each river use were found.

First of all, the 'Business As Usual' (BAU) experiment (experiment 0) is determined. This experiment covers the reality where no action is taken (no policy is implemented) and no changes occur in the scenario variables. After the BAU experiment, it is interesting to study what effect each policy or scenario has on the system behaviour when it is implemented individually. This is done in experiments 1 to 3. Experiment 1 studies the construction of a side channel within the existing river system under normal scenario conditions, so a stable river bed at -3.5m above NAP and a normal water inflow. Experiment 2 studies the river system as it is now, without side channel, under extreme water inflow. Experiment 3 studies the effect of river bed lowering at a rate of 5 cm/year. Another interesting issue is found in the side channel connectivity; the shipping industry fears that side channels that are connected at both ends would draw too much water from the main channel during low flow periods. Therefore, experiment 4 studies a side channel that is connected to the main channel on both sides under low water inflow, and experiment 5 studies a side channel that is only connected at its downstream end under low water inflow. Furthermore, it is interesting to study the effect of a side channel on flooding (of the floodplain). For flood protection, less water in the floodplain is required for dike strength issues and less flooding over the winter dike is of course desirable. For environment, on the other hand, water in the floodplain is seen as a positive process. Therefore, experiment 6 studies the effects of high water inflow with a constant river bed level and no side channel, and experiment 7 studies the effects of high water inflow with a lowering river bed (which increases the main channel's capacity) and a side channel. The results of the latter two experiments can then be compared to see what the effects are on flood protection and environment and their conflicting values. In *table 8* an overview of the side channel, water inflow, and river bed level above NAP configurations for each experiment is given. Appendix G2 indicates the exact variable values that need to be implemented for each experiment.

Table 8: Simulation experiments

Experiment	**Side channel**	**Inflow in m³/s**	**River bed level above NAP (at t=18250)**
BAU (null-experiment)	No side channel	Normal inflow	-3.5 m
EXP1	Connected on both sides (no threshold)	Normal inflow	-3.5 m
EXP2	No side channel	Extreme inflow	-3.5 m
EXP3	No side channel	Normal inflow	-6 m
EXP4	Connected on both sides (no threshold)	Low inflow	-3.5 m
EXP5	Connected downstream (threshold)	Low inflow	-3.5 m
EXP6	No side channel	High inflow	-3.5 m
EXP7	Connected on both sides (no threshold)	High inflow	-6 m

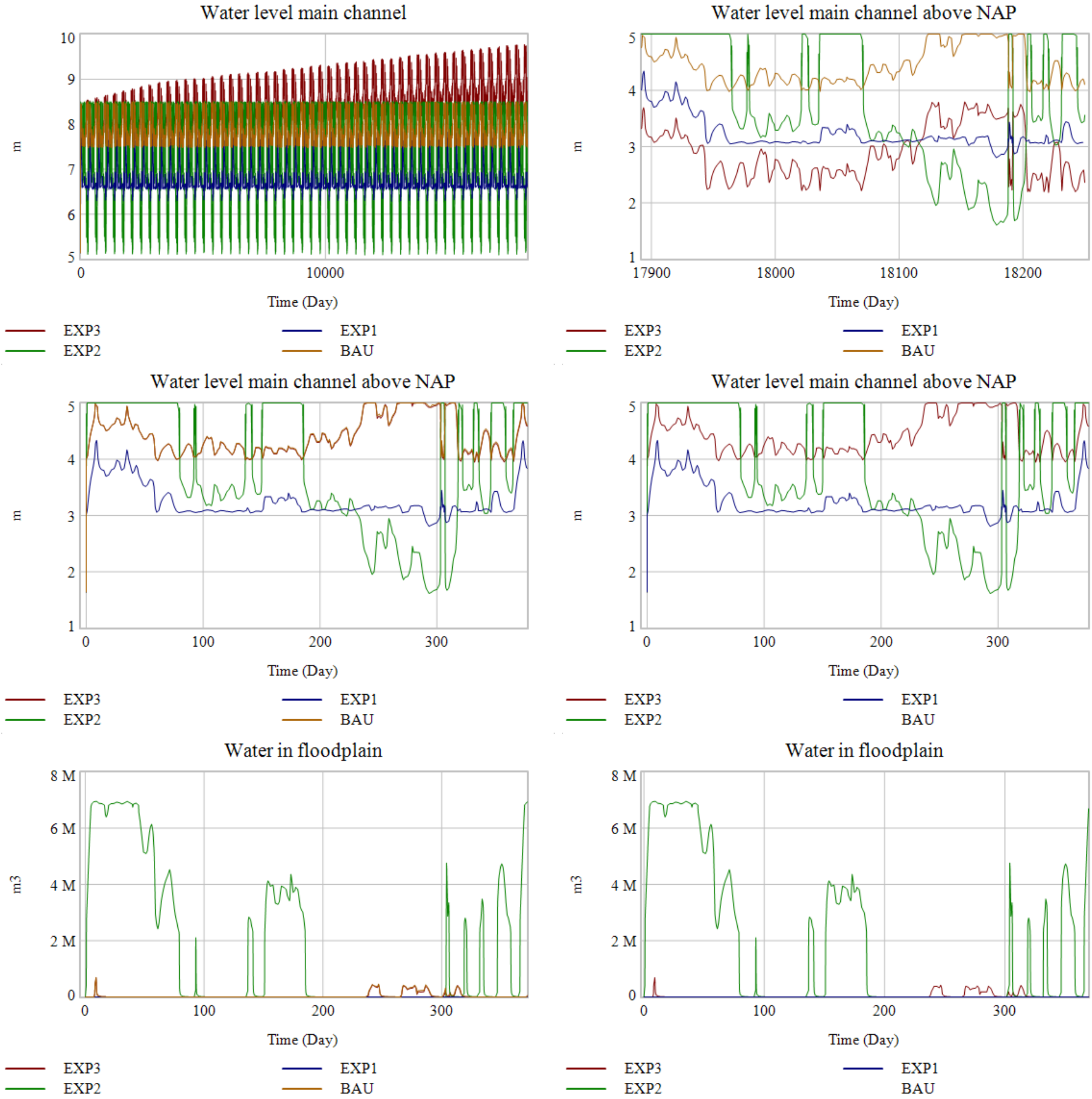
11. Model results

This chapter further answers sub-question 5 by providing the model results for the experiments that were defined in chapter 10. In section 11.1 the results of the Business As Usual experiment are compared with experiment 1 (construction of a side channel), experiment 2 (extreme water inflow), and experiment 3 (river bed lowering). Section 11.2 discusses the comparison of the results of the Business As Usual experiment with experiment 4 (side channel connected on both sides and low water inflow) and experiment 5 (side channel connected downstream and low water inflow). In section 11.3, the Business As Usual experiment is compared with experiment 6 (high water inflow) and experiment 7 (side channel connected on both sides, high water inflow, and river bed lowering). Finally, in section 11.4, the results of all experiments are compared and the results of the decision analysis are presented.

11.1 Comparison BAU, EXP1, EXP2, and EXP3

In this section, the results of the experiments BAU, EXP1, EXP2, and EXP3 are compared. These experiments each differ on only one aspect from the BAU experiment, either the side channel configuration, the water inflow or the river bed level has been changed.

In *figure 38* the effects of each experiment on the river system are shown. Mostly, graphs are zoomed in to show detailed results within a year – either the first year, day 0 to 365, or the last year, day 17885 to 18250. Sometimes, the trend over the full simulation period of 50 years is considered interesting and therefore a graph of the full period – day 0 to 18250 – is included. The top left figure indicates that the water level does not drop below the 4 meter minimum, so the water level is never too low for navigation. Especially under extreme conditions (EXP2) this is unexpected, since the low inflow periods should result in (extremely) low water levels. This might be caused by model configurations. The three figures regarding the water level of the main channel above NAP show that the water level fluctuates most under EXP2, which is the experiment with extreme water inflows. In addition, the water level in EXP3 (river bed lowering) is observed to be equal to BAU at the start of the model runs, but at the end of the model runs it is around 2 meters lower. The graphs regarding the amount of water in the floodplain indicate that little floodplain flooding occurs in the BAU experiment, and that this is not changed for EXP3; even though the river is lowered, the water level in the main channel still sometimes exceeds the summer dike height. In EXP1 the side channel results in such a water level lowering that no more flooding of the floodplain occurs. Only if the summer dike was lowered or removed, would water be able to flow into the floodplain. EXP2 (with extreme water inflows) shows a strong increase in floodplain flooding. Finally, actual flooding over the winter dike only occurs in EXP2, due to the extremely high inflow peaks.



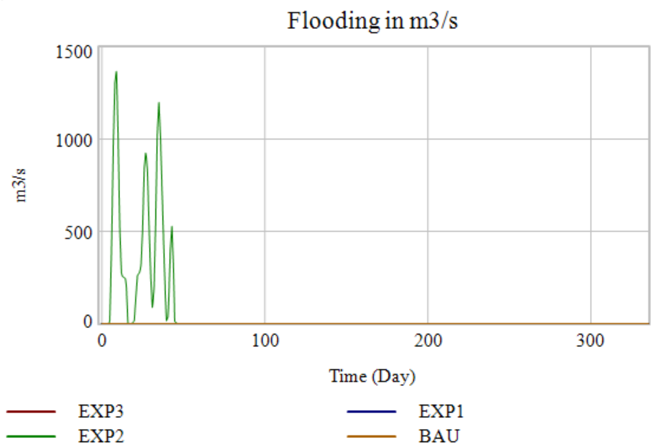


Figure 38: Effect of BAU, EXP1, EXP2, and EXP3 on the river system. The top-left graph indicates the water level in the main channel over the whole simulation. The graphs called 'Water level main channel above NAP' provide more detail on the water level above NAP in the last year (top-right graph) and the first year (graphs on the second row) of the simulation. The two graphs on the third row show the amount of water in the floodplain for the first year of the simulation. The bottom-left graph indicates how much flooding occurred for each experiment in the first year of the simulation.

The effects of the different experiments on the river system in turn influence the criteria that were designed for each of the three river uses; environment, navigation, and flood protection. The output for each of the criteria is included in *table 9*. The colours in this table are assigned per row, so per criterion, and indicate whether the experiment scores well (green) or poorly (red) on this criterion, relative to the scores of the other experiments. As an example, the total cargo capacity has 8.59E+09 as its highest value, and 5.24E+09 as its lowest value. Since the cargo capacity needs to be as high as possible, the former value scores best (green), and the latter value scores poorest (red). The table shows that BAU, EXP1, and EXP3 have similar results, and that the results of EXP2 are opposite to these. This can be explained by the fact that in EXP2 more flooding of the floodplain occurs, which leads to vegetation erosion and therefore to more space for scrub and forest development. At the same time the extreme water inflows of EXP2 have a negative effect on navigation due to current speeds and on flood protection due to dike failure mechanisms and flooding over the winter dike. Another interesting observation is that construction of the side channel does not appear to hamper navigation by lowering the water level, as is feared by the shipping industry. However, the side channel was only evaluated for normal water inflows in this experiment, and should still be tested for performance under low water inflow conditions.

Table 9: Comparable criteria output BAU, EXP1, EXP2, and EXP3

Criteria	**Run**			
	BAU	**EXP1**	**EXP2**	**EXP3**
Max grass ↓	0.5	0.5	0.5	0.5
Min grass ↓	0.2513	0.3178	0.1651	0.2832
Area under % grass graph ↓	4949	5817	3680	5632
Max reeds ↑	0.598	0.6139	0.5316	0.6136
Min reeds ↑	0.1	0.1	0.1	0.1
Area under % reeds graph ↑	9917	10430	8427	10360
Max scrub ↑	0.2	0.2	0.2	0.2
Min scrub ↑	0.06322	0.0534	0.08808	0.0537
Area under % scrub graph ↑	1522	1024	2048	1024
Max forest ↑	0.2036	0.2037	0.2034	0.2036
Min forest ↑	0.00899	0.00512	0.04901	0.00515
Area under % forest graph ↑	512	392.9	1024	445.6
% days suitable channel ↑	55.0%	95.3%	58.1%	79.6%
% days side channel flow ↑	0%	100%	0%	0%
Total cap ↑	8.59E+09	8.59E+09	5.24E+09	8.59E+09
% days 0 cap ↓	3.1%	3.1%	36.6%	3.1%
% days decrease due to low water ↓	0%	0%	0%	0%
% days decrease due to high water ↓	0%	0%	0%	0%
% days decrease due to high current ↓	0.1%	0.1%	0.3%	0.1%
Max flooding ↓	0	0	1394	0
Total flooding ↓	0	0	7.36E+10	0
% days flooding ↓	0%	0%	9.7%	0%
% days outward macro-instability ↓	0%	0%	0%	0%
% days inward macro-instability ↓	0%	0%	8.6%	0%
% days piping ↓	0%	0%	27.6%	0%
% days dike erosion ↓	0%	0%	8.5%	0%
% days dike breach ↓	0%	0%	0%	0%

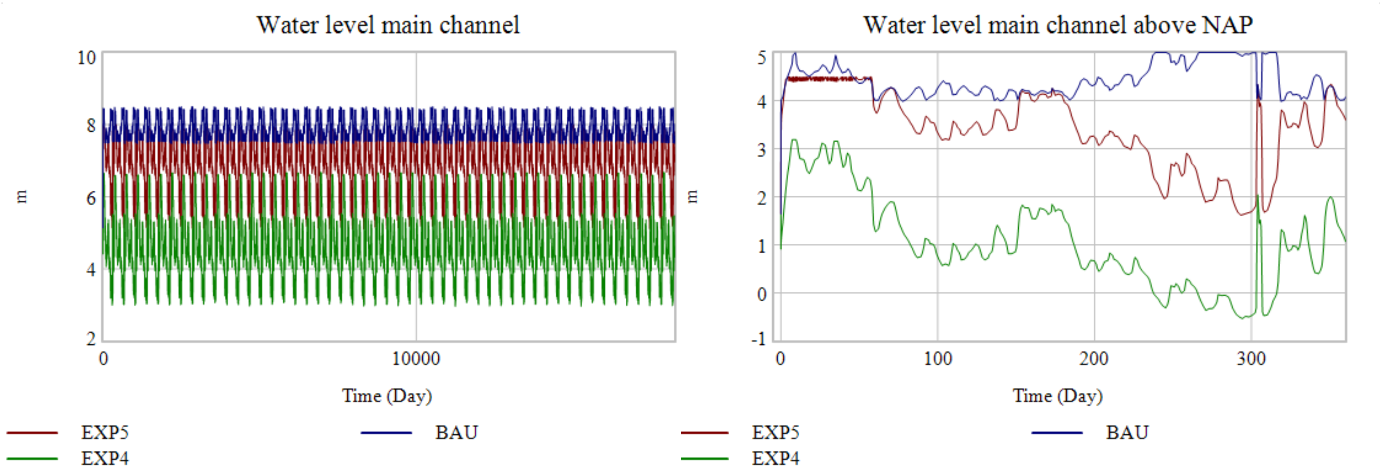
11.2 Comparison BAU, EXP4, EXP5

In this section, the results of the experiments BAU, EXP4, and EXP5 are compared. The design of these experiments is shortly recalled in *table 10*. Experiment 4 and 5 each study a different side channel configuration; in experiment 4 the side channel is connected on both sides, while in experiment 5 the side channel is only connected at its downstream end.

Table 10: Experiment designs BAU, EXP4, and EXP5

Experiment	**Side channel**	**Inflow in m^3/s**	**River bed level above NAP (at t=18250)**
BAU	No side channel	Normal inflow	-3.5 m
EXP4	Connected on both sides (no threshold)	Low inflow	-3.5 m
EXP5	Connected downstream (threshold)	Low inflow	-3.5 m

The graphs in *figure 39* show the effects of each experiment on the river system. First of all, the water level in the main channel is observed to be significantly lower for a side channel that is connected on both sides than for a side channel that is only connected on one side. Therefore, the fear of the shipping industry that side channels might undermine the cargo capacity appears legitimate. The top left graph also shows that only connecting the side channel to the main channel on its downstream end indeed leads to less water level drop. Another effect of EXP4 and EXP5 is the decrease in floodplain flooding; due to the low water inflow and the relatively high capacity of the river channels, the water level will not exceed the summer dike height. This leads to the conclusion that constructing side channels is only beneficial from an environmental perspective if this is accompanied by a summer dike lowering or removal, since the side channel will decrease the water level in the river's channels and reduce floodplain flooding otherwise. Actual flooding over the winter dike did not occur in the BAU experiment nor in EXP4 and EXP5 with a lower water inflow.



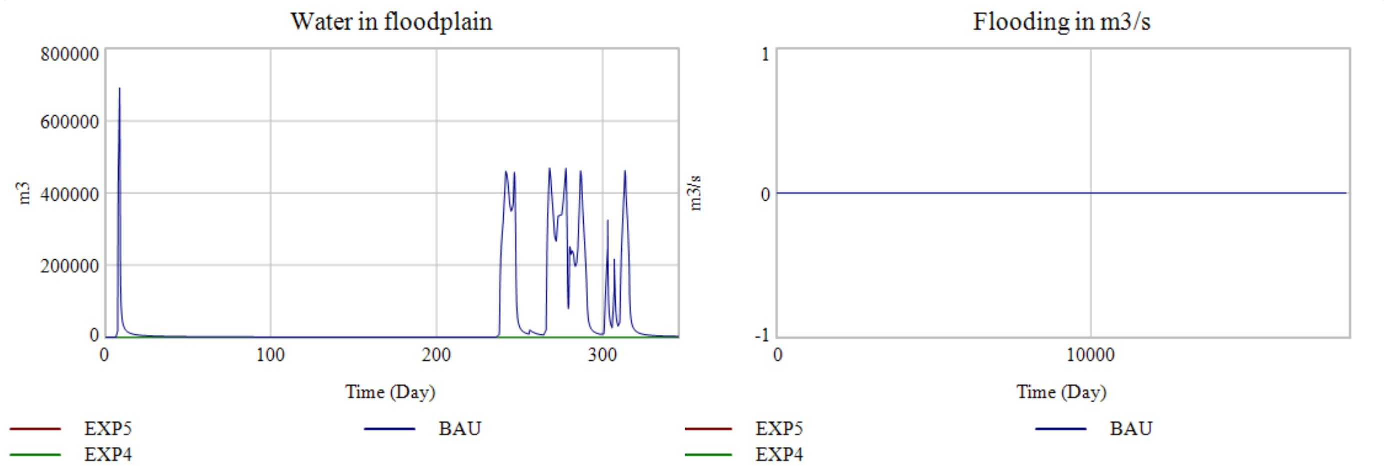


Figure 39: Effect of BAU, EXP4, and EXP5 on the river system. The top-left graph shows the water level in the main channel over the whole simulation. The top-right figure shows the water level in the main channel above NAP for the first year of the simulation. The bottom-left graph indicates the amount of water in the floodplain for the first year of the simulation. The bottom-right graph shows that over the whole simulation no flooding occured in these experiments.

Table 11: Comparable criteria output BAU, EXP4, and EXP5

Criteria	**Run**		
	BAU	**EXP4**	**EXP5**
Max grass ↓	0.5	0.5	0.5
Min grass ↓	0.2513	0.3178	0.3178
Area under % grass graph ↓	4949	5817	5817
Max reeds ↑	0.598	0.6139	0.6139
Min reeds ↑	0.1	0.1	0.1
Area under % reeds graph ↑	9917	10430	10430
Max scrub ↑	0.2	0.2	0.2
Min scrub ↑	0.06322	0.0534	0.0534
Area under % scrub graph ↑	1522	1024	1024
Max forest ↑	0.2036	0.2037	0.2037
Min forest ↑	0.00899	0.00512	0.00512
Area under % forest graph ↑	512	392.9	392.9
% days suitable channel ↑	55.0%	100%	100%
% days side channel flow ↑	0%	100%	14.0%
Total cap ↑	8.59E+09	9.19E+09	9.40E+09
% days 0 cap ↓	3.1%	0%	0%
% days decrease due to low water ↓	0%	9.6%	0%
% days decrease due to high water ↓	0%	0%	0%
% days decrease due to high current ↓	0.1%	0.0%	0.0%
Max flooding ↓	0	0	0
Total flooding ↓	0	0	0
% days flooding ↓	0%	0%	0%
% days outward macro-instability ↓	0%	0%	0%
% days inward macro-instability ↓	0%	0%	0%
% days piping ↓	0%	0%	0%
% days dike erosion ↓	0%	0%	0%
% days dike breach ↓	0%	0%	0%

The changed behaviour of the river system also influences the criteria for environment, navigation, and flood protection. The effects of each experiment on the criteria is given in *table 11*. Again, the scores of each experiment have been evaluated relative to the score of the other experiments. Green indicates that the experiment scores best on the specific criterion, and red indicates that it scores poorest. The result that stands out most, since it is unexpected, is the fact that the experiments result in an increased cargo capacity relative to the BAU experiment. It would be expected that the cargo capacity would decrease due to the fact that the water level is lowered by the combination of a lower water inflow and an extra channel that requires water. The explanation for this phenomenon is that the current speed is often above the maximum limit for navigation in the BAU experiment. This leads to a reduction in cargo capacity. During lower water inflow periods, the current speed will be lower and therefore, the cargo capacity will not be decreased as much. In EXP4 (a side channel connected on both sides), the cargo capacity is decreased due to the low water level, but the decrease due to a too high current speed is so much lower than in the BAU experiment, that the total cargo capacity in EXP4 is higher than in BAU. Another remarkable insight from the table was already mentioned based on the graphs in *figure 38*; the construction of side channels has a negative effect on rough vegetation (scrub and forest) in the floodplain. This is caused by reduced floodplain flooding due to the lower water levels.

11.3 Comparison BAU, EXP6, EXP7

In this section, the results of the experiments BAU, EXP6, and EXP7 are compared. The design of these experiments is shortly recalled in *table 12*.

Table 12: Experiment designs BAU, EXP6, and EXP7

Experiment	**Side channel**	**Inflow in m³/s**	**River bed level above NAP (at t=18250)**
BAU	No side channel	Normal inflow	-3.5 m
EXP6	No side channel	High inflow	-3.5 m
EXP7	Connected on both sides (no threshold)	High inflow	-6 m

EXP6 and EXP7 are run to test what would happen to the three river uses if water inflows increased significantly. In EXP6, there is no side channel and no river bed lowering, while in EXP 7 a side channel is constructed and the river bed lowers to -6m above NAP at the end of the model run. Therefore, in EXP7 the capacity of the river's channel(s) is higher than in EXP6. This is clearly visible in the water level above NAP graphs in *figure 40*; where EXP6 results in higher water levels, the water levels in EXP7 are lower, and sometimes even below the BAU water level. Both EXP6 and EXP7 increase floodplain flooding, but for EXP7 this flooding reduces over the model run (due to river bed lowering). Furthermore, flooding over the winter dike occurs for both experiments, which indicates that the current river system is not adequate to deal with extremely high water inflows.

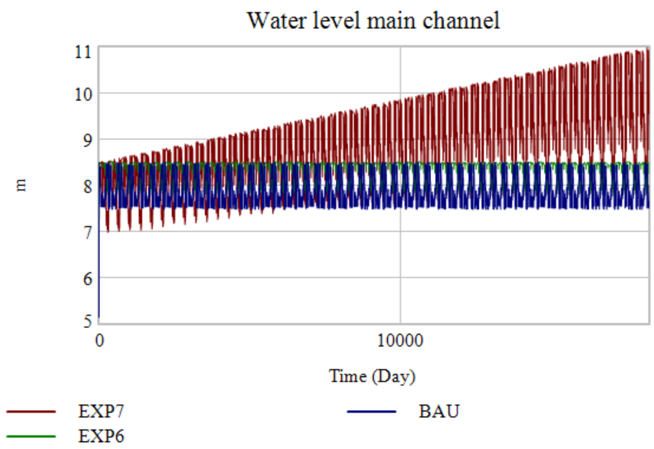


Figure 40: Effect of BAU, EXP6 and EXP7 on the river system. The top-left graph shows the water level in the main channel over the whole simulation. The two graphs on the second row indicate the water level in the main channel above NAP; the left graph shows the first year of the simulation and the right graph shows the last year of the simulation. The graphs on the third row show the amount of water in the floodplain, the left graph for the first year and the right graph for the last year of the simulation. The bottom graphs indicate the amount of flooding over the winter dike that occurs in the first year (left) and last year (right) of the simulation.

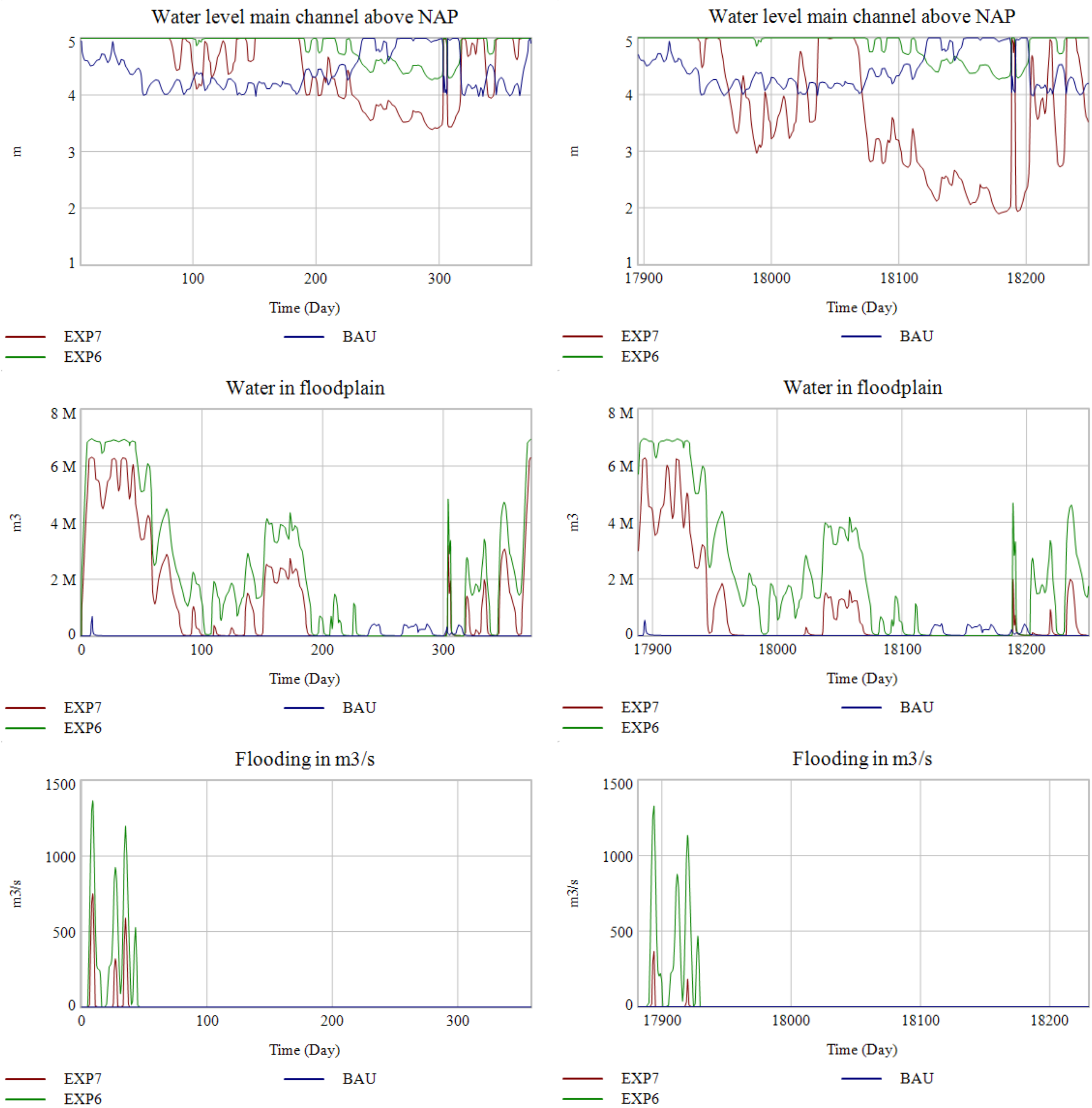


Table 13 presents the results of each experiment on the environmental, navigation, and flood protection criteria. Both EXP6 and EXP7 result in negative effects on flood protection; dike failure mechanism might occur more often and flooding over the winter dike increases. On the other hand, the increase in floodplain flooding benefits environmental aspects in the floodplain; scrub and forest obtain more space to develop due to erosion of reeds. Another environmental aspect relates to the side channel that provides shelter for species in the river channel; only EXP7 (where a side channel is constructed) improves this. Navigation is negatively influenced by both EXP6 and EXP7, but this is due to the high water inflow and can therefore not be influenced by human interventions.

Table 13: Comparable criteria output BAU, EXP6, and EXP7

Criteria	Run		
	BAU	EXP6	EXP7
Max grass ↓	0.5	0.5	0.5
Min grass ↓	0.2513	0.0702	0.1899
Area under % grass graph ↓	4949	2028	4096
Max reeds ↑	0.598	0.4305	0.5587
Min reeds ↑	0.1	0.1	0.1
Area under % reeds graph ↑	9917	8132	8571
Max scrub ↑	0.2	0.2	0.2
Min scrub ↑	0.06322	0.09995	0.06549
Area under % scrub graph ↑	1522	2048	1642
Max forest ↑	0.2036	0.2035	0.2042
Min forest ↑	0.00899	0.07296	0.02135
Area under % forest graph ↑	512	2048	720.5
% days suitable channel ↑	55.0%	8.9%	70.6%
% days side channel flow ↑	0%	0%	100%
Total cap ↑	8.59E+09	1.82E+09	1.82E+09
% days 0 cap ↓	3.1%	74.5%	74.5%
% days decrease due to low water ↓	0%	0%	0%
% days decrease due to high water ↓	0%	0%	0%
% days decrease due to high current ↓	0.1%	0.1%	0.1%
Max flooding ↓	0	1392	770.1
Total flooding ↓	0	7.32E+10	1.04E+10
% days flooding ↓	0%	9.6%	2.4%
% days outward macro-instability ↓	0%	0%	0%
% days inward macro-instability ↓	0%	8.6%	0%
% days piping ↓	0%	27.6%	14.8%
% days dike erosion ↓	0%	8.5%	1.8%
% days dike breach ↓	0%	0%	0%

11.4 Decision analysis

The previous sections described the results of the different experiments grouped by interesting combinations. In this section, an important comparison is made to answer sub-question 5. For this purpose, a scorecard is constructed of the full experimental output. These experiments analysed the effects of different side channel configurations under different water inflow scenarios, the table with experimental configurations is included in *table 14*.

Table 14: Experiment designs

Experiment	Side channel	Inflow in m^3/s	River bed level above NAP (at t=18250)
BAU	No side channel	Normal inflow	-3.5 m
EXP1	Connected on both sides (no threshold)	Normal inflow	-3.5 m
EXP2	No side channel	Extreme inflow	-3.5 m
EXP3	No side channel	Normal inflow	-6 m
EXP4	Connected on both sides (no threshold)	Low inflow	-3.5 m
EXP5	Connected downstream (threshold)	Low inflow	-3.5 m
EXP6	No side channel	High inflow	-3.5 m
EXP7	Connected on both sides (no threshold)	High inflow	-6 m

A scorecard evaluates each experiment based on the base case (BAU in this research) per criterion, by dividing the criterion score of the experiment by the criterion score of the base case (De Haan et al., 2009). Next, colours are assigned to each cell based on the desired direction (increase or decrease) of the criterion. If a criterion should be as high as possible, experiments that increase the value of this criterion relative to BAU are coloured green, while experiments that decrease the value of the criterion relative to BAU are coloured red. This facilitates visual comparison of the experiments. *Table 15* shows the scorecard for the selected experiments. An important remark regards the criteria with value 0 for BAU; the results of the experiments are then assigned a value between 100% and 200% based on the highest value in the row. This is done to make them comparable. The criteria where BAU scores 0 are:

- *% days side channel flow*
- *% days decrease due to low water*
- *% decrease due to high water*
- *Max flooding*
- *Total flooding*
- *% days flooding*
- *% days outward macro-instability*
- *% days inward macro-instability*
- *% days piping*
- *% days dike erosion*
- *% days dike breach*

In the next sections, the best policy options are discussed from each perspective (environment, navigation, and flood protection), followed by an analysis of the conflicts between them.

Table 15: Scorecard experiments

Criteria	Run							
	BAU	**EXP1**	**EXP2**	**EXP3**	**EXP4**	**EXP5**	**EXP6**	**EXP7**
Max grass ↓	100%	100%	100%	100%	100%	100%	100%	100%
Min grass ↓	100%	126%	66%	113%	126%	126%	28%	76%
Area under % grass graph ↓	100%	118%	74%	114%	118%	118%	41%	83%
Max reeds ↑	100%	103%	89%	103%	103%	103%	72%	93%
Min reeds ↑	100%	100%	100%	100%	100%	100%	100%	100%
Area under % reeds graph ↑	100%	105%	85%	104%	105%	105%	82%	86%
Max scrub ↑	100%	100%	100%	100%	100%	100%	100%	100%
Min scrub ↑	100%	84%	139%	85%	84%	84%	158%	104%
Area under % scrub graph ↑	100%	67%	135%	67%	67%	67%	135%	108%
Max forest ↑	100%	100%	100%	100%	100%	100%	100%	100%
Min forest ↑	100%	57%	545%	57%	57%	57%	812%	237%
Area under % forest graph ↑	100%	77%	200%	87%	77%	77%	400%	141%
% days suitable channel ↑	100%	173%	106%	145%	182%	182%	16%	128%
% days side channel flow ↑	100%	200%	100%	100%	200%	114%	100%	200%
Total cap ↑	100%	100%	61%	100%	107%	109%	21%	21%
% days 0 cap ↓	100%	100%	1163%	100%	0%	0%	2367%	2367%
% days decrease due to low water ↓	100%	100%	100%	100%	200%	100%	100%	100%
% days decrease due to high water ↓	100%	100%	100%	100%	100%	100%	100%	100%
% days decrease due to high current ↓	100%	100%	267%	100%	0%	0%	101%	101%
Max flooding ↓	100%	100%	200%	100%	100%	100%	200%	155%
Total flooding ↓	100%	100%	200%	100%	100%	100%	200%	114%
% days flooding ↓	100%	100%	200%	100%	100%	100%	200%	125%
% days outward macro-instability ↓	100%	100%	100%	100%	100%	100%	100%	100%
% days inward macro-instability ↓	100%	100%	200%	100%	100%	100%	200%	100%
% days piping ↓	100%	100%	200%	100%	100%	100%	200%	153%
% days dike erosion ↓	100%	100%	200%	100%	100%	100%	200%	122%
% days dike breach ↓	100%	100%	100%	100%	100%	100%	100%	100%

11.4.1 Environmental perspective

If the results of the experiments are analysed from a purely environmental perspective, the most important conclusion is that although constructing a side channel (preferably connected on two sides) is beneficial for channel ecology, it does have an important negative side-effect; less flooding of the floodplain occurs which has a negative impact on floodplain rejuvenation and therefore on floodplain vegetation diversity. For this reason, construction of a side channel should be accompanied by summer dike removal or lowering in order to be beneficial for nature. Furthermore, the scorecard shows that both types of side channels have a positive effect on the channel river conditions, but that the effects of a channel that is connected at both ends are stronger since it provides year-round shelter for aquatic species.

The influence of the water inflow and river bed level scenarios on environmental criteria differs. Little difference exists between EXP1 (normal water inflow) and EXP4 (low water inflow), which can be explained by the fact that both reduce floodplain flooding to 0, so erosion reduction occurs at the same rate. The low water flow in EXP4 even increases the number of days with suitable channel flow, since the current speed is lower. Both experiments exclude river bed lowering, but this is not expected to have a significant influence, since floodplain flooding is already 0 for both scenarios. The effects of EXP2 and EXP7 do differ significantly from the former two experiments; due to the higher water inflow (and despite river bed lowering) more floodplain flooding occurs in these experiments, which increases erosion and therefore enhances the development of scrub and forest. In EXP2, the absence of a side channel obviously does not benefit the side channel flow.

11.4.2 Navigation perspective

If the issue is regarded from a navigational perspective, the most important conclusion is that a side channel should preferably be connected to the main channel on one side, its downstream end. The reason for this is that the side channel otherwise draws too much water away from the main channel during low water inflow periods and therefore reduces the water level. Another interesting result is the fact that the maximum allowed current speed for navigation is actually the most limiting factor for navigation in the model. Lower water inflows resulted in a higher total cargo capacity, because they lead to a lower current speed. However, the maximum allowed current speed is based on an assumption, so in reality the decrease of cargo capacity due to current speed might deviate from the values found in this research. Chapter 13 deals more elaborately with this issue.

The influence of the water inflow and river bed lowering scenarios on the navigation criteria is large. Under normal water inflow conditions, the construction of a side channel that is connected on two sides does not have negative effects on cargo capacity. However, under low inflow conditions the configuration of a side channel matters more; in EXP4 (side channel connected on both ends) the cargo capacity is lower than in EXP5 (side channel connected downstream). EXP6 (high water inflow without side channel) and EXP7 (high water inflow with side channel) show that under high water inflow conditions, the construction of a side channel does not have any effect on the cargo capacity.

11.4.3 Flood protection perspective

From a flood protection perspective, construction of a side channel is beneficial, whether it is connected on one side or on both sides. This can best be observed by comparing EXP6 and EXP7; both experience a high water inflow, but EXP6 does not contain a side channel, while EXP7 does. The flooding and dike failure mechanisms resulting from the high water inflow are significantly lower for EXP7 than for EXP6. EXP7 does include river bed lowering as well, which leads to an extra decrease in water levels, so an extra analysis of EXP7 without river bed lowering would be necessary to determine the exact positive effect of a side channel under high water inflows.

11.4.4 What conflicts are found in the experiments?

After defining the effects of different side channel configurations and water inflow scenarios separately for each river use, it is interesting to analyse whether conflicting interests exists between the three river uses. *Table 16* indicates for each side channel configuration and water inflow scenario whether it results in a positive or negative effect on each river use. This table indicates that side channels are beneficial or neutral for all river uses during high water inflow periods. During low water inflow periods, however, the effect of a side channel is not always beneficial. Since the water inflow in the Rhine is expected to become more extreme, longer periods of low inflow are expected and this needs to be taken into account when evaluating policy options. Therefore, no single side channel configuration can be found that satisfies all three river uses. Solutions that satisfy two river uses can be found, especially if combined with other policies. For navigation and flood protection a side channel that is connected on one side would suffice. For environment and flood protection, a side channel that is connected on two sides combined with summer dike removal would be beneficial. Environment and navigation, however, do not share a beneficial option.

Table 16: Effects of different side channel configurations and water inflow scenarios on river uses

Water inflow scenario	Side channel configuration	Effect on environment	Effect on navigation	Effect on flood protection
High inflow	Connected on 1 side	Positive	No effect	Positive
	Connected on 2 sides	Positive	No effect	Positive
Low inflow	Connected on 1 side	Ambiguous	No effect	No effect
	Connected on 2 sides	Ambiguous	Negative	No effect

Part 4

Conclusion and discussion

12. Conclusion

This thesis aims to provide insight in conflicts between environment, navigation, and flood protection related to nature-based water management in the Rhine. For that purpose an integrated, high-level model is developed that evaluates the construction of a side channel under different water inflow scenarios and its effects on the three river uses. This model is the first integrated model that included both environmental and navigational aspects of river management. It enables making a connection between the different fields of study that are normally researched separately. Moreover, the model allows for easy exploration of other nature-based water management policies, as is discussed in section 13.3. This chapter answers the research question that was defined for this thesis: '*What conflicts arise between environment, navigation, and flood protection when nature-based water management policies are implemented under different water flow scenarios and how can insights in these conflicts be used in the policy-making process?*'. The research question is built up of two smaller questions and is therefore answered in two sections; first the conflicts around nature-based water management are discussed, followed by the resulting insights that are useful for the policy-making process.

12.1 Conflicts regarding nature-based water management

Table 16 in chapter 11 showed the effects of different side channel configurations on environment, navigation, and flood protection based on the model that was developed. From this table it is derived that conflicts concercing a side channel do not arise during periods of high water inflow – regardless of the side channel's configuration. Due to the high water inflow, decrease of the water level in the main channel is not problematic for navigation. In addition, the high water inflow ensures a water flow through the side channel and at the same time sufficient floodplain flooding for the environment. Finally, the side channel reduces flooding.

During low water inflow periods, the model showed ambiguous effects of a side channel on the environment; while it enhances river channel ecology, it also reduces floodplain flooding and therefore floodplain rejuvenation. That is why construction of a side channel should be accompanied by summer dike removal in order to be entirely beneficial for the environment. Summer dike removal as a nature-based water management policy can also be tested with the model that was developed in this research, but it is expected that this will result in conflicts with land-uses in the floodplains (mostly agriculture), because it will result in more floodplain flooding.

Furthermore, the model shows that solutions for conflicts between environment and flood protection and between navigation and flood protection can be found. A side channel that is connected on both its ends – combined with summer dike removal – reduces flooding and enhances river ecology. A side channel that is connected on one end – its downstream end – preserves a sufficiently high water level for navigation during low water inflows and reduces flooding during high water inflows. However, between environment and navigation no such compromise exists. A side channel that is only connected on its downstream end has a small positive effect on river channel ecology, but the model shows that this is much smaller than it could be when the side channel is connected on both ends. On the other hand, a side channel that is connected on both ends reduces the water level in the main channel during low water inflow periods and hinders navigation.

A perfect side channel that satisfies all river uses is non-existent and it is up to decision-makers, politicians, and society to decide which river use is given priority. Another option would be to search for other solutions, such as the Longitudinal Training Dam (LTD). Since the LTD creates a shore channel within the main river channel, instead of a separate side channel, it provides shelter for aquatic species without drawing too much water from the main channel during low water inflow periods. The LTD would therefore solve the conflict between the environment and navigation. However, the LTD is a new concept and should first be analysed more and monitored for a longer period of time to identify if it is indeed beneficial – or neutral – for all river uses.

12.2 Insights for policy-makers

The model that was developed in this research can also analyse river channel widening, floodplain widening, summer dike removal, and changes in floodplain vegetation management. Therefore, the model enables identifying conflicts with regard to several nature-based water management options, which is useful for decision-makers since it enables them to compare policy options.

Based on the conflicts discussed in the previous section, several conclusions regarding policy-making are drawn. First, the conflicts between river uses do not necessarily arise regarding a policy – a side channel –, but can also concern the configuration of that policy – connected on one side versus connected on two sides. Therefore, it is important to first determine whether the conflict concerns the overall policy or its configuration when deciding about nature-based water management. Secondly, the conflicts differ for different external scenarios, such as changes in water inflow due to climate change. As the water inflow is expected to change and nature-based water management is influenced by this, further evaluations of nature-based water management and its effect on river uses should consider different water inflow scenarios. Third, attention should be paid to compromises that are made in the policy-making process. Gertjan Geerling mentioned that policies that are supposed to be beneficial for nature are often changed in the process to accomodate other river uses (e.g. navigation) and thuslobby groups lose their purpose for nature. This research shows that that is also true for side channels; the side channel that is only connected on its downstream end can be seen as a compromise between nature and navigation and it indeed eliminates the negative effects of a side channel on navigation, but it strongly reduces the benefits for nature. Therefore, it is important to include representatives of each river use during the complete decision-making process and to re-evaluate the effectiveness of policies after each iteration. Finally, for nature-based water management to be truely effective for environmental purposes, integration of several measures is required. Moreover, both the river channel and the floodplain are important for the environment, so ideally measures should be taken that benefit both. An example is construction of a side channel combined with summer dike removal.

Other insights for policy-making are related to path dependencies in river management. First, removal of the summer dikes along rivers would enhance environmental river-floodplain processes significantly, but this option is often not considered because people consider them essential. With the model that was developed in this research, it is possible to analyse the effect of summer dike removal. Secondly, the 'vegetatielegger', which determines the maximum amount of vegetation for each vegetation class in the floodplain strongly influences floodplain vegetation development; regardless of the amount of floodplain flooding, the same vegetation equilibrium will be reached due to human intervention. If the floodplain was enlarged, changes could be made to the norms in the 'vegetatielegger' without decreasing the water discharge capacity of the floodplain.

13. Discussion

13.1 Results

The results of this research are based on a model that was built with river information, such as the relation between discharge and current speed, for Gameren. However, the model is not an exact representation of this location, since it mainly serves as a first version of a theoretical model with the purpose of combining different fields of study in one model and illustrating the conflicting interests between environment, navigation, and flood protection in general. The model can be applied to specific case study locations by altering the model parameters.

The main result of the model is a scorecard that indicates whether the different experiments result in positive or negative effects on the criteria for each river use. This enabled simple comparison of effects and the identification of conflicts. An interesting result, found in section 11.4.2, was that current speed is the most limiting factor for navigation. However, the maximum current speed was assumed, so the effect could be less in reality. Another important assumption is the relation between water discharge and current speed for the river channels. This relation is based on measurements, instead of being calculated. Additionally, it is assumed that the maximum current speed is 1.8 m/s, which is the measured current speed at the discharge at which the summer bed of the Waal is full (3000 m^3/s). If changes in the river are made, this relation should also be changed, but this should then be done manually in the model. Another issue that strongly influences model behaviour is vegetation removal when the limit of the 'vegetatielegger' is reached. In the model, it is assumed that removal of the rough vegetation classes (reeds, scrub, and forest) is based on their share in their sum. So there will always be removal of all three classes, while in reality a choice exists between them. If more reeds was removed while saving scrub and forest, this could lead to a different pattern of vegetation development.

The results of this research are mostly applicable to the Dutch branches of the Rhine, since the experts are Dutch and the interviews focussed on issues in the Netherlands. However, the Rhine stretches upstream of the Netherlands towards Iffezheim are normalised just as the Dutch branches, so similar issues are present there and the model results are applicable to this part of the Rhine. From Iffezheim upstream, the German Rhine has many sluices which strongly change the behaviour of the river, and introduce an extra source of conflict between navigation and environment (since barrages are considered to have the worst effect on natural river behaviour and ecology). Therefore, this model is not usable for the Rhine stretches that are confined by sluices and the results of this research cannot be applied to those stretches. Generalization of the results to other rivers is possible as long as those rivers exhibit similar properties; they should be normalized rivers without sluices, and model parameters and configurations need to be adapted to the specific river characteristics.

13.2 Methods

In this thesis, three main methods were used; a literature review, expert interviews, and system dynamics modelling. The order of research had both positive and negative effects; on the one hand, performing the literature review and expert interviews first enabled an extensive exploration of the issue and an open view towards processes and problems. On the other hand, during the modelling process it became clear that some vital information was missing. This information had to be obtained from literature. With regard to the results, the two parts lead to a good combination of qualitative and quantitative analyses, where ideas and perspectives that were discovered in the literature review and expert interviews could be quantified and analysed in-depth with the model.

13.2.1 Literature review and expert interviews

The literature review and expert interviews were suitable methods to conceptualize the model that was developed in this research. The three-step approach (literature – interviews – literature) ensured triangulation. A limitation of this research is that a second round of expert interviews to validate the model has not been performed. This is recommended for further research.

13.2.2 System dynamics modelling

System dynamics modelling is a modelling technique that is often used for policy modelling, representing continuous systems with many feedback loops. In general, this type of modelling is suitable for many strategic issues. Since this thesis relates to an integrated analysis of three river-use interests, it is acceptable that the most important processes for each river-use are simplified, since this simplification is informed by experts so that no relevant processes or details are overlooked.

The research problem was divided into four components during the modelling process; the river, the environment, the navigation, and the flood protection system. They were first modelled separately, which resulted in plausible model output. The river and the flood protection sub-models and the combined model, however, exhibited some difficulties.

In the river sub-model, this difficulty was related to the principle of conservation of mass that needs to be ensured when modelling a hydraulic system. If a water flow from a river channel into the floodplain occurs, this should happen immediately, otherwise the water in the channel can rise above its maximum. To ensure this in the system dynamics model, the time step had to be set to a very small value, but this resulted in computational and storage problems. The smallest possible time step (0.00104167 days) was thus chosen for the river sub-model, and therefore also for the combined model. This resulted in a slight overtopping of the channel capacity, so a slight underestimation of the water volume in the floodplain. Conservation of mass was not achieved, but this did not lead to the incorrect result that flooding did not occur while actually it should. Accordingly, the model is not usable for exact flood water level calculations, but can still be used appropriately to analyse conflicting interests in different experiments.

In the flood protection sub-model, the dike failure mechanisms formed a difficulty. In reality, these processes are very complex, and depend on many more factors than just water levels. Simplifying them for use in this model required many assumptions and predictions about these processes are not very reliable. Therefore, the choice was made only to indicate the ‘possibility’ of occurrence of each mechanism, without indicating an exact likelihood. For the purpose of this research, this is adequate enough and the part of the flood protection sub-model that measures flooding due to overflow over the winter dike works adequately as well.

The difficulty in the combined model is related to the time scales on which processes in each of the sub-models are measured; whereas environmental analysis requires a run-time of several decades, the river system requires a very small time step to generate accurate results. Not only does this lead to computational and storage problems, it can also lead to numerical problems in the succession of the different vegetation types to the next type. In the natural succession process, grass will develop into reeds until no grass is left, which means that the succession from grass to reeds will decline towards 0 and assume a very small value. When this happens, an integration of this value over the time step – which is also very small – cannot be performed accurately. When the time step was set to 1, which was tested in the separate environment model, natural succession was modelled plausibly, which showed that the issue in the combined model was indeed caused by numerical integration. In the real river system, complete natural succession does not occur; due to erosion and human vegetation removal, rough vegetation (reeds, scrub, and forest) is removed or set-back and therefore the amount of each vegetation class will not reach 0 so soon and the model can still be used. Potentially, the numerical integration issue could be solved by adjusting the model run settings such that the environmental model is run at a time step of 1 day, and after each time step its result would be stored and used for all time steps in the river model that lie in-between. Then, the last results of the river model would be used as input for the next time step of the environment model. This can be done in Vensim or in a programming language such as Python, which could be tried in further research.

The issue with numerical integration in the combined model shows the difficulty of developing an integrated model that includes a river, an environmental, a navigational, and a flood protection system. The model operates right at the edge of what is (numerically) possible, and therefore contributes to scientific knowledge.

13.3 Applicability of the model

The model that was developed in this research can be used as a first test when plans for side channel construction are made; this test can indicate possible conflicts and enables decision-makers to anticipate this by testing different side channel and river system configurations to try to find a satisfactory solution for all river uses. The advantage of using a high-level, integrated model for this purpose instead of using separate models for each river use is that the assumptions regarding the river system are exactly the same and need to be changed only once, and that results for the different river uses can be compared easily. Next to analysing a side channel, the model is also suitable for the analysis of four other policies; river channel widening, floodplain widening, summer dike removal, and changes in floodplain vegetation management. Besides, it can be used to analyse path dependencies (see section 12.2) by changing model parameters.

The LTD that was mentioned as a possible suitable alternative for a side channel is conceptually similar to a side channel and for that reason it would be expected that this measure can be analysed by the same model. However, the LTD creates a shore channel and a navigation channel within the main channel. Therefore, conservation of mass between these two channels has to be present in the model for an adequate representation. This can numerically not be achieved by this model. Also other issues that require exact calculations for the water levels or water volumes in the different river system components cannot be studied with this model.

13.4 Recommendations

13.4.1 Scientific recommendations

Expert validation of the model is required to build more confidence in the model results and a case study could be performed with the model to further determine its applicability to real river stretches. These are relatively small research steps that are focussed on improving the usability of the current model and the reliability of the current model output. Further research that focusses on the modelling method regards changing the model settings so that the sub-models are run at different time steps to investigate whether this solves some of the numerical and computational difficulties that arose in this version of the model. Other proposals for further research focus on extending the model and including other policy options in the analysis. Policy options that could be included, without altering the model significantly, are summer dike removal, different processes of human vegetation removal, river channel widening, and floodplain widening. Another policy that is relevant to study further is the longitudinal training dam (LTD), because it might be a solution for the conflicts between the environment and navigation regarding side channels. However, a further study of the LTD cannot be performed with the model that was developed in this research. A last remark for further research is that it should focus on low water inflow scenarios, since high water inflows cause less problems between the three river uses.

13.4.2 Societal recommendations

Recommendations for policy-makers are threefold. First, they are encouraged to use integrated approaches such as this model to explore the effects of nature-based water management in a multi-stakeholder situation. This enables them to identify conflicts in an early stage, but also to find other measures or configurations that result in less conflicts. Secondly, it is recommended for policy-makers to include representatives of each river use during the complete decision-making process and to re-evaluate the effectiveness of policies after each iteration to ensure that compromises do not reduce the effectiveness of the policy. Finally, it is recommended to analyse policy configurations on a small scale – because conflicts often concern configurations instead of overall policies –, but at the same time study combinations of different policies on a larger scale – since for environmental purposes an integrated approach is required.

Bibliography

Ahmad, S., & Prashar, D. (2010). Evaluating municipal water conservation policies using a dynamic simulation model. *Water Resources Management*, *24*(13), 3371-3395.

Arnaud, F., Piégay, H., Schmitt, L., Rollet, A. J., Ferrier, V., & Béal, D. (2015). Historical geomorphic analysis (1932–2011) of a by-passed river reach in process-based restoration perspectives: The Old Rhine downstream of the Kembs diversion dam (France, Germany). *Geomorphology*, *236*, 163-177.

Baptist, M. J., Penning, W. E., Duel, H., Smits, A. J., Geerling, G. W., Van der Lee, G. E., & Van Alphen, J. S. (2004). Assessment of the effects of cyclic floodplain rejuvenation on flood levels and biodiversity along the Rhine River. *River Research and Applications*, *20*(3), 285-297.

Beijk, V. A. W., Coonen, M. A. G., van den Heuvel, R. H. C., & Treurniet, M. M. (2017). Smart watermanagement–case Nederrijn-Lek. *Netherlands Centre for River Studies*.

Berendsen, H. J., & Stouthamer, E. (2000). Late Weichselian and Holocene palaeogeography of the Rhine–Meuse delta, the Netherlands. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *161*(3-4), 311-335.

Bormann, H., & Pinter, N. (2017). Trends in low flows of German rivers since 1950: Comparability of different low-flow indicators and their spatial patterns. *River Research and Applications*, *33*(7), 1191-1204.

Bosschieter, C. G. (2005). *Klimaatverandering en binnenvaart: Effecten op de binnenvaart van meer extreem lage (en hoge) waterstanden op de Rijn* (master's thesis). Delft University of Technology, Delft, The Netherlands.

Broekhans, B. (2017). *Understanding international grand challenges* [Powerpoint slides]. Retrieved February 1, 2018, from: https://brightspace.tudelft.nl/d2l/le/content/36247/viewContent/551067/View.

Clifford-Holmes, J. K., Slinger, J. H., Musango, J. K., Brent, A. C., & Palmer, C. G. (2014). Using system dynamics to explore the water supply and demand dilemmas of a small South African municipality. In *32nd International Conference of the System Dynamics Society, Delft, The Netherlands, 20-24 July 2014; Authors version*. System Dynamics Society.

Clifford-Holmes, J. K., Slinger, J. H., de Wet, C., & Palmer, C. G. (2017). Modelling in the 'Muddled Middle': A Case Study of Water Service Delivery in Post-Apartheid South Africa. *Social Systems Engineering: The Design of Complexity*, 215.

Collas, F. P. L., Buijse, A. D., van den Heuvel, L., van Kessel, N., Schoor, M. M., Eerden, H., & Leuven, R. S. E. W. (2018). Longitudinal training dams mitigate effects of shipping on environmental conditions and fish density in the littoral zones of the river Rhine. *Science of The Total Environment*, *619*, 1183-1193.

Convention on the Protection of the Rhine, Fr.-Ger.-Lux.-Neth.-Switz., April 12, 1999, *treatydatabase.overheid.nl, 009164*.

Cron, N., Quick, I., & Vollmer, S. (2015). Quantitative evaluation of hydromorphological changes in navigable waterways as contribution to sustainable management. In *Conflict Resolution in Water Resources and Environmental Management* (pp. 245-262). Springer, Cham.

Curran, A., De Bruijn, K. M., & Kok, M. (2017). Influence of water level duration on dike breach triggering in system behaviour. *NCR DAYS 2018*, 146.

Deltares (2017). Het Verhaal van de Rivier – Een eerste versie. Retrieved February 25, 2018, from: https://www.helpdeskwater.nl/onderwerpen/waterveiligheid/ programma-projecten/rivierkennis/eerste-product/@179058/verhaal-rivier/.

Demmers, I.M.A.A. (2018). *Nature-based solutions for water management*. Retrieved July 20, 2018, from: https://www.wur.nl/en/show-longread/Nature-based-solutions-for-water-management.htm.
Denzin, N. K. (2012). Triangulation 2.0. *Journal of mixed methods research*, *6*(2), 80-88.
De Haan, A., Willemse, W. P. A. C., de Heer, P., Vos, S. C., & Bots, P. W. G. (2009). *Inleiding technische bestuurskunde.* Amsterdam: Boom Lemma Uitgevers.
De Ruijsscher, T.V., Naqshband, S., & Hoitink, A.J.F. (2018). Flow bifurcation at a longitudinal training dam: a physical scale model. *Netherlands Centre for River Studies.*
Den Haan, R. J., Arevalo, V. C., Van der Voort, M. C., & Hulscher, S. J. M. H. (2018). Prototyping Virtual River. *NCR DAYS 2018*, 76.
Diaz-Redondo, M., Egger, G., Marchamalo, M., Hohensinner, S., & Dister, E. (2017). Benchmarking Fluvial Dynamics for Process-Based River Restoration: the Upper Rhine River (1816–2014). *River Research and Applications*, *33*(3), 403-414.
Dirkx, W. J., Winkels, T. G., van Beek, L. P. H., & Bierkens, M. F. P. (2018). Towards a quantitative assessment of the influence of heterogeneity on piping. *NCR DAYS 2018*, 154.
Duró, G., Uijttewaal, W., Crosato, A., & Kleinhans, M. (2016). Side channels and erosion of natural banks. *RiverCare Knowledge Dissemination Day, 2016.*
Eerden, H. (2013). Pilot Langsdammen Waal: Projectplan realisatiefase II monitoren & inregelen - projectfase MIRT4. Concept Projectplan versie 1.0 inclusief Bijlage A t/m D. Ministerie van Infrastructuur en Milieu, RWS Oost Nederland, Arnhem. Bijlage D: Monitoringsplan Pilot Langsdammen Waal versie 1.0 dd. 30 september 2013.
Eker, S., Slinger, J., Daalen, E., & Yücel, G. (2014). Sensitivity analysis of graphical functions. *System Dynamics Review*, *30*(3), 186-205.
EU Water Framework Directive, October 23, 2000, *O.J. L 327 0001 - 0073.*
Ford, A. (1996). Testing the snake river explorer. *System Dynamics Review*, *12*(4), 305-329.
Ford, F. A. (1999). *Modeling the environment: an introduction to system dynamics models of environmental systems*. Island press.
Forrester, J. W. (2009). Some basic concepts in system dynamics. *Sloan School of Management, Massachusetts Institute of Technology, Cambridge*.
Frings, R. M. (2015). Sand and Gravel on the Move: Human Impacts on Bed-Material Load Along the Lower Rhine River. In *Geomorphic Approaches to Integrated Floodplain Management of Lowland Fluvial Systems in North America and Europe* (pp. 9-26). Springer New York.
Forseth, T., Harby, A., Ugedal, O., Pulg, U., Fjeldstad, H. P., Robertsen, G., ... & Skoglund, H. (2014). Handbook for environmental design in regulated salmon rivers.
Geerling, G., & Van Kouwen, L. (2011). *Handvatten voor nevengeulen in de Rijntakken*. Deltares.
Gensen, M. R., Warmink, J. J., & Hulscher, S. J. (2018). Large-scale uncertainties in river water levels. *NCR DAYS 2018*, 122.
Gilvear, D. J., Spray, C. J., & Casas-Mulet, R. (2013). River rehabilitation for the delivery of multiple ecosystem services at the river network scale. *Journal of environmental management*, *126*, 30-43.
Groene Ruimte. (2018). *Dossier Kaderrichtlijn Water*. Retrieved April 23, 2018, from: https://www.groeneruimte.nl/dossiers/krw/home.html#maatregel
Grondwaterformules.nl (2018). *Doorlatendheid k*. Retrieved June 15, 2018, from: http://grondwaterformules.nl/index.php/vuistregels/ondergrond/doorlatendheid-per-grondsoort.
Harezlak, V., Hulscher, S., Augustijn, D., Leuven, R., & Geerling, G. (2016). Floodplain rehabilitation: linking processes to patterns. *RiverCare Knowledge Dissemination Days 2016.*

Hartmann, T., & Spit, T. (2016). Legitimizing differentiated flood protection levels–consequences of the European flood risk management plan. *Environmental Science & Policy, 55*, 361-367.
ICPR (2015a). *Internationally Coordinated Management Plan 2015 for the International River Basin District of the Rhine*. Retrieved January 17, 2018, from: https://www.iksr.org/fileadmin/user_upload/Dokumente_en/.../*CMP_2015_-_en.pdf.*
ICPR (2015b). *K6 Categories of Waters (natural, artificial and heavily modified Surface water bodies).* Retrieved March 18, 2018, from: https://www.iksr.org/en/water-framework-directive/river-basin-management-plan-2015/.
ICPR (2015c). *Rhine 2020 – Program on the sustainable development of the Rhine*. Retrieved January 28, 2018, from: https://www.iksr.org/en/international-cooperation/rhine-2020/.
Jonkeren, O., Jourquin, B., & Rietveld, P. (2011). Modal-split effects of climate change: The effect of low water levels on the competitive position of inland waterway transport in the river Rhine area. *Transportation Research Part A: Policy and Practice, 45*(10), 1007-1019.
Keefer, D. L., Kirkwood, C. W., & Corner, J. L. (2004). Perspective on decision analysis applications, 1990–2001. *Decision analysis, 1*(1), 4-22.
Kierharingvliet.nl. (2018). *Informatie over het project Kierbesluit*. Retrieved June 6, 2018, from: https://www.kierharingvliet.nl/index.html.
Koedijk, O. C., van der Sluijs, A., & Steijn, M. L. W. (2017). Richtlijnen vaarwegen 2017: Kader verkeerskundig vaarwegontwerp Rijkswaterstaat. *ISBN 978-90-9030674-2*.
Kurstjens, G. (2016). *Effect van langsdammen op stroomdalflora langs de Waal – 0-situatie na aanleg.* Retrieved January 29, 2018, from: https://www.ark.eu/nieuws/2016/ onderzoek-invloed-langsdammen-op-stroomdalflora.
Le, T. B., Crosato, A., Mosselman, E., & Uijttewaal, W. S. J. (2018). On the stability of river bifurcations created by longitudinal training walls. Numerical investigation. *Advances in Water Resources*.
Loucks, D. P., & Van Beek, E. (2017). Water resource systems planning and management: An introduction to methods, models, and applications. Springer.
Louka, E. (2008). *Water law & policy: governance without frontiers*. Oxford University Press.
Mirchi, A., Madani, K., Watkins, D., & Ahmad, S. (2012). Synthesis of system dynamics tools for holistic conceptualization of water resources problems. *Water resources management, 26*(9), 2421-2442.
Ministerie van Infrastructuur en Milieu. (2014a). *Maatregelprogramma Rijn 2016-2021.* Retrieved April 23, from: https://www.rijksoverheid.nl/binaries/rijksoverheid/documenten/ beleidsnota-s/2015/12/14/samenvatting-maatregelprogramma-rijn-2016-2021/samenvatting-maatregelprogramma-rijn-2016-2021.pdf.
Ministerie van Infrastructuur en Milieu. (2014b). *Schematiseringshandleiding macrostabiliteit.* Retrieved June 17, 2018, from: https://www.helpdeskwater.nl/publish/pages/132667/ 05_shmacrostabiliteit_31jan2017.pdf.
Niesten, I., & Becker, A. (2018). Nourishments as part of the future Dutch river management: insights from a pilot. *NCR DAYS 2018, 34*.
Park, G. J. (2007). Design of experiments. *Analytic Methods for Design Practice*, 309-391.
Pfeiffer, M., & Ionita, M. (2017). Assessment of Hydrologic Alterations in Elbe and Rhine Rivers, Germany. *Water, 9*(9), 684.
Plum, N., & Schulte-Wülwer-Leidig, A. (2014). From a sewer into a living river: the Rhine between Sandoz and Salmon. *Hydrobiologia, 729*(1), 95-106.
Pruyt, E. (2013). Small system dynamics models for big issues: Triple jump towards real-world complexity.

Renner, T., Meijerink, S., & van der Zaag, P. (2017). The evolution of regional cross-border water regimes, the case of Deltarhine. *Journal of Environmental Planning and Management*, 1-21.
Rijcken, T. (2017). *EMERGO: The Dutch flood risk system since 1986* (Doctoral dissertation). Retrieved January 25, 2018, from: https://repository.tudelft.nl/islandora/object/uuid:1e7e1b0e-727c-4703-b4f0-60432d739b9b.'
Rijkswaterstaat. (2004). *Evaluatie nevengeulen Gamerensche Waard 1996 - 2002*. Retrieved June 15, 2018, from: http://edepot.wur.nl/91652.
Rijkswaterstaat. (2014a, October 16). *Rijkswaterstaat lanceert vegetatielegger.* Retrieved March 15, 2018, from: https://www.rijkswaterstaat.nl/over-ons/nieuws/nieuwsarchief/p2014/10/Rijkswaterstaat-lanceert-Vegetatielegger.aspx.
Rijkswaterstaat. (2014b, October). *Toelichting op de legenda van de Vegetatielegger.* Retrieved June 5, 2018, from: https://www.rijkswaterstaat.nl/water/waterbeheer/bescherming-tegen-het-water/waterkeringen/leggers/vegetatielegger/index.aspx.
Rijkswaterstaat. (2018a). *Vegetatielegger*. Retrieved June 15, 2018, from: https://demo-geoservices. rijkswaterstaat.nl/vegetatielegger/.
Rijkswaterstaat. (2018b). *Waterinfo*. Retrieved June 23, 2018, from: http://waterinfo.rws.nl/#!/nav/bulkdownload/alle-groepen/.
Room for the River (2018). *Dutch Water Programme Room for the River.* Retrieved February 28, 2018, from: https://issuu.com/ruimtevoorderivier/docs/factsheet_dutch_water_programme_ uk__47425562a3293d?workerAddress=ec2-54-89-43-103.compute-1.amazonaws.com.
Ruimte voor Levende Rivieren. (2018). *Ruimte voor Levende Rivieren – Achtergronddocument.* Retrieved June 6, 2018, from: https://www.levenderivieren.nl/sites/default/files/Achtergrond%20Ruimte%20voor%20Levende%20Rivieren_1.pdf.
Sellmeijer, J. B. (2006). Numerical computation of seepage erosion below dams (piping). In *Third International Conference on Scour and Erosion* (pp. 596-601).
Slinger, J. H. (1986). A mathematical modelling approach to effective flood management of a freshwater wetland and associated pastoral system.
Slinger, J. H. (1997). Modelling the physical dynamics of estuaries for management purposes.
Sterman, J. D. (2000). *Business dynamics: systems thinking and modeling for a complex world* (No. HD30. 2 S7835 2000).
Sterman, J. D. (2002). All models are wrong: reflections on becoming a systems scientist. *System Dynamics Review*, *18*(4), 501-531.
Tank-Nielsen, C. (1980). Sensitivity analysis in system dynamics. *Jorgen Randers.(ed.).*
Tulib (2018). *Making a search plan.* Retrieved January 31, 2018, from: http://tulib.tudelft.nl/searching-resources/making-a-search-plan/.
't Hart, R., De Bruijn, H., & De Vries, G. (2016). Fenomenologische beschrijving – Faalmechanismen WTI. Retrieved June 5, 2018, from: http://publications.deltares.nl/1220078_000.pdf.
Van Baars, S. (2004). Peat dike failure in the Netherlands. *European water management online*, *3*, 1-11.
Van der Lei, T. E., Enserink, B., Thissen, W. A., & Bekebrede, G. (2011). How to use a systems diagram to analyse and structure complex problems for policy issue papers. *Journal of the Operational Research Society*, *62*(7), 1391-1402.
Van der Meer, J. W. (2008). Erosion strength of inner slopes of dikes against wave overtopping. Preliminary conclusions after two years of testing with the Wave Overtopping Simulator. *Summary Report*.
Van Laarhoven, S., Tuijnder, A.P., Kabout, J., & Kleinhans, M.G. (2018). Modelling assessment of the effectiveness of groyne lowering as a measure for bed stabilization. Netherlands Centre for River Studies.

Van Slobbe, E., Werners, S. E., Riquelme-Solar, M., Bölscher, T., & van Vliet, M. T. (2016). The future of the Rhine: stranded ships and no more salmon?. *Regional environmental change*, *16*(1), 31-41.
Van Teijlingen, E. (2014). Semi-structured interviews. In *PGR Workshop December*. Retrieved January 31, from: https://intranetsp.bournemouth.ac.uk/documentsrep/ PGR%20Workshop% 20-%20Interviews%20Dec%202014.pdf.
Van Vuren, S., Paarlberg, A., & Havinga, H. (2015). The aftermath of "Room for the River" and restoration works: Coping with excessive maintenance dredging. *Journal of Hydro-environment Research*, *9*(2), 172-186.
Vermaat, J. E., Wagtendonk, A. J., Brouwer, R., Sheremet, O., Ansink, E., Brockhoff, T., ... & Giełczewski, M. (2016). Assessing the societal benefits of river restoration using the ecosystem services approach. *Hydrobiologia*, *769*(1), 121-135.
Vorogushyn, S., Merz, B., & Apel, H. (2009). Development of dike fragility curves for piping and micro-instability breach mechanisms. *Natural Hazards and Earth System Sciences*, *9*(4), 1383-1401.
Vreugdenhil, H., Slinger, J., & Kater, E. (2008). Adapting scale use for successful implementation of Cyclic Floodplain Rejuvenation in the Netherlands. In *Adaptive and Integrated Water Management* (pp. 301-321). Springer, Berlin, Heidelberg.
Vreugdenhil, H.S.I. (2010). *Pilot Projects in Water Management - Practicing Change and Changing Practice* (Doctoral dissertation). Retrieved February 28, 2018, from: https://repository.tudelft.nl/islandora /object/uuid%3A91bda74b-cf5d-4caf-8159-1e57650291cc?collection=research.
Wasserstraßen- und Schifffahrtsamt Freiburg (2018). *Geschiebezugabe*. Retrieved June 5, 2018, from: http://www.wsa-freiburg.de/wir_ueber_uns/leistungen/unterhaltung/ geschiebezugabe.html.
Winz, I., Brierley, G., & Trowsdale, S. (2009). The use of system dynamics simulation in water resources management. *Water resources management*, *23*(7), 1301-1323.
WWAP (2018). *The United Nations World Water Development Report 2018: Nature-based Solutions*. Paris, UNESCO.
Zwolsman, J. J. G., & Van Bokhoven, A. J. (2007). Impact of summer droughts on water quality of the Rhine River-a preview of climate change?. *Water Science and Technology*, *56*(4), 45-55.

Appendices

Appendix A: Interviews

The second method used to answer sub-question 1, 2, and 3 is conducting expert interviews. This appendix explains the choice of the interview method, the setup of the interviews, the summaries of the interviews, and the results from the interviews.

A1 Choice of interview method

The interviews have been conducted with an open approach, which means that no fixed interview protocol is used. The advantage of this type of interview is that it allows for an in-depth conversation focused on the specific area of expertise of the interviewee. Since this research examines the nature-based water management policies in the Rhine from multiple perspectives, experts with various backgrounds and areas of expertise need to be interviewed. An interviewee working on flood protection cannot answer the exact same questions as an interviewee focused on shipping. In an open interview, some questions are predetermined, but the order can be changed during the interview and questions can be omitted or added (Van Teijlingen, 2014). This is useful if the interviewee mentions a process, policy etcetera that was not expected by the interviewer beforehand, but that turns out to be relevant. The interviewer can than decide to continue asking questions on this subject, even though it was not included in the interview outline. On the other hand, if a certain topic is outside the scope of the interviewee's expertise, questions about this topic can be omitted during the interview.

A2 Interview setup

This section explains how the interviews were prepared. First of all, the main topics that are relevant for the research are identified. Then, the choice for certain experts is explained. Finally, the questions and outline of the interview are determined.

Topics

In order to decide which experts to interview, a set of topics that cover sub-questions 1, 2, and 3 need to be identified. As discussed in chapter 3, sub-question 1, 2, and 3 are:

1. What are the hydrological and morphological processes and water flow variations in the Rhine and how do they interact with environment, navigation, and flood protection?
2. What are the requirements for environment, navigation, and flood protection in the Rhine?
3. What nature-based water management policies have resulted from the international agreements on the Rhine and which is most interesting to study further?

Sub-question 1 is broad and covers many topics. First of all, information about the hydrological and morphological processes in rivers needs to be collected. Furthermore, the specific processes in the Rhine need to be identified. This can be done by analysing the normalisation of the Rhine and its effect on hydrology and morphology. Finally, the effect of hydrological and morphological processes on all three interests needs to be determined. To answer sub-question 2, it is necessary to examine the three interests in detail. For sub-question 3 information on regulations and examples of nature-based water management policies are required.

After some grouping and sequence changing, the following list of topics is identified:

1. Topic 1: River hydrology and morphology
2. Topic 2: History of Rhine normalisation
3. Topic 3: River ecosystems
4. Topic 4: Navigation

5. Topic 5: Flood protection
6. Topic 6: Nature-based water management policies

Topic 1 and 2 provide answers for sub-question 1, topic 3, 4, and 5 provide answers for sub-question 1 and 2, and topic 6 answers sub-question 3.

Choice of experts

The experts that will be interviewed are required to have knowledge about at least one, and preferably several of the topics listed in the previous section. A preliminary list of 13 experts on the topics was drafted based on the professors' professional networks. It was decided that a number of six experts would be interviewed, to limit time consumption but at the same time have sufficient responses. The six experts were chosen based on the spread of their knowledge over the six topics and on their perspective. Different perspectives are necessary to avoid biased answers to questions. This means that at least one expert needs to work from a navigational perspective, one from a flood protection perspective and one from an environmental perspective. *Table A1* shows the six experts and their expertise, and *table A2* shows the perspective they have.

Table A1: Topics covered by experts

Expert	Topic 1	Topic 2	Topic 3	Topic 4	Topic 5	Topic 6
Dr. ir. Cornelis van Dorsser				**X**		
Prof. dr. Frans Klijn	X	X			**X**	X
Drs. Daphne Willems			**X**			X
Dr. Gertjan Geerling			**X**			X
Dr. ir. Erik Mostert						**X**
Dr ir. Astrid Blom	**X**	**X**				

As can be seen in *table A1*, all topics are covered by the experts. Most topics are in the field of expertise of more than one expert, except navigation and flood protection. However, these topics are extensively covered by literature, so much information has been found via that method.

Table A2: Perspectives of experts

Expert	Navigational perspective	Flood protection perspective	Environmental perspective	Neutral
Dr. ir. Cornelis van Dorsser	X			
Prof. dr. Frans Klijn		X		
Drs. Daphne Willems			X	
Dr. Gertjan Geerling			X	
Dr. ir. Erik Mostert				X
Dr ir. Astrid Blom				X

From *table A2*, it becomes clear that all perspectives are present, but that the environmental perspective is slightly dominating. This has been compensated by an extra in-depth literature study on flood protection and navigation issues.

The information about the experts' expertise in the previous tables is supplemented with a brief professional biography of each expert. These biographies are shown in *table A3*.

Table A3: Brief biographies of interviewees

Expert	**Brief professional biography**
Dr. ir. Cornelis van Dorsser	Lecturer and researcher at the section Rivers, Ports, Waterways and Dredging Engineering of the Department of Hydraulic Engineering and Geosciences at TU Delft and working for an inland shipping company. PhD project on 'the Very Long Term Development of the Dutch Inland Waterway Transport System up to the year 2100'.
Prof. dr. Frans Klijn	Specialist in Adaptive Delta Planning at Deltares and Professor at TU Delft, with broad experience on River Basin Management and in environmentally sound planning, with special emphasis on resilience strategies for flood risk management. Involved in Room for the River from an early stage.
Drs. Daphne Willems	International fresh water expert at World Wildlife Fund. Previously worked at Rijkswaterstaat and as an independent advisor, for Room for the River among other projects. Background in biology, with a specialisation on river ecology.
Dr. Gertjan Geerling	Working at Deltares in the field of freshwater ecology, river monitoring, and the effectiveness of nature development projects. PhD at Nijmegen University on safety, shipping, and nature in river systems, with a focus on nature and monitoring.
Dr. ir. Erik Mostert	Lecturer and researcher in the Water management group at TU Delft, focussing on legal aspects and formal institutions for water management, collaboration and adaptation processes in water management, and the EU Water Framework Directive.
Dr ir. Astrid Blom	Associate Professor in river morphodynamics at TU Delft. In her research engineering and geosciences are combined; how does the system react to natural changes and human interventions? An example is the effect of river normalisation.

Interview outline

This section contains the interview outline. This outline is meant as a guide and will not be strictly followed from beginning to end; questions might be added or omitted while conducting the interview. The questions are grouped by the topics that have been explained before. An important note is that each expert is only asked questions regarding the topics listed for him or her in *table A1*.

Interview outline

Date: ___________________ Expert: _________________ Duration: ________________

Part 1 – Introduction

Thank you for agreeing on helping me with my thesis about nature-based water management policies and conflicting river use interests in the Rhine. I am a master's student of the master's programme Engineering and Policy Analysis at Delft University of Technology. In my thesis I study the possibly conflicting interests of environment, navigation and flood protection related to nature-based water management policies in the Rhine. This interview provides me with information that will be used as input for a policy model. I will also interview other experts in related fields, in order to obtain an objective and complete view on the issue.

This interview will take approximately 45 minutes. To make sure I can capture all information and at the same time converse with you, I would like to record this interview on my phone. Also, I would like to use the information you provide in my thesis, with proper referencing. Are you okay with this?

First I will ask you some background questions about your work and then we will continue with the questions related to your expertise and my thesis.

Part 2 – Background information expert

Organisation and function: ____
Function description: ____
Main expertise: ____
Years of experience: ____
Academic background: ____

Part 3 - Questions

River hydrology and morphology

1. How does a natural river deal with changes in water flow?
2. How does the unnatural Rhine deal with differences in water flow?

3. How does erosion/sedimentation occur in a natural river?
4. How does this differ for fine and coarse sediment?
5. How do these processes occur in the Rhine?

6. What is the influence of river hydrology on river morphology?
7. What is the influence of river morphology on river hydrology?

Rhine history

8. What changes have been made (by humans) to the Rhine over the past centuries?
9. What was the purpose of these changes?
10. What were the effects of these changes?

11. What was the spatial scope of these effects?
12. What was the temporal scope of these effects?

River ecosystems

13. How are ecosystem processes in the Rhine influenced by water flow?
14. How are ecosystem processes in the Rhine influenced by river morphology?
15. What is the direct effect of engineering structures on ecosystem processes?

16. What conditions (influenced by water flow and river morphology) are necessary for riverine ecosystems?
17. Are these static conditions (e.g. minima or maxima) or dynamic conditions?
18. Are these conditions met at present?
19. How could these conditions be improved?

Navigation

20. What is the minimum water level necessary for inland transport transportation in the Rhine?
21. Does the duration of the low water level influence the navigability of the Rhine?
22. Are there other requirements for navigation?

23. Which other river processes can hinder navigability?
24. Do the difficulties between different stretches of the Rhine differ?

Flood protection

25. What are the main flood protection measures in the Rhine?
26. How is a choice between these made?
27. Are floodplains along the Rhine free of economic activity?

28. Which trade-offs and choices have been made in the Room for the River policies?
29. Which criteria were considered most important and which criteria were considered less important?
30. What are, in your opinion, strengths of the Room for the River policies? And weaknesses?
31. What are the effects of Room for the River?

Environmental flow policies

32. How does the Water Framework Directive influence environmental flow policies?
33. How does the Convention on the Protection of the Rhine influence environmental policies?
34. Which considerations were important when drawing these agreements?
35. Are there other agreements that play a role in environmental flow policies?
36. Do the agreements overlap or contradict each other?

37. How are different perspective (environment, navigation, flood protection) taken into account when deciding for a certain environmental flow policy?
38. Which one is most important?
39. Which trade-offs are made?
40. What do think about these trade-offs? Have the right choices been made in your opinion?

A3 Interview processing

Each interview was conducted face to face. The duration was set to 45 minutes to one hour beforehand, but deviations (either due to time constraints of the respondent or extra time required for wrapping up the conversation) were allowed. *Table A4* shows the interview schedule including the duration of each interview.

Table A4: Interview details

Expert	Date	Time	Duration
Dr. ir. Cornelis van Dorsser	04.04.2018	15.15	00:27
Prof. dr. Frans Klijn	05.04.2018	13.00	00:53
Drs. Daphne Willems	06.04.2018	10.00	00:58
Dr. Gertjan Geerling	11.04.2018	11.00	01:08
Dr. ir. Erik Mostert	12.04.2018	10.00	00:51
Dr ir. Astrid Blom	20.04.2018	11.00	00:29

The interviews were recorded and afterwards summarised by the interviewer. Summarising instead of transcribing reduced the time consumption of the interview processing process and allowed for organizing the interview into sub-sections. Below, all interview summaries are included.

Interview summary dr. ir. Cornelis van Dorsser

Personal Background
Mr. Van Dorsser studied naval architecture at TU Delft and transport economics at Erasmus University Rotterdam. His graduation projects were focused on inland shipping innovations. After graduation he worked at Royal HaskoningDHV on harbour and inland shipping projects for several years, before starting his PhD at TU Delft. The topic of his PhD thesis is a 100 year vision on the Dutch inland shipping branch. Currently, Mr. Van Dorsser works part time at TU Delft, Mercurius Group, and the Dutch inland shipping organisation. As a researcher at TU Delft, he focuses on harbours, inland shipping, future trends and developments, and economy and logistics.

Shipping on the Rhine
Have a look at PhD thesis.

The standard ship on the Rhine is 110m in length and 11.45m in breadth. Nowadays, larger ships are being used more and more. However, for most canals the maximum length is 86m and the maximum width is 9.5m. Because of the differences in infrastructures on the different Rhine stretches, there is actually quite some diversity in the fleet. More information on this can be found in the PhD thesis. Navigational infrastructure is designed based on the river's characteristics and ship dimensions are based on navigational infrastructure dimensions, such as canals, sluices et cetera. However, waterway administrators (for example Rijkswaterstaat in the Netherlands) base the dimensions of new sluices on the dimensions of the existing fleet. Instead they should focus on the type of ship that skippers would want to use, e.g. one that is more efficient or emits less CO_2. However, this change in thinking is difficult to coordinate along the whole Rhine, because of its international character and because of the long lifetime of bridges, sluices et cetera. The best option would be to broaden sluice at the end of its lifetime.

There are two types of cargo; weight-driven cargo (also called displacement-driven or bulk cargo) and volume-driven cargo. There are also two types of containers; continental containers and deep-sea containers. The former are 2.50m wide, and are in general a bit higher, broader, and longer than the latter. Their size is equal to the size of a lorry. Halve of the fleet uses this type of containers now, and the idea was that a ship with four layers of these containers can just pass below the 9.10m limit. However, this is only possible with enough draught, so in practice only three layers of containers are possible. Deep-sea containers are 2.40-2.44m wide. Ships with four rows of these containers fit exactly on the Rhine, but four rows of continental containers is too much.

There are two types of routes on the Rhine; a route between a sea harbour and an inland harbour and a route between two inland harbours. On the former route, the cargo always consists of a certain quantity of export or import products. Because of this, there is always a minimum amount of cargo in the ship, although the height of this minimum differs between the outward journey and the way back. On the latter route, the trade balance is less balanced, which means that ships do not necessarily carry a minimum amount of cargo and might be empty. This causes the ship to be higher in the water which in turn can cause trouble with bridges. The maximum height of ships and cargo is now 9.10m or 7.00m (caused by bridge height), but Mr. Van Dorsser argues that these should be heightened to allow for higher ships. The bridge height should be based on empty ships with maximum ballast. However, heightening bridges is expensive and when new bridges are designed people are still stuck in the standard dimensions which also have the lowest costs.

Agreements on navigation on the Rhine
The waterway standards in Europe are called CEMT-classes. These standards are used quite strictly and amendments are usually not carried out because it is too expensive, even though other ship dimensions might be more efficient. This clashes with the European ideas on efficiency and CO_2-emission reduction. This can be seen as a clash between short and long term goals; the waterway administrators are too busy with waterway maintenance on a tight budget. Until now, short term goals were winning, but that seems to change now. However, in Belgium a quay is being heightened until the old standard of 9.10m instead of making it accessible for ships with 4 layers of cargo. In France, a quay of 7, is being built, since that is the current standard. This could also be caused by political interests, such as the possibility that the new canal might have a negative influence on the harbour of Le Havre.

Since the act of Mannheim (1868) hindrance of navigation on the Rhine is not allowed. This is also the cause of the fact that fuel taxes do not have to be paid. The CCNR (Central Commission for the Navigation of the Rhine) is the main body governing agreements on shipping on the Rhine. Because Switzerland is included in this agreement, it has a supra-EU status, making its regulations more important than EU regulations. This is useful, because inland shipping in the EU contributes only a small percentage of the economy, while inland shipping is more important in the Rhine-bordering countries. This enables the CCNR to keep more focus on inland shipping.

Requirements for navigation
Have a look at the course material.

As said before, there are two types of cargo, and these also have different requirements. For weight-driven cargo draught is most important; deeper loading leads to more efficiency. The ship adapts to the waterway, because a certain space between the ship and the river bed should remain open. In case of a rough river bed, this space needs to be larger than in case of a smooth river bed. The breadth and width of a ship are given, but the draught can be altered by altering the load in the ship. This happens on a gradual scale. For volume-driven cargo (such as cars, containers et cetera), there are three requirements; weight (usually not relevant), volume, and stability of the ship (against capsizing). The volume is determined by the amount of containers that fit, but if 2.7 containers fit on the ship, this results in 2 containers loading. This makes the alteration of the load on this type of ships happen in discrete steps. The stability of the ship is determined by its centre of gravity, which in turn is determined by the height of the ship and the height of the cargo. Stability is the most important requirement; the ship can be operating on 80% of its capacity based on volume, because it is limited by stability.

Draught and height of bridges are the most important requirements. At low water, draught becomes problematic, and at high water, bridge height becomes problematic. Draught depends on the total weight of the ship, so it is possible to change ballast. However, this has only a limited effect, because the containers have a set weight.

An increased flow velocity increases the power that is needed to navigate a ship upstream. Therefore more fuel is needed and the travel time increases. At times of high water (which mostly leads to a higher flow velocity), some areas in Germany have extra regulation for navigation. For example a prohibition to overtake, a limit on cargo that is allowed to be shipped, or even a total prohibition to navigate. These rules are set to maintain navigation safety. Tight turns are unsafe with high water. Besides, if the quays are already flooded, waves from passing ships might harm the buildings. Also in areas where the dikes are weak, waves from passing ships might damage them more. However, the solution should be to strengthen the dikes instead of limiting navigation.

Low water flow
If the water level gets below 1.5m, navigation becomes problematic. This has two reasons; first of all, the ships screw will not be completely submerged at this water level. This results in inefficiency or even makes navigation impossible. The second reason is that almost no cargo can be carried at this water level. Most ships have a draught of 80-90cm when they are empty, so at 1.5m water depth only limited loading is possible. For smaller ships navigation becomes problematic at 1.2m water depth.

Inland shipping companies have a few ways to increase capacity at low water levels;
- ➔ Navigate faster
- ➔ Navigate longer (24/7) by hiring extra personal
- ➔ Use more ships

Climate change will have a small effect on inland shipping until 2050, but after that the effect might increase and it could become impossible to navigate the Rhine a few months per year. This will not be solved with current solutions and Room for the River will not be helpful. Instead, more canalisation is necessary, so less Room for the River.

Interview summary prof. dr. Frans Klijn

Environmental flow policies

Environmental flows only concern water quantity and the minimum water quantity that is necessary to sustain ecosystems, so your research is not about environmental flows. Try to come up with a better phrasing for the type of policy that you examine. Perhaps there is something in the Water Framework Directive. An interesting document might be 'Wat wil de rivier zelf eigenlijk?' This has been written for the Dutch Delta Programme. Rivers have been altered by humans in such a way that they are completely optimized for shipping and discharge of high water levels. This negatively influenced ecological functions of rivers. Nature needs a natural river regime. Nowadays the river regime has very unnatural vertical fluctuations because of the dikes. Furthermore, the floodplains are relatively high and the river bed is very deep, which decrease the frequency of water reaching the floodplains.

River morphology

Dutch rivers erode more and more because the sediment inflow from upstream has decreased. A natural river has a balanced sediment inflow and outflow, but the Rhine has many barrages, from Iffezheim upstream, stopping the sediment inflow from Switzerland, while erosion continues. Moreover, many stretches of the river are dredged for shipping purposes. Downstream of the barrages, sediment nourishment takes place, which is necessary for a smooth slope of the river bed. The river bed contains solid surfaces (for example in the IJffel) that are not lowered by erosion, so they will form obstacles for ships. At the Dutch-German border a similar problem seems to arise; on the German side, rocks have been deposited, but on the Dutch side the river bed is unprotected. This causes the Dutch side of the river bed to lower, while the German side remains at the same level. In the Netherlands, dredging is only allowed if the dredged sediment is used as nourishment elsewhere in the river. This results in downstream dredging, upstream nourishment and inner bend dredging, outer bend nourishment.

Technical flood protection

We could continue with heightening dikes, but the surrounding land is subsiding at the same time. Furthermore, the floodplains are rising due to sedimentation of 0.5 to 1 cm per year and the river bed is carving itself down due to erosion. The height difference between land and water is increasing, so the damage in case of a flood is also increasing.

Room for the River

In Room for the River thinking, we are actually going back from regulated rivers to more natural rivers. The main narrative used in Room for the River was the argument that it would increase flood protection, with only ecological argumentation it would probably not have been implemented. Giving rivers more space has always had multiple goals. In the '70's and '80's the ecological revival contested the then prominent vision that economic goals always have priority. In that time, the first ideas for Room for the River originated. They argued that the water safety issues could be solved with higher dikes or more space for rivers, but that integrated water management and more attention for ecology and the value of nature was necessary. During that time, also ideas for weir systems and flood storage areas were introduced. Have a look at 'Landschap als geheugen'. At that time the new ideas were not implemented, but the floods in '93 and '95 were an extra push to implement the new ideas of Room for the River. The fact that the ideas were already there, and that they had been pitched years before, made policymakers more willing to consider a different solution than the well-known option of heightening or strengthening the dikes that had been the solution for years. The fact that new solutions were ready caused a change in flood management in the Netherlands.

About 30 Room for the River projects have been implemented, but there was no uniform policy-making or implementation process. The different Room for the River options can be ordered as follows:

1. Dike diversion, because we need to use this option while it is still possible. In a few years there might be too many buildings close to the river to make dike diversion feasible.
2. Bypass
3. Clearance of floodplains, removing all obstacles for high water discharge
4. Floodplain excavation

This order is also based on the cost-effectiveness of each measure. Besides, from a nature perspective obtaining more land in the floodplains is desirable because this is less culturally dominated (e.g. by fertilizers). Besides, changing the official function of land in the floodplains is easier than of land within the dikes. An interesting document is 'Is ruimte voor de rivieren ook ruimte voor natuur?'. When looking from the perspective of effectiveness, the water level lowering achieved for an investment is most important, so cost-effectiveness. The total budget for Room for the River was 2.4 billion euros. 'De Blokkendoos' is a tool that helps to combine several measures in the most optimal manner. The costs of each measure are compared by using m water level lowering per million € or m^2 (water level lowering times length of the river stretch where this occurs) water level lowering per million €. Another important aspect, is spread of the measures along a river, so that they do not all work at the same location.

When a river is given more space, the water level upstream will lower, while the water level downstream does not change. The sea level (h) and the water discharge (Q) are the boundary conditions. When a lowering of the water level downstream is desired, the only option is to reduce Q.

In Nijmegen, a dike diversion with side channel has been realised. The Waal strongly narrows in Nijmegen, so it was urgent to change the situation. The first idea was to create a bypass behind Lent, but this was socially undesirable, so in the end a dike diversion was created. The bypass would have been more effective and cost-efficient, but the social opinion differed (and was stronger). Also political interests play an important role in deciding which measure to implement.

Spatial quality is a broad concept, it covers nature, green areas in cities, but also industry. In each Room for the River project the spatial quality concept has been used differently. However, it was a very important objective. Order of objectives in Room for the River:

1. Cost-effectiveness
2. Lowering water level and spatial quality

The budget and the amount of water level lowering were easily controlled by calculations, but spatial quality is more difficult to check. A quality team covering all Room for the River projects ensured the spatial quality of projects. Landscape architects et cetera were hired to enhance spatial quality. Recently, an evaluation of spatial quality, water level lowering, and nature has been send to the Dutch parliament. The result of the evaluation is positive; the aimed water level lowering has been achieved and the costs did not exceed the budget. A possible explanation why the costs were limited is the fact that contractors had lowered their prices because of the financial crisis. Furthermore, there was a tight budget and strict control over this.

There are several very good examples of Room for the River; Nijmegen-Lent (large water level lowering), dike diversions along the IJssel and the bypass Veessen-Wapenveld (most land added to floodplains), the Noordwaard (best outcome for nature), and lowering of the groynes in the Waal (large increase in spatial quality). In the Noordwaard a large intertidal zone is created where the bird diversity increased. A disadvantage of the Noordwaard is its location; it is located far downstream, and will be affected by sea level rise relatively soon, which decreases its effectiveness. The Noordwaard is therefore not very effective for flood protection. Along the IJssel, the owners of the land in the floodplains, farmers, have been involved intensively. The groynes in the Waal have been lowered with 1.5m and now all look the same. They had been built one by one over a period of 150 years, so they all looked different. Now they are similar and unobtrusive. Lowering the groynes increases the water discharge. A negative effect on shipping was expected but did not occur. This can be explained by the fact that the river had lowered itself significantly due to erosion, but the groynes remained at the same level. Therefore the groynes were recently actually a lot higher than when they were built and they could be lowered without consequences.

Other environmental policies

A lesser example are the longitudinal training dams (LTD's) in the Waal. The LTD's actually created a canal in a river, which stops the interaction between the river and the beaches. This can cause them to turn into mud pools. However, the LTD's are relatively new and monitoring need to check whether this will actually happen. Furthermore, the interaction between river and floodplain is stopped. Another downside of the LTD is that it forms an enormous wall between the beach and the river is created during low water. This makes the LTD very technical and not adding to spatial quality. Besides, external effects occur. In the Netherlands the argument of spatial quality is used to build the LTD's, but to obtain enough rocks for the large wall rocks are blown out of the hills in the Ardennes. This causes the problem to relocate. LTD's also need more rock than groynes, because groynes are built near the shore in shallow water while the LTD's are located in water of 4 to 5 meters depth. Another issue with LTD's is that recreational shipping is separated completely from commercial shipping, which decreases the fun of recreational shipping. To conclude, LTD's are basically a step further away from natural rivers than groynes. For shipping, groynes or an LTD have a similar effect, and the spatial quality decreases. A better option would be to create a real side channel through the floodplain; than two shores instead of one plus a rock wall would be achieved.

Nature

Nature has never been an objective in itself, but spatial quality, covering nature, did become an objective at a certain moment. Officially, nature only covers areas outside cities. Within cities green areas do deliver spatial quality and economic value but not nature.

When the hydraulic roughness of vegetation on floodplains becomes too high, the water flow is obstructed too much and mowing becomes necessary. The guideline for the roughness of vegetation is that a certain starting point needs to be maintained. Grassland is the easiest vegetation in a floodplain.

Multi-functional use of rivers

The order of importance in water management is as follows;

1. Water safety and controlling risks always needs to be handled first
2. Then water resources management determines which use receives how much water
    a. Drinking water is always number 1
3. Quality of the living environment is in third place. This concerns groundwater levels, water quality, nature, landscape quality et cetera

Technical solutions for flood protection are necessary in the Netherlands, without it the Netherlands would not exist. We therefore need to search for a balance between flood protection, landscape quality and nature, and economic functions. Currently, this balance is not achieved; there is too much focus on technical solutions, while the river should get more natural space to deal with high water.

We are in a lock-in situation with shipping. On the one hand it is a useful transportation mode, considering CO_2-emissions per tonne shipped, so it should be supported. On the other hand, the shipping industry is allowed to use polluting fuels that have already been banned for road transport. Furthermore, ships are getting bigger and bigger, demanding bigger waterways and more space. However, if you ask individual skippers what type of ship they prefer, they indicate to be fine with smaller, shallower ships that are adapted to the river. The traders (who pay for shipment) on the other hand want to ship their goods as cheap as possible, therefore demanding more containers or bulk per ship, which increases the size of ships. A river can only support a waterway of a certain size by itself. Enlarging the waterway is possible, but depend on large sums of money, mostly from government subsidies. A shift should be made from the waterway adapting to ships towards ships adapting to the waterway. Another issue with bigger and bigger ships, is that it becomes impossible to turn in the waterway, which makes the system vulnerable.

Constructing a canal next to the natural river is sometimes a better option then trying to alter the natural river for shipping purposes. The canal needs to be filled only once and afterwards there are only minor water losses at the sluices. In France, many canals have been constructed parallel to natural rivers, making it unnecessary to alter and disadvantage the natural river.

Interview summary drs. Daphne Willems

Personal background

Ms. Willems studied biology, focused on rivers, in Wageningen. After that she started working for Rijkswaterstaat, at the institute for fresh water and waste water treatment. Then she worked as an independent advisor on river projects, on the question how water safety could be connected to nature, recreation and other 'soft' values. She has been involved in many Room for the River projects, mainly focuses on the floodplains. Her commissioners were municipalities, nature organisations, sand extractors, et cetera. She is currently working at the Dutch branch of WWF on projects on South-American rivers. Her knowledge of Dutch branches of the Rhine is mainly focused on the Waal and the IJssel.

Rhine normalisation and its effects

The most important effects of river normalisation are:

- Decreasing the frequency of flooding (in the floodplains). This is already controlled near Lobith, where the discharge distribution between the Waal, IJssel, and Nederrijn is determined. At a certain water discharge, more water is diverted to the Waal, because the Lek (following the Nederrijn) can handle a limited amount of water. In the future, probably more water will be led through the IJssel (but this needs to be checked). Another influence on the frequency of flooding is the fact that rivers have lowered their bed by erosion, causing the floodplains to be relatively higher, lowering the frequency of flooding to 0. All processes related to this are therefore also impeded.
- Sedimentation is reduced. This is related to the first effect; if flooding becomes less frequent, sediment cannot reach the floodplains. In a natural system, a sandy edge is located right next to the main channel, because at this point the heaviest sediment is deposited in case of flooding. Behind this, the water will stop flowing and the clay will be deposited. This difference in soil ensures habitat diversity and species diversity. If the process of sedimentation is stopped, habitat diversity will decrease.
- Paralysing the river. The Nederrijn is completely controlled by barrages, and is therefore fairly unnatural. At low discharges, which occur 4 months per year, there is almost no flow. The barrages do have fish passages, but without flowing water the system is dead. Check whether the small water flow that does occur is a policy or if it is caused by leakage through the barrages (Rijkswaterstaat).

River morphology

The power of rivers is included in its dynamics; water needs to flow, high and low waters need to occur, and everything (including the floodplains) needs to be interconnected. Nowadays, many rivers, including the Rhine, are restricted in their natural movement and in their width, causing them to lower their bed by erosion. The Waal is lowered 1cm each year by this process. All dynamics are now restricted to the main channel, instead of being spread throughout the whole river system. Moreover, passing ships increase the dynamics in the main channel by causing wave action (up to 1 meter).

In a natural situation, side channels weave themselves through the main channel of a river. Firstly, a side channel flows along the river and is connected to the main channel both at its upstream beginning and its downstream end. After a while, sedimentation takes place in the side channel and the upstream connection will be cut off. This causes the side channel to slowly dry out and in the end disappear again. A new side channel will then be formed elsewhere.

Nature

Because the frequency of flooding has decreased, the river has lowered its bed by erosion, and the floodplains are now relatively high, the floodplains have dried out. Another reason for this is the fact that the groundwater level in the floodplains has decreased due to the relatively low position of the river.

Because all river dynamics are now restricted to the main channel of the river, the dynamics of the main channel are now too high for nature, while the dynamics in other parts of the system (the floodplains) are now too low for nature. This led to narrowing of habitats, which in turn decreases species diversity.

Species need very specific circumstances to survive, for example small pioneering plants need the sandy edge next to the main channel. For those, it is necessary that new sand is deposited on the sandy edge continuously. The optimum would be that a river dune is formed, such as happened in the Millingerwaard, where also sand from the beach has been blown on the sandy edge. This would lead to real natural rivers, but in the Netherlands this does not exist anymore. The dune in the Millingerwaard experiences too little dynamics, and therefore roughness. Along the Vecht there are also several dead river dunes.

The most important criterion for nature is variation; rolling shores instead of steep embankments increase variation in dry/wet, sand/clay, frequency of flooding et cetera.

Other criteria for nature (have a look at 'Ruimte voor levende rivieren')

- Current
- Swamps
- Connectivity
  - Land connectivity; this allows animals to flee in case of high water
  - Connectivity between main river and creeks; for spawning
  - Connectivity between upstream and downstream part of main river; fish passages next to sluices

Nowadays, water temperature only plays a small role. In the 1980's, cooling water from industry caused a 6 degrees Celsius temperature rise. That has now been reduced again. Temperature rise still has negative effects, but these are limited and smaller than the criteria mentioned before.

Vegetation in the floodplains is often removed to improve the transfer of high water levels. This is understandable from a safety point of view, because there is simply too little space to discharge the high water volumes. Flow lines in the floodplains have been calculated in the floodplains that in case of high water discharge the largest amount of water. These flow lines have to be kept bare. Closer to the dikes, forest is allowed for two reasons. First of all, because the flow velocity is lower at that location. Second, because the trees protect the dike against wave action. However, the roots of the trees are not allowed to grow into the dike, because this undermines its strength.
70% of all land in the floodplains has an agricultural function. However, this is already a lot less than used to be, because much land has been transformed to nature.

Haringvliet sluices are finally being opened, but the opening is too small to sufficiently allow fish to move upstream. This also negatively influences Germany and France.

Actually, nature is quite flexible, species will adapt or they will disappear and other species will appear. This is different for sediment of course, this is being held back and there is no natural replacement downstream.

Technical flood protection
The strict confinement of rivers is too tight no matter how much dikes are heightened. For that reason, Room for the River was such a good idea. It lowered the water levels and the river obtained more space for its natural behaviour. Also from a safety point of view, allowing the river more space is the best option. On the short term, heightening dikes seems cheaper, but on the long term it is not.

An issue with dikes that is occurring a lot recently is piping. This is caused by seepage under the dike, which can induce erosion and undermine the strength of the dike. This process is caused by the constant contact between the dike and the river because there is not enough floodplain area between it as buffer. A wider floodplain can reduce the undermining power of groundwater flows underneath dikes.

Currently, dikes are reinforced to counteract piping and because the economic value behind the dikes has increased (allowing less flood risk). Dike maintenance is a continuous process, so the time is also continuously right for new ideas.

Room for the River
Room for the river tries to increase habitat diversity in the floodplains by creating side channels. However, the shipping industry had such a big influence on the decisions made that the side channels are only connected to the main channel on one side, which reduces the natural dynamics of a river system. In Room for the River projects, they did take the natural course of the river into account by creating them at locations where they were historically situated. The historical location could be found by traces in the soil or by consulting historical maps. If the side channel is created at the right location, the river is usually able to maintain the side channel by itself. Therefore, creating a side channel at the right location reduces maintenance costs. Rijkswaterstaat, however, usually chooses to connect the side channel to the main channel only at the downstream end. The upstream end is closed because all water needs to be available for shipping in the main channel during low water levels. For this reason, a side channel is successful in increasing landscape quality, but not in increasing value for nature. Willows will grow easily next to this type of side channel. A slight increase in habitat availability occurs, but not enough and not the right type for the species that are banned from the main channel because of the heightened dynamics, because the side channel experiences too little dynamics. Besides, a side channel that is only connected to the main river at its downstream end needs more maintenance because it will be filled with sediment (lower flow velocity).

The project Nijmegen-Lent required the demolition of about 50 houses, which caused large resistance against the project at first. However, compensation for homeowners was sufficient and in the end people are happy with the result. It used to be a huge bottleneck, but now there is literally more space for the river. Very good example for other countries.

Room for the River was very educational and the evaluation ('Rijn in beeld') shows that it did benefit nature. Besides this, it also delivered benefit for safety, recreation, and economic goals. The benefit for nature, however, could be bigger than it is now, but this is progressing knowledge. Room for the River shows that it is possible to combine aspects of a river (safety and nature), which is unique in the world. Room for the River was three times as expensive as heightening dikes in the same areas would have been, but this is mostly based on a short term vision. Two years ago it seemed that society wanted to work on dikes again instead of on space, but luckily this has turned again.

Other environmental policies
An interesting example are the longitudinal training dams (LTD's) in the Waal. They have been constructed on a stretch of 10km (check this). It might be interesting to talk to X of Bureau Stroming, because they monitor the LTD's. During low water, the LTD's obstruct the view on the river from the floodplains. All you see is the stone wall and the flags of ships. This decrease the landscape quality in the area. Besides, the river has actually been confined even more. The effects of LTD's on nature cannot be determined yet, because they have been constructed fairly recently. A positive effect that is already known is that they decrease the wave action of ships on the shores, therefore creating sheltered habitat. However, as long as the floodplains are not more included in the river systems, the efforts are not very useful. With the LTD we have a main channel without nature, a shore channel with a little nature (as far as we know), and a floodplain that is still too high for nature. The whole system should be involved to improve nature. An advantage of the LTD is that it becomes easier to let side channels a bit more free, because it does not directly influence shipping anymore. The Dutch LTD's have been paid with money for safety, money for the Water Framework Directive, and money from the shipping industry, but there is too little effect on nature to justify the WFD money. The idea is that more LTD's will be built if the pilot appears to work, but this is not necessarily a good idea. Basically, the shipping system is completely detached from the rest, which is not how integrated water management is supposed to be.

Sediment nourishment is a second example. HKV and WNF are currently researching sediment flows. The river lowering its bed by erosion is a problem for shipping because there are solid layers in the river bed which will then become exposed and form obstacles. This happens for example near Nijmegen. Ships change their load in order to pass these obstacles. Preventing more river bed lowering serves multiple goals; both for shipping and for nature. Sediment nourishment is useful, but it is not solving the cause of the problem. On the Waal continuous dredging takes place, and the sediment is deposited elsewhere in the river. Dredging is not harmful for nature, since it happens in the main channel, where nature is absent anyway. There are several ways to re-involve the floodplains in the sediment system of the main channel; by constructing side channels or by removing summer dikes. Summer dikes have been constructed to protect agricultural land from smaller floods. Because of these summer dikes, the floodplains are even less frequently flooded and dry out more. Without the summer dikes, the floodplains would be more connected to the main channel and therefore they would be involved in the erosion process, decreasing the erosion in the main channel (have a look at the HKV study 'Ruimte voor levende rivieren – een pilot op de Middenwaal').

Multi-functional use of rivers
There are so many different uses of rivers that it would be better if these were coupled to achieve an optimal system. However, this is currently not the case. We need more information on how this coupling could be achieved. The Netherlands is a good example of way too extensive river normalisation, causing the system to dysfunction. Now this starts to happen at other places in the world as well. It is therefore essential to share the Dutch knowledge of what went wrong and how this could be avoided (without acting too magisterial) and to try to combine river uses from the start, instead of needing damage control in a few decades.
Priorities in rivers are

1. Safety

2. Economic benefits
3. Nature

However, it would be better to combine the three aspects in measures. A good example are willows reducing wave action. The shipping industry will see the benefit of combined measures as well, because of climate change. Talking to Schuttevaer (shipping branch organisation) might be useful.

Another example of combining goals is trying to increase the water uptake in the river system (broader than the floodplains). Then more water would be stored during high water periods, which would become available again during low water. This would create a more robust system, which is also useful for shipping (less high water and less low water), and agriculture (more water availability in summer). The current system does not store too much water, the focus is on discharging the water as fast as possible. A small increase in initiatives that change swamps and creeks to store more water is observed.

While nature needs variation, engineers are used to work with strict boundaries and designs.

Another solution for multi-functional use of rivers would be to allow the river more space. Then shipping, flood protection and nature would exist in the same river peacefully. The larger distance between the main channel and the shore would decrease wave action and allow nature to thrive. An example of this is Gameren, where a large floodplain with several side channels (that are connected at two sides or one side) is realised. The results for nature are very promising. The floodplain width is 1km, so it is possible to achieve this elsewhere as well. Of course, one needs to be pragmatic and choose the sites for this type of measure carefully.

Case study ideas

- Munnikerland (Where the Waal transitions into the Merwede)
  - Large space for nature
  - Huge climate dike
- Nijmegen-Lent
- Longitudinal Training Dams
- Overdiep-Sporen
- Noordwaard

Interview summary dr. Gertjan Geerling

Personal background
Originally, Mr. Geerling is a chemical ecologist, but he focuses on rivers. During his PhD he researched the relationship between safety, shipping, and nature in river systems, with a focus on nature and (aerial) monitoring. He answered questions such as 'what are the natural dynamics of a river system?', and 'how do these dynamics change for normalised rivers?'. Nowadays, he researches the effectiveness of nature development projects. For this purpose he is developing a vegetation map that is regularly updated by satellite data in order for Rijkswaterstaat to decide whether the vegetation is within its limits.

Rhine normalisation and its effects
Normalised rivers cannot develop into a varied (sub) system, because the dynamics of the system are lost by fixed shores, sluices et cetera.

River morphology
Dynamics in hydrology also influence morphological processes; it causes sediment transport, erodes and changes shores, and deposits silt and sand in the floodplains. The morphological processes are just as important for nature.

Nature
The most important river process for nature is variability and dynamics over time. Species living in a river system are adapted to disruptive processes such as floods and different water levels, which cause different flow velocities. Some plant species are used to being flooded temporarily, others are not. Rivers controlled by barrages have lost almost all their dynamics and therefore many species. The effect of barrages is the most important effect of river normalisation, even more than river straightening. This is because basically lakes are created instead of rivers. 6 months per year (check this), in summer, the water level should be very low in these areas, but the sluices do not allow this. This has altered the type of species occurring in these rivers. The Dutch Nederrijn is an example of such a river with barrages. Reintroducing natural shores is less effective in this type of rivers, because the river dynamics are missing. However, it is often the only possible measure to improve nature (slightly).

However, the dynamics of rivers should not be too high either; ships increase the river dynamics, and because of the limited space for rivers, species are forced to live in the main channel next to the ships, while the dynamics are too high there. Increased dynamics by ships would not be a problem if the river had sufficient space for sheltered habitat. Another negative effect of ships is that they increase sound.

A steep shore causes an abrupt transition from not flooded to flooding, while a natural shore has a gradual slope that results in gradual flooding. Besides, a natural shore causes larger areas to be flooded, in which pools are formed, different plant species occur et cetera. A natural shore also erodes, but the shipping sector fears that this process occurs too irregularly and that sediment is deposited randomly in the main channel. A measure against shore erosion is either strengthening shores or allowing natural shores, but partly excavating them beforehand and removing the sediment. Although the latter is slightly more natural, both measures do not induce natural processes. Shores around bridges and sluices are never allowed to be natural or dynamic, because this could undermine the safety of the structure.

When nature is 'created', this is not the way the area should remain, it is only the start of a process. Therefore, extra space should be available for changes. This space should be awarded beforehand. Besides, nature needs quite a long time to develop, it takes at least more than 10 years before a result can be determined. Also, the long-term effect of measures is difficult to determine, because nature does not follow strict rules.

A side channel can erode, willows can grow on its shores, or it can silt up. A natural river continuously changes its course; side channels silt up, and a new side channel is formed elsewhere. In order for this to happen, the river needs the freedom and the space to do so. This is almost impossible nowadays, because this would harm shipping too much. However, an option would be to allow side channels to silt up, and then to create a new side channel at a suitable location.

In some floodplains in the Netherlands, nature is allowed some freedom. Rijkswaterstaat would like to limit this for safety reasons, but Staatsbosbeheer would like to allow nature more freedom. Preferably, Rijkswaterstaat indicates exactly where trees may grow and where they may not grow, but of course nature cannot be directed that precisely. Flexibility is key in solving this issue; if more space is created, the exact location of the trees becomes less important. Nature then has the freedom to choose. A good example of this is Gelderse Poort, a project that started in the 1990's. A plan had been made beforehand, but spontaneous development of nature is allowed. The boundary conditions consist of percentages that are allowed for each type of nature (e.g. 25% forest is allowed). Another nice example is the Millingerwaard.

The question whether something can be called nature when it needs human maintenance (e.g. moors and meadows) is an ongoing discussion between ecologists. It cannot according to Mr. Geerling, but of course those areas do contain important species. Nature that is completely free is almost impossible to achieve in the Netherlands, because there are always other interests that need to be taken into account. A solution would be to create a canal next to the river and to split the functions of the river.

The nature in floodplains as we know it now is actually also unnatural. Removing the clay from the soil has led to the current vegetation of willows.

Determining specific criteria to which the river must abide for nature to thrive is difficult. As mentioned before, variation is key. Ecologists work a lot with reference rivers and their own experience when drafting plans. However, focus is the dynamic river.

Temperature, nutrient availability et cetera are also important for river ecosystems, but that is more related to water quality. The water quality of Dutch rivers has already increased a lot over the past decades. Now, the focus is on improving the dynamic aspects of rivers.
The Haringvliet is now finally being opened. Without this measure, other measures to improve connectivity for fish was not effective, because the door to the river was closed.

Room for the River
Room for the River combines an increase in water discharge with nature development. Side channels, water retention areas et cetera reintroduce river dynamics, so it was definitely a good start. To ensure both water discharge capacity and nature to have benefit from Room for the River measures, extra space needs to be allowed for the project. Then, nature can develop itself more freely, while the water discharge capacity is still sufficient without the need to cut down

the vegetation. This needs to be coordinated by Staatsbosbeheer, nature organisations and Rijkswaterstaat.

Other environmental policies
Instead of building barrages, it would be better to create a canal next to the natural river. This way, navigation is separated from flood safety nature allowing nature to develop more. The natural river would then only need to deal with two interests. France is an example, they have many canals. It is quite a bold plan, but good to keep in mind when discussing options. Difficult to say whether enough space is available for this plan, but it could bring economic benefit to the surrounding villages.

The upstream part of the IJssel is not used a lot for shipping. Therefore, we could ask the question whether shipping should use this river at all. We could also optimise that river for nature and flood protection only and direct ships via the other rivers.

Longitudinal Training Dams (LTD's): at first, Mr. Geerling was sceptical about this project, mostly because its long-term effects are unknown. A disadvantage might be that the main channel is made smaller, and if the shore channel silts up this could decrease the water discharge capacity. However, it is unknown whether this will happen. In case it does happen, Rijkswaterstaat is willing to alter the dams, for example by creating more water inlets, to increase the water flow in the shore channel. Until now, an increase in habitat diversity has been observed. Also, behind the LTD it is quieter than before, which is beneficial for fish. Until now, ecologists are positive about the project, but it still needs to prove its worth for the long-term. Water is allowed to enter the shore channel during low water periods. Concluding, the project is too new to discuss its effectiveness already.

Cyclic floodplain maintenance: coupling of multiple floodplains. Vegetation is allowed to grow on them one by one, so there is always a floodplain with sufficient habitat, but also always one with a high water discharge capacity.

Multi-functional use of rivers
If too many compromises are made, plans for nature will not work. If there is too much focus on landscape quality, the area will probably become more like a park than nature, because people make decisions focused on what they think is beautiful instead of what natural processes would bring to the area. Choices between beautiful nature and natural nature need to be made. Sometimes, you need to give nature its freedom (within boundary conditions). If nature areas are also used as recreational areas, people need to be aware of the behaviour of the animals in this area. For example, cattle and horses are very protective of their young ones and can be dangerous when approached then. In the Netherlands we are not used to nature containing dangers. Choices between different combinations of uses need to be made per location; historical landscapes or areas with a high value for nature already should be maintained.

If nature is not included in a regulation or law, it will not receive attention because it does not provide economic benefit. Besides, giving nature a value is difficult; only when focused on humans (landscape quality) does it have a value. Giving nature a value is undesirable though, because then nature will be exploited. That is why the WFD is so important; now nature has to be taken into account as an importance of its own, without attaching other interests to it.

Flood safety and navigation are normally given most importance in projects. However, if a project is financed by the WFD, nature is most important. Projects are also slightly different depending what focus they have; a side channel can be built for nature or for high water discharge. If projects combine uses, it becomes an administrative hassle who needs to pay what. You should be able to find this via Rijkswaterstaat.

Even if nature is taken into account at the design stage of a project, it often gradually disappears from the plan in successive stages. It happens that in the end the original ecological goal is simply not met anymore because too many changes have been made to the original plan. This is caused by the fact that it takes many years to design and implement a plan, and often the designers of the plan are not present during the implementation phase. If later on in the process changes are made (for example due to demands from shipping), without consulting an ecologist or checking against the original goals of the plan, the ecological goals are easily overlooked. An example is a project where the sediment supply to the floodplains had to be increased. The idea was that the river could bring sand into the floodplains during floods. In this case the floodplains had been arranged to fit this goal, but the rest of the plan had been changed. The shores were not been given freedom to erode and remained strengthened with rocks, so the source of the sand disappeared and the whole plan failed. SmartRivers is an initiative that tries to counteract this problem.

Water Framework Directive
The WFD has resulted in many new measures or alterations of existing measures. The goal of the WFD is that heavily modified water bodies need to obtain 'good ecological potential'. This is determined by first identifying the human pressure on water bodies and then determining how much potential those water bodies have to improve. So, arguments are constructed based on the modified river, not the natural one. This results in feasible goals and reasonable expectations. Countries were allowed to draft their own indicators for this good ecological potential (because each country has different ways of monitoring), but the indicators need to be compatible within the international river basin.

The most important effect of the WFD is that nature receives attention at all and that it is a factor that needs to be taken into account. Besides, money has been made available. Another advantage is that the WFD works at river basin level, and therefore improves cooperation between countries. This has strongly improved the Rhine.

A disadvantage of the WFD is that it focuses too much on controllable output. First, indicators for success are determined, such as the number of species that are present in a river stretch. From this indicator, it is calculated how many kilometres of side channels need to be created. This latter, easier to measure, variable overshadows the original indicator. Too much emphasis is put on measurable goals, while the real effect can only be seen in natural processes. Some side channels do not deliver any ecological potential, but they do count for the kilometres. Rijkswaterstaat now tries to loosen the focus on the hard criteria and tries to focus on the original goals. An example that shows that the WFD's criteria should sometimes be loosened is the Lus van Linne (in the Maas). Part of the shore had been caved in due to a high water, and created a smooth shore that was completely covered with aquatic plants and forest after a while (a natural process). However, this part of the Maas is controlled by barrages, so it has more characteristics of a pool than of a river. However, according to the WFD this area is a river and therefore indicators related to river species were the ones that had to be used. If the ecological potential of the area was checked against pool indicators, the score would be very high. But now, the score was very low. This disadvantage is known, and there are thoughts about changing the classification of barraged waters.

However, the strict criteria of the WFD are necessary for its successful implementation, otherwise nothing would happen.

Actors and interests

Nature organisations are very good at telling the story of rivers to the public, and when the public supports a goal, the government has to join as well. Therefore, educating the public about rivers, nature, and the possibilities is essential.

Shipping has a very strong lobby and directly contacts the ministry instead of talking to Rijkswaterstaat first. Therefore, they have much power.

Different actors think on different timescales and physical scales. Nature needs several decades to develop, so ecologists have a long-term vision. Rijkswaterstaat has a yearly budget it needs to justify, so it thinks on a shorter term. Besides, the time nature needs exceeds the tenure of civil servants and there will probably be a new European directive within this time. This indicates an important pitfall; that we keep on changing plans and keep on interfering with nature. Ecologists also think on bigger physical scales, because nature needs connected areas to develop properly. Other actors think more on project basis. Besides, ecologists and engineers have a fundamentally different way of thinking; engineers think in strict guidelines, minimum requirements and a fixed result. Ecologists think in boundary conditions, starting conditions and a developing result.

SmartRivers works according to two main principles; first of all, the characteristics of the river need to be taken as a starting point. Secondly, ecological goals need to be taken into account in every step of the planning process.

Case study ideas

- Gelderse Poort
- Millingerwaard

Interview summary dr. ir. Erik Mostert

Personal background
Mr Mostert studied public administration and law, and afterward did his PhD on environmental impact assessments at TU Delft. Now he teaches water law, among other courses. His research is focused on legal aspects and formal institutions of water, the Water Framework Directive (WFD), and cooperation and adaptation processes. The latter comprises international cooperation, but also public participation and cooperation between experts and water administrators. In the WFD all these research areas meet.

Influences on the WFD
The European environmental policy means to improve the environment in general. If no European policy on environmental issues would exist, while we do have free movement of people, goods, services, and capital, industry would move to the country with the lowest environmental standards. This would not result in a level playing field and would create a downward pressure on national environmental standards. Therefore, it would be made very difficult for individual countries to improve environmental standards. This is comparable to the problem with tax on dividends.

On an international level the counter power against the WFD was negligible, even from shipping. On the Dutch national level, however, there was a strong lobby against the WFD from the agricultural sector after the WFD had entered into force.

Origin of the WFD
The previously mentioned general environmental policies were drafted before the WFD. Kaika&Page have extensively discussed the realisation of the WFD. The first European directives on water date to 1972/1973 and were focused on specific functions of water; water with special species of fauna, or drinking water. After this, a directive on dangerous substances and standards on the emissions of individual substances were established. From 1980 until the beginning of the 1990's, several directives on specific sources of pollution came into use, for example the directive on nitrates (for agriculture) and the directive on urban wastewater. In the middle of the 1990's, the European Commission (EC) decided that a directive on ecology and water was missing. First, a directive was drafted that did not amuse the Netherlands and several other member states, because there were already many, badly coordinated directives. Therefore, they asked to draft an integrated framework directive, which is the WFD.

The WFD was not accepted at once, because according to an early draft river basin authorities should be appointed, the directive is fairly ambitious, and discussion was ongoing about the question whether the goals should be binding. River basin authorities basically conflict with the general working of the EU, namely that member states are responsible for the implementation of directives. Besides, member states were not willing to transfer authority to an international organisation. This has been solved by giving the river basin authorities only a coordinating task. The goal of the WFD is to achieve a good water status. The EC was very ambitious and therefore set high goals. The European Parliament (EP), first in its environmental working group and later plenary, was even more ambitious. But the Council of the European Union (in this case formed by the ministers responsible for water and environment) was less ambitious, because their countries would have to implement the plan. Binding standards need to be formulated very accurately or else they make little sense, so this resulted in the extensive appendices of the WFD. These appendices explain how to describe water bodies, how to define good ecological potential et cetera. Member states were not happy with the binding standards, so exceptions were created.

Then, environmental organisations and the EP thought the exceptions to be too extensive, so exceptions on the exceptions were drafted. In the end a compromise was made with help of a conciliation committee. This was a take it or leave it moment, but since all parties stood willing towards the WFD in general, they agreed to the current, complex WFD.

The WFD is not an example of clear and simple legislation. Are the standards binding or not? If they are binding, are member states obliged to deliver results or to make due effort? This was unknown until 1 July 2015, when the European Court of Justice gave its judgement in the Weser case. From this it was derived that the WFD is binding and contains obligations to deliver results. In this case, shipping played a role, since it was about dredging necessary for shipping that might harm the ecological potential.

Content and extra clarification of the WFD

Article 4 of the WFD explains the conditions to extend deadlines or lower the goals. The main conditions are; that it is either technically not feasible to reach a good status or potential in time, or the costs to achieve this are 'disproportionate'. The WFD also contains definitions of artificial and heavily modified water bodies and when to assign these classifications. Besides the text of the actual WFD, in 2002 the common implementation strategy was developed. This strategy is meant to help member states with the implementation of the WFD with guidance documents. In these documents the WFD has been (unofficially) explained, to increase agreement about WFD implementation in the case of transboundary rivers. There is also a guidance document about the definition of rivers (natural, highly modified or artificial). The guidance documents are not binding, so their use may differ.

Implementation of the WFD

The I5 project compared the implementation of the WFD in the Netherlands, Germany, and France. In the Netherlands a bottom-up approach was used. The river basin management plans are included in the national 'nota waterhuishouding', but the environmental goals are included in provincial plans. This needs coordination between different government levels. Rijkswaterstaat and the regional water authorities (waterschappen) are responsible for the execution of the plans. In practice, the water managers (water beheerders) have identified measures that have reasonable costs and formulated goals. First, nearly all water bodies were classified as artificial or heavily modified. (This means that the ecological objectives are a bit lower: to reach a good ecological "potential" instead of "status." The goals of "good chemical status" for surface and groundwater bodies and "good quantitative status" for groundwater bodies are not affected.) If a good water status was not reached yet and would not be reached before 2015, deadlines were extended. The Dutch authorities used the argument of technical feasibility; re-meandering of the river was found technically not feasible because it took too much time to acquire the necessary land. But actually, land acquisition is not a technical issue. Besides, the Dutch government decided not to use its right to expropriate in this case due to political reason.

In Germany and France, goals were specified on a regional level but implementation took place at the local level, so they used a more top-down approach. This resulted in more ambitious goals, but it is unclear whether they will be reached and who will execute the plans. At the end of the I5 project, these countries were still in the first phase of plan development, and implementation of the WFD had not started.

Effects of the WFD
If a country is unable to reach good ecological potential, the WFD has several exceptions that allow it to lower or postpone goals. Whether the WFD is effective cannot be determined yet, because many countries, including the Netherlands, use the possibility of lowering or postponing goals. Until now, the Netherlands has not received a fine for this. In 2021, the Netherlands will have postponed twice (for a period of six years) and is then still allowed to lower the goals.

The Dutch WFD goals are not very ambitious, but because the implementation took place bottom-up and the measures were the starting point, a lot has been done. Therefore, the WFD was not very effective in terms of ambition, but it was in terms of practical changes. Of course there is debate about the effect of measures and whether they brought back sufficient river dynamics. In the agricultural sector not too much has happened, while this is an important source of diffuse pollution.

It would be interesting to compare the French and German effectiveness of the WFD because of their different, top-down, approach, and because there should be results now.

Evaluation and documentation of the WFD
The EC recently started a large project to evaluate the effectiveness of the WFD and the FD (Flood Directive). 200 interviews will be conducted with different involved parties in all member states. But 10 interviews per member state is not much to show clear results.

Besides, every six years the member states write new plans and evaluations of previous plans at river basin level. Because these are written by the member states themselves, they mainly tell a positive story, while negative aspects are written down discretely. Detailed examination of the text and other documents is required to find out what is actually said. Besides, the international Rhine river basin management plan is very general, for more detail you need the national plans (and in the German case also the plans of the Länder). The international document contains the goals, summaries of analyses and monitoring results, and a summary of the programme of measures. In the Netherlands there is not one document called programme of measures, but several plans (per water authority et cetera) containing measures that together constitute the programme of measures. In 2015, factsheets with an overview of goals and measures per waterbody have been made.

In 2009 and 2015, also overviews of the river basin management plans in which the Netherlands are involved (Rijn, Maas, Schelde, and Eems) have been made. In 2009 this overview included the number of water bodies that were classified as artificial or heavily modified, and how many already had a good ecological status. 95-98% of all water bodies were classified as artificial or heavily modified, which induced a lot of criticism. Therefore, they just decided to leave out this information in 2015 (interviewee's interpretation).

To monitor the ecological status, the metrics developed by the STOWA (Stichting Toegepast Onderzoek WAterbeheer) are used. This is a cooperation between water authorities to conduct relevant research. They developed a standard to measure the ecological status of water bodies on a scale of 0 to 1. The water managers use this standard for monitoring purposes; they count the number of a certain species of flora and fauna and other factors and based on the STOWA standard an ecological score is calculated.

Rhine

Cooperation in the Rhine started well before the WFD (around 1950), but the WFD resulted in an intensification and partly a change in the topics on which cooperation took place. For more information read Mr Mostert's article about cooperation in the Rhine. It is hard to determine which international agreements resulted in the improvement of the Rhine. Some people argue that the improvement of the water quality in the Rhine, which already happened before 2000, was the result of good cooperation in the international Rhine Commission. Others say that it was caused by the European directive on dangerous substances from 1976. Other opinions are that it is the result of the industry that was already changing, the cooperation about the North Sea, activities of drinking water companies and environmental action groups, or the increasing attention of the public for environmental issues. In the end, a combination of all the above causes will have resulted in a clean Rhine.

Other agreements on the Rhine

The cooperation in the Rhine was made official in 1963, but it took until after 1970 before much action took place. At the same time, regulations on European level were initiated. This was on Germany's request, because they did not want the Rhine to be the only river basin with high environmental standards (again because of the level playing field). In 1986 the Sandoz disaster took place, leading to attention for water quality and political will. This resulted in the Rhine Action Plan (RAP), which is not legally binding and therefore could be drafted quite quickly. Furthermore, it had an appealing goal; bringing back the salmon. Most of the goals of the RAP have been achieved, but actually the most severe pollution of the 1960's and 1970's had already been reduced before the Sandoz disaster, so it is unclear how much of the positive effects can be attributed to the RAP.

The new RAP exists next to the WFD, but because the WFD is binding and the RAP is not, the WFD receives most attention. The RAP is useful, however, in involving Switzerland in the aim of improving environmental quality.

Connection FD and WFD

The synchronization between the FD and the WFD is described in the FD, since this is the newest directive. In principal, plans need to be drafted for the same area, the frequency of planning is the same, and the organisational structures should be compatible. Currently, the FD and WFD are two separate appendices to the national plan, but there are plans to integrate them next time. The authorities for FD and WFD implementation are largely the same ones (Rijkswaterstaat, regional water authorities). This can be the same in other countries, but different divisions of the same organisation may execute the task. .

Multi-functional use of rivers

The WFD has little effect on shipping if the river is not changed. Reintroducing meandering in rivers could be a problem though, because the costs increase. Shipping could be a reason to classify water bodies as artificial or heavily modified, which allows you to keep them straightened. Dredging or constructing new sluices could influence the achievability of the WFD goals. If that is the case, strong arguments are required why this measure is really necessary.

Dams have a large effect on the WFD goals, there have been court cases about this.

Case study ideas

Take a random factsheet or maintenance plan and you have countless examples of measures.

Interview summary dr. ir. Astrid Blom

Personal background
Ms Blom studied civil engineering at TU Delft and did her graduation project on river hydraulics. After that, she went to the University of Twente for a PhD on movement of sand and gravel in river. Nowadays, she is associate professor river hydraulics at TU Delft. Her research focuses on the boundary between engineering and geosciences; how does the river system react to measures and to natural changes (on a large scale). For example, she studies the effects of river normalisation: what has happened, how long do the effects last, how can problems be limited, et cetera.

Hydrology
With an increasing water discharge, the water flow velocity increases, and therefore also the sediment transport capacity. For the river bed morphology (slope and coarseness), the probability distribution of occurring water discharges is important. The extreme water discharges have minor impact, because they do not occur often. Extreme discharges do result in a very high sediment transport capacity, but their effect on the river's morphology is negligible. An exception would be when the extreme discharge triggers the collapse of a soil layer. If this would happen near the Pannerdenskanaal, the discharge distribution over the Rhine distributaries changes completely, while the whole system is designed for this distribution. The water discharges that happen most often, influence the bed slope and bed coarseness of the river. This indicates that there is a difference in focus between water safety and river morphology research; for water safety the extreme discharges are most important, while for river morphology this is less important.

Natural river bed morphology
A natural river has three ways to alter itself:

1. It can change its bed slope: this influences the water depth at a certain water discharge. There are two ways to change the bed slope:
    a. By tilting the river bed around a certain pivot point. This is usually the sea level downstream, because that is fixed. This leads to upstream erosion.
    b. By changing the sinuosity of a river, so by making the river longer or shorter.
2. It can change its width: by the difference between outer bend erosion and inner bend sedimentation.
3. It can change the composition of its bed: for example by coarsening it.

Normalised river bed morphology
Normalised rivers have only two ways to alter itself:

- They can change its bed slope, but only by tilting, not by changing the sinuosity
- They can change the composition of their bed

The response of rivers to normalisation is a very slow process and it is still going on

Rhine bed morphology
The effect of normalisation is now visible in the Rhine; the lowering of the river bed is an effect of the river trying to change its bed slope. A narrower river needs less slope to transport sediment. Because the pivot point of the river slope is the sea level and the river wants to lower its slope, upstream erosion is taking place.

Furthermore, coarsening of the river bed is takin place; a gulf of coarse sediment is moving downstream. The Upper Rhine has changed from a sand river into a gravel river over the past twenty years, and this process appears to move downstream. However, measurements are infrequent, only at project locations the bed composition is measured. The cause of this coarsening is the influx of coarser sediment from upstream for two reasons. First of all, Germany has been counteracting erosion by sediment nourishment since 1978. The sediment used for this is relatively coarse. At the beginning sediment nourishment took place downstream of the Iffezheim barrage, but now it is also done just upstream of the German-Dutch border. Secondly, the German Rhine erodes and cuts into older soil layers (Pleistocene) that are coarser than the higher layers (Holocene). It is not easy to determine which reason has more impact, Ms Blom thinks it is the former. Research into this is ongoing.

The Upper Rhine stopped eroding about 30 years ago and is now relatively stable. This is probably caused by the coarser bed; coarse sediment requires a higher sediment transport capacity of the water.

A river reacts on bed coarsening by changing in such a way that it will be able to transport sediment again. This processes works as follows; if the bed is too coarse and the slope too small, sedimentation takes place upstream which increases the slope, and then the transport capacity.

River bed erosion in the Waal causes lowering of the bed by 5cm per year. If the gulf of coarse sediment reaches this area, the bed slope will increase again.

Interesting document about river bed erosion in the Rhine: de waterviewer/flows.

At first you would expect that the lowering of the river bed is beneficial for water safety, because the water levels will lower accordingly. The problem is that the bed does not erode evenly along the whole river, because some stretches of the bed are difficult to erode. This is caused by natural solid soil layers and by man-made structures that enhance shipping. Such solid structures, built to broaden the river, are constructed at Sint Andries and Nijmegen for example. These structures influence the secondary flow in the river bends. The outer bend is fixed, which causes the inner bend to deepen. In sharp bends, this is a necessary measure for navigation. Because these structures are not lowered to the same level as the river bed, they form obstacles for shipping during low water. The bottle neck for the draught of ships between the Ruhr area and Rotterdam used to be in Germany, but is now located at Sint Andries. This limits the load capacity of ships and therefore has economic consequences. Furthermore, the periods of low water flows are expected to increase due to climate change. Therefore, the combination of low discharges, river bed incisions, and the solid structures in the ground could create a problematic situation.

Fine sediment (floodplain morphology)
Fine sediment (mostly silt) results in a small accretion of the floodplains at a rate of about 1mm per year. In the period before river normalisation, this rate was higher. Now, the water flow is concentrated on the main channel and the interaction with the floodplains has been diminished. Due to the lowering of the river bed, the share of water that flows through the main channel is only increasing.

Side channels
Side channels are kept relatively small in the Netherlands, to avoid that it will draw too much of the water discharge. When the bed of the side channel erodes, more and more of the discharge will choose that route and more erosion will take place. This self-enhancing effect might in the

long run turn the side channel into the main channel. The rule of thumb is that a side channel is allowed to have a discharge of 2%. At the same time a side channel can act as a sediment trap, for fine sediment. Therefore, maintenance is required to keep the side channel open. Research on this maintenance is focused on maintaining sufficient discharge capacity and at the same time meeting ecological requirements. Besides a balance between not too much erosion and not too much sedimentation needs to be found. The most important criterion is that the side channel does not take over the main channel. Besides, side channels cause local sedimentation in the main channel, which needs to be dredged.

Other issues
Sea level rise cause the water level of rivers to rise at their downstream end, which results in sedimentation. This effect will slowly move upstream. Now it happens at a rate of 2-3 mm per year, but sea level rise is expected to accelerate. On the long term, this process will start interacting with bed erosion.

Combination of all issues
(i) Downstream the sea level will rise which causes a gulf of sedimentation moving upstream, (ii) a gulf of coarse sediment is moving downstream causing sedimentation, (iii) and bed erosion due to river normalisation is still occurring. In the future, these processes will start to work in the same areas and interact.

A4 Interview results

The interview summaries in the previous section give an overview of the information that was provided by each expert. However, in order to use it in this research, it is more convenient to group information per topic. Therefore, a table is created for each topic, which shows what information was retrieved and who provided this information. This way, it can easily be used in the next steps of the research. The first column contains the abbreviation of the name of the respondent that provided the information.

- CvD: Cornelis van Dorsser
- FK: Frans Klijn
- DW: Daphne Willems
- GG: Gertjan Geerling
- EM: Erik Mostert
- AB: Astrid Blom

Table A5: Interview results topic 1 – Hydrology and morphology

Expert	Statement
FK	In a natural river, sediment inflow and outflow are balanced
DW	The power of rivers is included in their dynamics; water needs to flow, variability in water level needs to occur, and the whole system should be interconnected
	In a natural system, side channels are weaved through the main channel, continuously changing its course and in the end disappearing due to sedimentation. Then a new side channel will be formed elsewhere
	When creating a side channel, it is important to take its natural course into account; then the river is usually able to sustain the side channel by itself
AB	With increasing discharge, the water flow velocity increases, and therefore also the transport of sediment
	A natural river has three ways to alter itself; by changing its slope, its width, or the composition of its bed. The first is achieved by erosion upstream or a change in sinuosity (making the river shorter or longer). The second by a difference in erosion in the outer bend and sedimentation in the inner bend. the third is achieved by coarsening the river bed
	A river reacts on coarsening of the river bed by increasing its slope by sedimentation, which then increases the sediment transport capacity
	For river bed morphology, extreme discharges are not that important, it is the bulk of the discharges (that occur most often) that are
	Side channels are kept relatively small in the Netherlands (2% of the discharge), because we do not want them to erode, then discharge a larger share of the water, erode more and become the main channel.
	However, side channels can also silt-up slowly, so then they need continuous maintenance to remain open
	Locally, side channels cause sedimentation in the main channel, but this is dredged out
	Another issue related to river morphology is sea level rise; this increases the water level downstream and causes sedimentation. This effect will slowly move upstream (2-3mm per year)
	(i) The sedimentation caused by sea level rise from downstream, (ii) the coarsening of the river bed from upstream, and (iii) the lowering of the river bed due to normalisation will at some point come together

Table A6: Interview results topic 2 – Rhine normalisation

Expert	Statement
FK	Dutch rivers are eroding because sediment influx from upstream has decreased by construction of barrages. Therefore, sediment nourishment takes place nowadays
	Floodplains in the Netherlands are rising due to sedimentation with a rate of 0.5 to 1 cm per year
DW	Nowadays, the Rhine is restricted in its natural movement and its width, causing it to lower its bed by erosion. The Waal is lowered 1cm per year
	All river dynamics are restricted to the main channel, instead of being spread over the whole system
AB	After normalisation, there are only two ways left for a river to change; it can lower its slope by erosion upstream (not by changing sinuosity anymore) and by coarsening its bed
	The response of rivers to normalisation measures is very slow, and still going on
	The lowering of the River bed is thus happening because its slope needs to be decreased (a narrower river needs less slope to transport sediment)
	Nowadays, the river bed of the Rhine is coarsening; coarse sediment is supplied from upstream due to two causes. First of all, Germany has already been supplying sediment to its rivers for several decades, and this happens with coarse sediment. Secondly, the German Rhine is also eroding, and is cutting into deeper layers of soil. These deeper layers are coarser.
	The Upper Rhine has been relatively stable in terms of erosion for 30 years, probably because the river bed is too coarse to be taken up by the water
	In the Waal erosion occurs at a rate of 5cm per year (the river bed is lowered 5cm per year)
	The problem with the lowering of the river bed is that it happens unevenly because the bed contains solid structures at some locations which will not lower. These solid structures can be natural or man-made. The man-made structures have been constructed to broaden rivers and reduce narrow bends
	Fine sediment is deposited in the floodplains at a rate of around 1mm per year, but this rate was higher before the normalisation. The interaction between main channel and floodplain has been decreased, and due to the lowering of the river bed more and more of the discharge will flow through the main channel

Table A7: Interview results topic 3 – River ecosystems

Expert	Statement
DW	Most important effects of normalisation on environment are decrease in flooding frequency, reduction of sedimentation, and paralysis of the river.
	The first effect is directly caused by normalisation measure that limit flooding, but is strengthened by the fact that the river bed is subsiding due to river normalisation
	The second effect is caused by the first. Less sedimentation reduces habitat diversity
	The last effect is caused by barrages, dams, and sluices. They completely halt natural variations in water discharge, resulting in a dead system
	Another effect is that floodplains are drying out, because the river bed is lowered and the groundwater level has decreased to accommodate for this
	Because all river dynamics are now restricted to the main channel, it has become too dynamic for nature
	The other parts of the river system (floodplains) experience too little dynamics for nature
	This all led to a decrease in habitat diversity
	The most important criterion for nature is variation
	Other important criteria are current, swamps, and connectivity. Water temperature does not play a role nowadays
	Vegetation in the floodplains is often removed, but trees is allowed closer to the dikes, because the flow velocity is smaller anyway, and because it protects the dikes against wave action
	Most side channels are only connected to the main channel at their downstream end (instead of on both ends) because shipping needs all water in the main channel during low water levels. If a side channel is only connected on one side, its natural dynamics are lost, and it will not increase value for nature to much because the dynamics are still too little
	There are two ways to re-involve floodplains in the sediment system of the main channel; by constructing side channels and by removing summer dikes. Summer dikes are constructed to protect agricultural land in the floodplains from smaller floods, while this flooding is necessary for sedimentation and nature
GG	The most important criterion for nature is variability over time and space. River ecosystems are adapted to the disruptive processes of flooding and water level variability
	The worst effect of river normalisation (on nature) are the barrages, not the river straightening. The reason for this is that barrages create lakes instead of rivers and therefore different species occur. Environmental measures such as reintroducing natural shores is less effective in these areas because the river dynamics are missing
	Too high dynamics are also not desirable. Now, because of the limited space for rivers, species are forced to live in the main channel next to ships which cause an excess of dynamics. This would be less of a problem if the river had more space and species could find sheltered habitat further away from the main channel
	Another problem is that shores are too steep and cause an abrupt transition from not flooded to flooding. A gradual slope would result in gradual flooding and a larger flooded area, therefore creating more habitat.
	Natural shores erode, but this is unfavourable for shipping, so most shores are protected. A compromise is to allow natural shore but to excavate them manually to remove the sediment and not harm shipping.
	Nature needs several decades to develop, so when nature is 'created' this is only a starting point and space for changes should be available
	Two things can happen to a side channel; it can erode or it can silt up. In a natural river system this would cause the continuous relocation of channels, but this is not desirable in our river system because of shipping demands. An option would be to allow side channels to silt up, and then manually create a new side channel
	Rijkswaterstaat does not like too much freedom for nature in the floodplains for safety reasons. Flexibility is key in solving this issue; if more space is created, the exact location of vegetation floodplains becomes less important. The boundary conditions can then be set at x% of the area for grassland, x% for forest et cetera
	There is a difference between natural nature and nature that is considered beautiful by people. If the focus is too much on the latter, natural processes are not necessarily be brought back. Therefore, choices need to be made; in some areas the focus should be on nature, and in other areas on landscape quality

Table A8: Interview results topic 4 – Navigation

Expert	Statement
CvD	The shipping fleet is quite diverse, because of the differences between the infrastructures of different Rhine stretches
	A vicious circle in thinking exists; ship dimensions are based on navigational infrastructures, and the waterway administrators base the dimensions of new constructions on the dimensions of the existing fleet
	The minimum norm for bridge height (the distance between the reference high water level and the bridge) is now 9.10m, but it would be better if this is heightened to allow for more efficient shipping
	Most ships have a draught of 80-90cm when they are empty
	Waterway requirements differ per cargo type. For weight-driven cargo draught is most important, this depends on the load and on the space required between the ship and the riverbed. For volume-driven cargo volume and stability of the ship are the most important requirement. The volume is determined by the amount of containers that fit on the ship and therefore by the bridge height
	During low water draught is the limiting factor, while during high water bridge height is limiting
	Another factor to take into account during high water is safety; both for ships (navigational safety) and for the dikes (the waves from ships might damage them)
	A water level below 1.5m becomes problematic, because the ships screw will not be completely submerged and because almost no cargo can be carried at this level. For smaller ships problems arise for a water level below 1.2m
	There are three solutions that shipping companies have for low water period; they navigate faster, they navigate longer (24/7), and they use more ships
	Climate change will have a small effect until 2050, but will increase low flow periods from that time onward. It is expected that the Rhine will become unnavigable for a few months per year, so more canalisation is necessary
AB	The solid structures in the soil that do not erode at the same level as the river bed form obstacles for shipping and limit their load carrying capacity

Table A9: Interview results topic 5 – Flood protection

Expert	Statement
FK	With Room for the River flood protection measures, we are going back to more natural rivers instead of continuing the process of dike heightening
	However, technical flood protection measure are necessary in the Netherlands, without it the country would not exist. We need to find a balance.
	Room for the River options (in order): dike diversion (should be done while there is still space available), bypass, floodplain clearance, floodplain excavation
	Giving a river more space results in a decreased water level upstream and no change in the water level downstream. To change the water level downstream, water should be extracted from the river
	Another measure that improved flood protection was the lowering of the groynes in the Waal; it resulted in a higher discharge capacity
	Nature has never been an objective in Room for the River, spatial quality (which covers nature) has
	Vegetation in floodplains is allowed as long as its hydraulic roughness does not exceed a certain level. If that happens, vegetation will be removed
DW	The strict confinement of rivers is too tight, no matter how high we make our dikes
	Currently, an important issue with dikes is piping; seepage under the dike causes erosion and undermines the strength of the dike

Table A10: Interview results topic 6 – Nature-based water management policies

Expert	Statement
FK	Room for the River options (in order): dike diversion (should be done while there is still space available), bypass, floodplain clearance, floodplain excavation
	Nature has never been an objective in Room for the River, spatial quality (which covers nature) has
	The Noordwaard is a good example of a measure that benefited nature. A large intertidal zone has been created where bird diversity increased
DW	A measure that would benefit all river uses is increasing the water uptake capacity of the river system (broader than just the floodplains). Then more water would be stored during high water periods, and this would become available during low water periods. The current system is focused on discharging the water as fast as possible.
	Another example of multi-functional river management is Gameren, where a large floodplain with several side channels is created. The results for nature are very promising, and flood protection is ensured by the side channels
GG	Cyclic floodplain maintenance is a strategy to allow nature to develop and also enable sufficient water discharge capacity. This is done by coupling floodplains, so that there is always one where vegetation is allowed to grow and another were vegetation is cut down for water discharge
	Construct a canal next to the natural river
	Side channels are nature-based solutions, but they have different effects when constructed for a different purpose. Side channels built for flood protection are not necessarily improving nature

When organising the information retrieved in the interviews per topic, it became clear that the pre-defined topic categories where not sufficient to categorize all information. Therefore, two extra topic categories have been added; 'Water framework directive' and 'multi-functional river management'. The tables below show information about these two topics.

Table A11: Interview results extra topic 1 – Water Framework Directive

Expert	Statement
GG	The most important effect of the WFD is that nature receives attention at all and has become a factor that needs to be taken into account. Furthermore, money has been made available and the cooperation between countries in a river basin has improved
	A disadvantage of the WFD is that the focus is too much on controllable output. Natural indicators are not easy to measure, so easier criteria have been developed such as kilometres of side channel. Some side channels do not deliver any ecological potential but do count for the WFD
	Another issue is the classification of water bodies; barraged rivers are still seen as rivers, while they actually have more characteristics of lakes or pools
EM	The WFD is important to create a level playing field; if we do have free movement of people, goods, services, and capital, but we do not have a European policy on environmental norms, industry would move to the country with the lowest environmental norms, which would create a downward pressure on these norms in the whole EU
	Drafting the WFD was quite a hassle; the EC and the EP were very ambitious, but the member states (responsible for implementation) were not. This resulted in many exceptions and a complex directive
	It took until 2015 before it was determined whether the WFD norms were binding or not, and if member states were obliged to deliver results or to make due effort. The European Court of Justice determined that the norms are binding, and member states need to deliver results.
	However, many possibilities for postponement and lowering of targets, which the Netherlands is all using (and other countries as well). Therefore, we cannot yet determine whether the WFD is successful
	The Dutch goals are not very ambitious, but because implementation took place bottom-up, a lot has happened
	The river basin management plans that are written every six years provide a summary of the programme of measures and furthermore a very biased evaluation of previous measures. To find specific measures that are implemented, you have to look at the factsheets per waterbody (Netherlands)
	The cooperation on the Rhine started well before the WFD in the International Commission for the Protection of the Rhine. Nowadays, this exists next to the WFD, but since the WFD is binding and the other agreements not, WFD receives more attention. The other agreements are useful, however, because Switzerland is involved who is not a member of the EU and therefore is not bound by the WFD
	The WFD should be synchronized with the FD, both work on the same scale (river basin)

Table A12: Interview results extra topic 2 – Multi-functional river management

Expert	Statement
FK	Flood protection is always the first priority, followed by water resources division (with drinking water on first priority, and including shipping), and then by quality of the living environment
	The shipping industry is very strong and demanding bigger and bigger waterways, while it should be the other way around; ships should adapt to the waterway
	A long-term solution would be to construct a canal for shipping next to the natural river
DW	Priorities in rivers are: 1. safety 2. economic benefit 3. nature, but combining all three aspects in measures would be ideal
GG	A solution could be to construct a canal next to the river and split the functions of the river
	If too many compromises are made, the plans for nature will not work
	If nature is not required to receive attention by regulation or law, it would always loose from the other river uses. That is why the WFD is so important
	Different actors think on different time and physical scales. Nature needs several decades to develop so ecologists have a very long-term vision. Rijkswaterstaat has a yearly budget it needs to justify, so it thinks on a shorter term. Ecologists also think on a bigger physical scale because nature needs connected areas to develop properly, while other actors think more on a project basis
	Besides, engineers and ecologists have a fundamentally different way of thinking; engineers think in strict guidelines and fixed results, while ecologists think in starting conditions and a developing result
EM	Shipping could be a reason to classify water bodies as heavily modified in the WFD. Further, shipping had little influence on the WFD

A5 Reflection on interviews

Much information has been obtained from the interviews, and all topics were covered by the experts' knowledge. The conversations were very helpful in defining the issues that arise when trying to integrate navigational, environmental, and flood protection use of rivers in a quantitative manner. Besides, the interviews aided in deciding on how to proceed with the second part of the research; the model. Finally, the interviews formed a thorough basis for the causal relations that were to be included into the model. However, quantitative input that was required for the model could not completely be retrieved from the interview results. This was due to the fact that the interviews were conducted before decisions on the model had been made, so specific questions that the interviewees definitely would have been able to answer were not asked. This problem could have been solved in two ways; either define (a rough idea of) the model before conducting the interview, so experts can be asked for quantitative information as well, or conduct a second round of interviews after decisions on the model have been made to define model parameters and ask questions that came up during the modelling process. For this research, most missing information could be filled in with information from literature, but it would have been more convenient to discuss the issues with experts.

Appendix B: Background on the Rhine River system

This appendix provides detailed information on the development of the Rhine from a natural river (section B1) to a normalised river (section B2).

B1 Natural rivers

In this thesis, a natural river is considered to be a river where no or very little human influence has altered its behaviour. As *figure 1* (in chapter 1) already showed, with this definition no natural rivers exist in the Netherlands and the Rhine is also almost completely modified. However, it is important to understand the natural behaviour of rivers if the effects of nature-based water management policies are to be analysed, since nature-based water management policies use the natural behaviour of rivers as inspiration and try to enable rivers to re-adopt more natural behaviour.

Literature on natural rivers

The most important aspects of a natural river are its hydrological and morphological processes, which are highly dynamic. The natural Rhine used to meander through the land, laterally relocating its bends, eroding bed material, and depositing the obtained sediment downstream or in the floodplains (Frings, 2015). Therefore, a continuous exchange of water, sediment, and biota existed between the river and its floodplains, and interfaces between aquatic and terrestrial areas were created that increased biodiversity (Diaz-Redondo, Egger, Marchamalo, Hohensinner & Dister, 2017). Erosion and sedimentation processes in the floodplains kept progression (growth) and regression (re-setting) of floodplain vegetation in balance (Diaz-Redondo et al., 2017), and enabled the rejuvenation of the floodplain and its vegetation. Due to the absence of dikes, floods would occur regularly and therefore, erosion and sedimentation of the land surrounding the river would happen frequently. Besides, without dams, barrages, and other man-made structures that regulate river flows, the water flow was more variable due to rainfall in the catchment area and snow storage or melting in the mountains of the catchment. The changes in the river's dimensions due to erosion and sedimentation influence the current speed (in m/s); a smaller cross-section leads to a higher current speed (Van Laarhoven, Tuijnder, Kabout & Kleinhans, 2018).

There are two types of sediment; fine and coarse. Fine sediment is transported through the river in suspension, which is a fast process, and is only deposited when the current speed is low, for example in the floodplains. Coarse sediment is found on the river bed, and is sometimes transported as bedload but often quickly deposited again (Frings, 2015).

Findings on natural rivers from interviews

The information on river morphology in this section is based on the interview with Astrid Blom, information on the influence of river hydrology and morphology on ecosystems is based on the interviews with Daphne Willems and Gertjan Geerling (see appendix A).

When the water discharge increases, the water current speed also increases. This results in an increased sediment transport capacity. A natural river has three ways to alter itself when a change occurs;

1. Changing its slope, which can be achieved by two processes:
    a. Erosion upstream (lower slope) or sedimentation upstream (higher slope)
    b. Change of its sinuosity

2. Changing its width by a difference in erosion in the outer bend and sedimentation in the inner bend
3. Changing the composition of its bed by coarsening it

Since the water level at sea is considered a given, changes in the river's slope are made upstream (by erosion or sedimentation). If the river's slope becomes too small or its bed too coarse, sedimentation will take place upstream, increasing the river's slope and therefore increasing its sediment transport capacity.

Another important aspect of natural rivers is that there is a constant process where new side channels are formed, old side channels are silted up, and side channels take over the main channel. When a side channel starts eroding, it will draw more and more water discharge from the main channel, causing an increase in erosion and a self-enhancing process which ends with the former side channel becoming the main channel. This self-enhancing process also works the other way around; if a side channel draws relatively little water discharge, sedimentation takes place and the side channel will silt up, which causes it to draw even less water. This leads to a varied ensemble of river channels, each with their own characteristics and habitats.

In a natural river, frequent flooding of the floodplains occurs, causing sedimentation in and erosion of the floodplains which enables floodplain rejuvenation. Right next to the river, heavy sediment is deposited because the current speed is still relatively high. Further inland, the current speed decreases and the finer sediment is deposited. This has two effects; first of all, an edge of heavy sediment is formed functioning as a small natural dike, and secondly different soil types lead to different habitats in the floodplain. Not only flooding leads to floodplain rejuvenation, but also the processes of outer bend erosion and inner bend sedimentation of the river's shores. Due to erosion and sedimentation of the shores, they have a gradual slope, which causes flooding to occur gradually. This in turn causes diversity in the sediment that is eroded in different zones of the floodplain, and therefore increases habitat diversity.

Reflection on natural rivers

From the previous two sections it is concluded that natural rivers are highly dynamic, and the processes are interdependent. The relatively high frequency of flooding makes economic activities in the floodplains vulnerable and risky and river meandering (erosion and sedimentation processes of the river bends) increase this risk, because it takes away land. The winding shape of the river, variations in water depth, and sedimentation in the navigation route make navigation difficult. Besides, the constant shifting of main and side channels make the river an unreliable route for transport. For the environment, however, the behaviour of the natural river is more convenient; natural floodplain rejuvenation takes place due to regular flooding and river bank erosion and sedimentation, a gradual slope of the river shore ensures gradual flooding, and the main channel and side channels are constantly relocating and changing their discharge capacity. All these processes ensure a high habitat diversity in the river system.

To summarize the most important processes in a natural river, their interdependencies, and their effects on environment, navigation, and flood protection a causal diagram has been constructed (see *figure B1)*. Box 2 explains how to read such a causal diagram.

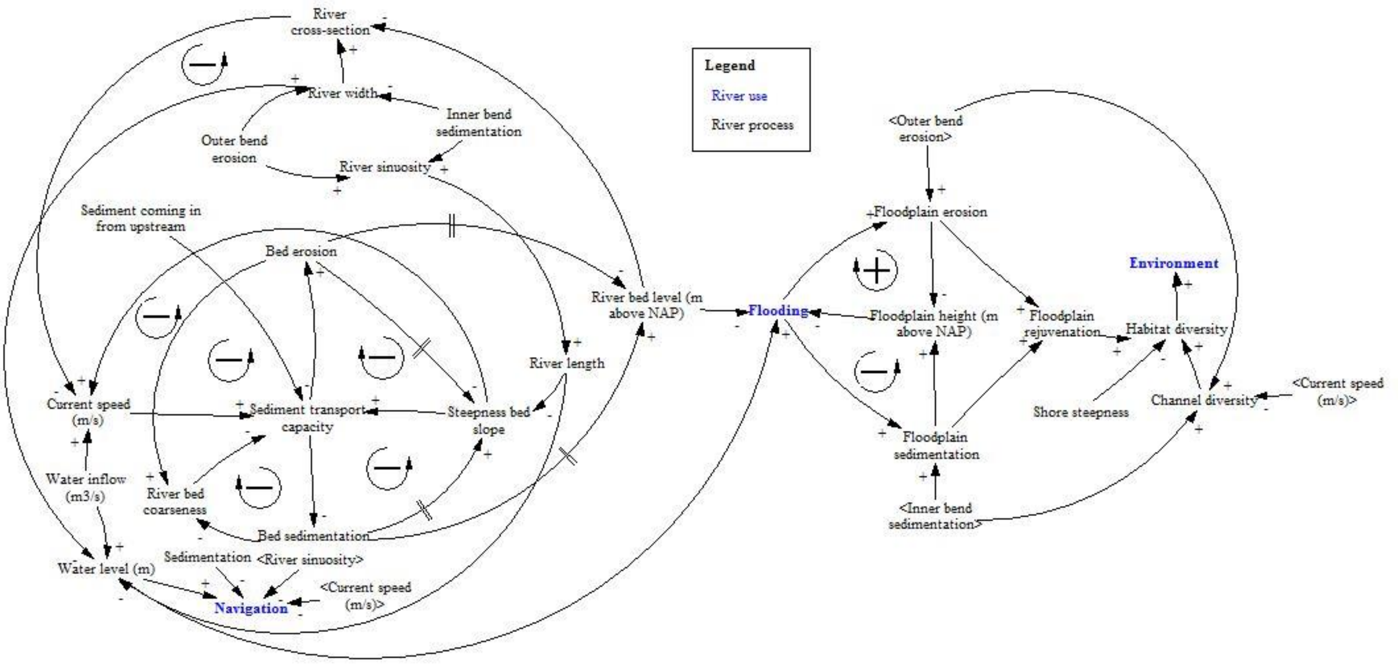


Figure B1: causal diagram natural river – derived from literature and interviews

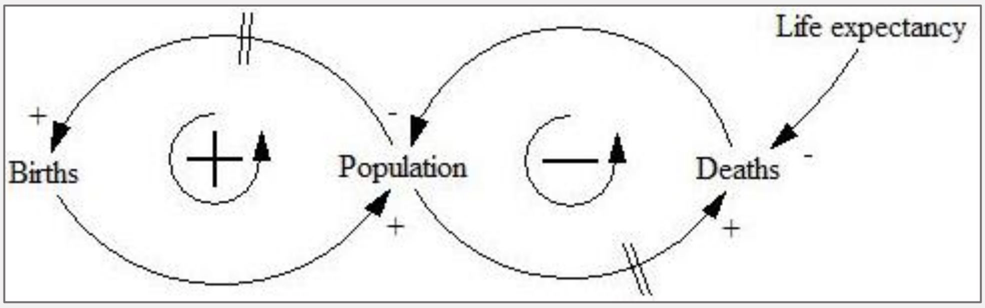
Figure B2 shows three simplified versions of the causal diagram in *figure B1* for environment, navigation, and flood protection separately. The colours in *figure B2* indicate whether a variable should rise (green) or decrease (red) to satisfy the interest of the river use. This already indicates that environment, navigation, and flood protection have very different demands for the river system. The most obvious conflict relates to flooding; regular flooding is necessary for environmental processes, but for flood protection this is undesirable. Another conflicting interest relates to river sinuosity; for navigation this is undesirable because it increases the length of the shipping route and because it makes navigation more difficult due to bends in the route, while for flood protection it is favourable because it increases the river length and therefore decreases the water level. River sinuosity is caused by erosion and sedimentation of the bends. This is another unwelcome process for navigation since sedimentation might cause accumulation of sediment and therefore obstructions to the navigation route. Erosion and sedimentation of the river bends is advantageous for the environment, however, because it increases habitat diversity in the river channel.

Box 2 - How to read a causal diagram

A causal diagram consists of variables, arrows between them with a polarity (+ or -), feedback loop signs, and delay marks (||).The easiest way to explain what all these symbols mean is by using a population model as an example. In this model, the arrow from Births to Population with polarity + indicates that the population increases when the number of births increases. The arrow from Population to Births with polarity + indicates that the number of births increases when the population increases. This results in a positive feedback loop (self-reinforcing behaviour), which is indicated with the round arrow with a + in it. However, if the population has been increased this does not immediately result in more births, since the new population members first have to mature. This results in a delayed increase of births, as is indicated by the delay symbol (||).

In addition to positive feedback loops, negative feedback loops exist, as is indicated by a round arrow with a – in it. A negative feedback loops results in balancing behaviour, as is the case with Population and Deaths. If the population grows, the number of deaths will also grow (with a delay, because people usually die after several decades), which then leads to a decline in the population.

Now that the symbols have been explained, there remains one important issue; direct and indirect effects. The number of deaths directly influences the population size. Life expectancy also influences Population, but indirectly via Deaths instead of directly; if the life expectancy increases, people will die at an older age, and therefore the number of deaths will decrease. This increases the population size. Since Life expectancy has a negative effect on Deaths, and Deaths has a negative effect on Population, the indirect (or secondary) effect of Life expectancy on Population is positive.



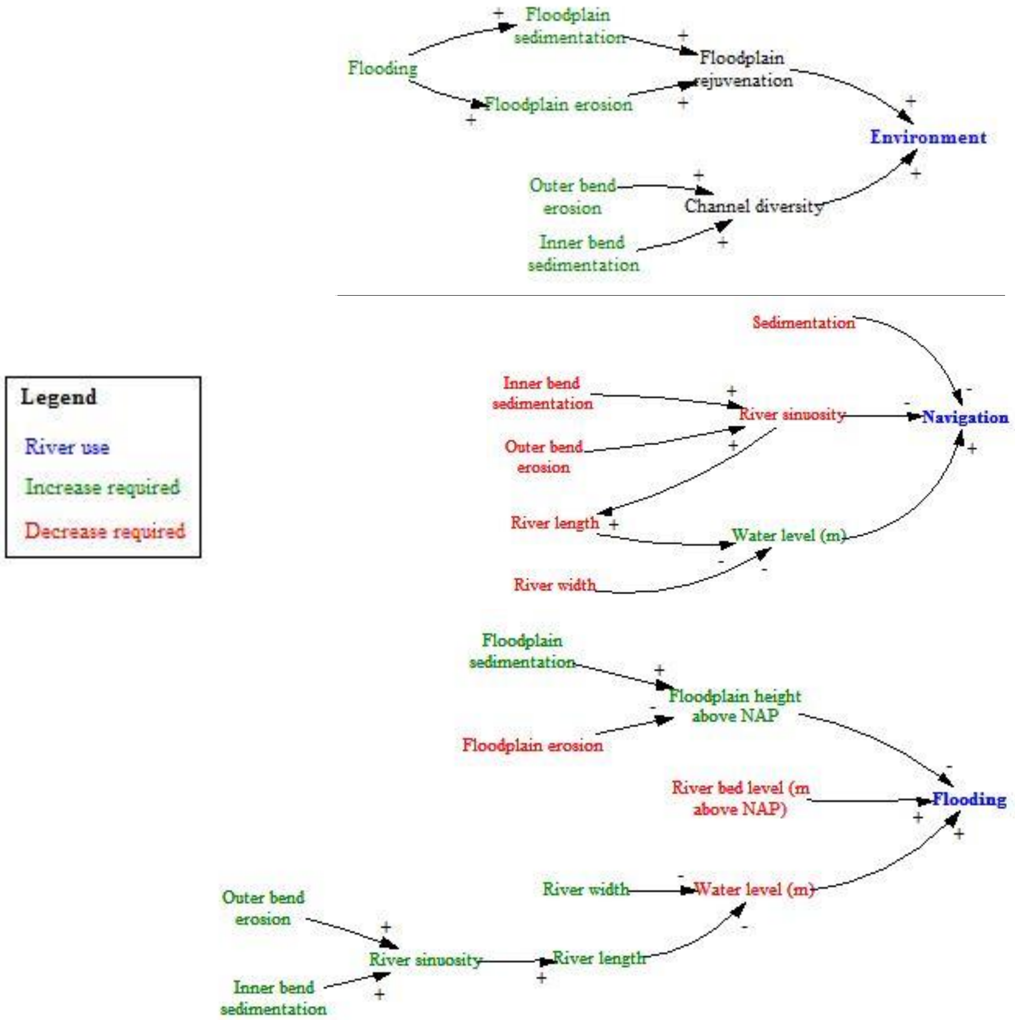


Figure B2: Conflicting interests in a natural river – derived from literature and interviews

However, all processes included in *figure B1 and B2* do occur in natural rivers, which leads to the conclusion that natural rivers are positive for environmental issues such as habitat diversity, but sub-optimal for navigation and flood protection. That is why over the past centuries measures have been taken in the Rhine to improve navigation and flood-protection. These normalisation measures will be discussed further in the next paragraph.

B2 Rhine normalisation

River normalisation is defined as the collection of measures that have been taken to straighten and deepen rivers, and to increase flood protection. Most large rivers have been normalised to some extent at some time. For the Rhine, this started around the twelfth century with embankments (Berendsen & Stouthamer, 2000). This paragraph provides a short overview of the normalisation measures in the Rhine and their effects on the hydrology and morphology of the river.

Literature on Rhine normalisation

Several quite different measures of river normalisation exist, but they have a few things in common; they resulted in less available space for the river's natural dynamics and often in higher water levels (Deltares, 2017). In addition, the river's cross-sectional area decreased and its bed slope increased, which resulted in an increased current speed that in turn increased the sediment transport capacity leading to more erosion of the summer bed (Van Laarhoven et al., 2018). Furthermore, rivers are disconnected from their floodplains, which negatively influences the balance between progression and regression of vegetation, and habitat diversity (Diaz-Redondo et al., 2017).

Reasons for river normalisation include navigability, flood protection, and hydropower production (Cron, Quick & Vollmer, 2015). Specific measures are bank protection, river straightening, deepening and narrowing of the main channel, and construction of barrages and dams (Cron et al., 2015). Frings (2015) adds embankment, bifurcation modification, and sediment mining to this list. Although Frings (2015) focused on the Lower Rhine, the measures taken in that reach are comparable to measures taken in other reaches. The measures and their consequences will be described below, largely based on information found in Frings (2015).

Bank protection served several human needs, such as navigation and flood protection, but also protection of property on the bank (Duró, Uijttewaal, Crosato & Kleinhans, 2016). It halted the meandering of rivers, because the protected bed and bank stretches could no longer erode. Besides, sediment bars could not be formed any longer, therefore lowering the sediment storage capacity in the river basin. This increased the flow velocity of a sediment particle; the travel time of an average particle travelling from the Lower Rhine to the Rhine delta decreased from 25000 to 65 years (Frings, 2015). *Figure B3* shows a visualisation of this process.

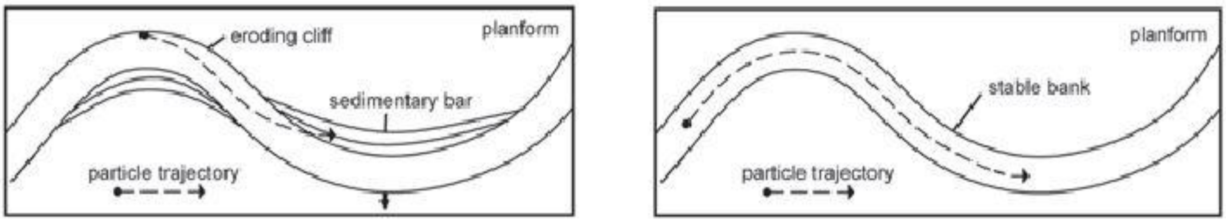


Figure B3: Bank protection and its effect (Frings, 2015)

River straightening has decreased meandering and the length of the river. This has led to an increase in the energy slope and the bed shear stress, and therefore to a coarser river bed (Frings, 2015), as can be seen in *figure B4*.

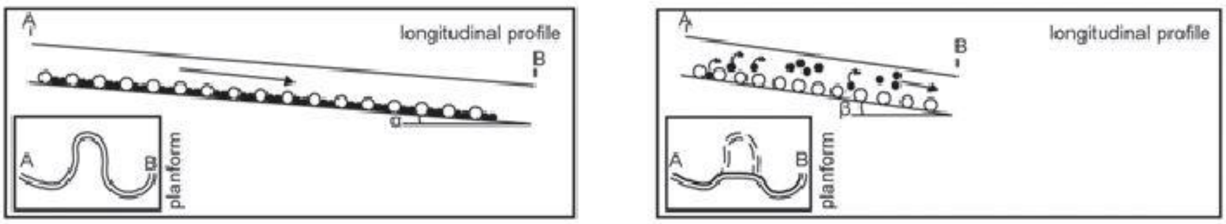


Figure B4: River straightening and its effects (Frings, 2015)

Narrowing of the Rhine was initiated because the importance of shipping increased and the main channel needed to be deepened. Groynes were constructed for this purpose. According to Frings (2015), river narrowing probably had the largest effect of all human interventions, because it fundamentally changed the river bed. The effects of river narrowing are an increased water depth, bed shear stress, and transport capacity. This left the river no choice but to erode (Frings, 2015). *Figure B5* shows this process.

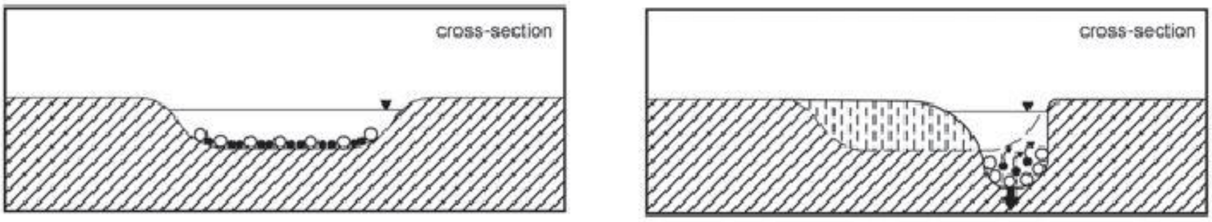


Figure B5: River narrowing and its effects (Frings, 2015)

Barrages were constructed in rivers to maintain a certain minimum water level, even during periods of low water flow, and dams are often constructed for hydropower production. These constructions interrupt the river's continuity, and therefore the transport of sediment and migration of fish along the river (Cron et al., 2015). This leads to an accumulation of sediment upstream of the construction, and a sediment deficit downstream of it. This deficit results in erosion and coarsening of the river bed (Frings, 2015). A visualisation of this process is shown in *figure B6.* Dams have another negative effect, namely that they change the hydrologic regime of the river; peak flows are partly stored and released during otherwise low flow periods (Arnaud, et al., 2015).

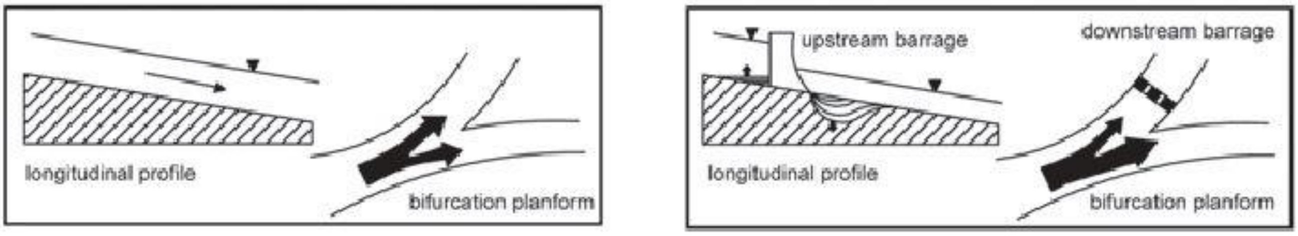


Figure B6: A barrage and its effects (Frings, 2015)

Embankments were constructed to protect the land along rivers from flooding. Therefore, the width of the water discharging area decreased during floods, which increased the water depth and bed shear stress in the main channel. *Figure B7* shows that this resulted in erosion of finer sediment from the river bed and therefore in coarsening of the bed material (Frings, 2015). Besides, embankments decreased flooding of the areas protected by the embankments.

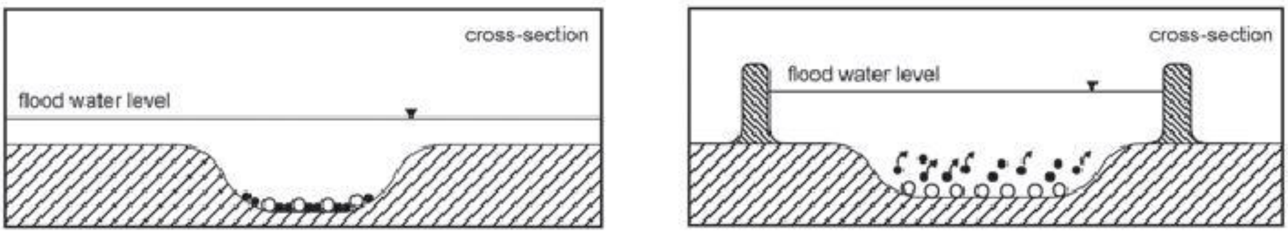


Figure B7: Embankment and its effects (Frings, 2015)

Bifurcation modification altered the amount of water that was discharged through each river arm, which also influences the sediment transport (see *figure B8*). The water discharge in the Waal decreased from 90% to 67% of the total Rhine discharge after bifurcation modification (Frings, 2015).

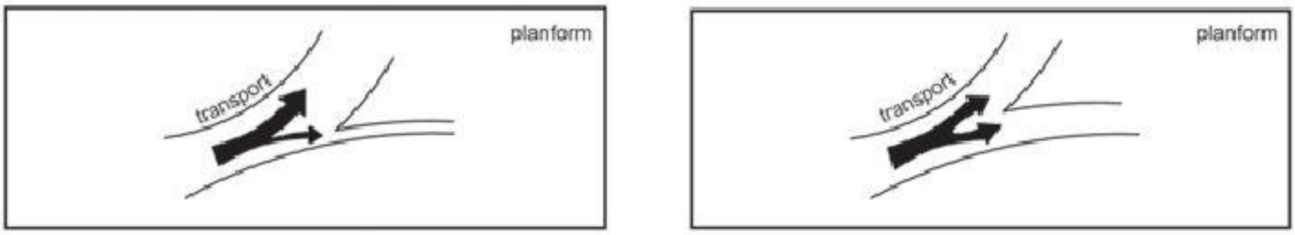


Figure B8: Bifurcation modification and its effects (Frings, 2015)

Sediment mining (or dredging) was conducted because it increases the water depth for navigation in the main channel. Furthermore, it increased the bed shear stress. Finally, it also led to a deficit of sediment downstream of the mining area, so the bed material at that location also started eroding (see *figure B9*).

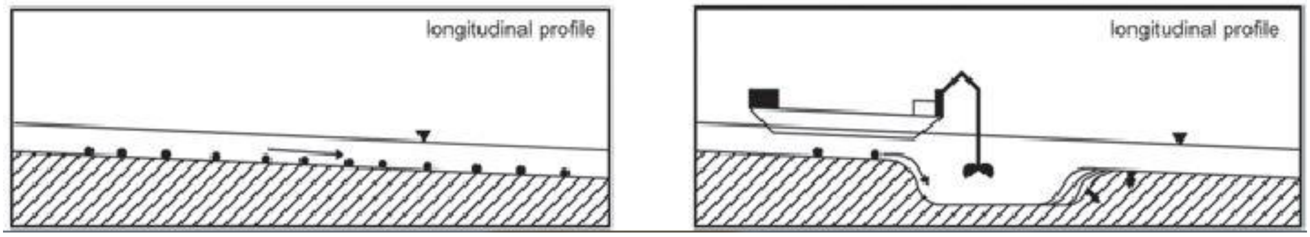


Figure B9: Sediment mining and its effects (Frings, 2015)

Findings on Rhine normalisation from interviews
Astrid Blom indicated that normalised rivers have only two ways left to alter themselves;

3. Changing its slope by upstream erosion
4. Coarsening of its river bed

The response of rivers to normalisation measures is very slow, and therefore still taking place. The lowering of the river bed in the Dutch distributaries of the Rhine is not only caused by the morphological processes described above, but according to Frans Klijn also by the barrages in the German Rhine that stop the sediment influx. This is being solved by sediment nourishment.

Reflection on Rhine normalisation
The normalisation measures have had, and still have, a large impact on the Rhine river system. The measures that were discussed in this section have been included in the causal diagram of a natural river to show how they affect the system. *Figure B10* shows this in full. The variables in purple indicate the normalisation measures that were taken.

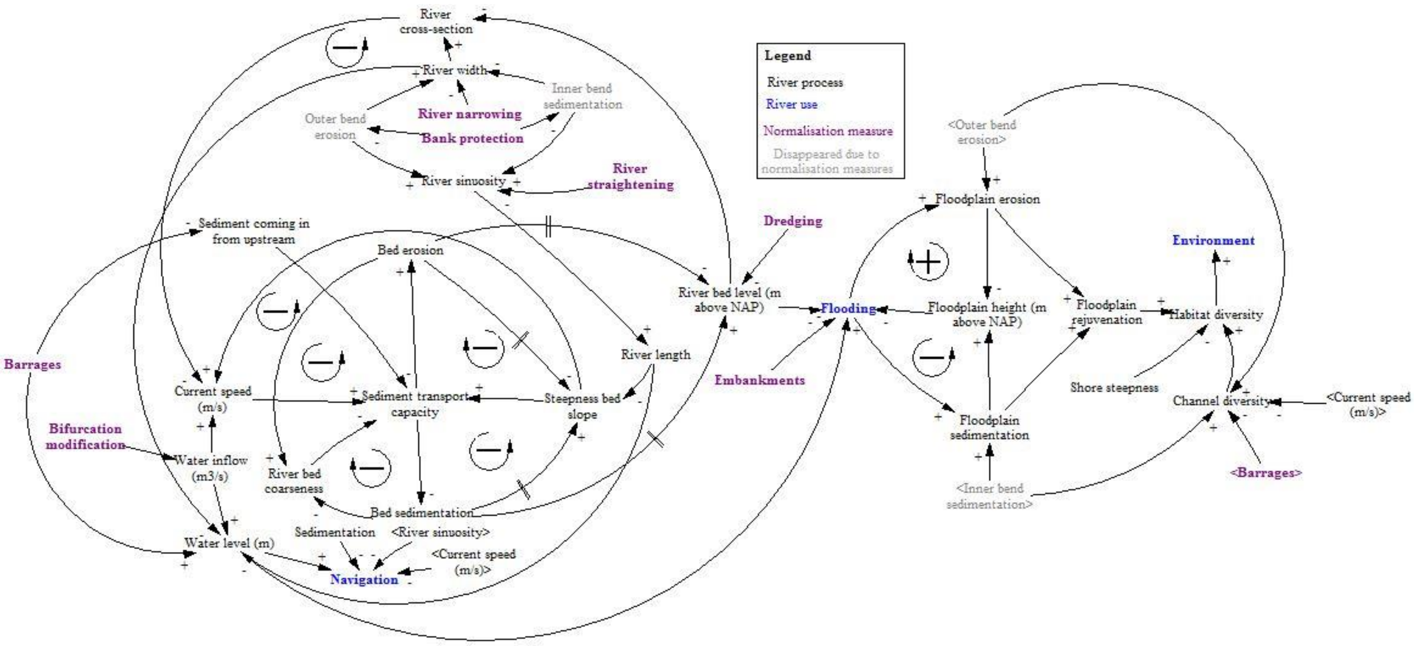


Figure B10: causal diagram river normalisation – derived from literature and interviews

In *figure B11*, for each river use the effect of the river normalisation measures is shown. The normalisation measures are again shown in purple. If a river use is coloured red the measures had a negative effect on it, if it is coloured green the measures were positive, and if it is coloured orange there were both negative and positive effects.

The normalisation strongly improved the circumstances for navigation in the Rhine; less sedimentation occurred, the river's sinuosity decreased, and the main channel was made narrower and deeper. However, normalisation strongly deteriorated circumstance for the environment; flooding became less frequent (or even absent), and bank protection curtailed erosion and sedimentation processes. For flood protection the effects of normalisation measures are not black or white. While embankments directly decreased flooding, and dredging lowered the river bed level and therefore also flooding frequency, river narrowing, river straightening, and bank protection increased the water level and therefore increased the risk of flooding. This leads to the preliminary conclusion that where natural rivers were favourable for the environmental aspects of rivers, normalisation measures lead to improved navigation.

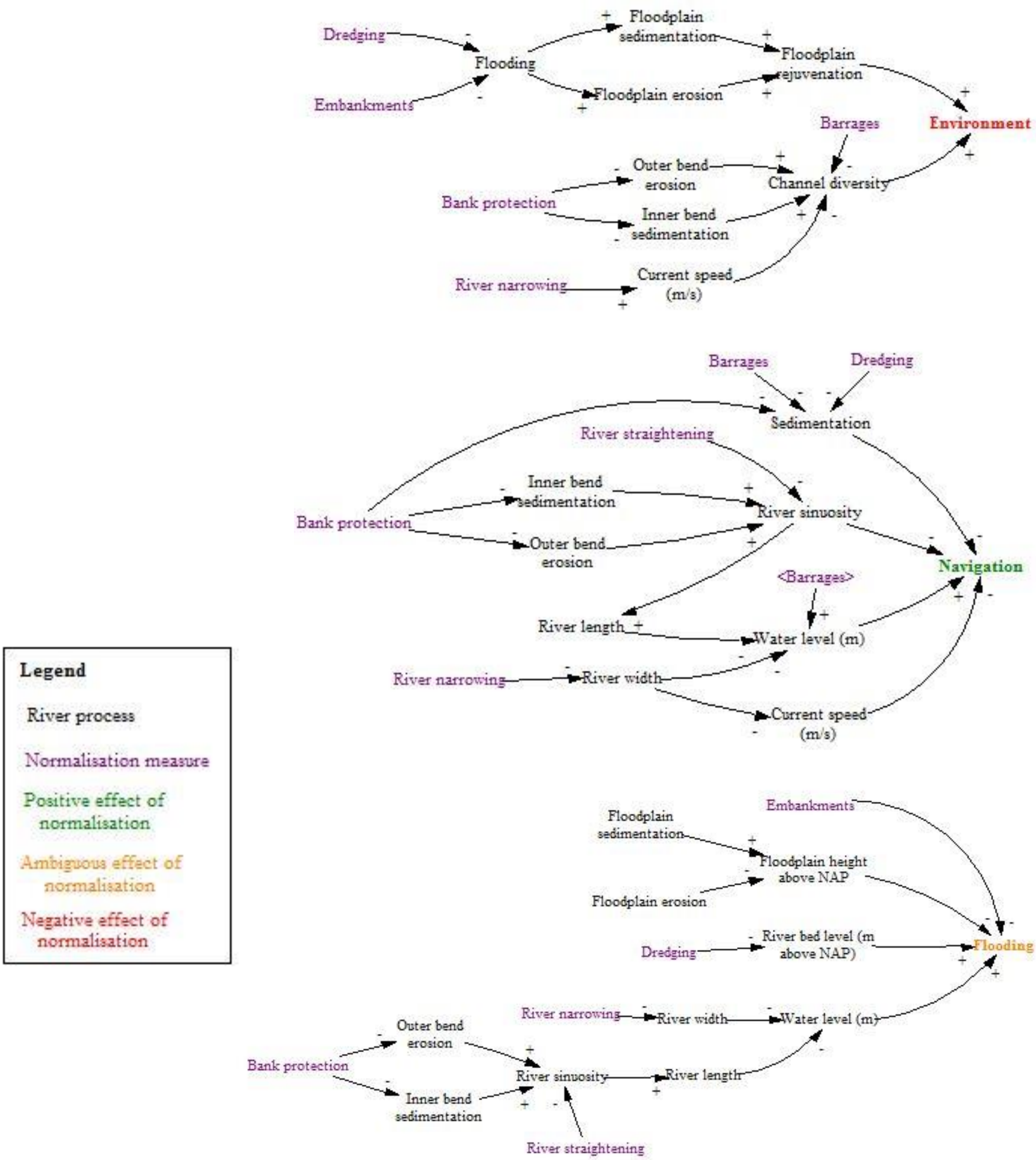


Figure B11: Effects of river normalisation on environment, navigation, and flood protection – derived from literature and interviews

Appendix C: International agreements on environmental issues in the Rhine

The attention for environmental aspects of rivers has increased near the end of the previous century, resulting in two international agreements focussing on the environmental issues in the Rhine River; the Water Framework Directive for the whole European Union (EU) and the Convention on the Protection of the Rhine (a newer version of earlier agreements) specifically focussed on the Rhine. These agreements will be discussed below, first based on literature and then based on expert interviews.

C1 Literature on international agreements

The agreements have been established in 1999 and in 2000. It may sound redundant to introduce two similar agreements, but it is actually useful. The reason for this is that Switzerland is not a member of the EU, and therefore not obliged to fulfil the requirements of the WFD (Louka, 2018), but it is part of the Convention on the Protection of the Rhine and can therefore be stimulated to fulfil the environmental requirements.

Convention on the Protection of the Rhine (1999)

The information in this section is retrieved from the actual text of the agreement (Convention on the Protection of the Rhine, 1999). Germany, France, Luxembourg, the Netherlands, and Switzerland are the cooperating countries in this agreement. The agreement is a follow-up of earlier agreements to enhance the water quality in the Rhine. However, this new agreement has a wider focus; sustainable development of ecosystems, improving sediment quality and improving flood prevention and protection. Its aims are the sustainable development of the Rhine ecosystem (water quality, species diversity, natural river processes, and habitats), drinking water production, sediment quality improvement, flood prevention and protection, and restoration of the North Sea. This agreement resulted in the Rhine 2020 programme, which is an extension of the Rhine Action Programme that was put into action in 1987.

Water Framework Directive (2000)

The Water Framework Directive (WFD) has several purposes; preventing further deterioration and protecting and enhancing the status of aquatic ecosystems, promoting sustainable, long-term water use, ensuring progressive reduction of groundwater pollution, and contributing to mitigating the effects of floods and droughts (EU Water Framework Directive, 2000). The implementation of the WFD needs to be coordinated at river basin level, therefore Austria, Liechtenstein, and Belgium are also involved. The WFD requires that an internationally coordinated river basin management plan is written every six years, in which an evaluation of the previous six years and plans for the next six years are included. The WFD distinguished natural water bodies from heavily modified and artificial ones, but almost the whole Rhine (93%) is classified as heavily modified (ICPR, 2015a). This influences the status that a water body must achieve; instead of a good status, a heavily modified water body must achieve a 'good ecological potential' status. The internationally coordinated river basin management plan 2015 of the Rhine contains more detailed measures of how to achieve a good ecological potential.

Although international coordination exists between countries within the Rhine River basin, for example when drafting the river basin management plan, policy harmonization across borders has not increased much due to the European water directives, as was found in a German-Dutch case study (Renner, Meijerink & van der Zaag, 2017).

C2 Findings on international agreements from interviews

In the interview with Erik Mostert, the international agreements have been discussed extensively, so most information is based on this interview. If information was retrieved from another interviewee, it is indicated.

Convention on the Protection of the Rhine (1999)

This convention is not legally binding for the countries involved. Agreements reached in this convention are merely guidelines, but countries will not be punished if they do not reach the set goals. Therefore, this agreement is considered less important than the WFD, which is binding. However, including Switzerland, not being an EU member state, in the Rhine River basin plans is acknowledged as being beneficial for the achievement of goals that are stated in the WFD.

Water Framework Directive (2000)

Although the WFD is officially binding, it includes many possibilities to postpone the achievement of goals, or to lower the goals. These possibilities are extensively used by the Netherlands and other EU countries. Furthermore, the Dutch goals related to the WFD are not very ambitious, but due to a bottom-up approach a lot has been accomplished. In Germany and France, this was exactly the other way around; the goals they set were very ambitious, but little have been reached so far due to a top-down approach.

According to Gertjan Geerling, the WFD – although it does have positive effects – focusses too much on measurable criteria such as the number of kilometres of side channels, instead of on the actual goal which is nature development. Some side channels are constructed in such a way that they provide little benefit for nature, but they do count for the WFD.

Appendix D: Model description

D1 Model equations

"% forest in non-grass vegetation zone 1"=IF THEN ELSE("Sum non-grass vegetation zone 1"=0, 0, Forest zone 1/"Sum non-grass vegetation zone 1")
- [Dmnl]

"% forest in non-grass vegetation zone 2"=IF THEN ELSE("Sum non-grass vegetation zone 2"=0, 0, Forest zone 2/"Sum non-grass vegetation zone 2")
- [Dmnl]

"% forest in scrub&forest zone 1"=IF THEN ELSE("Sum scrub&forest zone 1"=0,0,Forest zone 1/"Sum scrub&forest zone 1")
- [Dmnl]

"% forest in scrub&forest zone 2"=IF THEN ELSE("Sum scrub&forest zone 2"=0,0,Forest zone 2/"Sum scrub&forest zone 2")
- [Dmnl]

"% forest"=IF THEN ELSE(Floodplain zone 1 area=0, IF THEN ELSE(Floodplain zone 2 area=0, 0, (Forest zone 1+Forest zone 2)/(Floodplain zone 1 area+Floodplain zone 2 area)), (Forest zone 1+Forest zone 2)/(Floodplain zone 1 area+Floodplain zone 2 area))
- [Dmnl]

"% grass"=IF THEN ELSE(Floodplain zone 1 area=0, IF THEN ELSE(Floodplain zone 2 area=0, 0, ("Grass & farmland zone 1"+"Grass & farmland zone 2")/(Floodplain zone 1 area+Floodplain zone 2 area)), ("Grass & farmland zone 1"+"Grass & farmland zone 2")/(Floodplain zone 1 area+Floodplain zone 2 area))
- [Dmnl]

"% reeds in non-grass vegetation zone 1"=IF THEN ELSE("Sum non-grass vegetation zone 1"=0, 0, Reeds zone 1/"Sum non-grass vegetation zone 1")
- [Dmnl]

"% reeds in non-grass vegetation zone 2"=IF THEN ELSE("Sum non-grass vegetation zone 2"=0, 0, Reeds zone 2/"Sum non-grass vegetation zone 2")
- [Dmnl]

"% reeds"=IF THEN ELSE(Floodplain zone 1 area=0, IF THEN ELSE(Floodplain zone 2 area=0, 0, (Reeds zone 1+Reeds zone 2)/(Floodplain zone 1 area+Floodplain zone 2 area)), (Reeds zone 1+Reeds zone 2)/(Floodplain zone 1 area+Floodplain zone 2 area))
- [Dmnl]

"% scrub in non-grass vegetation zone 1"=IF THEN ELSE("Sum non-grass vegetation zone 1"=0, 0, Scrub zone 1/"Sum non-grass vegetation zone 1")
- [Dmnl]

"% scrub in non-grass vegetation zone 2"=IF THEN ELSE("Sum non-grass vegetation zone 2"=0, 0, Scrub zone 2/"Sum non-grass vegetation zone 2")

- [Dmnl]

"% scrub in scrub&forest zone 1"=IF THEN ELSE("Sum scrub&forest zone 1"=0, 0, Scrub zone 1/"Sum scrub&forest zone 1")

- [Dmnl]

"% scrub in scrub&forest zone 2"=IF THEN ELSE("Sum scrub&forest zone 2"=0, 0, Scrub zone 2/"Sum scrub&forest zone 2")

- [Dmnl]

"% scrub"=IF THEN ELSE(Floodplain zone 1 area=0, IF THEN ELSE(Floodplain zone 2 area=0, 0, (Scrub zone 1+Scrub zone 2)/(Floodplain zone 1 area+Floodplain zone 2 area)), (Scrub zone 1+Scrub zone 2)/(Floodplain zone 1 area+Floodplain zone 2 area))

- [Dmnl]

Actual gap=Gap between water level and bridge at reference high water level+Reference high water level above NAP-(IF THEN ELSE(Water level floodplain above NAP>Summer dike height above NAP, Water level floodplain above NAP, Water level main channel above NAP))

- [m]

Average duration of pipe formation=Winter dike width/Average permeability sand+Winter dike width/Average pipe development rate

- [Day]

Bare soil zone 1=MAX(Floodplain zone 1 area-Reeds zone 1-Scrub zone 1-Forest zone 1-"Grass & farmland zone 1", 0)

- [m^2]

Bare soil zone 2=MAX(Floodplain zone 2 area-Reeds zone 2-Scrub zone 2-Forest zone 2-"Grass & farmland zone 2", 0)

- [m^2]

"Capacity floodplain zone 1-3"=IF THEN ELSE(Summer dike height above NAP=Floodplain height above NAP, ((Horizontal floodplain width zone 1*2+Main channel width+Horizontal floodplain width zone 2*2)*(5-Maximum height floodplain zone 2 above NAP)+(5-Maximum height floodplain zone 2 above NAP)*((5-Maximum height floodplain zone 2 above NAP)/Winter dike height over width)+Horizontal floodplain width zone 2*(Maximum height floodplain zone 2 above NAP-Maximum height floodplain zone 1 above NAP)+(Horizontal floodplain width zone 1*2+Main channel width)*(Maximum height floodplain zone 2 above NAP-Maximum height floodplain zone 1 above NAP)+Main channel width*(Maximum height floodplain zone 1 above NAP-Floodplain height above NAP))*Length river reach+"Volume limit zone 1 (one side of river)"*2, (Horizontal floodplain width zone 1*(Summer dike height above NAP-Maximum height floodplain zone 1 above NAP)*2+Horizontal floodplain width zone 2*(Maximum height floodplain zone 2 above NAP-Maximum height floodplain zone 1 above NAP)+Horizontal floodplain width zone 2*(Summer dike height above NAP-Maximum height floodplain zone 2 above NAP)*2+(Summer dike height above NAP-Maximum height floodplain zone 2 above NAP)*((Summer dike height above NAP-Maximum height floodplain zone 2 above

NAP)/Winter dike height over width))*Length river reach+"Volume limit zone 1 (one side of river)"*2)

- [m^3]

Capacity side channel effect on side channel inflow=Maximum capacity side channel/(Maximum capacity side channel+Maximum capacity main channel)

- [Dmnl]

Cargo capacity= INTEG (Increase under favourable conditions-Decrease due to too high current-Decrease due to too high water-Decrease due to too low water, Initial cargo capacity)

- [tonnes]

Cargo capacity over whole run= INTEG (Count capacity, 0)

- [tonnes]

Count main above cap=IF THEN ELSE(Water in main channel>Maximum capacity main channel, (Water in main channel-Maximum capacity main channel), 0)

- [m^3/s]

Count 0 capacity=IF THEN ELSE(Cargo capacity=0, 1, 0)

- [Day/Day]

Count capacity=Cargo capacity

- [tonnes]

Count current=IF THEN ELSE(Decrease due to too high current>0, 1, 0)

- [Day/Day]

Count days flooding=IF THEN ELSE("Flooding in m3/s">0, 1, 0)

- [Day/Day]

Count dike breach=IF THEN ELSE("Dike breach?"=1, 1, 0)

- [Day/Day]

Count duration erosion=IF THEN ELSE(Flooding per m dike>(0.9*Minimum problematic flooding per dike m), TIME STEP/TIME STEP, 0)

- [Day/Day]

Count duration inward=IF THEN ELSE(Water level floodplain above NAP>(0.9*Reference high water level above NAP), TIME STEP/TIME STEP, 0)

- [Day/Day]

Count duration outward=IF THEN ELSE("Water level difference dike-river">=(0.9*Minimum problematic water level difference), TIME STEP/TIME STEP, 0)

- [Day/Day]

Count duration piping=IF THEN ELSE(Water level floodplain above NAP>=(0.9*"Critical water level piping (above NAP)"), TIME STEP/TIME STEP, 0)

- [Day/Day]

Count erosion=IF THEN ELSE(Possibility of dike erosion due to overflow>0, 1, 0)
- [Day/Day]

Count forest="% forest"
- [Dmnl]

Count grass="% grass"
- [Dmnl]

Count high=IF THEN ELSE(Decrease due to too high water>0, 1, 0)
- [Day/Day]

Count inward=IF THEN ELSE("Possibility of inward macro-instability">0, 1, 0)
- [Day/Day]

Count low=IF THEN ELSE(Decrease due to too low water>0, 1, 0)
- [Day/Day]

Count outward=IF THEN ELSE("Possibility of outward macro-instability">0, 1, 0)
- [Day/Day]

Count piping=IF THEN ELSE(Possibility of piping>0, 1, 0)
- [Day/Day]

Count reeds="% reeds"
- [Dmnl]

Count scrub="% scrub"
- [Dmnl]

Count side channel flow days=IF THEN ELSE(Water in side channel>0.01, 1, 0)
- [Day/Day]

Count suitable channel days=IF THEN ELSE("Current speed main channel within limits?"=1,1,IF THEN ELSE("Current speed side channel within limits?"=1, 1, 0))
- [Day/Day]

Count zone 1=IF THEN ELSE(Inundation width zone 1>=0.5*Horizontal floodplain width zone 1, TIME STEP/TIME STEP, 0)
- [Day/Day]

Count zone 2=IF THEN ELSE(Inundation width zone 2>=0.5*Horizontal floodplain width zone 2, TIME STEP/TIME STEP, 0)
- [Day/Day]

*"Critical water level piping (above NAP)"=(*1/CBligh)*Winter dike width+Maximum height floodplain zone 2 above NAP
- [m]

Current speed floodplain=Vegetation effect on current speed floodplain*Water volume effect on current speed floodplain*Maximum current speed floodplain
- [m/s]

Current speed main channel=Water discharge effect on current speed main channel*Maximum current speed channels
- [m/s]

"*Current speed main channel within limits?*"=IF THEN ELSE(Current speed main channel>Lower limit current speed, IF THEN ELSE(Current speed main channel<=Upper limit current speed, 1, 0), 0)
- [Dmnl]

Current speed side channel=Maximum current speed channels*Water discharge effect on current speed side channel*Width effect on current speed side channel
- [m/s]

"*Current speed side channel within limits?*"=IF THEN ELSE(Current speed side channel>Lower limit current speed, IF THEN ELSE(Current speed side channel<=Upper limit current speed, 1, 0), 0)
- [Dmnl]

Decrease due to too high current=IF THEN ELSE(Current speed main channel>Maximum current speed for navigation, Cargo capacity/TIME STEP, 0)
- [tonnes/Day]

Decrease due to too high water=IF THEN ELSE(No shipping allowed to prevent wave action on dikes=1, Cargo capacity/TIME STEP, IF THEN ELSE(Cargo capacity>Potential cargo capacity during high water, (Cargo capacity-Potential cargo capacity during high water)/TIME STEP, 0))
- [tonnes/Day]

Decrease due to too low water=IF THEN ELSE(Cargo capacity>Potential cargo capacity during low water, (Cargo capacity-Potential cargo capacity during low water)/TIME STEP, 0)
- [tonnes/Day]

Delay time dike water level=(ABS(Water level floodplain above NAP-Water level floodplain previous timestep)+Winter dike width)/Average permeability sand
- [Day]

"*Dike breach?*"=IF THEN ELSE(Possibility of dike erosion due to overflow>0.9, IF THEN ELSE("Possibility of inward macro-instability">0.9, 1, IF THEN ELSE("Possibility of outward macro-instability">0.9, 1, IF THEN ELSE(Possibility of piping>0.9, 1, 0))), IF THEN ELSE("Possibility of inward macro-instability">0.9, IF THEN ELSE("Possibility of outward macro-instability">0.9, 1, IF THEN ELSE(Possibility of piping>0.9, 1, 0)), IF THEN ELSE("Possibility of outward macro-instability">0.9, IF THEN ELSE(Possibility of piping>0.9, 1, 0), 0)))
- [Dmnl]

Duration erosion= INTEG (Count duration erosion-Reset duration erosion, 0)
- [Day]

Duration inward= INTEG (Count duration inward-Reset duration inward, 0)
- [Day]

Duration of flooding effect on dike erosion=WITH LOOKUP (Duration erosion/(0.9*Minimum problematic duration of flooding per dike m), ([(-10000,0)-(1e+06,1)],(-10000,0),(0,0),(0.99,0),(1.35168,0.0263158),(1.60856,0.144737),(1.8104,0.355263),(1.92049,0.587719),(2,1),(1e+08,1)))
- [Dmnl]

Duration of inundation zone 1= INTEG (+Count zone 1-Reset zone 1, 0)
- [Day]

Duration of inundation zone 2= INTEG (+Count zone 2-Reset zone 2, 0)
- [Day]

"Duration of water level difference effect on outward macro-instability"=WITH LOOKUP(Duration outward/(0.9*Minimum problematic duration of water level difference), ([(-10000,0)-(2,1)],(-10000,0),(0,0),(0.99,0),(1.41284,0.0350877),(1.69419,0.135965),(1.87156,0.355263),(1.95719,0.609649),(2,1),(1e+08,1)))
- [Dmnl]

"Duration of water level effect on inward macro-instability"=WITH LOOKUP (Duration inward/(0.9*Minimum problematic duration of exceedance high water), ([(-10000,0)-(1e+08,1)],(-10000,0),(0,0),(0.99,0),(1.33945,0.0219298),(1.66361,0.114035),(1.84709,0.298246),(1.94495,0.495614),(2,1),(1e+08,1)))
- [Dmnl]

Duration of water level effect on piping=WITH LOOKUP (Duration piping/Average duration of pipe formation, ([(-10000,0)-(2,1)],(-10000,0),(0,0),(0.379205,0.0570176),(0.703364,0.135965),(1,0.25),(1.32722,0.425439),(1.66972,0.688596),(2,1),(1e+08,1)))
- [Dmnl]

Duration outward= INTEG (Count duration outward-Reset duration outward, 0)
- [Day]

Duration piping= INTEG (Count duration piping-Reset duration piping, 0)
- [Day]

Erosion sedimentation multiplier zone 1= WITH LOOKUP (Duration of inundation zone 1, ([(-1e+06,0)-(15,1)],(-1e+06,0),(0,0),(1.78899,0.0307018),(3.34862,0.118421),(4.3578,0.27193),(5,0.5),(5.82569,0.701754),(7.88991,0.872807),(10.8716,0.95614),(15,1),(1e+08,1)))
- [Dmnl]

Erosion sedimentation multiplier zone 2= WITH LOOKUP (Duration of inundation zone 2, ([(-1e+06,0)-(15,1)],(-1e+06,0),(0,0),(1.78899,0.0307018),(3.34862,0.118421),(4.3578,0.27193),(5,0.5),(5.82569,0.701754),(7.88991,0.872807),(10.8716,0.95614),(15,1),(1e+08,1)))
- [Dmnl]

Fitting under bridge effect bulk=WITH LOOKUP (Actual gap, ([(-1,0)-(10,1.5)],(-1000,0),(0,0),(3.64,0), (3.65,0.1),(4.9,0.16),(5.4,0.33),(5.6,0.55),(5.7,1),(100,1)))
- [Dmnl]

Fitting under bridge effect containers=WITH LOOKUP (Actual gap, ([(0,0)-(12,1.5)],(-1000,0),(0,0), (2.89,0),(2.9,0.25),(5.49,0.25),(5.5,0.5),(8.09,0.5),(8.1,0.75),(10.69,0.75),(10.7,1),(100,1)))

- [Dmnl]

Flooding due to overflow=IF THEN ELSE(Water in floodplain<=Maximum capacity floodplain, 0, (Water in floodplain-Maximum capacity floodplain)/TIME STEP)

- [m^3/Day]

"*Flooding in m3/s*"=Flooding due to overflow/Seconds in 1 day

- [m^3/s]

Flooding per m dike="Flooding in m3/s"/Length river reach

- [m^3/s/m]

Flooding per m dike effect on dike erosion=WITH LOOKUP (Flooding per m dike/(0.9*Minimum problematic flooding per dike m), ([(0,0)-(5,1)],(0,0),(0.99,0),(1.88073,0.0219298),(2.98165,0.122807), (3.83792,0.27193),(4.44954,0.438596),(4.81651,0.710526),(5,1),(1000,1)))

- [Dmnl]

Floodplain vegetation roughness="% reeds"*Roughness reeds+"% scrub"*Roughness scrub+"% forest"*Roughness forest+"% grass"*"Roughness grass & farmland"

- [Dmnl]

Floodplain zone 1 area=Horizontal floodplain width zone 1*Length river reach

- [m^2]

Floodplain zone 2 area=Horizontal floodplain width zone 2*Length river reach

- [m^2]

"Forest removal (human) zone 1"=IF THEN ELSE(Human intervention floodplain vegetation=0, 0, IF THEN ELSE(("Sum non-grass vegetation zone 1"-("Maximum reeds, scrub & forest"*Floodplain zone 1 area))>0, ("Sum non-grass vegetation zone 1"-("Maximum reeds, scrub & forest"*Floodplain zone 1 area))*"% forest in non-grass vegetation zone 1"/Vegetation removal time, IF THEN ELSE(("Sum scrub&forest zone 1"-("Maximum scrub & forest"*Floodplain zone 1 area))>0, ("Sum scrub&forest zone 1"-("Maximum scrub & forest"*Floodplain zone 1 area))*"% forest in scrub&forest zone 1"/Vegetation removal time, IF THEN ELSE((Forest zone 1-(Maximum forest*Floodplain zone 1 area))>0, (Forest zone 1-(Maximum forest*Floodplain zone 1 area))/Vegetation removal time, 0))))

- [m^2/Day]

"Forest removal (human) zone 2"=IF THEN ELSE(Human intervention floodplain vegetation=0, 0, IF THEN ELSE(("Sum non-grass vegetation zone 2"-"Maximum reeds, scrub & forest"*Floodplain zone 2 area)>0, ("Sum non-grass vegetation zone 2"-"Maximum reeds, scrub & forest"*Floodplain zone 2 area)*"% forest in non-grass vegetation zone 2"/Vegetation removal time, IF THEN ELSE(("Sum scrub&forest zone 2"-"Maximum scrub & forest"*Floodplain zone 2 area)>0, ("Sum scrub&forest zone 2"-"Maximum scrub & forest"*Floodplain zone 2 area)*"% forest in scrub&forest zone 2"/Vegetation removal time, IF THEN ELSE((Forest zone 2-Maximum forest*Floodplain zone 2 area)>0, (Forest zone 2-Maximum forest*Floodplain zone 2 area)/Vegetation removal time, 0))))

- [m²/Day]

"*Forest set-back zone 1*"=Forest zone 1*Erosion sedimentation multiplier zone 1*Erosion rate forest

- [m²/Day]

"*Forest set-back zone 2*"=Forest zone 2*Erosion sedimentation multiplier zone 2*Erosion rate forest

- [m²/Day]

Forest zone 1=INTEG (Succession scrub to forest zone 1-"Forest removal (human) zone 1"-"Forest set-back zone 1", "Initial % forest zone 1"*Floodplain zone 1 area)

- [m²]

Forest zone 2=INTEG (Succession scrub to forest zone 2-"Forest removal (human) zone 2"-"Forest set-back zone 2", "Initial % forest zone 2"*Floodplain zone 2 area)

- [m²]

"*Grass & farmland set-back zone 1*"=Erosion sedimentation multiplier zone 1*Erosion rate grass*"Grass & farmland zone 1"

- [m²/Day]

"*Grass & farmland set-back zone 2*"=Erosion sedimentation multiplier zone 2*Erosion rate grass*"Grass & farmland zone 2"

- [m²/Day]

"*Grass & farmland zone 1*"=INTEG ("Forest removal (human) zone 1"+Pioneering zone 1+"Reeds removal (human) zone 1"+"Scrub removal (human) zone 1"-"Grass & farmland set-back zone 1"-Succession grass to reeds zone 1, "Initial % grass zone 1"*Floodplain zone 1 area)

- [m²]

"*Grass & farmland zone 2*"=INTEG ("Forest removal (human) zone 2"+Pioneering zone 2+"Reeds removal (human) zone 2"+"Scrub removal (human) zone 2"-"Grass & farmland set-back zone 2"-Succession grass to reeds zone 2, "Initial % gras zone 2"*Floodplain zone 2 area)

- [m²]

Increase under favourable conditions=IF THEN ELSE(Fitting under bridge effect containers=1, IF THEN ELSE(Fitting under bridge effect bulk=1, IF THEN ELSE(Water level main channel above NAP>=Minimum water level for full capacity above NAP,IF THEN ELSE(Current speed main channel<=Maximum current speed for navigation, IF THEN ELSE(No shipping allowed to prevent wave action on dikes=0, (Maximum cargo capacity-Cargo capacity)/Cargo capacity adjustment time, 0), 0), 0), 0), 0)

- [tonnes/Day]

Inflow:INTERPOLATE::=GET XLS DATA('NormalInflow.xlsx', 'NormalInflow', 'A' , 'B2')

- [m³/s]

"*Inflow (m3/day)*"=Inflow*Seconds in 1 day

- [m³/Day]

Inundation width zone 1=IF THEN ELSE(Water level floodplain above NAP<=(Floodplain height above NAP+0.01), 0, IF THEN ELSE(Water in floodplain<0.1, 0, IF THEN ELSE((Water in floodplain/2)<="Volume limit zone 1 (one side of river)", SQRT((Water level floodplain above NAP-Floodplain height above NAP)^2+((Water in floodplain)/Length river reach/(Water level floodplain above NAP-Floodplain height above NAP))^2), SQRT((Maximum height floodplain zone 1 above NAP-Floodplain height above NAP)^2+(Horizontal floodplain width zone 1)^2))))

- [m]

Inundation width zone 2=IF THEN ELSE(Water level floodplain above NAP=0,0,IF THEN ELSE(Water in floodplain=0, 0, IF THEN ELSE(Water level floodplain above NAP<=Maximum height floodplain zone 1 above NAP, 0, IF THEN ELSE(Water level floodplain above NAP<=Maximum height floodplain zone 2 above NAP, SQRT((Water level floodplain above NAP-Maximum height floodplain zone 1 above NAP)^2+((((Water in floodplain/2)-"Volume limit zone 1 (one side of river)")/Length river reach-(Water level floodplain above NAP-Maximum height floodplain zone 1 above NAP)*Horizontal floodplain width zone 1)/((Water level floodplain above NAP-Maximum height floodplain zone 1 above NAP)/0.5))^2), SQRT((Maximum height floodplain zone 2 above NAP-Maximum height floodplain zone 1 above NAP)^2+Horizontal floodplain width zone 2^2)))))

- [m]

Low water level effect=WITH LOOKUP ((Water level main channel above NAP-River bed level above NAP), ([(0,0)-(5,1.5)],(0,0),(0.6,0),(1,0.2),(1.2,0.28),(2,0.61),(2.6,0.83),(3,0.92),(4,1),(20,1)))

- [Dmnl]

Lower capacity main channel=(River bed width*(Floodplain height above NAP-River bed level above NAP)+Horizontal shore width*(Floodplain height above NAP-River bed level above NAP))*Length river reach

- [m^3]

Main channel above max cap= INTEG (Count main above cap, 0)

- [m^3]

"Main channel to floodplain in m3/s"=Water main channel to floodplain/Seconds in 1 day

- [m^3/s]

Main channel width over height=Main channel width/(Summer dike height above NAP-River bed level above NAP)

- [Dmnl]

Maximum capacity floodplain=((Main channel width+Side channel width+2*(Horizontal floodplain width zone 1+Horizontal floodplain width zone 2))*(Winter dike height above NAP-Summer dike height above NAP)+(Winter dike height above NAP-Summer dike height above NAP)/Winter dike height over width*(Winter dike height above NAP-Summer dike height above NAP))*Length river reach+"Capacity floodplain zone 1-3"

- [m^3]

Maximum capacity main channel=Length river reach*((River bed width*(Floodplain height above NAP-River bed level above NAP)+Horizontal shore width*(Floodplain height above NAP-River bed level above NAP))+Main channel width*(Summer dike height above NAP-Floodplain height above NAP))

- [m^3]

Maximum capacity side channel=IF THEN ELSE(Summer dike height above NAP<=Side channel bed above NAP,0,(Summer dike height above NAP-Side channel bed above NAP))*Length river reach*Side channel width

- [m^3]

Minimum water level for full capacity above NAP=Minimum water level for full capacity+River bed level above NAP

- [m]

No shipping allowed to prevent wave action on dikes=IF THEN ELSE(IF THEN ELSE(Water level floodplain above NAP>Summer dike height above NAP, Water level floodplain above NAP, Water level main channel above NAP)>"Maximum water level where shipping is allowed (for dike protection) above NAP", 1, 0)

- [Dmnl]

Number of days decreased capacity due to too high current=INTEG (Count current, 0)

- [Day]

Number of days decreased capacity due to too high water=INTEG (Count high, 0)

- [Day]

Number of days decreased capacity due to too low water=INTEG (Count low, 0)

- [Day]

Number of days with 0 cargo capacity=INTEG (Count 0 capacity, 0)

- [Day]

Number of days with flooding=INTEG (Count days flooding, 0)

- [Day]

Number of days with possibility of dike breach=INTEG (Count dike breach, 0)

- [Day]

Number of days with possibility of dike erosion=INTEG (Count erosion, 0)

- [Day]

"*Number of days with possibility of inward macro-instability*"=INTEG (Count inward, 0)

- [Day]

"Number of days with possibility of outward macro-instability"=INTEG (Count outward, 0)

- [Day]

Number of days with possibility of piping=INTEG (Count piping, 0)

- [Day]

Number of days with side channel flow=INTEG (Count side channel flow days, 0)

- [Day]

"Number of days with suitable channel(s)"=INTEG (Count suitable channel days, 0)
- [Day]

"Outflow (m3/day)"=*"*Outflow in m3/s"*Seconds in 1 day
- [m^3/Day]

"*Outflow in m3/s"*=Water in main channel/Length river reach*Current speed main channel
- [m^3/s]

Pioneering zone 1=IF THEN ELSE(Erosion sedimentation multiplier zone 1=0, Bare soil zone 1/Delay time pioneering, 0)
- [m^2/Day]

Pioneering zone 2=IF THEN ELSE(Erosion sedimentation multiplier zone 2=0, Bare soil zone 2/Delay time pioneering, 0)
- [m^2/Day]

Possibility of dike erosion due to overflow=Flooding per m dike effect on dike erosion*Duration of flooding effect on dike erosion
- [Dmnl]

"Possibility of inward macro-instability"=*"*Duration of water level effect on inward macro-instability"*"Water level effect on inward macro-instability"
- [Dmnl]

"Possibility of outward macro-instability"=*"*Water level difference effect on outward macro-instability"*"Duration of water level difference effect on outward macro-instability"
- [Dmnl]

Possibility of piping=Duration of water level effect on piping*Water level effect on piping
- [Dmnl]

Potential cargo capacity during high water=(Maximum cargo capacity*Fitting under bridge effect containers*"% container ships"+Maximum cargo capacity*Fitting under bridge effect bulk*(1-"% container ships"))
- [tonnes]

Potential cargo capacity during low water=Maximum cargo capacity*Low water level effect
- [tonnes]

"Reeds removal (human) zone 1"=IF THEN ELSE(Human intervention floodplain vegetation=0, 0, IF THEN ELSE(("Sum non-grass vegetation zone 1"-"Maximum reeds, scrub & forest"*Floodplain zone 1 area)>0, ("Sum non-grass vegetation zone 1"-"Maximum reeds, scrub & forest"*Floodplain zone 1 area)*"% reeds in non-grass vegetation zone 1"/Vegetation removal time, IF THEN ELSE((Reeds zone 1-Maximum reeds*Floodplain zone 1 area)>0, (Reeds zone 1-Maximum reeds*Floodplain zone 1 area)/Vegetation removal time, 0)))
- [m^2/Day]

"Reeds removal (human) zone 2"=IF THEN ELSE(Human intervention floodplain vegetation=0, 0, IF THEN ELSE(("Sum non-grass vegetation zone 2"-"Maximum reeds, scrub &

forest"*Floodplain zone 2 area)>0, ("Sum non-grass vegetation zone 2"-"Maximum reeds, scrub & forest"*Floodplain zone 2 area)*"% reeds in non-grass vegetation zone 2"/Vegetation removal time, IF THEN ELSE((Reeds zone 2-Maximum reeds*Floodplain zone 2 area)>0, (Reeds zone 2-Maximum reeds*Floodplain zone 2 area)/Vegetation removal time, 0)))

- [m²/Day]

"Reeds set-back zone 1"=Erosion sedimentation multiplier zone 1*Reeds zone 1*Erosion rate reeds

- [m²/Day]

"Reeds set-back zone 2"=Erosion sedimentation multiplier zone 2*Reeds zone 2*Erosion rate reeds

- [m²/Day]

Reeds zone 1=INTEG (Succession grass to reeds zone 1-"Reeds removal (human) zone 1"-"Reeds set-back zone 1"-Succession reeds to scrub zone 1, "Initial % reeds zone 1"*Floodplain zone 1 area)

- [m²]

Reeds zone 2=INTEG (Succession grass to reeds zone 2-"Reeds removal (human) zone 2"-"Reeds set-back zone 2"-Succession reeds to scrub zone 2, "Initial % reeds zone 2"*Floodplain zone 2 area)

- [m²]

Reset duration erosion=IF THEN ELSE(Flooding per m dike<=(0.9*Minimum problematic flooding per dike m), Duration erosion/TIME STEP, 0)

- [Day/Day]

Reset duration inward=IF THEN ELSE(Water level floodplain above NAP<=(0.9*Reference high water level above NAP), Duration inward/TIME STEP, 0)

- [Day/Day]

Reset duration outward=IF THEN ELSE("Water level difference dike-river"<(0.9*Minimum problematic water level difference), Duration outward/TIME STEP, 0)

- [Day/Day]

Reset duration piping=IF THEN ELSE(Water level floodplain above NAP<(0.9*"Critical water level piping (above NAP)"), Duration piping/TIME STEP, 0)

- [Day/Day]

Reset zone 1=IF THEN ELSE(Inundation width zone 1<0.5*Horizontal floodplain width zone 1, Duration of inundation zone 1/TIME STEP, 0)

- [Day/Day]

Reset zone 2=IF THEN ELSE(Inundation width zone 2<0.5*Horizontal floodplain width zone 2, Duration of inundation zone 2/TIME STEP, 0)

- [Day/Day]

River bed level above NAP= WITH LOOKUP (Time, ([(0,-6)-(18250,10)],(0,-3.5),(18250,-3.5)))

- [m]

River bed width=Main channel width-2*Horizontal shore width

- [m]

"Scrub removal (human) zone 1"=IF THEN ELSE(Human intervention floodplain vegetation=0, 0, IF THEN ELSE(("Sum non-grass vegetation zone 1"-"Maximum reeds, scrub & forest"*Floodplain zone 1 area)>0, ("Sum non-grass vegetation zone 1"-"Maximum reeds, scrub & forest"*Floodplain zone 1 area)*"% scrub in non-grass vegetation zone 1"/Vegetation removal time,IF THEN ELSE(("Sum scrub&forest zone 1"-"Maximum scrub & forest"*Floodplain zone 1 area)>0, ("Sum scrub&forest zone 1"-"Maximum scrub & forest"*Floodplain zone 1 area)*"% scrub in scrub&forest zone 1"/Vegetation removal time, IF THEN ELSE((Scrub zone 1-Maximum scrub*Floodplain zone 1 area)>0, (Scrub zone 1-Maximum scrub*Floodplain zone 1 area)/Vegetation removal time, 0))))

- [m^2/Day]

"Scrub removal (human) zone 2"=IF THEN ELSE(Human intervention floodplain vegetation=0, 0, IF THEN ELSE(("Sum non-grass vegetation zone 2"-"Maximum reeds, scrub & forest"*Floodplain zone 2 area)>0, ("Sum non-grass vegetation zone 2"-"Maximum reeds, scrub & forest"*Floodplain zone 2 area)*"% scrub in non-grass vegetation zone 2"/Vegetation removal time, IF THEN ELSE(("Sum scrub&forest zone 2"-"Maximum scrub & forest"*Floodplain zone 2 area)>0, ("Sum scrub&forest zone 2"-"Maximum scrub & forest"*Floodplain zone 2 area)*"% scrub in scrub&forest zone 2"/Vegetation removal time, IF THEN ELSE((Scrub zone 2-Maximum scrub*Floodplain zone 2 area)>0, (Scrub zone 2-Maximum scrub*Floodplain zone 2 area)/Vegetation removal time, 0))))

- [m^2/Day]

"Scrub set-back zone 1"=Erosion sedimentation multiplier zone 1*Scrub zone 1*Erosion rate scrub

- [m^2/Day]

"Scrub set-back zone 2"=Erosion sedimentation multiplier zone 2*Scrub zone 2*Erosion rate scrub

- [m^2/Day]

Scrub zone 1=INTEG (Succession reeds to scrub zone 1-"Scrub removal (human) zone 1"-"Scrub set-back zone 1"-Succession scrub to forest zone 1,"Initial % scrub zone 1"*Floodplain zone 1 area)

- [m^2]

Scrub zone 2=INTEG (Succession reeds to scrub zone 2-"Scrub removal (human) zone 2"-"Scrub set-back zone 2"-Succession scrub to forest zone 2, "Initial % scrub zone 2"*Floodplain zone 2 area)

- [m^2]

Side channel inflow=IF THEN ELSE(Water level main channel above NAP<=(Side channel bed above NAP+Side channel threshold), 0, "Inflow (m3/day)"*Capacity side channel effect on side channel inflow*Water level effect on side channel inflow)

- [m^3/Day]

"Side channel inflow in m3/s"=Side channel inflow/Seconds in 1 day

- [m^3/s]

Side channel outflow="Side channel outflow in m3/s"*Seconds in 1 day

- [m^3/Day]

"Side channel outflow in m3/s"=Water in side channel/Length river reach*Current speed side channel

- [m^3/s]

"Side channel to floodplain in m3/s"=Water side channel to floodplain/Seconds in 1 day

- [m^3/s]

Side channel width over height=IF THEN ELSE(Side channel width=0, 0, Side channel width/(Summer dike height above NAP-Side channel bed above NAP))

- [Dmnl]

Steepness main channel shore=(Floodplain height above NAP-River bed level above NAP)/Horizontal shore width

- [Dmnl]

Succession grass to reeds zone 1="Grass & farmland zone 1"/Delay time succession grass to reeds

- [m^2/Day]

Succession grass to reeds zone 2="Grass & farmland zone 2"/Delay time succession grass to reeds

- [m^2/Day]

Succession reeds to scrub zone 1=Reeds zone 1/ Delay time succession reeds to scrub

- [m^2/Day]

Succession reeds to scrub zone 2=Reeds zone 2/ Delay time succession reeds to scrub

- [m^2/Day]

Succession scrub to forest zone 1=Scrub zone 1/ Delay time succession scrub to forest

- [m^2/Day]

Succession scrub to forest zone 2=Scrub zone 2/ Delay time succession scrub to forest

- [m^2/Day]

"Sum non-grass vegetation zone 1"=Reeds zone 1+Scrub zone 1+Forest zone 1

- [m^2]

"Sum non-grass vegetation zone 2"=Reeds zone 2+Scrub zone 2+Forest zone 2

- [m^2]

"Sum scrub&forest zone 1"=Scrub zone 1+Forest zone 1

- [m^2]

"Sum scrub&forest zone 2"=Scrub zone 2+Forest zone 2

- [m^2]

Sum vegetation zone 1="Grass & farmland zone 1"+"Sum non-grass vegetation zone 1"

- [m^2]

Sum vegetation zone 2="Grass & farmland zone 2"+"Sum non-grass vegetation zone 2"
- [m^2]

Total flooding=INTEG (Flooding due to overflow,0)
- [m^3]

Total floodplain inundation width=Inundation width zone 1+Inundation width zone 2
- [m]

Total forest=INTEG (Count forest, 0)
- [Dmnl]

Total grass=INTEG (Count grass, 0)
- [Dmnl]

Total reeds=INTEG (Count reeds, 0)
- [Dmnl]

Total scrub=INTEG (Count scrub, 0)
- [Dmnl]

Vegetation effect on current speed floodplain=WITH LOOKUP (Floodplain vegetation roughness, ([(0,0)-(1,1)],(0,1),(1,0.25)))
- [Dmnl]

"Volume limit zone 1 (one side of river)"=0.5*Horizontal floodplain width zone 1*(Maximum height floodplain zone 1 above NAP-Floodplain height above NAP)*Length river reach
- [m^3]

Water discharge effect on current speed main channel=WITH LOOKUP (Inflow, ([(0,0)-(40000,1)],(0,0.1),(908,0.2778),(1573,0.6111),(3000,1),(40000,1)))
- [Dmnl]

Water discharge effect on current speed side channel= WITH LOOKUP ("Side channel inflow in m3/s", ([(0,0)-(40000,10)],(0,0.1),(908,0.2778),(1573,0.6111),(3000,1),(40000,1)))
- [Dmnl]

Water flowing to downstream floodplain="Water to downstream floodplain in m3/s"*Seconds in 1 day
- [m^3/Day]

Water in floodplain=INTEG (Water main channel to floodplain+Water side channel to floodplain-Flooding due to overflow-Water flowing to downstream floodplain, 0)
- [m^3]

Water in main channel=INTEG ("Inflow (m3/day)"-"Outflow (m3/day)"-Side channel inflow-Water main channel to floodplain, Initial water level*Main channel width*Length river reach)
- [m^3]

Water in side channel=INTEG (Side channel inflow-Side channel outflow-Water side channel to floodplain, Initial water level side channel*Length river reach*Side channel width)
- [m^3]

"Water level difference dike-river"=IF THEN ELSE(Water level in dike above NAP<=Water level floodplain above NAP, 0, Water level in dike above NAP-Water level floodplain above NAP)
- [m]

"Water level difference effect on outward macro-instability"= WITH LOOKUP ("Water level difference dike-river"/(0.9*Minimum problematic water level difference), ([(0,0)-(2,1)],(0,0),(0.99,0),(1.41896,0.0701754),(1.68196,0.210526),(1.83486,0.429825),(1.90826,0.618421),(2,1),(1000,1)))
- [Dmnl]

Water level difference side channel main channel=IF THEN ELSE(Water level side channel above NAP>Side channel bed above NAP, Water level side channel above NAP - Water level main channel above NAP, 0)
- [Dmnl]

"Water level effect on inward macro-instability"=WITH LOOKUP (Water level floodplain above NAP/(0.9*Reference high water level above NAP), ([(0,0)-(2,1)],(0,0),(0.99,0),(1.41896,0.0701754), (1.68196,0.210526),(1.83486,0.429825),(1.90826,0.618421),(2,1),(1000,1)))
- [Dmnl]

Water level effect on piping=WITH LOOKUP (Water level floodplain above NAP/(0.9*"Critical water level piping (above NAP)"), ([(0,0)-(2,1)],(0,0),(0.99,0),(1.41896,0.0701754),(1.68196,0.210526), (1.83486,0.429825),(1.90826,0.618421),(2,1),(1000,1)))
- [Dmnl]

Water level effect on side channel inflow=WITH LOOKUP (IF THEN ELSE(Water level main channel=0,0,Water level difference side channel main channel), ([(-5,0)-(5,10)],(-1000,10),(-5,10),(-3.01223,9.51754),(-2.00306,9.03509),(-1.02446,7.67544),(-0.535168,5.83333),(-0.229358,3.15789),(0,1),(0.382263,0.561404),(1.26911,0.210526),(2.64526,0.0701754),(5,0),(1000,0)))
- [Dmnl]

Water level floodplain above NAP=WITH LOOKUP (Water in floodplain, ([(0,0)-(7.725e+06,10)],(-1000,0),(0,0),(1e-06,3),(50000,3.5),(300000,4),(1.109e+06,5),(7.725e+06,9),(1e+15,9)))
- [m]

Water level floodplain previous timestep= DELAY FIXED (Water level floodplain above NAP, TIME STEP, Water level floodplain above NAP)
- [m]

Water level in dike above NAP=DELAY1(Water level floodplain above NAP, Delay time dike water level)
- [m]

Water level main channel=MIN(IF THEN ELSE(Water in main channel>Maximum capacity main channel,(Summer dike height above NAP-River bed level above NAP),IF THEN ELSE(Water in main channel>Lower capacity main channel, ((Floodplain height above NAP-River bed level above NAP)+((Water in main channel-Lower capacity main channel)/Length river reach/Main channel width)), Water in main channel/Length river reach/(River bed width+Horizontal shore width))), (Summer dike height above NAP-River bed level above NAP))

- [m]

Water level main channel above NAP=River bed level above NAP+Water level main channel

- [m]

Water level side channel=IF THEN ELSE(Water in side channel=0,0,Water in side channel/Side channel width/Length river reach)

- [m]

Water level side channel above NAP=IF THEN ELSE(Water level side channel=0,0,Side channel bed above NAP+Water level side channel)

- [m]

Water main channel to floodplain=IF THEN ELSE(Water in main channel=Maximum capacity main channel, 0, IF THEN ELSE(Water in main channel>Maximum capacity main channel, (Water in main channel-Maximum capacity main channel)/Time channel to floodplain, IF THEN ELSE(Water level floodplain above NAP>Summer dike height above NAP, MIN((Water in floodplain-"Capacity floodplain zone 1-3"), (Maximum capacity main channel-Water in main channel))/Time floodplain to channel*-1, 0)))

- [m^3/Day]

Water side channel to floodplain=IF THEN ELSE(Water in side channel=Maximum capacity side channel, 0, IF THEN ELSE(Water in side channel>Maximum capacity side channel, (Water in side channel-Maximum capacity side channel)/Time channel to floodplain, IF THEN ELSE(Water level floodplain above NAP>Summer dike height above NAP, MIN((Water in floodplain-"Capacity floodplain zone 1-3"),(Maximum capacity side channel-Water in side channel))/Time floodplain to channel*-1,0)))

- [m^3/Day]

"Water to downstream floodplain in m3/s"=IF THEN ELSE(Water in floodplain<=0, 0, IF THEN ELSE(Summer dike height above NAP=Floodplain height above NAP, (Water level floodplain above NAP-Summer dike height above NAP)*Main channel width*Current speed main channel+(Water level floodplain above NAP-Summer dike height above NAP)*Side channel width*Current speed side channel+(Water in floodplain/Length river reach-(Water level floodplain above NAP-Summer dike height above NAP)*(Side channel width+Main channel width))*Current speed floodplain, IF THEN ELSE(Water level floodplain above NAP<=Summer dike height above NAP, Water in floodplain/Length river reach*Current speed floodplain, ((Water level floodplain above NAP-Summer dike height above NAP)*(Main channel width)*Current speed main channel+(Water level floodplain above NAP-Summer dike height above NAP)*(Side channel width)*Current speed side channel+(Water in floodplain/Length river reach-((Water level floodplain above NAP-Summer dike height above NAP)*Main channel width))*Current speed floodplain))))

- [m^3/s]

Water volume effect on current speed floodplain=WITH LOOKUP (Water in floodplain, ([(0,0)-(1e+08,1)],(-2e+06,0),(0,0),(500000,1),(1e+08,1)))

- [Dmnl]

Width effect on current speed side channel=WITH LOOKUP (IF THEN ELSE(Side channel width over height=0, 0, Main channel width over height/Side channel width over height), ([(1,0)-(100,10)],(0,0),(0.519878,0.087719),(0.844037,0.263158),(0.93578,0.570175),(1,1),(8.26606,4.42982),(15.2294,5.74561),(25.8257,6.79825),(41.8716,7.5),(67.6055,7.89474),(100,8)))

- [Dmnl]

Winter dike height over width=(Winter dike height above NAP-Maximum height floodplain zone 2 above NAP)/(0.5*Winter dike width)

- [Dmnl]

D2 Model parameters

Table D1: Model paramaters

Variable	Unit	Value	Uncertainty range	Source	Remarks
% container ships	Dmnl	0.14	0.14	Van Dorsser (2017)	
Average permeability sand	m/day	15	3 - 30	Grondwaterformules.nl (2018)	
Average pipe development rate	m/day	1	0.5 - 2	Vorogushyn (2009)	Assumes seepage has already taken place
Cargo capacity adjustment time	day	2	0.25 - 30	Educated guess	
CBligh	Dmnl	15	[18, 15, 12, 9, 4]	Sellmeijer (2006); DINOloket (2019)	[fine silty sand, moderate fine sand, course sand, fine gravel, course gravel]
Delay time pioneering	day	730	365 - 1460	Encyclopaedie Brittanica (2018)	2 year
Delay time succession reeds to scrub	day	16790	7665 - 25915	Encyclopaedie Brittanica (2018)	50 years - 4 years
Delay time succession scrub to forest	day	18250	25915 - 36500	Encyclopaedie Brittanica (2018)	100 years - 50 years
Delay time succession grass to reeds	day	730	365 - 1460	Encyclopaedie Brittanica (2018)	4 years - 2 years

Variable	Unit	Value	Uncertainty range	Source	Remarks
Erosion rate forest	Dmnl	0.00001	0.000001 - 0.0001	Educated guess	
Erosion rate grass	Dmnl	0.001	0.0001 - 0.01	Educated guess	
Erosion rate reeds	Dmnl	0.0001	0.00001 - 0.001	Educated guess	
Erosion rate scrub	Dmnl	0.0001	0.00001 - 0.001	Educated guess	
Floodplain height above NAP	m	3.0	3	AHN (2018)	
Gap between water level and bridge at reference high water level	m	9.1	9.1	Interviewee Van Dorsser	
Horizontal shore width	m	125	25 - 125	Assumption	
Horizontal floodplain width zone 1	m	50	25-200	Assumption	
Horizontal floodplain width zone 2	m	150	50 - 300	Assumption	
Initial % forest zone 1	Dmnl	0.2	0 - 1	Assumption	
Initial % forest zone 2	Dmnl	0.2	0 - 1	Assumption	
Initial % grass zone 1	Dmnl	0.5	0 - 1	Assumption	
Initial % grass zone 2	Dmnl	0.5	0 - 1	Assumption	
Initial % reeds zone 1	Dmnl	0.1	0 - 1	Assumption	
Initial % reeds zone 2	Dmnl	0.1	0 - 1	Assumption	
Initial % scrub zone 1	Dmnl	0.2	0 - 1	Assumption	
Initial % scrub zone 2	Dmnl	0.2	0 - 1	Assumption	
Initial cargo capacity	tonnes	2500000	0 - 5000000	Bosschieter (2005)	
Initial river bed level above NAP	m	-3.5	-3.5	Sieben (2009)	
Initial water level	m	3	0 - 12	Assumption	
Initial water level side channel	m	0	0 - 12	Assumption	
Length river reach	m	2000	500 - 3000	Distance measure google maps	
Lower limit current speed	m/s	0.01	0.01 - 0.5	Educated guess	
Main channel width	m	300	200 - 600	Distance measure google maps	
Maximum cargo capacity	tonnes	500000	400000-600000	Bosschieter (2005)	
Maximum current speed channels	m/s	1.8	1.6 - 2.2	Rijkswaterstaat 2004	
Maximum current speed floodplain	m/s	0.25	0.2 - 0.4	Ruimte voor levende rivieren (2018)	
Maximum current speed for navigation	m/s	1.7	1.1 - 1.8	Educated guess	
Maximum forest	Dmnl	0.5667	0 - 0.75	Rijkswaterstaat (2014b); Rijkswaterstaat (2018)	
Maximum height floodplain zone 1 above NAP	m	3.5	3.5	AHN (2018)	
Maximum height floodplain zone 2 above NAP	m	4	4	AHN (2018)	

Variable	Unit	Value	Uncertainty range	Source	Remarks
Maximum reeds	Dmnl	0.6667	0 - 1	Rijkswaterstaat (2014b); Rijkswaterstaat (2018)	
Maximum reeds, scrub & forest	Dmnl	0.5667	0 - 1	Rijkswaterstaat (2014b); Rijkswaterstaat (2018)	
Maximum scrub	Dmnl	0.2333	0 - 0.5	Rijkswaterstaat (2014b); Rijkswaterstaat (2018)	
Maximum scrub & forest	Dmnl	0.5667	0 - 0.75	Rijkswaterstaat (2014b); Rijkswaterstaat (2018)	
Maximum water level where shipping is allowed (for dike protection) above NAP	m	9	5 - 10	Educated guess	
Minimum problematic duration of exceedance high water	day	14	2 - 25	Educated guess	
Minimum problematic duration of flooding per dike m	day	0.25	1/24 - 5	Van der Meer (2008)	6 hours
Minimum problematic duration of water level difference	day	2	0.25 - 10	Educated guess	
Minimum problematic flooding per dike m	m^2/s	0.05	0.05 - 0.15	Van der Meer (2008)	50 l/s/m; Ranges from 50 to above 125
Minimum problematic water level difference	m	3	1 - 10	Educated guess	
Minimum water level for full capacity	m	4	4	Bosschieter (2005)	
Reference high water level above NAP	m	8.75	8 - 9.5	Rijkswaterstaat 1986	Maatgevende hoogwaterstand (1/1250) at Haaften
Roughness forest	Dmnl	0.75	0.4 - 0.9	Educated guess	
Roughness grass & farmland	Dmnl	0.1	0 - 0.5	Educated guess	
Roughness reeds	Dmnl	0.4	0.1 - 0.6	Educated guess	
Roughness scrub	Dmnl	1	0.5 - 1	Educated guess	
Seconds in 1 day	s/day	86400	86400	Calculated	
Side channel bed above NAP	m	-3.5	-3.5 – 5	Assumption	
Side channel threshold	m	0	0 – 8.5	Assumption	
Side channel width	m	0	0 – 75	Assumption	
Summer dike height above NAP	m	5	0 - 5	AHN (2018)	
Time floodplain to channel	day	0.020833	(1/24)*(1/2) - (1/24)	Educated guess	30 minutes
Time channel to floodplain	day	0.004167	(1/24)*(1/10) - (1/24)*(1/2)	Educated guess	6 minutes
Upper limit current speed	m/s	1	0.5 - 1.8	Educated guess	
Vegetation removal time	day	14	5 - 30	Educated guess	
Winter dike height above NAP	m	9	5 - 15	AHN (2018)	
Winter dike width	m	45	30 - 60	Distance measure google maps	

Appendix E: Model verification

Model verification has the purpose of checking whether the model has been coded correctly, whether the units are consistent with the real world and within the model, and whether the numerical simulation is accurate (Pruyt, 2013). Vensim will alert the modeller to many numerical errors or errors in coding already when performing test runs during the modelling process. If equations are incomplete or incorrect, the model will not run and Vensim will show an error message and direct the modeller to the equation with the error. However, even when the model is finished and apparently runs without errors, this does not automatically mean that the model is correct. Therefore, several checks have been performed. The first is the causal relations check, the second is the unit check, and the third is the numerical simulation check. How these checks work and their results for each of the sub-models in this research is explained in more detail in the following sections.

E1 Causal relations check

In the model conceptualization phase, the relations between real-world river aspects have been simplified into causal diagrams that indicate which aspect influences which other aspects. This resulted in causal relations (either positive or negative) from one variable to another. If the causal relation is positive in reality (so an increase in the first variable results in an increase of the second variable), it should be positive in the causal diagram and in the actual model as well. The causal relations check compares the causal diagrams of each sub-model with the actual implementation in a stock-flow diagram to determine whether the direction of the causal relations has been modelled correctly.

River sub-model

The river sub-model contains three stock variables; *Water in side channel*, *Water in main channel*, and *Water in floodplain*. For each of these stock variables, their causal diagram and a picture of their stock-flow structure is shown in *figure E1, E2,* and *E3*. For *Water in side channel* the causal relations have been translated correctly; it is increased by *Side channel inflow* and decreased by *Side channel outflow,* and *Water side channel to floodplain.* The latter variable is called *Inflow floodplain* in the causal diagram, because there it was aggregated with the flow from the main channel to the floodplain. When translating the causal diagram into an actual model, it became clear that the inflow into the floodplain had to be split, since the side channel and main channel are represented by separate stocks in the model.

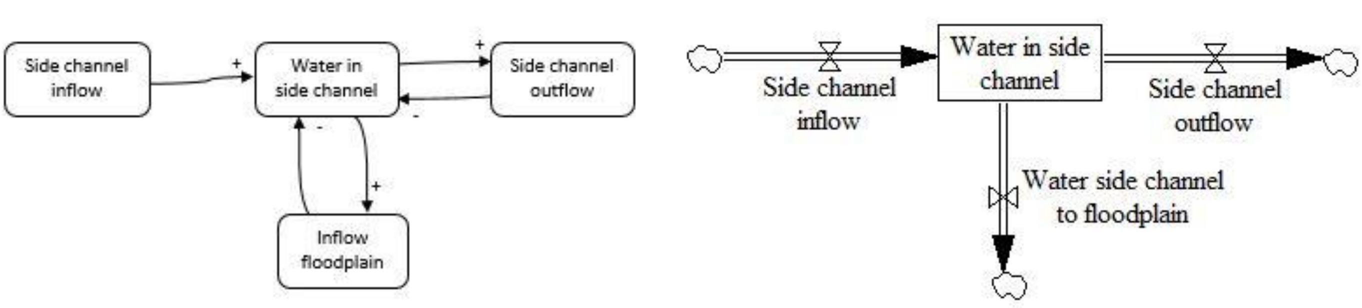


Figure E1: Causal diagram and stock-flow structure of Water in side channel

For *Water in main channel* the causal relations are modelled correctly as well; it is increased by *Inflow (m^3/day),* and decreased by *Side channel inflow, Outflow (m^3/day),* and *Water main channel to floodplain.* Two important notes need to be made. First of all, in the causal diagram the inflow is indicated in m^3/s, whereas in the stock-flow structure it is indicated in m^3/day. The reason for this is that discharge data is usually given in m³/s, and therefore it is convenient for comparison if this is the unit for inflow and outflow. The model, however has 'day' as a unit for time (the reasoning behind this is explained in section E3), and therefore needs flow variables to have x/day as their unit. In the model, the inflow in m³/day is calculated by multiplying the inflow in m³/s with the number of seconds in one day (86400). The second note has already been discussed for *figure E1*; in the causal diagram, *Inflow floodplain* comprised both the inflow into the floodplain from the main channel and from the side channel, while in the actual model this flow had to be split.

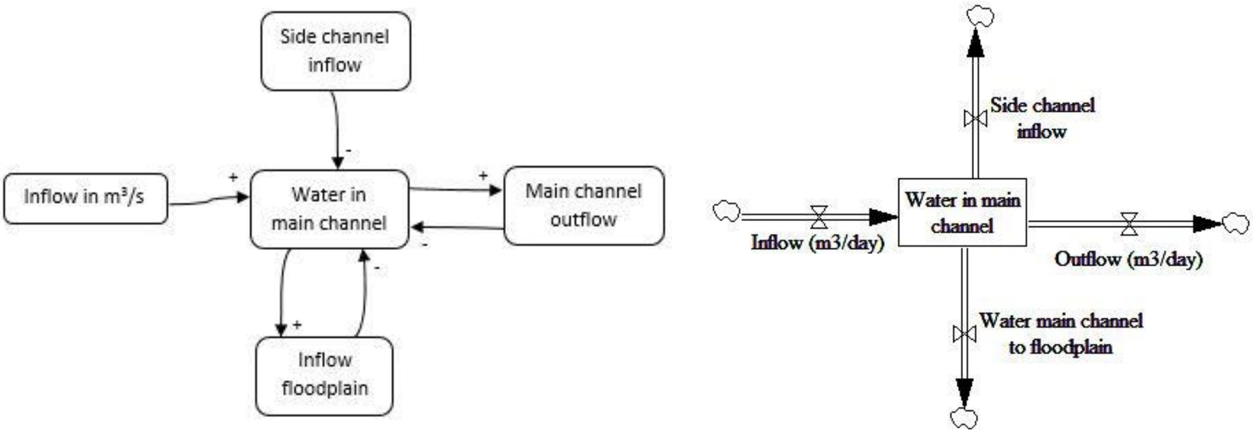


Figure E2: Causal diagram and stock-flow structure of Water in main channel

Also for *Water in floodplain* the causal relations were translated into stock-flow structures correctly. The inflow is split into *Water main channel to floodplain* and *Water side channel to floodplain*, and the outflow consists of *Flooding over winter dike* and *Water flowing to downstream floodplain*.

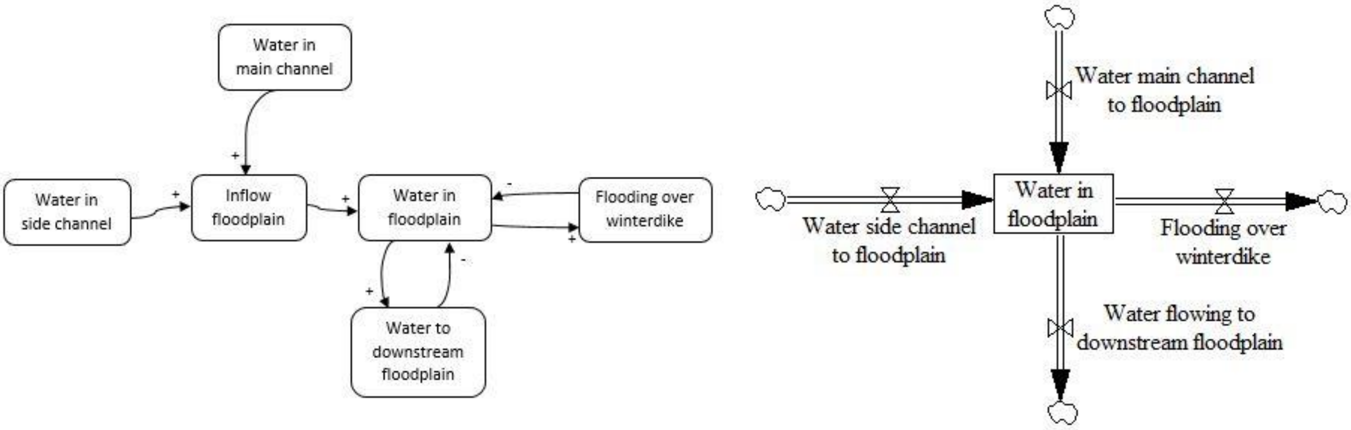


Figure E3: Causal diagram and stock-flow structure of Water in floodplain

Environment sub-model

The environment sub-model contains eight stock variables, but this is twice the same structure with four stock variables (for zone 1 and for zone 2 of the floodplain), so it will only be explained for the structure of zone 1. The stocks are *Grass & farmland zone 1, Reeds zone 1, Scrub zone 1,* and *Forest zone 1*. *Figure E4, E5, E6,* and *E7* show their causal diagrams and stock-flow structure. The figures show that the directions of the causal relationships have been implemented correctly in the model. There are two differences between the causal diagrams and the stock-flow structures. First of all, in the causal diagrams, erosion/sedimentation floodplain directly influences the share of a vegetation class, while in the model it influences (for example) *Grass &*

farmland set-back zone 1 that in turn influences *Grass & farmland zone 1*, which then determines the share of grass in the total floodplain area. The reason for this difference is that the causal diagram is a relatively high level diagram, whereas the model is very detailed. The second difference is that *Human vegetation removal* is a single variable in the causal diagrams, while it had to be split into three different flows in the model. This is also due to the fact that the causal diagram does not contain all details.

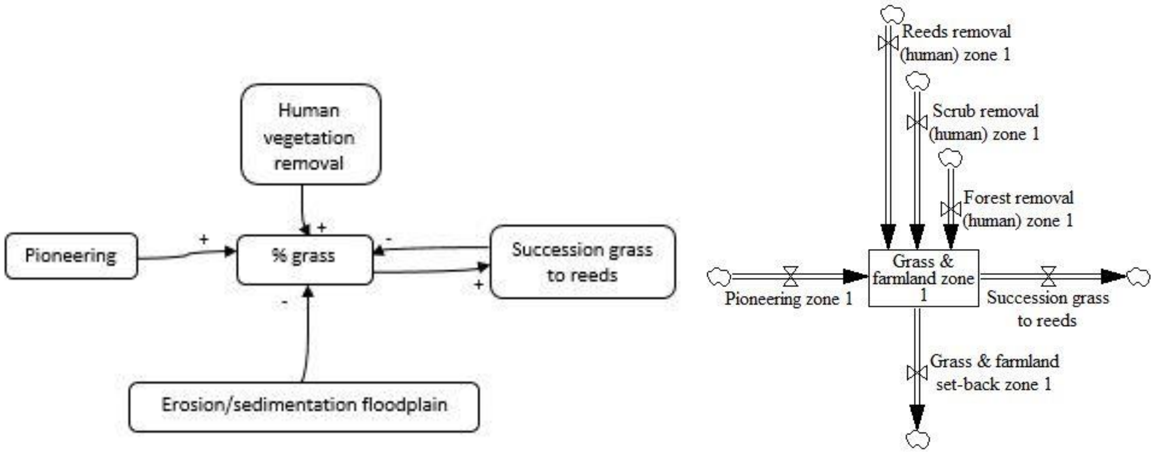


Figure E4: Causal diagram and stock-flow structure of Grass & farmland

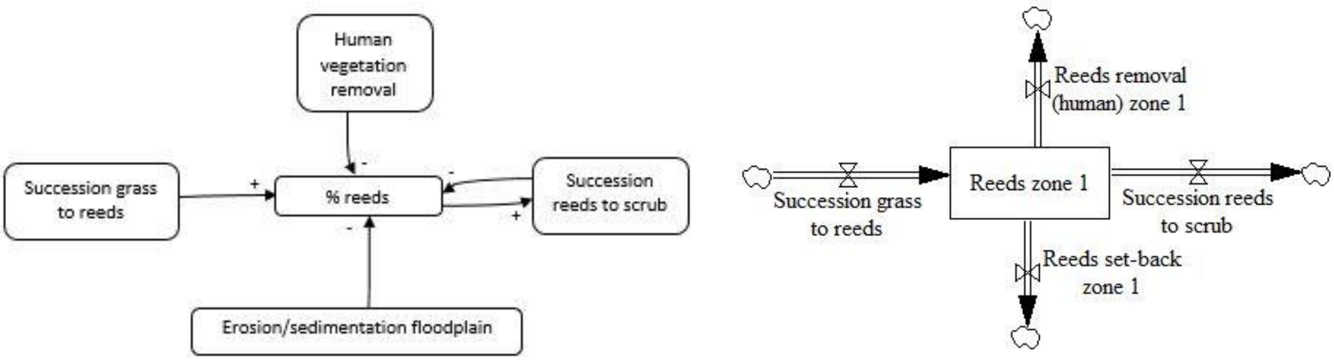


Figure E5: Causal diagram and stock-flow structure of Reeds

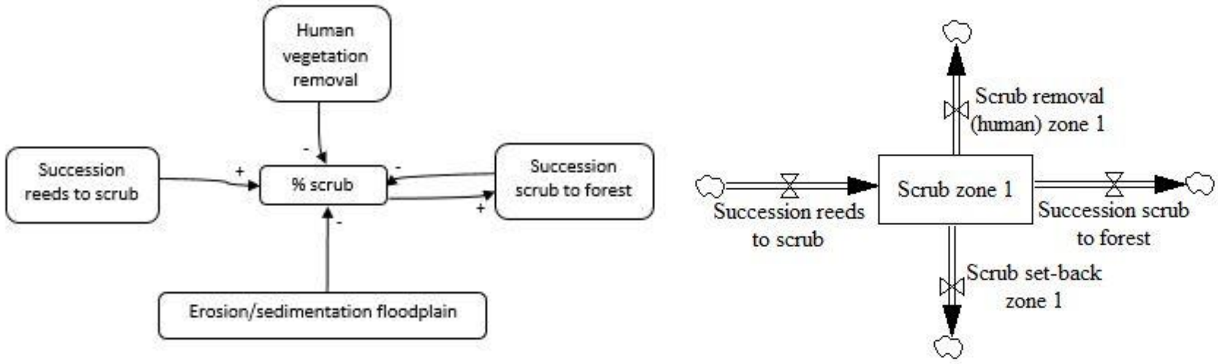


Figure E6: Causal diagram and stock-flow structure of Scrub

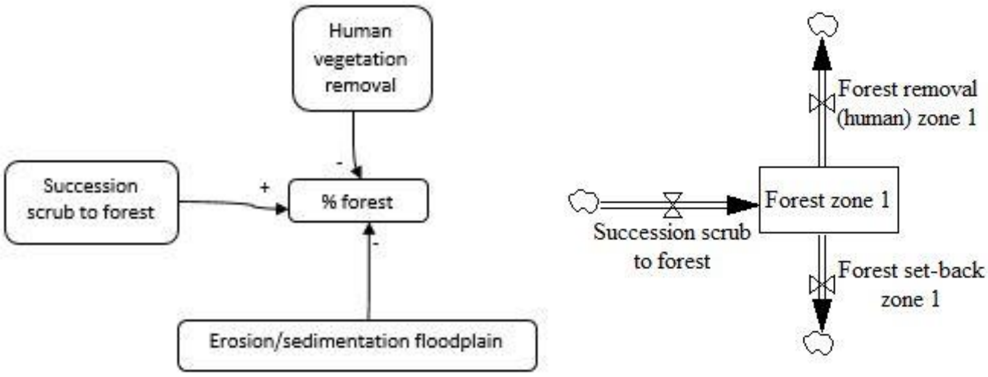


Figure E7: Causal diagram and stock-flow structure of Forest

Navigation sub-model
The navigation sub-model contains only one stock variable; *Cargo capacity*. The directions of all causal relations have been implemented correctly in the stock-flow structure, as can be seen in *figure E8*.

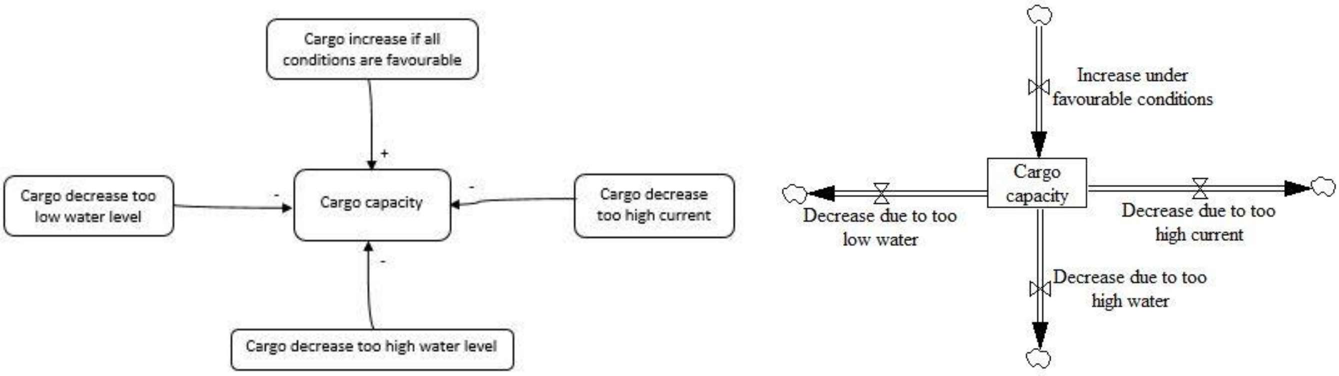


Figure E8: Causal diagram and stock-flow structure of Cargo capacity

Flood protection sub-model
The flood protection sub-model does not contain any stock-flow structures, except for the purpose of counting time or determining the duration of a certain event. These have been implemented to be able to store and compare outputs of the models under different input conditions, but have not been included in the causal diagrams because they do not represent key processes in the system. Therefore, no causal diagrams and stock-flow structures were compared for this sub-model.

E2 Unit check

Two steps had to be taken within the unit check; the consistency of model units with real-world units had to be determined and the consistency of units within the model had to be inspected. The former was done by presenting a table of variables and their units, and comparing this with real world river processes. The latter was done within Vensim, where it was checked whether the unit on the left hand side of the equation (the variable that is calculated) is equal to the unit on the right hand side (the variables in the formula). These two unit checks have been performed for each sub-model separately.

River sub-model

Unit consistency check (real-world)

Table E1: Real-world unit consistency river

Variable	Unit	Real-world consistent?	Variable	Unit	Real-world consistent?
Capacity floodplain zone 1-3	m^3	V	*Seconds in 1 day*	s/day	V
Current speed floodplain	m/s	V	*Side channel bed above NAP*	m	V
Current speed main channel	m/s	V	*Side channel inflow*	m^3/day	X
Current speed side channel	m/s	V	*Side channel inflow in m^3/s*	m^3/s	V
Flooding due to overflow	m^3/day	X	*Side channel outflow*	m^3/day	X
Flooding in m^3/s	m^3/s	V	*Side channel outflow in m^3/s*	m^3/s	V
Floodplain height above NAP	m	V	*Side channel threshold*	m	V
Floodplain vegetation roughness	Dmnl	X	*Side channel to floodplain in m^3/s*	m^3/s	V
Horizontal floodplain width zone 1	m	V	*Side channel width*	m	V
Horizontal floodplain width zone 2	m	V	*Steepness main channel shore*	Dmnl	V
Horizontal shore channel width	m	V	*Summer dike height above NAP*	m	V
Inflow (m^3/day)	m^3/day	X	*Time channel to floodplain*	day	V
Inflow in m^3/s	m^3/s	V	*Time floodplain to channel*	day	V
Initial water level	m	V	*Volume limit zone 1 (one side of river)*	m^3	V
Initial water level side channel	m	V	*Water flowing to downstream floodplain*	m^3/day	X
Length river reach	m	V	*Water in floodplain*	m^3	V
Main channel to floodplain in m^3/s	m^3/s	V	*Water in main channel*	m^3	V
Main channel width	m	V	*Water in side channel*	m^3	V
Maximum capacity floodplain	m^3	V	*Water level floodplain above NAP*	m	V
Maximum capacity main channel	m^3	V	*Water level main channel*	m	V
Maximum capacity side channel	m^3	V	*Water level main channel above NAP*	m	V
Maximum current speed channels	m/s	V	*Water level side channel*	m	V
Maximum current speed floodplain	m/s	V	*Water level side channel above NAP*	m	V
Maximum height floodplain zone 1 above NAP	m	V	*Water main channel to floodplain*	m^3/day	X
Maximum height floodplain zone 2 above NAP	m	V	*Water side channel to floodplain*	m^3/day	X
Outflow (m^3/day)	m^3/day	X	*Water to downstream floodplain in m^3/s*	m^3/s	V
Outflow in m^3/s	m^3/s	V	*Winter dike height above NAP*	m	V
River bed level above NAP	m	V	*Winter dike height over width*	Dmnl	V
River bed width	m	V	*Winter dike width*	m	V

Table E1 shows the variables in the river sub-model, their units, and whether they are consistent with the real-world phenomenon they represent. Most variables have a unit that is consistent with the real world, but there are some exceptions. The most important one is the unit m^3/day, which is usually not used in hydrology. A better unit is m^3/s, since most hydrographs are drawn with that unit. The model, however, uses day as its unit for time, and therefore requires input in that unit. Therefore, all variables that are calculated in m^3/day, are also calculated in m^3/s, to make the model output comparable to the real world and to make the output easier understood by hydrologists. Another unit that is not similar to the real-world, is the Dimensionless unit of

Floodplain vegetation roughness. The hydraulic roughness of a channel or floodplain can for example be indicated by Manning's n-value, which is not necessarily between 0 and 1 and is also not dimensionless. However, since this research tries to simplify the river system, and the exact floodplain vegetation is not an outcome of interest, making this variable dimensionless (and between 0 and 1) is a satisfactory solution.

Unit consistency check (Vensim)
12 unit errors were found for this model. Six of these were related to lookups with a dimensioned input, the other seven were caused by Vensim's inability to calculate with units. *Table E2* explains the unit errors and how they have been solved. If variables were 'Disregarded, but included in sensitivity analysis', this means that they have been analysed in the model validation process (see appendix F and chapter 9).

Table E2: Model unit consistency river

Variable	**Error type**	**Explanation**	**What has been done?**
Floodplain vegetation roughness	Dimensioned lookup	Lookup based on *Time*, because this variable is output of another sub-model. When the models are combined, this error will disappear.	Disregarded
Inflow in m^3/s	Dimensioned lookup	Lookup based on Time, because it is a time series input	Disregarded
Water discharge effect on current speed floodplain	Dimensioned lookup	Lookup functions with input in m^3/s, but necessary	Disregarded
Water discharge effect on current speed main channel	Dimensioned lookup	Lookup functions with input in m^3/s, but necessary	Disregarded
Water discharge effect on current speed side channel	Dimensioned lookup	Lookup functions with input in m^3/s, but necessary	Disregarded
Water level floodplain above NAP	Dimensioned lookup	Lookup functions with input in m^3, but necessary	Disregarded
Maximum capacity main channel	Right and left hand units do not match	Variable has unit m^3, formula m*m*m	Disregarded
Maximum capacity side channel	Right and left hand units do not match	Variable has unit m^3, formula m*m*m	Disregarded
Water in main channel (initial value)	Right and left hand units do not match	Variable has unit m^3, formula m*m*m	Disregarded
Water in side channel (initial value)	Right and left hand units do not match	Variable has unit m^3, formula m*m*m	Disregarded
Water level side channel	Right and left hand units do not match	Variable has unit m, formula $m^3/m/m$	Disregarded
Water to downstream floodplain in m^3/s	Right and left hand units do not match	Within the formula, addition of unit m^3/m with m*m	Disregarded

Environment sub-model

Unit consistency check (real-world)

Table E3: Real-world unit consistency environment

Variable	Unit	Real-world consistent?
% forest in non-grass vegetation	Dmnl	V
% forest in scrub&forest	Dmnl	V
% forest	Dmnl	V
% grass	Dmnl	V
% reeds in non-grass vegetation	Dmnl	V
% reeds	Dmnl	V
% scrub in non-grass vegetation	Dmnl	V
% scrub in scrub&forest	Dmnl	V
Bare soil	m^2	V
Current speed main channel	m/s	V
Current speed side channel	m/s	V
Delay time pioneering	day	V
Delay time succession grass to reeds	day	V
Delay time succession reeds to scrub	day	V
Delay time succession scrub to forest	day	V
Duration of inundation	day	V
Erosion rate forest	Dmnl/day	X
Erosion rate grass	Dmnl/day	X
Erosion rate reeds	Dmnl/day	X
Erosion rate scrub	Dmnl/day	X
Erosion sedimentation multiplier	Dmnl	V
Floodplain height above NAP	m	V
Floodplain vegetation roughness	Dmnl	X
Floodplain area	m^2	V
Forest removal (human)	m^2/day	V
Forest set-back	m^2/day	V
Forest	m^2	V
Grass & farmland set-back	m^2/day	V
Grass & farmland	m^2	V
Horizontal floodplain width	m	V
Initial % forest zone 1	Dmnl	V
Initial % forest zone 2	Dmnl	V
Initial % grass zone 1	Dmnl	V
Initial % grass zone 2	Dmnl	V
Initial % reeds zone 1	Dmnl	V
Initial % reeds zone 2	Dmnl	V
Initial % scrub zone 1	Dmnl	V
Initial % scrub zone 2	Dmnl	V
Inundation width	m	V
Length river reach	m	V
Lower limit current speed	Dmnl	V
Maximum forest	Dmnl	V
Maximum reeds, scrub & forest	Dmnl	V
Maximum height floodplain above NAP	m	V
Maximum reeds	Dmnl	V
Maximum scrub	Dmnl	V
Maximum scrub & forest	Dmnl	V
Percentage of vegetation after human intervention	Dmnl	V
Pioneering	m^2/day	V
Reeds removal (human)	m^2/day	V
Reeds set-back	m^2/day	V
Reeds	m^2	V
Roughness forest	Dmnl	X
Roughness grass & farmland	Dmnl	X
Roughness reeds	Dmnl	X
Roughness scrub	Dmnl	X
Scrub removal (human)	m^2/day	V
Scrub set-back	m^2/day	V
Scrub	m^2	V
Succession grass to reeds	m^2/day	V
Succession reeds to scrub	m^2/day	V
Succession scrub to forest	m^2/day	V
Sum non-grass vegetation	m^2	V
Sum scrub&forest	m^2	V
Sum vegetation	m^2	V
Upper limit current speed	m/s	V
Vegetation removal time	day	V
Volume limit floodplain	m^3	V
Water in floodplain	m^3	V
Water in side channel	m^3	V
Water level floodplain above NAP	m	V

Most variables have units that are relevant for the real world (as can be seen in *table E3*). However, two issue were found regarding to real-world consistency. The first issue has already been mentioned in the discussion of the real-world consistency of the units in the river model;

roughness of a river channel or floodplain usually does not have a dimensionless unit. The second issue regards the erosion rate of the four vegetation types. This is usually indicated by the amount of material that is eroded per unit of time, so m^2/day would be suitable. In the model, however, it is chosen to give these variables the unit Dmnl/day and to multiply this with the area that covers the vegetation class in question (resulting in m^2/day erosion). The erosion therefore actually indicates a percentage of erosion per day.

Unit consistency check (Vensim)
8 unit errors were found for this sub-model. Four were related to lookups with a dimensioned input, the other four were caused by Vensim's inability to calculate with units. *Table E4* explains the unit errors and how they have been solved.

Table E4: Model unit consistency environment

Variable	Error type	Explanation	What has been done?
Current speed main channel	Dimensioned lookup	Lookup based on *Time*, because this variable is output of another sub-model. When the models are combined, this error will disappear.	Disregarded
Current speed side channel	Dimensioned lookup	Lookup based on *Time*, because this variable is output of another sub-model. When the models are combined, this error will disappear.	Disregarded
Erosion sedimentation multiplier	Dimensioned lookup	Lookup functions with input in day, but necessary	Disregarded, but included in sensitivity analysis
Floodplain area	Right and left hand units do not match	Variable has unit m^2, formula m*m	Disregarded
Inundation width zone 1	Right and left hand units do not match	Within the formula, addition of unit m*m with $m^3*m^3/(m*m*m*m)$	Disregarded
Inundation width zone 2	Right and left hand units do not match	Within the formula, addition of unit m^3/m with m*m	Disregarded
Volume limit	Right and left hand units do not match	Variable has unit m^3, formula m*m*m	Disregarded
Water in side channel	Dimensioned lookup	Lookup based on *Time*, because this variable is output of another sub-model. When the models are combined, this error will disappear.	Disregarded

Navigation sub-model

Unit consistency check (real-world)
All variables in the navigation sub-model have units that are consistent with the real-world phenomena they represent (see *table E5*).

Table E5: Real-world unit consistency navigation

Variable	Unit	Real-world consistent?	Variable	Unit	Real-world consistent?
% container ships	Dmnl	V	*Maximum cargo capacity*	tonnes	V
Actual gap	m	V	*Maximum current speed for navigation*	m/s	V
Cargo capacity	tonnes	V	*Maximum water level where shipping is allowed (for dike protection) above NAP*	m	V
Cargo capacity adjustment time	day	V	*Minimum water level for full capacity*	m	V
Current speed main channel	m/s	V	*Minimum water level for full capacity above NAP*	m	V
Decrease due to too high current	tonnes/day	V	*Potential cargo capacity during high water*	tonnes	V
Decrease due to too high water	tonnes/day	V	*Potential cargo capacity during low water*	tonnes	V
Decrease due to too low water	tonnes/day	V	*Reference high water level above NAP*	m	V
Gap between water level and bridge at reference high water level	m	V	*River bed level above NAP*	m	V
Increase under favourable conditions	tonnes/day	V	*Water level main channel above NAP*	m	V
Initial cargo capacity	tonnes	V			

Unit consistency check (Vensim)

The unit check unveiled four unit errors in the navigation sub-model, see *table E6*.

Table E6: Model unit consistency navigation

Variable	Error type	Explanation	What has been done?
Water level main channel above NAP	Dimensioned lookup	Lookup based on *Time*, because this variable is output of another sub-model. When the models are combined, this error will disappear.	Disregarded
Fitting under bridge effect bulk	Dimensioned lookup	Lookup functions with input in m, but necessary	Disregarded
Fitting under bridge effect containers	Dimensioned lookup	Lookup functions with input in m, but necessary	Disregarded
Low water level effect	Dimensioned lookup	Lookup functions with input in m, but necessary	Disregarded

Flood protection sub-model

Unit consistency check (real-world)

Table E7 shows the variables that are present in the flood protection sub-model and their units. Most units are consistent with the real-world phenomena they represent. However, the four variables indicating the possibilities of the four dike failure mechanisms do not completely correspond with the real-world phenomena they represent. The variables in the model only indicate whether a mechanism might occur or not, they do not indicate the exact likelihood of the occurrence. In reality, more exact likelihoods are calculated for each failure mechanisms, but more detailed models are required for this. Since this research merely wants to show the possible conflicts that could arise between flood protection and the other river uses, less detail is tolerated.

Table E7: Real-world unit consistency flood protection

Variable	Unit	Real-world consistent?
Average duration of pipe formation	day	V
Average permeability of sand	m/day	V
Average pipe development rate	m/day	V
Cbligh	Dmnl	V
Critical water level piping (above NAP)	m	V
Duration erosion	day	V
Duration inward	day	V
Duration outward	day	V
Duration piping	day	V
Extreme rainfall event	mm	V
Flooding in m^3/s	m^3/s	V
Flooding per m dike	$m^3/s/m$	V
Length river reach	m	V
Maximum floodplain height above NAP	m	V
Minimum problematic duration of exceedance high water	day	V
Minimum problematic duration of flooding per m dike	day	V
Minimum problematic duration of water level difference	day	V
Minimum problematic flooding per dike m	$m^3/s/m$	V
Minimum problematic water level difference	m	V
Possibility of dike erosion due to overflow	Dmnl	X
Possibility of inward macro-instability	Dmnl	X
Possibility of outward macro-instability	Dmnl	X
Possibility of piping	Dmnl	X
Reference high water level above NAP	m	V
Water level difference dike-river	m	V
Water level floodplain above NAP	m	V
Water level floodplain previous time step	m	V
Water level in dike above NAP	m	V
Winter dike width	m	V

Unit consistency check (Vensim)

Three issues were found using the unit check for this sub-model, as is described in *table E8*.

Table E8: Model unit consistency flood protection

Variable	Error type	Explanation	What has been done?
Flooding in m^3/s	Dimensioned lookup	Lookup based on *Time*, because this variable is output of another sub-model. When the models are combined, this error will disappear.	Disregarded
Water level floodplain above NAP	Dimensioned lookup	Lookup based on *Time*, because this variable is output of another sub-model. When the models are combined, this error will disappear.	Disregarded
Flooding per m dike	Right and left hand units do not match	Variable has unit m^2/s, formula $m^3/m/s$	Unit of variable has been changed into $m^3/s/m$

E3 Numerical simulation check

The last model verification step relates to the model settings that determine the numerical model integration. System dynamics modelling simulates continuous behaviour of complex systems by calculating values for each variable over small time intervals. Therefore it is very important that the time step between each calculation and the numerical integration method are chosen correctly.

The choice of integration method for this model is Runge-Kutta4 (RK4), which is more accurate than Euler (for the same time step), but does not compromise the computational capacity of the computer too much. The fixed version of RK4 uses the user-defined time step, while the automatic version decreases the time step if this is necessary for sufficient accuracy. In this research RK4 fixed was chosen, because the time step is already so small that a further decrease might increase the model run time and the size of the output files too much.

For the choice of the time step, a guideline exists; first, the time step is set to $\frac{1}{10}$ of the smallest time variable or delay time in the model. The model is run for this time step, and then the time step is halved and the model is run again. If the two runs produce the same system behaviour, the largest time step was sufficiently small. If not, the time step should be halved again and the same test needs to be performed. For each sub-model, the necessary time step was determined, and the smallest of these time steps was chosen as the time step for the combined model. In the next four sections, it is explained how the time steps were determined for each sub-model. It resulted in a necessary time step of 0.00104167 days, which was required for accurate numerical integration of the river sub-model.

River sub-model

The smallest time variable in the river sub-model is *Time channel to floodplain*, which should have a value that is very small (< 1 minute) to make sure that the water in the river channels does not exceed its maximum. However, this would result in an even smaller time step, which would cause computational and storage problems. Therefore, it was chosen to set this variable to 6 minutes, and to allow the time step to be less than 10 times as small as this variable (but at least 4 times as small). The model had therefore to be tested with a time step of 1.5 minutes, which is 0.00104167 days, and a time step of 0.75 minutes. The latter time step, however, led to computational problems, so instead the model was tested with a time step of 2 minutes (0.001389 days) to check whether the model behaviour changed when changing the time step. *Figure E9* shows that there was no difference between the two model runs, and therefore it was concluded that a time step of 1.5 minutes is sufficiently small. An important note is that with a value of 6 minutes for *Time channel to floodplain*, the water in the main channel at the peak of a flood will exceed its maximum, which means that the amount of water in the floodplain is actually larger than the model reports.

Environment sub-model

The smallest time constant in the environment sub-model is *Vegetation removal time* with a value of 14 days. However, since the unit for time is days, the time step should not be bigger than 1 day. This was thus the first time step to try, and its results were compared with the results of a run with a time step of 0.5 days. As *figure E10* shows, there was no difference between the outputs of the two runs, so a time step of 1 day would be sufficiently accurate for the environment sub-model.

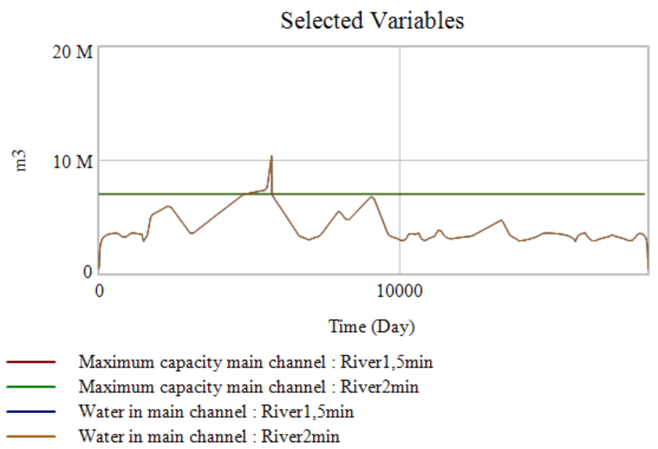


Figure E9: River sub-model output with time step 0.001389 and time step 0.00104167

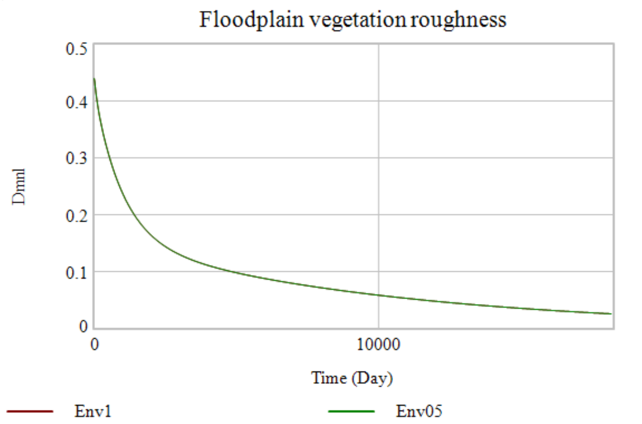


Figure E10: Environment sub-model output with time step 1 and time step 0.5

Navigation sub-model

The smallest time constant in the navigation sub-model is 2 days, so the first test run for the determination of the necessary time step has been performed with a time step of 0.2 days, and the second run has been performed with a time step of 0.1 days. The outputs of these runs were the same, as can be seen in *figure E11*.

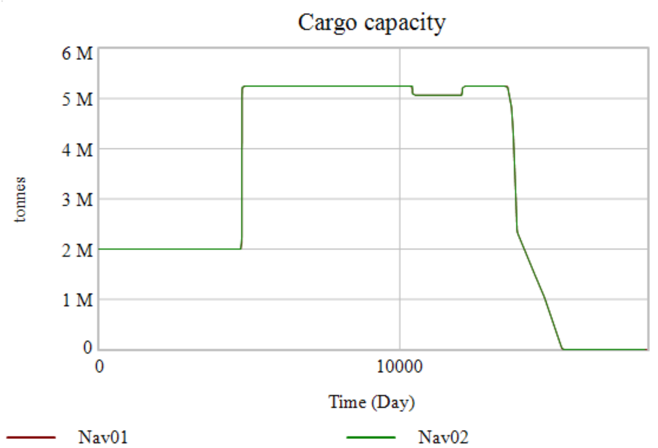


Figure E11: Navigation sub-model output with time step 0.2 and time step 0.1

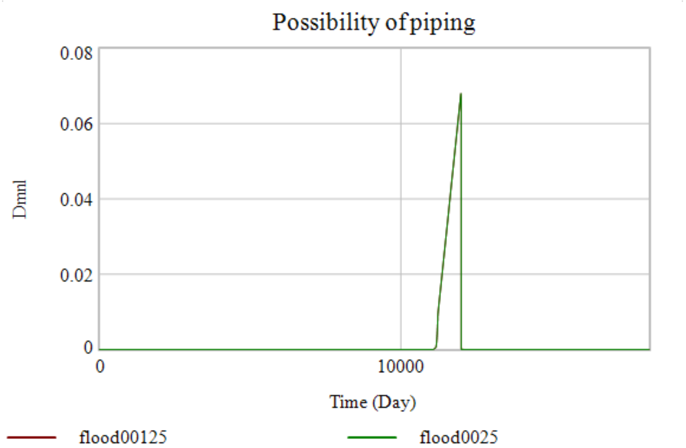


Figure E12: Flood protection sub-model output with time step 0.025 and time step 0.0125

Flood protection sub-model

In the flood protection sub-model, the smallest time constant is 0.25 days for the variable *Minimum problematic duration of flooding per m dike*. Therefore, the first time step that was tried is 0.025 days and the second one 0.0125 days. As can be seen in *figure E12*, the outputs of the two runs were identical, and therefore a time step of 0.025 days was considered small enough for the flood protection sub-model.

Appendix F: Model validation

Validation of a system dynamics model is about testing whether the model is useful for its purpose (Pruyt, 2013). However, validation tests should not be used to 'prove' that the model is right, but to show how assumptions, the model structure, and the choice of parameter values influence the model behaviour and to evaluate whether this behaviour approaches reality (Sterman, 2000). Model validation is an iterative process; it should be performed after completion of each model version. However, for early model versions a quick validation is sufficient, while in the end more detailed and refined tests are required (Pruyt, 2013). Only the results of the last validation iterations are discussed in this report. Validation tests can be divided into three categories which all contain several test options; (i) direct structure tests, (ii) structure-oriented behaviour tests, and (iii) behaviour reproduction tests. Direct structure tests analyse the model structure without simulation, structure-oriented behaviour tests require the model to run and then compare model behaviour with real or anticipated behaviour, and behaviour reproduction tests statistically compare model behaviour with real behaviour (Pruyt, 2013). Since this model does not represent an actual case with real-world data, but is meant as a first version of a theoretical model, the latter validation test category could not be used. Instead, the model structure was qualitatively compared with real-world river systems and ecological processes. This was done for each sub-model separately.

According to Pruyt (2013), one of the direct structure tests, together with the extreme conditions test and sensitivity analysis (both structure-oriented behaviour tests) are very important. When using the extreme conditions test, the model is simulated under extreme conditions of certain parameters or stock variables and it is analysed whether the model behaviour is still plausible under these conditions. This test is viewed as relevant in this research because future scenarios of extreme (both high and low) water discharge are tested. Sensitivity analysis tests whether relatively small changes in parameters, initial values, functions, and model structures lead to a change in model behaviour. Of the direct structure tests, face validation was considered most appropriate for this research. When performing face validation, experts are asked to explain whether they consider the model structures, equations and behaviour adequate and plausible. The sub-models in this research represent strongly simplified behaviour of detailed and complex behaviour in the real world. Experts can determine whether this simplification was undertaken correctly. Due to time constraints, the face validation could not be performed for this research, but it is recommended that this is undertaken in further research.

Concluding, the model is qualitatively compared with real-world system behaviour and the extreme conditions test and sensitivity analysis are used as validation methods. These methods will be explained in more detail in the next sections, where their results will be discussed as well.

F1 Qualitative comparison of model with real-world processes

In qualitative model validation, the characteristics of the real sub-system are compared with the processes included in the sub-model. This is not done by comparing model output with real (historical) data, but by checking if essential characteristics of the system are present in the model. The qualitative validation has been performed for each sub-model separately.

River sub-model

Several important characteristics of a river system should be present in the river sub-model. First of all, the current speed in a river channel increases for higher water inflows and for narrower channels. The former relation was included in the river sub-model by the variable *Water* *discharge effect on current speed*, which consists of a lookup function that increases current speed for increasing discharges. The latter relation was only included for the river's side channel. For the main channel it was excluded, because the width of the channel was already included in the *Water discharge effect on current speed*. For the side channel, *Width effect on current speed side channel* provides the relation between the current speed and the width of the channel. Secondly, the current speed in the floodplain depends on the amount and the roughness of the vegetation in the floodplain. This was included in the model by the variable *Vegetation effect on current speed floodplain*. A third characteristic of a river system relates to the conservation of mass and momentum, which means that no discrete shifts in current speed, water level et cetera should exist between two consecutive river elements. In the model, only the water level of the main channel and the side channel are kept close to each other. The current speed in the side channel does not follow the current speed in the main channel smoothly. Next, water should only flow into the floodplain when the water volume in the main or side channel reaches its maximum capacity. At that moment, the water level in the channel should be equal to the summer dike (if present), or the floodplain height. *Figure F1* shows that this is true for the model. Finally, flooding over the winter dike should only occur when the water volume in the floodplain reaches its maximum. At that moment, the water level in the floodplain should be equal to the winter dike height. The graph in *figure F2* indicates that this is indeed the case for the model.

Some river characteristics have not been included in the model, mainly for simplification purposes. Firstly, a natural river channel does not have a constant current speed over its cross-section, while in this model the current speed is considered homogenous over the cross-section. Next, the channel dimensions of a river system are more diverse than the trapezium (main channel) or even rectangular shape (side channel) that are assumed in the model.

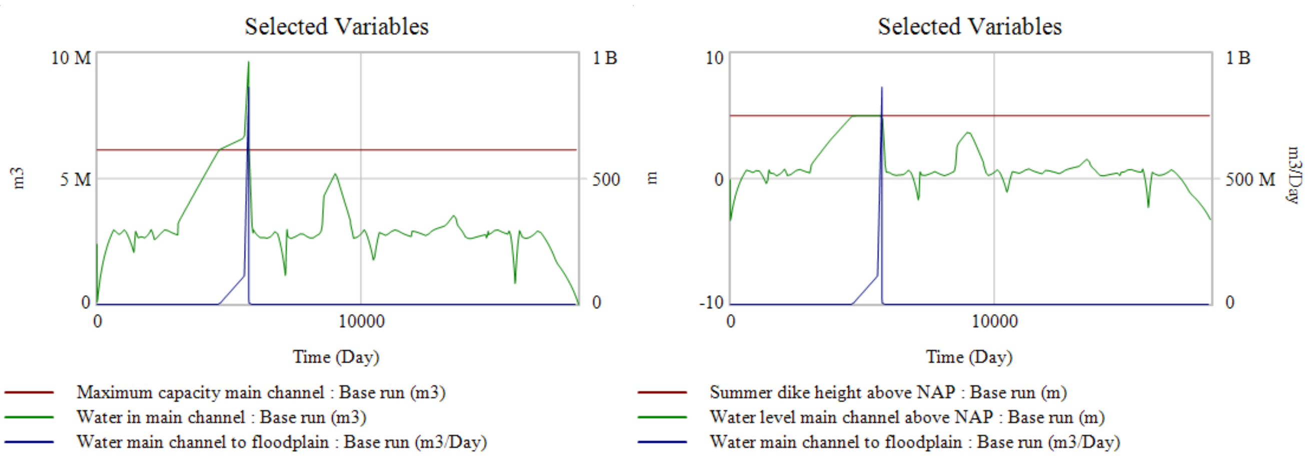


Figure F1: Water flow from the main channel into the floodplain. The left figure shows water quantities and water flow to floodplain, the right figure shows water levels and water flow to floodplain

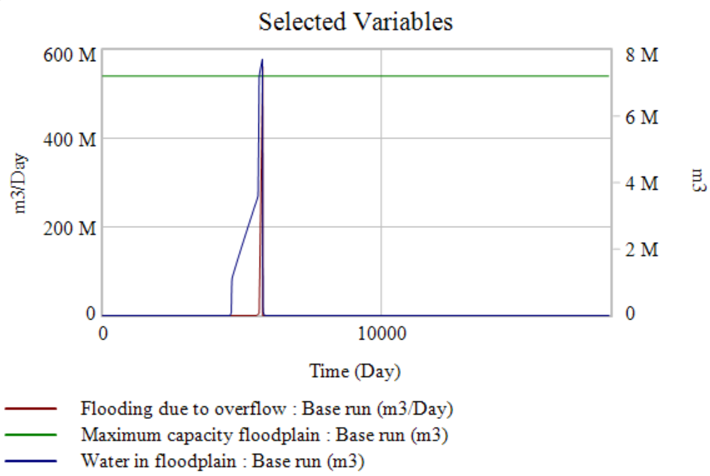
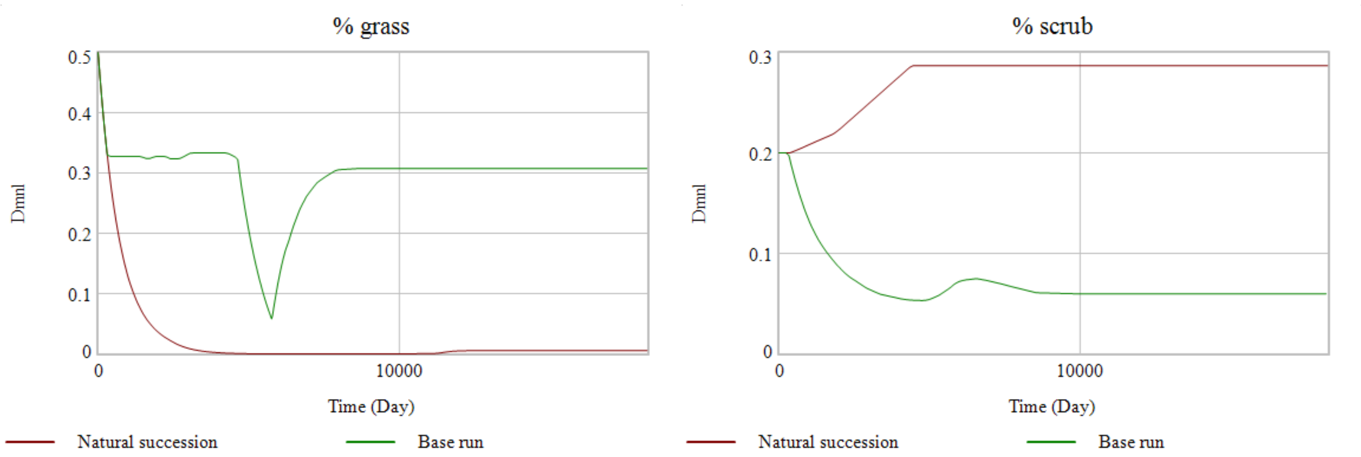


Figure F2: Flooding over the winter dike

Environment sub-model

In the environment sub-system and sub-model the vegetation succession process is most important. If natural succession were not hampered by human intervention and flooding, all vegetation would have developed into forest after many decades. *Figure F3* shows that the model partly exhibits the correct behaviour; the amount of grass in the floodplain indeed reduces to 0% due to succession towards reeds. Also, reeds first increase because of the input from grass, but later decrease as the succession from grass approaches 0. However, in reality reeds and scrub should reach 0% as well after several decades, just as grass does. This is not achieved in the model; the amount of reeds, scrub, and forest remains constant after a while. The explanation for this can be found in the numerical simulation of the model. If the time step is set to 1, the behaviour of the vegetation classes performs plausibly, but the combined model requires a much smaller time step that causes problems. This can be explained by an example. Say the amount of reeds is 1m², and the succession time from reeds to scrub is 16790 days. Then the succession of reeds to scrub is 1/16790 = 0.00005956 m²/day. If this is integrated to determine the new value for scrub, it is multiplied by the time step, which is 0.00104167 days. This results in a value of 0.000000062 m² that should be added to the amount of scrub. This is such a small amount that numerical errors occur, which can result in the unusual behaviour as is present in *figure F3*. Since human intervention and erosion and sedimentation processes are present in the model, this numerically odd behaviour is not expected to occur in the model.



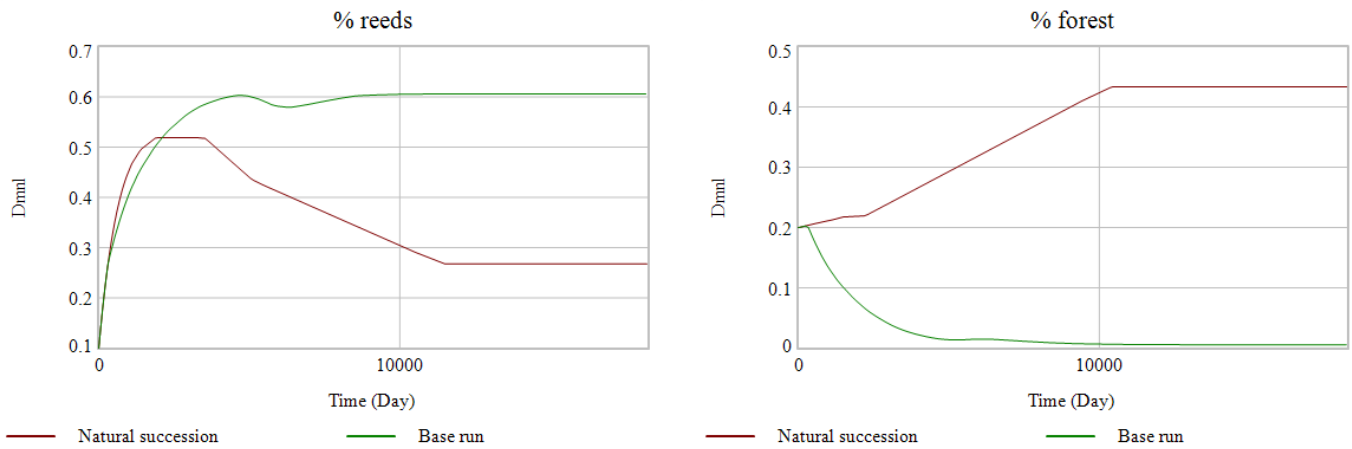


Figure F3: Natural succession floodplain vegetation (red line) and succession influenced by human intervention and erosion (green line)

Navigation sub-model

For navigation, the suitable water level lies between a lower and upper value. These lower and upper values are not fixed, but gradual; if the water level decreases, first larger ships are hampered in their navigation and later also smaller ships. The same is true for the upper limit; first only one layer of containers needs to be removed, then two, and if the water level is extremely high, even bulk ships might experience limitations. *Figure F4* shows that the cargo capacity indeed changes when the water level reaches a lower or upper limit. Another characteristic of navigation is that the current speed should not be above a maximum critical value. *Figure F5* shows the current speed, its maximum, and the resulting cargo capacity.

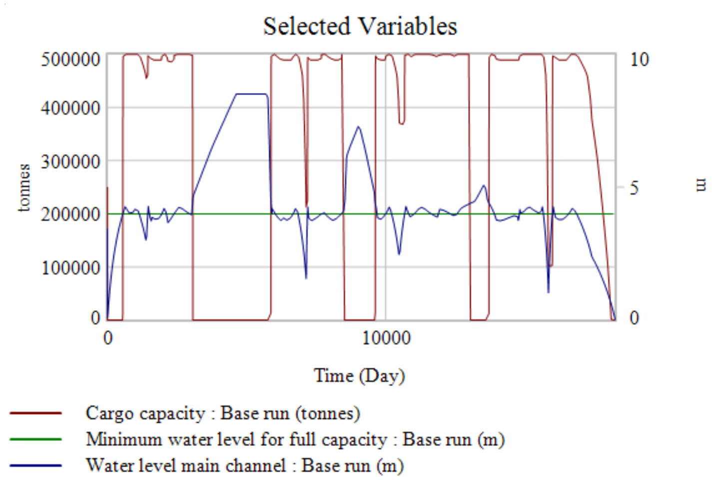


Figure F4: Cargo capacity and water level

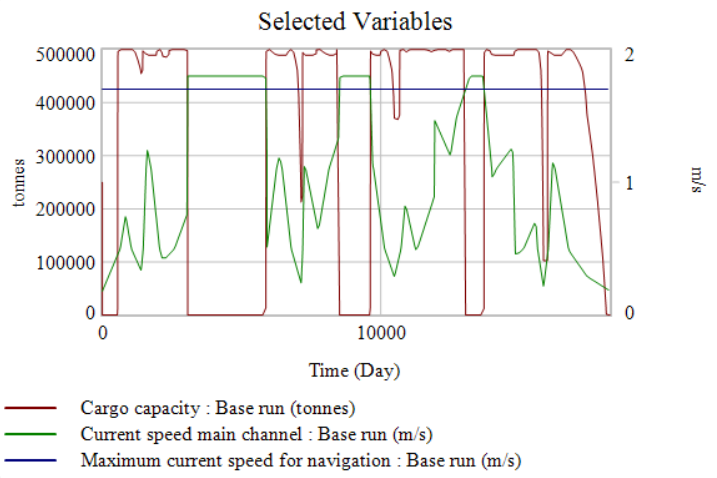


Figure F5: Cargo capacity and current speed

Flood protection sub-model

For the flood protection model, the most important characteristic is the increase in the possibility that dike failure mechanisms occur, and the number of days that these occur, when the duration of the water level/flooding increases. This is provided for in the four lookup functions; *Duration of water level difference effect on outward macro-instability, Duration of water level effect on inward macro-instability, Duration of water level effect on piping,* and *Duration of flooding effect on dike erosion*. Another important characteristic is that the possibility of each failure mechanism increases owing to a higher water level or a higher rate of flooding. This is captured in the variables *Water level difference effect on outward macro-instability, Water level effect on inward macro-instability, Water level effect on piping,* and *Flooding per m dike effect on erosion*.

F2 Extreme conditions tests

These validation tests analyse the model response to extreme conditions and check whether this is plausible. In addition, these tests help to determine under which parameter values the model remains plausible. First, it is determined which input variables need to be tested, and for which outcomes of interest the behaviour is analysed. Then, the model is run for extreme values of the input variables and the output graphs of the outcomes of interest are generated and analysed.

In appendix D2 the full list of model parameters (either external parameters, scenario parameters, or policy parameters) has been included. Not all these variables are tested in the extreme conditions test, but only the ones that are expected to have an interesting effect. First of all, the two scenario variables – *Inflow in m³/s* and *River bed level above NAP* – need to be tested, since they might be assigned very large or very small values in the experiments. Other parameters that require testing are parameters with either an estimated value, or parameters that have potentially large (and disruptive) effects on the model and its behaviour. *Table F1* provides a list of all variables that are tested under extreme conditions, their base value, their extreme values, and the outcomes of interest. The outcomes of interest are chosen based on the sub-models that are influenced by the specific input variable. If all sub-models are affected, an outcome of interest from all of these models is chosen. If only one sub-model is affected, the outcomes of interest are chosen from this sub-model.

An important note is that the base run for the extreme conditions test is not equal to the business as usual experiment. First of all, the water inflow in the base run is not representative of actual water discharges in the Waal, and secondly, the base run for the extreme values tests contains a side channel, while the business as usual experiment does not. The reason for this is that the side channel forms an important part of the model and should therefore be validated. The configurations of the side channel in the base run are as follows:

- *Side channel width:* 30m
- *Side channel bed level:* -3.5m
- *Side channel threshold*: 0m

A second important note is that some small mistakes in the model were found and solved during the extreme conditions tests. This has slightly altered model behaviour, and therefore the base run can only be compared to extreme runs within each test (per variable) and not between tests. The model documentation in chapter 8 contains information about the latest model version, and therefore the correct model.

Table F1: Input variables for the extreme conditions tests and their outcomes of interest

Variable	Unit	Why this variable?	Base value	Lower value	Upper value	Outcome of interest 1	Outcome of interest 2	Outcome of interest 3	Outcome of interest 4
Inflow in m^3/s	m^3/s	Scenario variable that might attain extreme values	*Figure F6*	*Figure F7*	*Figure F8*	*Water in floodplain*	*Cargo capacity*	*Possibility of piping*	*% grass*
Erosion rate forest	Dmnl	Parameter with estimated value and possibly large effect	0.00001	0	1	*% grass*	*% forest*	*Pioneering*	*Forest removal (human)*
Erosion rate grass	Dmnl	Parameter with estimated value and possibly large effect	0.001	0	1	*% grass*	*% forest*	*Pioneering*	
Initial % vegetation [grass, reeds, scrub, forest]	Dmnl	Parameter with estimated value and possibly large effect	[0.5, 0.1, 0.2, 0.2]	[0, 0, 0, 0]	[0.1, 0.1, 0.1, 0.7]	*% grass*	*% forest*	*Forest removal (human)*	
Main channel width	m	Parameter with possibly large effect	400	50	800	*Water level main channel*	*Water in floodplain*	*Cargo capacity*	*% grass*
Roughness reeds	Dmnl	Parameter with estimated value and possibly large effect	0.4	0	1	*Flooding in m^3/s*	*Floodplain vegetation roughness*	*Current speed floodplain*	
Horizontal floodplain width (zone 1&2 combined)	m	Parameter with possibly large effect	200	0	1000	*Flooding in m^3/s*	*% grass*	*Grass & farmland*	
Maximum reeds, scrub & forest	Dmnl	Parameter with possibly large effect	0.6667	0	1	*% scrub*	*Floodplain vegetation roughness*	*Current speed floodplain*	*Flooding in m^3/s*
River bed level above NAP (at t=18250)	m/day	Scenario variable with unknown effect	-3.5	-28.5	1.5	*Water level main channel above NAP*	*Water in floodplain*	*Cargo capacity*	*% grass*

Inflow in m³/s

The variable *Inflow in m³/s* is one of the scenario variables. Since it is expected that climate change will cause longer periods of very high and very low water levels, this research tests the influence of these changes on conflicts in river use. Therefore, the model should be able to handle these very high and very low water levels, and therefore high and low water inflow. The model was tested under extremely low water flows (*figure F7*), which means that that the water flow hardly exceeds the water discharge that is nowadays exceeded 90% of the year, and under extremely high water flows (*figure F8*), which means that the water flow exceeds the water discharge that is now only exceeded 10% of the year. The normal water flow is shown in *figure F6*.

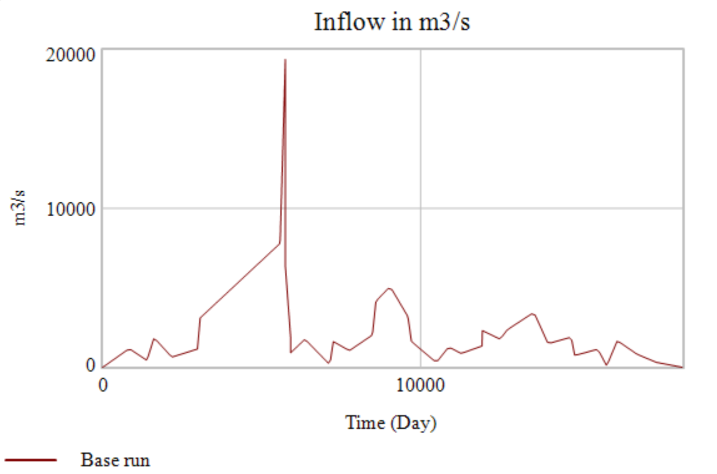


Figure F6: Water inflow base run

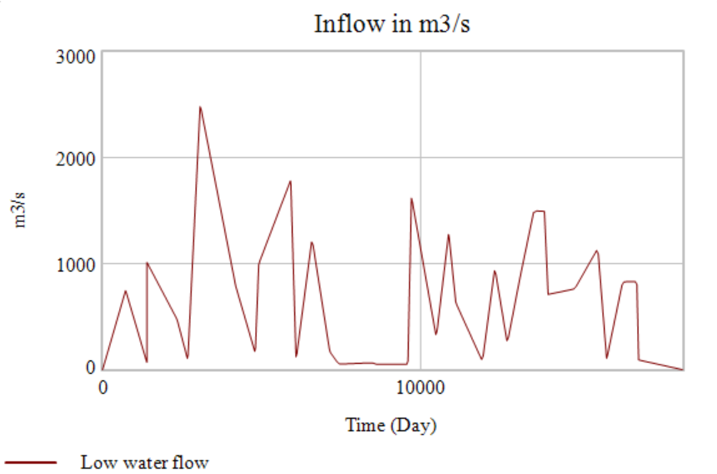


Figure F7: Water inflow during low flow period

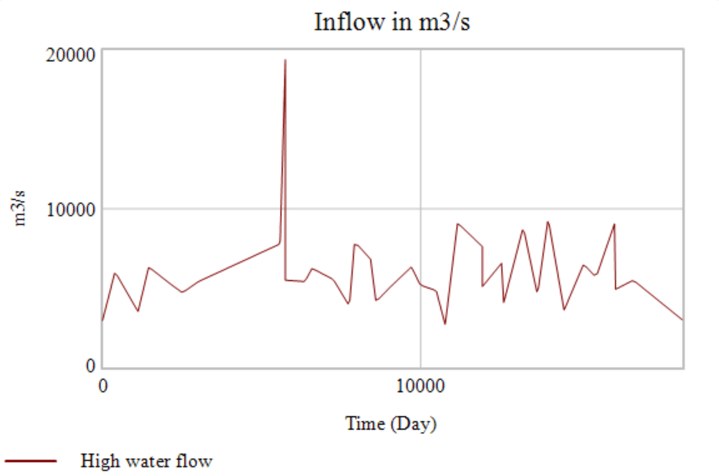


Figure F8: Water inflow during high flow period

Dynamic hypothesis
Extreme values of water inflow were expected to have a big influence on processes in all four sub-models. First of all, it was expected that the amount of water in the floodplain will increase due to a high water flow and decrease due to a low water flow. The reason for this is that the river channels will reach their maximum sooner during a high water flow. For flooding the same pattern was expected; more flooding was expected during high flows, and less during low flows. Due to the increased amount of water in the floodplain during high flows, more erosion and sedimentation takes place, so less grass (and other vegetation) will be present. During low flows, less erosion and sedimentation takes place, so it was expected that there will be more grass. The other three vegetation classes will still be removed by human intervention, so less change was expected in their share in the total floodplain vegetation. The cargo capacity was expected to decrease for both extreme water inflows; during high flows the water level and current speed become too high for navigation, and during low flows the water level becomes too low.

Extreme conditions results
Figure F9 and *table F2* show that most of the dynamic hypothesis was correct. The cargo capacity indeed decreases for both high and low water flows, but for low water flow, the decrease was smaller than expected. Most of the time, at least some cargo capacity is available, while it was expected that the decrease due to too low water would be higher. Besides, higher water flows result in more water in the floodplain, and therefore more erosion/sedimentation and less vegetation (temporarily). Also, more water in the floodplain increases the risk of piping under the winter dike. While the graphs were useful for comparing general behavioural trends, it was difficult to derive the exact difference between model runs. Therefore the table below is included. This table indicates that while the water in the floodplain increases significantly with increasing water flow, the total flooding increases only slightly. This is caused by the fact that even the high water flow run contains only one very large flood peak. The cargo capacity over the whole run shows that the cargo capacity is lowest during the high flow run. The low flow run results in 0 days with possibility of piping, while the high flow run increases the number of days relative to the base run.

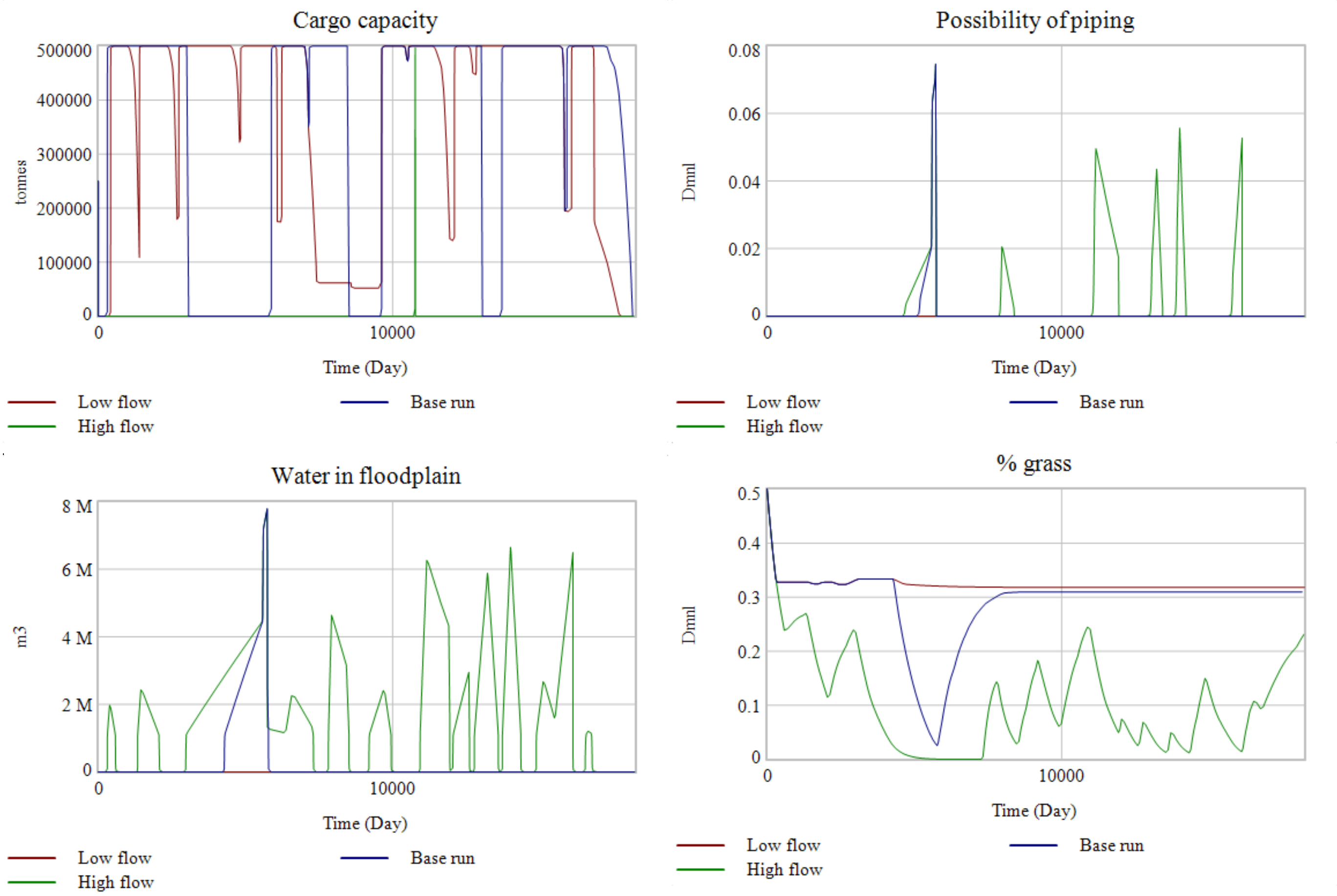


Figure F9: Extreme conditions results for inflow in m^3/s

Table F2: Extreme conditions results for inflow in m^3/s

	Inflow in m^3/s [m^3/s]	**Total flooding [m^3]**	**Cargo capacity over whole run [tonnes]**	**Number of days with possibility of piping [days]**
Base value	*Figure F6*	4.49E+10	6.31E+09	684.1
Lower extreme value	*Figure F7*	0	6.80E+09	0
Upper extreme value	*Figure F8*	4.5E+10	6.82E+06	3993

Conclusion

The behaviour of the model for different water flows was very similar to the expected behaviour and real-world river system behaviour.

Erosion rate forest

The erosion rate at which forest disappears during flooding is an assumed variable that was expected to have a large effect on the model behaviour. Therefore the model was run for an extremely low value (0) and an extremely high value (1).

Dynamic hypothesis

It was expected that a low value of forest erosion results in a larger share of forest during floodplain inundation periods, since the other vegetation classes are partly removed, while forest is not. However, when forest is not removed by erosion/sedimentation more and more forest will be present due to succession and it will in turn be removed by human intervention.

Therefore, in the end the effect of the erosion rate is small, but it might change the shape of the graph for *% forest*. When more forest is removed by human intervention, the % grass was expected to rise slightly, since human intervention sets forest back to grass, and erosion/sedimentation to bare soil. Furthermore, less pioneering was expected when the erosion rate of forest was lower, again because human intervention sets forest back to grass instead of bare soil. For the high value of forest erosion the opposite behaviour was expected, so more set-back due to erosion and less due to human intervention.

Extreme conditions results

Figure F10 shows that the dynamic hypothesis was partly correct. Most importantly, the graphs for *% grass* and *% forest* indeed did not change significantly in the long run. Besides, human forest removal was indeed lower at a high erosion rate of the forest, but that was mostly caused by the fact that there was hardly any forest in the floodplain at that time. If there would be more forest present in the floodplain, forest removal by human intervention would probably be at a rate equal to the base run, because the share of reeds and/or scrub would be too high. Pioneering was a little higher at high forest erosion, which was caused by the fact that a slightly larger area was set-back to bare soil. The first part of the dynamic hypothesis, regarding lower forest erosion was not correct. Probably this was caused by the fact that the base value for forest erosion is already very low (0.00001). Since more difference was found between the base run and low erosion for grass erosion (next section), this is confirmed as the right explanation.

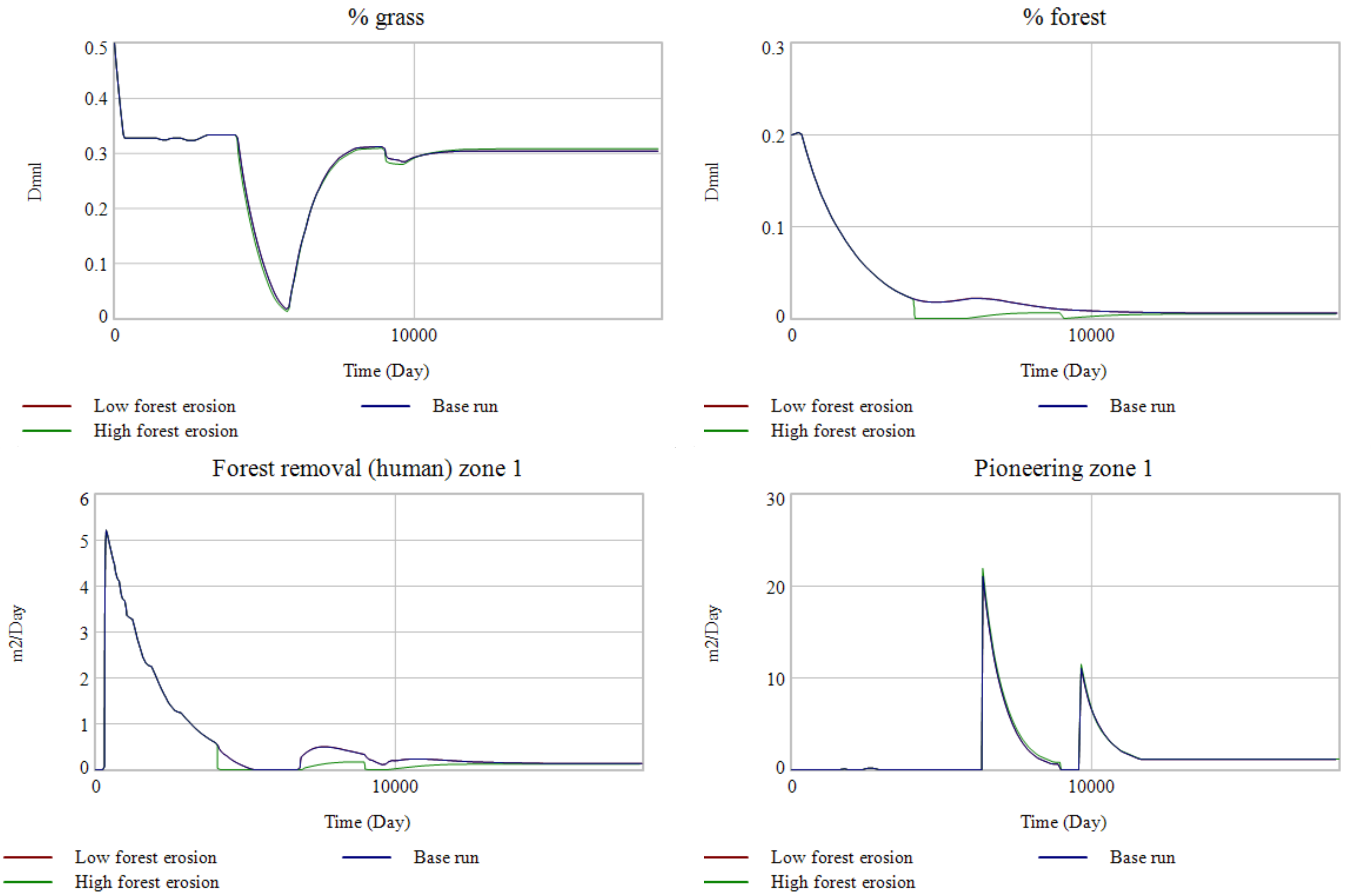


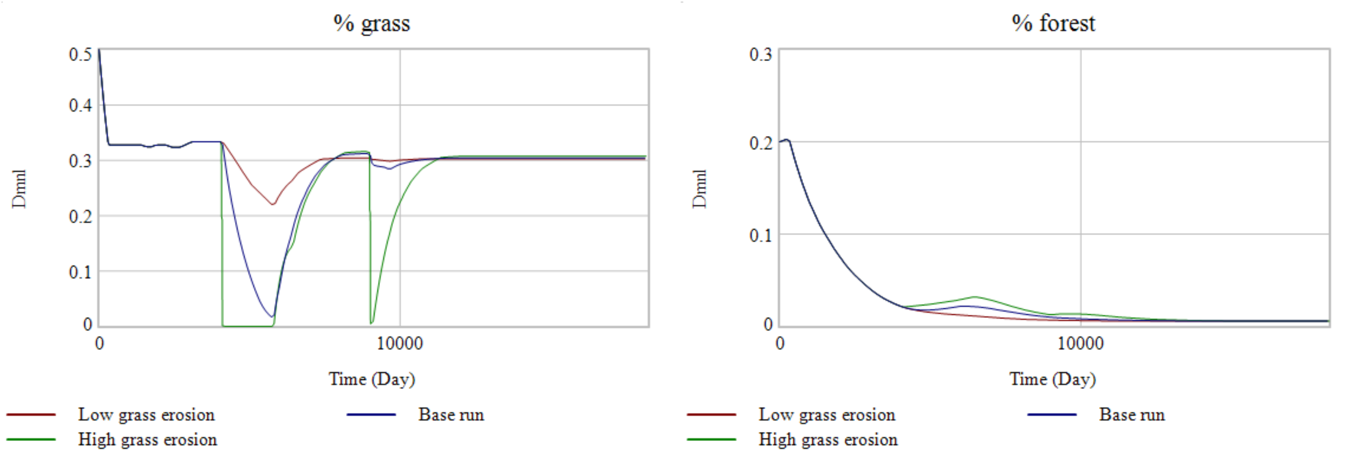
Figure F10: Extreme conditions results for erosion rate forest

Conclusion
Altering the erosion rate for forest only has a temporary effect (during floodplain inundation), and it does not influence the model behaviour in the long-term. The reason for this is that floodplain inundation only occurs for a small share of the total run time of the model and that the effect of human intervention in the floodplain has a strong influence on the amount of vegetation when erosion/sedimentation is absent. In reality, this behaviour is observed as well; floodplain inundation occurs rarely, while human vegetation removal is standard procedure.

Erosion rate grass
The erosion rate at which grass disappears during flooding, is an assumed variable that was expected to have a large effect on the model behaviour. Therefore the model was run for an extremely low value (0) and an extremely high value (1).

Dynamic hypothesis
The dynamic hypothesis was the same as for erosion rate forest; changing the erosion rate has a temporary effect on the % grass, but does not alter the model behaviour in the long term.

Extreme conditions results
Figure F11 shows that this was indeed the case; a higher erosion rate for grass led to a stronger temporary decrease of the % grass during floodplain inundation compared to the base run. This then led to a temporary increase in pioneering because a larger share of the floodplain consists of bare soil. More erosion of grass also showed a small effect on % forest; it led to more forest. This may sound wrong because if there is less grass, it would result in less succession towards forest, but an important side effect occurred; because less grass was available, less succession towards reeds occurred, and therefore, the share of non-grass vegetation was below its maximum for a while, allowing forest to grow.



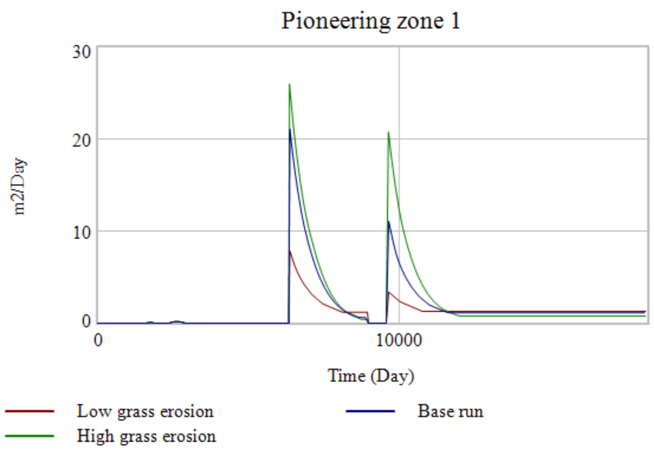


Figure F11: Extreme conditions results for erosion rate grass

Conclusion
Altering the erosion rate of grass strongly influences the vegetation in the floodplain during floodplain inundation periods. In the runs included in this section, floodplain inundation did not occur very often, and therefore the erosion rate of grass only had a minor influence on the long-term behaviour of floodplain vegetation. This indicates that other processes (such as succession and human intervention) are more important. If floodplain inundation occurs for longer, however, erosion will become a more and more important factor determining floodplain vegetation. This corresponds to behaviour in real river systems, where little flooding occurs in the floodplains, but vegetation is removed by humans on a regular basis.

Initial % vegetation
The initial % of each vegetation class was assumed to have a large effect on model behaviour (at least for the environment sub-model). Therefore the model was run for extremely low values of each vegetation class [0, 0, 0, 0] and for an extremely high value for forest and low values for the other vegetation classes [0.1, 0.1, 0.1, 0.7].

Dynamic hypothesis
Succession works in only one direction, and therefore starting with a large share of forest was expected to result in more forest over the whole model run if no set-back was considered. However, human intervention and flooding set forest back to grass or bare soil at regular intervals. Especially human intervention was expected to occur immediately (since the maximum share of forest, scrub, and reeds together is 2/3, which they exceed immediately). Therefore, only minor changes were expected in the behaviour of the vegetation in the floodplain.

Extreme conditions results
Figure F12 shows that the behaviour of the floodplain vegetation indeed only changed marginally. At the start of the model run with a high initial share of forest, a lot was removed by human intervention, because it was above the permitted level. The share of forest vegetation shows that no matter its initial value, in the end the same equilibrium level will be achieved. It is expected that as long as human intervention cuts down reeds, scrub, and forest when they reach a maximum value, this equilibrium will be reached.

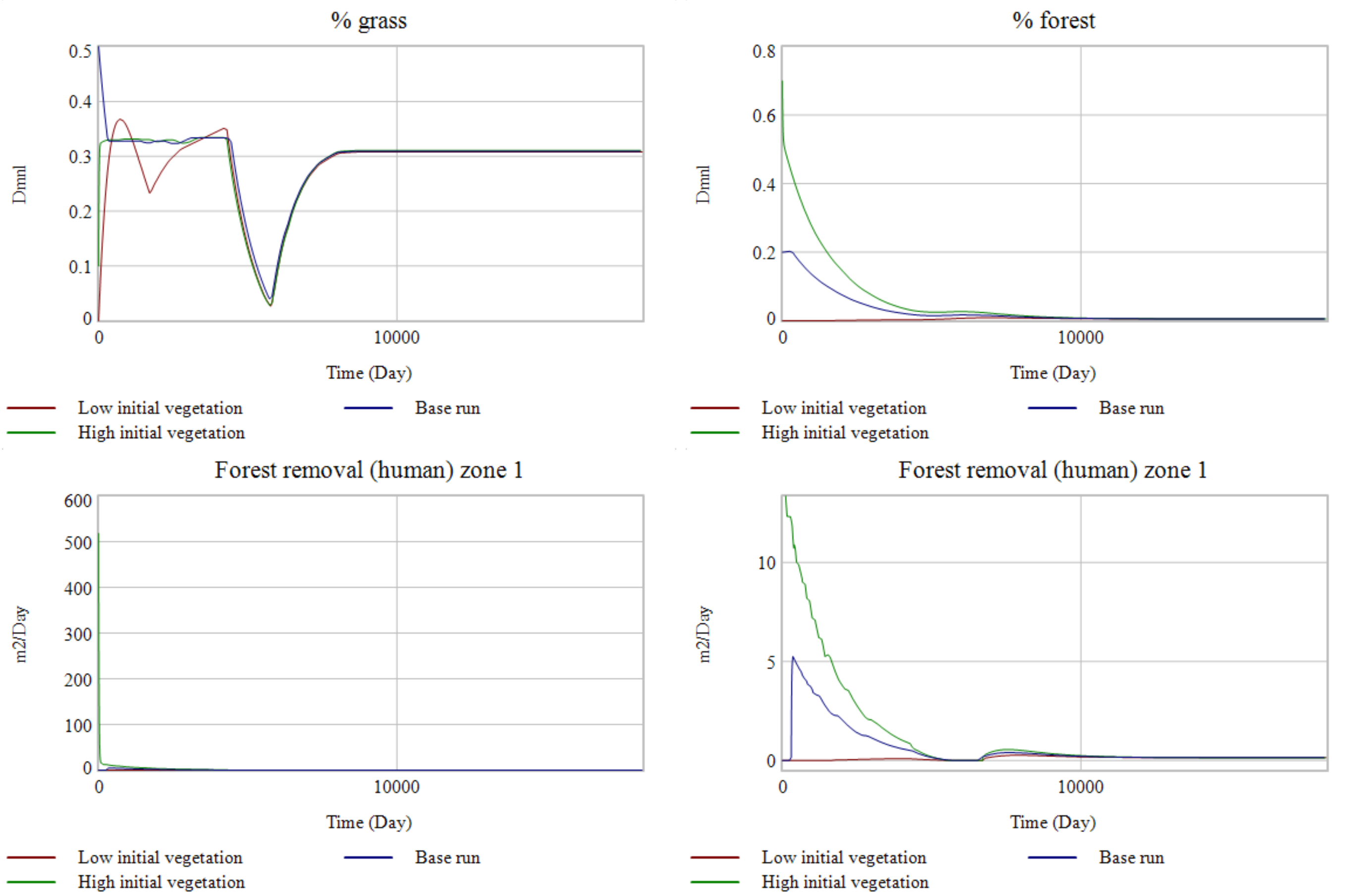


Figure F12: Extreme condition results for initial % vegetation

Conclusion

The initial values for the share of the vegetation classes in the floodplain temporarily have a large influence on the model behaviour. However, due to human intervention that does not allow nature to grow and develop freely, the behaviour of the model will be similar on the long-term, no matter which initial values are chosen. In reality, this behaviour might be a little different; in the model, vegetation of all three classes causing roughness (reeds, forest, and scrub) is removed when their share reaches the maximum value, while in reality a choice exists which vegetation to remove. It is in reality thus possible to remove more reeds and less forest, which is not possible in the model.

Main channel width

The width of the main channel was expected to have a large effect on the model behaviour. After all, it determines the main channel capacity, influencing water flowing to the floodplain, and the water level, influencing navigation. Therefore, the width of the main channel has been tested for a low value (50m), and a high value (1000m). When the main channel width is altered it needs to be checked whether the horizontal shore width is still smaller than the main channel width.

Dynamic hypothesis

When widening the main channel, the maximum capacity of the river increases, and therefore it was expected that the amount of water in the floodplain would decrease. At the same time, a wider river channel would lead to a decrease in the water level and therefore to a decrease in the cargo capacity. Narrowing the main channel was expected to have the opposite effect.

Extreme conditions results

Figure F13 and *table F3* indeed indicate that a wider river channel reduced the water level and therefore the cargo capacity. Furthermore it reduced water in the floodplain and therefore erosion and sedimentation processes in that area.

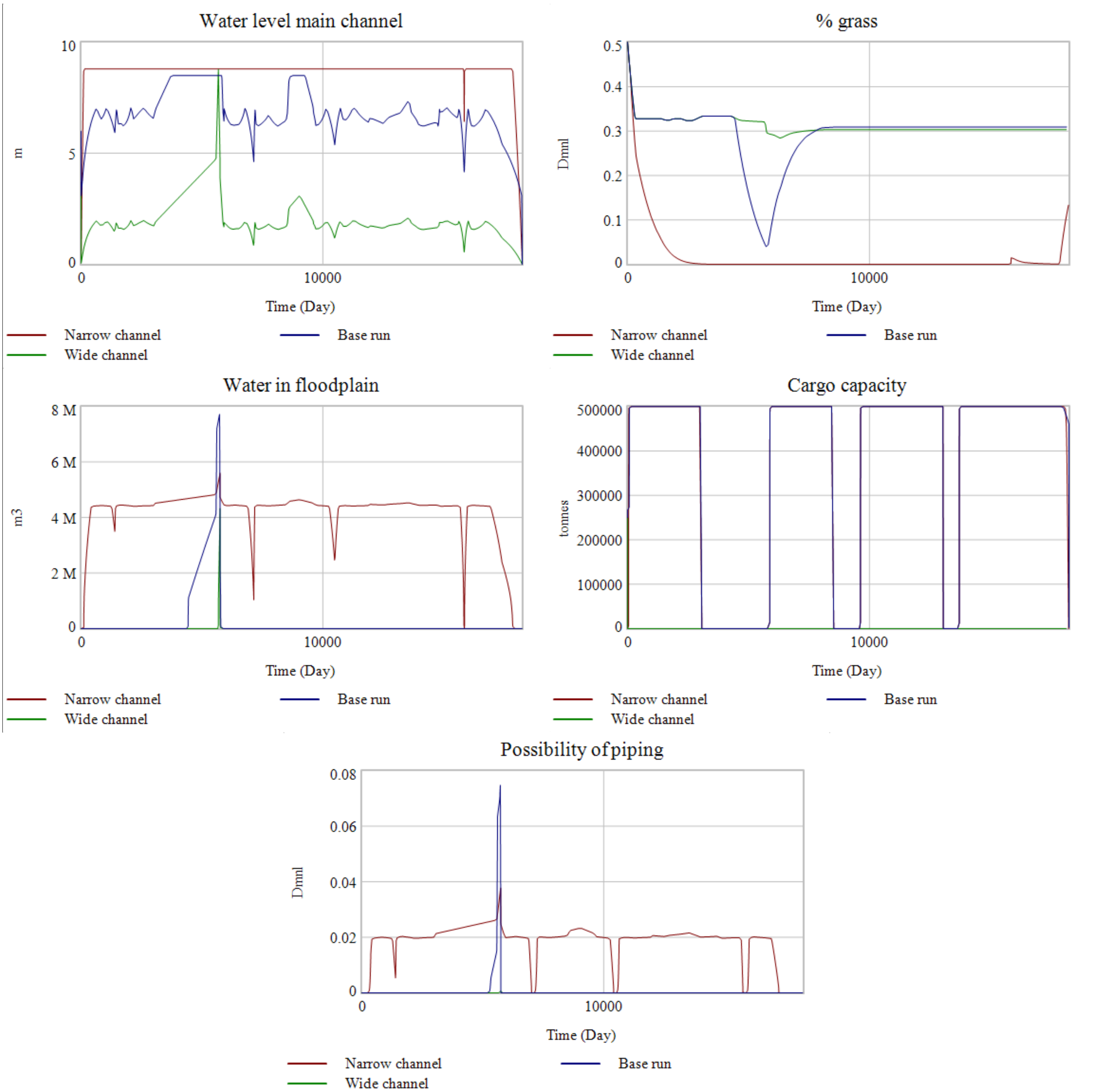


Figure F13: Extreme conditions results for main channel width

Table F3: Extreme conditions results for main channel width

	Main channel width [m]	Total flooding [m^3]	Cargo capacity over whole run [tonnes]	Number of days with possibility of piping [days]
Base value	400	4.49E+10	6.31E+09	684.1
Lower extreme value	50	1.4E+12	6.56E+09	16100
Upper extreme value	1000	0	36570	24.42

Conclusion

This test shows that the model mimics this river system behaviour sufficiently. Besides, this test sheds an interesting light on the nature perspective on river systems; ecologists argue for wider river system so that species can seek shelter from the high dynamics in the river system, but this reduces floodplain flooding which is a necessary process for floodplain ecology. Changing the channel width also changes the relation between discharge and current speed, which should be done manually in this model.

Roughness reeds

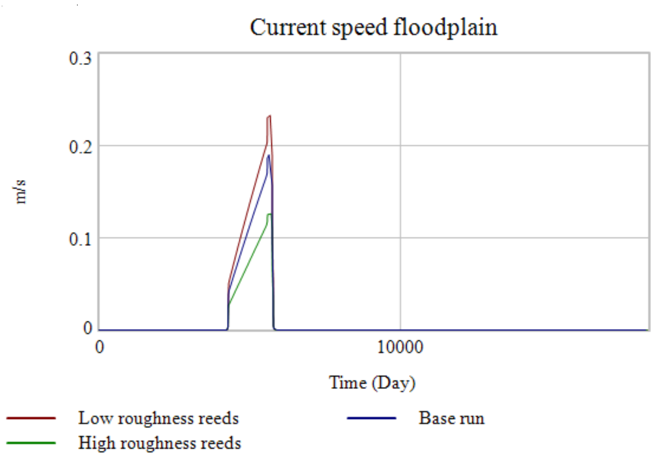
The value for this parameter is assumed and therefore the effect of different values on the model behaviour needs to be tested. The roughness of each vegetation class is given in percentages, so a value between 0 and 1. The normal roughness of reeds is set to 0.4, the lower extreme value was set to 0, and the upper extreme value to 1.

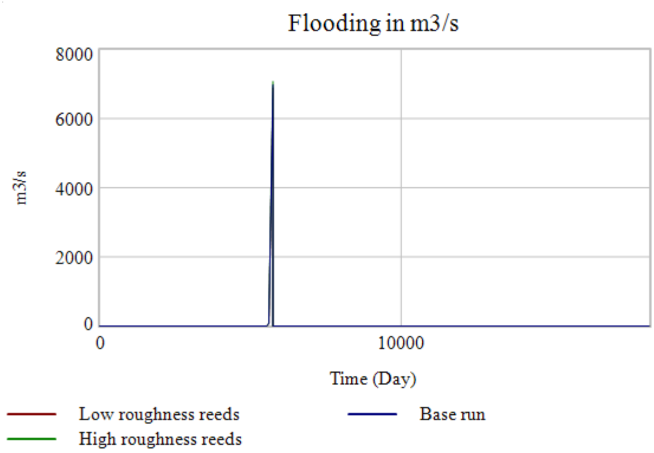
Dynamic hypothesis

Increasing the roughness of reeds was expected to lead to a higher vegetation roughness and therefore to a lower current speed in the floodplain and more flooding. Decreasing the roughness of reeds was expected to have the opposite effect.

Extreme conditions results

Figure F14 and *table F4* show that the dynamic hypothesis was indeed correct. The floodplain vegetation roughness approaches 1, which is its maximum value, when the roughness of reeds was set to 1. This was caused by the fact that the share of reeds in the total floodplain vegetation was large. As the total vegetation roughness influences the current speed in the floodplain directly, this variable is lower for higher reeds roughness. Due to the lower current speed, less water will flow towards the downstream floodplain and more will be spilled over the winter dike (flooding). The table indicates that the difference in total flooding between low and high reeds roughness was around 2.9 billion m^3.





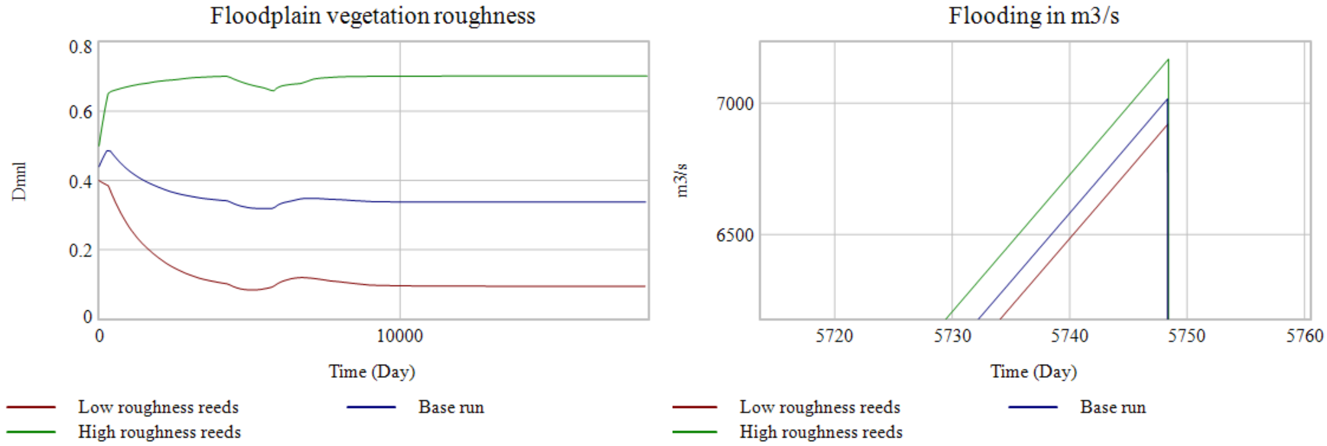


Figure F14: Extreme conditions results for roughness reeds

Table F4: Extreme conditions results for roughness reeds

	Roughness reeds [Dmnl]	Total flooding [m³]
Base value	0.4	4.49E+10
Lower extreme value	0	4.38E+10
Upper extreme value	1	4.67E+10

Conclusion
The roughness value for reeds has quite a large effect on the model behaviour. This will also be true for the other three vegetation classes. It is therefore important to ascertain and assign these variables correct values.

Horizontal floodplain width
The floodplain width has a large influence on the system's behaviour; it determines the capacity for water storage and for vegetation growth. It has been tested for an extremely low value (0m) and an extremely high value (1000m). This included the side channel width. When the floodplain width is altered, the lookup function determining the water level in the floodplain needs to be altered as well.

Dynamic hypothesis
Lowering the floodplain width was expected to increase flooding, since water cannot be stored anymore. Besides, no vegetation can be present if there is no floodplain. On the other hand, an increase in the floodplain width was expected to lead to less flooding, and more vegetation. However, only the absolute amount of vegetation will change, not the share of each vegetation class in the total vegetation. This is due to model configurations; the maximum share of each vegetation class is an external parameter, independent of the size of the floodplain.

Extreme conditions results
Figure F15 and *table F5* show that flooding indeed increased for a smaller floodplain and decreased for a larger floodplain. Also it influenced the amount of grass in the floodplain (as well as the other three vegetation classes). The share of grass in the total vegetation was similar for each of the floodplain sizes. This is due to the fact that the maximum share of the vegetation classes is indicated by an external factor. In reality, the maximum share of vegetation is based on the discharge capacity of the floodplain, so if the floodplain is extended, the same discharge capacity would be achieved while at the same time allowing a larger share of rough vegetation classes.

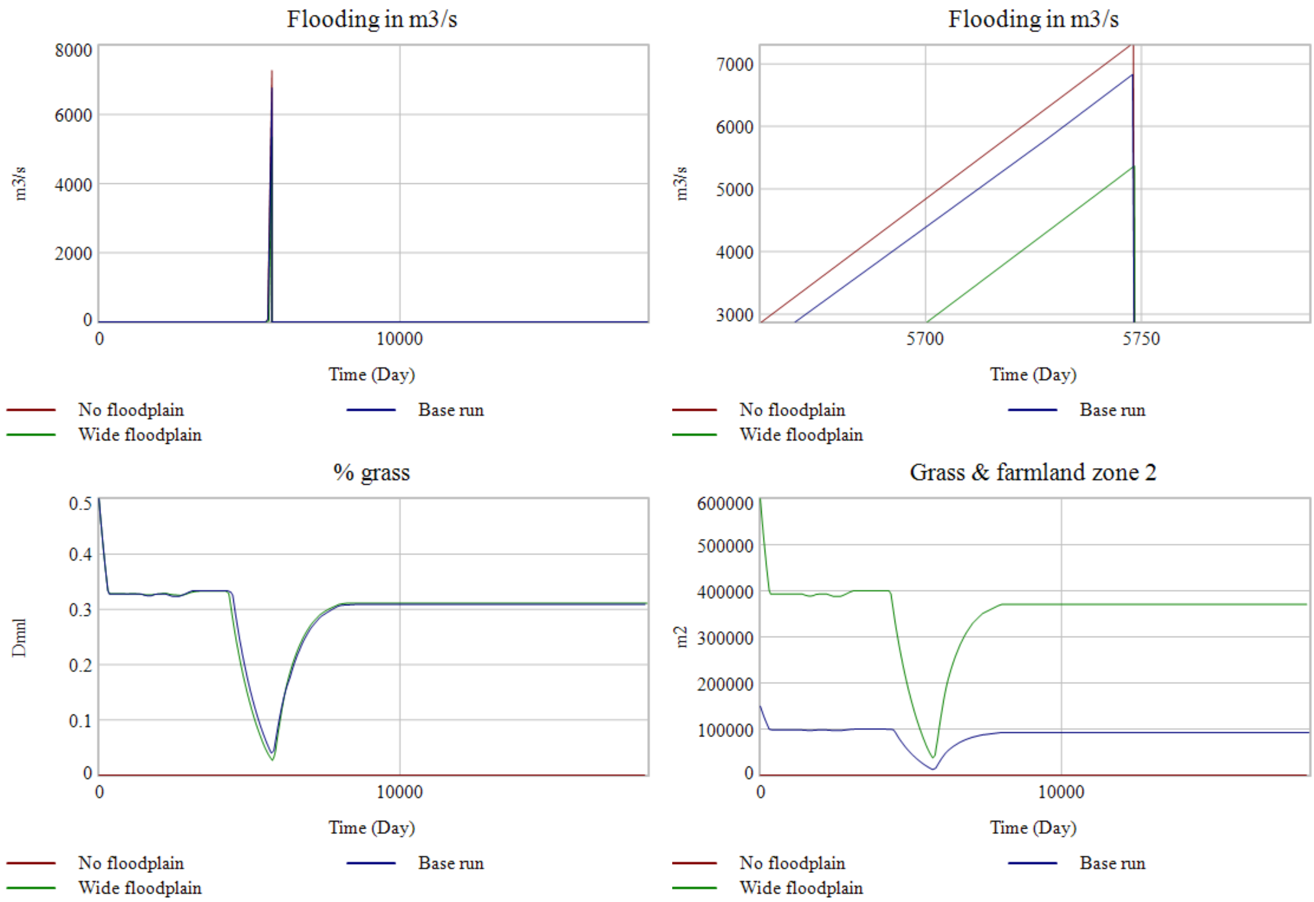


Figure F15: Extreme conditions results for horizontal floodplain width

Table F5: Extreme conditions results for horizontal floodplain width

	Horizontal floodplain width [m]	**Total flooding [m³]**
Base value	200	4.49E+10
Lower extreme value	0	4.81E+10
Upper extreme value	1000	2.56E+10

Conclusion

The model responds to changes in the floodplain width as expected. However, the model does contain a flaw with regard to the maximum share of rough vegetation classes; in reality this share is not fixed, but based on local river characteristics, so on locations with a wider floodplain a larger share of rough vegetation is allowed. This is now not automatically accommodated in the model. Nevertheless, the maximum shares for each vegetation class can be altered manually, if the effects of a wider floodplain are studied.

Maximum reeds, scrub & forest

As discussed in the previous test (changing the floodplain width), the maximum shares of each vegetation class in the total vegetation are considered external parameters in the model, while in reality these are not fixed parameters with an equal value for every river stretch. Therefore, this test analysed the effects of changing one of these parameters. The maximum share of reeds, scrub & forest (combined) was set to an extremely low value (0) and an extremely high value (1). Its base value is derived from the 'vegetatielegger' at location Gameren.

Dynamic hypothesis

Increasing the maximum allowed share of rough vegetation was expected to lead to an increase in the amount of vegetation of these classes. At the same time, the amount of grass was expected to decrease because succession towards further classes takes place and only little set-back due to erosion causes rough vegetation to decrease. If more rough vegetation would be allowed, the floodplain's vegetation roughness would increase and its current speed would decrease. This would increase flooding.

Extreme conditions results

Figure F16 and *table F6* indicate that the dynamic hypothesis was correct. A higher share of scrub was present when its maximum was higher, and this also led to a higher vegetation roughness and a lower current speed in the floodplain.

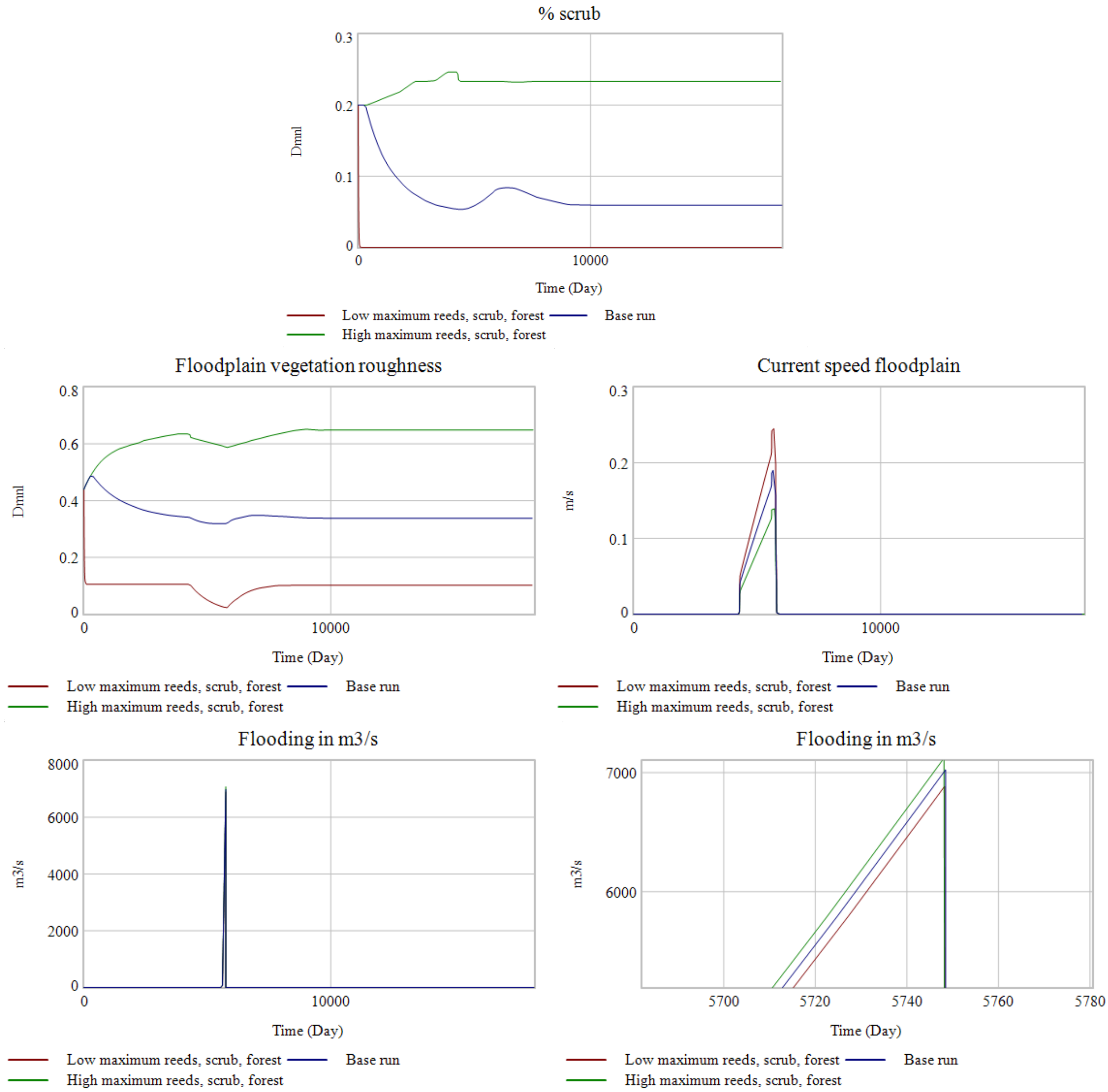


Figure F16: Extreme conditions results for maximum reeds, scrub & forest

Table F6: Extreme conditions results for maximum reeds, scrub & forest

	Maximum reeds, scrub, forest [Dmnl]	**Total flooding [m³]**
Base value	0.6667	4.49E+10
Lower extreme value	0	4.34E+10
Upper extreme value	1	4.63E+10

Conclusion

The model responds to changes in the maximum share of rough vegetation as expected. The effects of the changes are significant; instead of 5% scrub at the end of the base run, 25% scrub was present at the end of the run without a limit on rough vegetation (when its maximum share is 1). This reflects real system behaviour.

Rate of river bed lowering

After running this test for the first time, it was discovered that the relation between water volume and water level did not take changes in the river bed level into account. Therefore, this relation was adjusted, but this implied that the base run had to be altered. After adjusting the relation, the test was performed again, with a lower extreme value of a river bed at -28.5m above NAP after 50 years (lowering rate of 50 cm/year) and an upper extreme value of 1.5m (heightening rate of 10 cm/year).

Dynamic hypothesis

It was expected that lowering of the river bed would lead to less water in the floodplain, since the height difference between the river bed and the floodplain would increase. Lowering of the river bed was expected to have no effect on the cargo capacity, since the water level (not relative to NAP) was not expected to change significantly. On the other hand, it was expected that an increase of the river bed (due to sedimentation) would cause trouble for navigation, since the height difference between the river bed and the summer dike would decrease. Increase of the river bed was also expected to increase the water in the floodplain, since it decreases the capacity of the main channel.

Extreme conditions result

See *figure* F17 and *table F7*. Extreme river bed lowering or heightening has extreme effects on the river itself and on flooding, but it does not significantly change the behaviour of floodplain vegetation, cargo capacity or dike strength. Lowering of the river bed level directly influences the water level in the main channel above NAP, since this will drop with the river bed drop. Heightening the river bed level makes the water level above NAP reach its maximum value sooner, since the height difference between the floodplain and the river bed is reduced. Only at the end of the river bed heightening run is the water level too low for navigation. River bed lowering also results in less frequent flooding as expected.

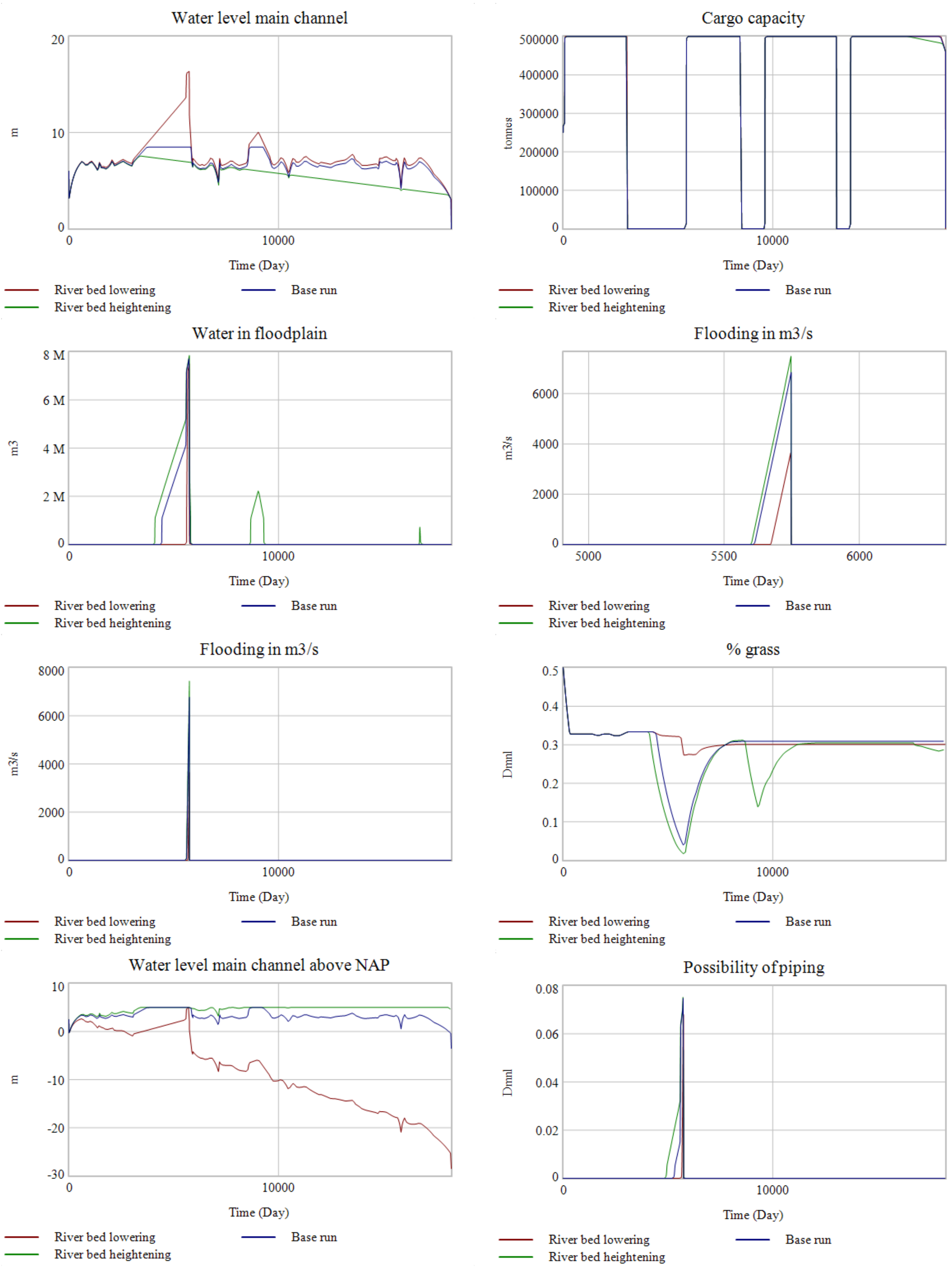


Figure F17: Extreme conditions results rate of river bed lowering

Table F7: Extreme conditions results rate of river bed lowering

	River bed level above NAP (at t=18250)	Total flooding [m³]	Cargo capacity over whole run [tonnes]	Number of days with possibility of piping [days]
Base value	-3.5	4.28E+10	6.58E+09	536.8
Lower extreme value	-28.5	1.3E+10	6.58E+09	122.5
Upper extreme value	1.5	5.08E+10	6.58E+09	940.9

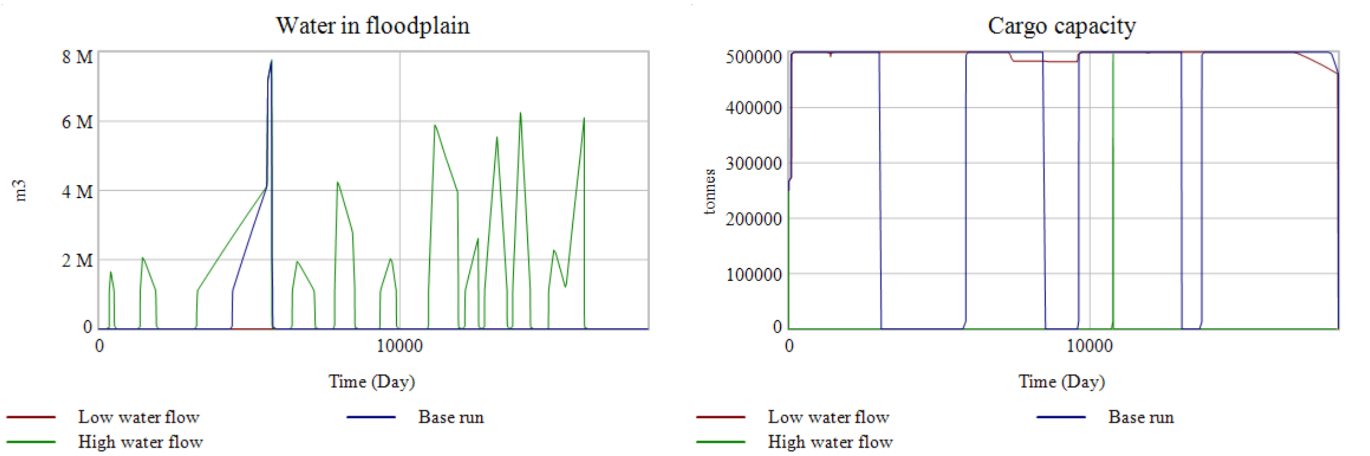
Conclusion
River bed heightening or lowering results in the expected model behaviour, although its effect is not as strong as would be expected. This can be explained by the fact that most effects of river bed lowering are related to the groundwater level, which is disregarded in this model.

The relation between water volume and water level has a significant effect, and since this relation had to be changed the extreme conditions test for water inflow was performed a second time to see how the model behaviour had changed.

Inflow in m³/s (round 2)
The extreme conditions test for water inflow was performed a second time, to test if the model behaviour was still plausible after the changes made in the relation between water volume and water level. The same lower and upper extremes are used (*figure F7* and *F8)*.

Dynamic hypothesis
It was expected that the behaviour of the model would essentially still be the same, but that shifts in behaviour might have occurred, or that certain maximum or minimum water levels would not be reached. The effect of low water on cargo capacity for example, was expected to be reduced relative to the first test of water inflow, because the new relation between water volume and water level has increased water levels slightly.

Extreme conditions results
The model behaviour was still as expected after the change in water volume – water level relationship (see *figure F18* and *tableF8*).



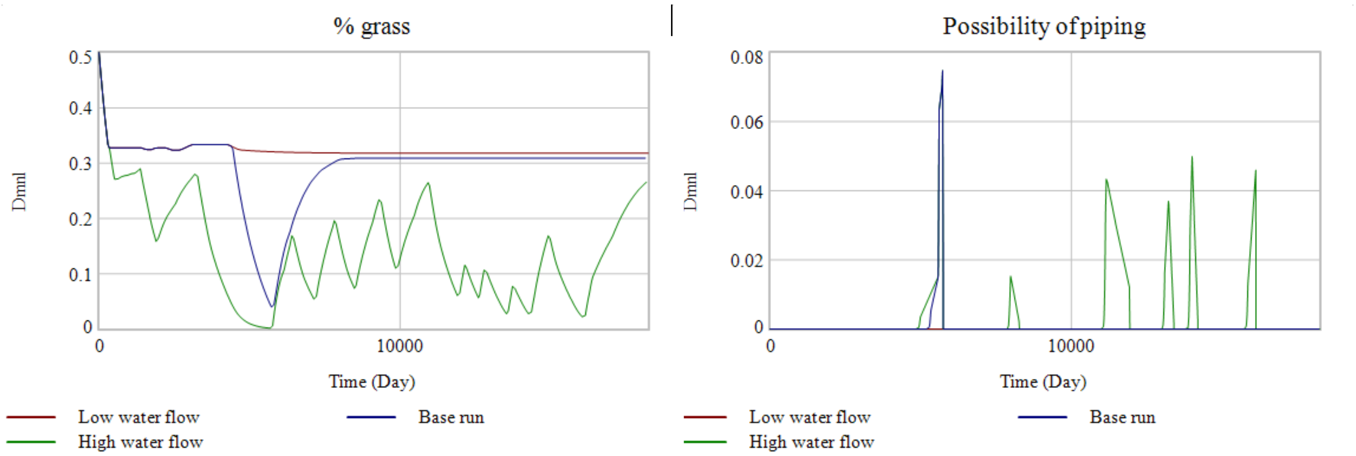


Figure F18: Extreme conditions results for water inflow in m³/s (round 2)

Table F8: Extreme conditions results for water inflow in m³/s (round 2)

	Inflow in m³/s [m³/s]	**Total flooding [m³]**	**Cargo capacity over whole run [tonnes]**	**Number of days with possibility of piping [days]**
Base value	*Figure F6*	4.28E+10	6.58E+09	536.8
Lower extreme value	*Figure F7*	0	8.78E+09	0
Upper extreme value	*Figure F8*	4.28E+10	6.82E+06	3416

Conclusion

The model still exhibits plausible behaviour after changing the relation between water volume and water level.

F3 Sensitivity analysis

This type of model validation tests (automatic or manually) whether small changes in parameters and graphical, lookup functions lead to a change in model output. This helps the modeller to identify parameters that require accurate measurement, to locate errors in the model, to identify inputs that have little effect on the output or on the other hand have a large effect, and to improve his or her understanding of the model (Pruyt, 2013).

Since sensitivity analysis tests the response of the model to small changes in parameters, the range of parameter values that have been tested were determined by lowering or raising the nominal parameter value so that the full range of uncertain values is covered. Manual tests have been performed for each variable separately, to determine its individual effect.

Table F9 indicates the variables that were included in the sensitivity analysis, why they were chosen, their base value, their lower and upper values and their outcomes of interest. Most importantly, the variables that contain a lookup graph that is based on assumptions had to be tested, since a high degree of uncertainty around the exact shape and values of these graphs exist (Eker, Slinger, Van Daalen & Yücel, 2014). Although Eker et al. (2014) introduce a perturbation-based method for testing the sensitivity of model behaviour to the form of graphical functions, in this research it is chosen to manually change the lookup graphs into two alternative forms spanning the range of uncertainty. In this way, insights on the consequences for model behaviour are obtained directly and an additional complex method is not applied.

The lookup graphs examined in the sensitivity tests are only the lookups in the river sub-model, since these do not only influence the river system but also the other three sub-systems. The lookups in the flood protection sub-model that determine the effect of water level and duration on the four dike failure mechanisms are known to be very uncertain, but their effect is limited to the failure mechanism they influence. Therefore, these lookups were excluded from the sensitivity analysis. Other variables that required sensitivity analysis were time-variables. The reason for this is that time variables can significantly alter the timing of certain behaviour and therefore alter the model behaviour as a whole. The 'minimum problematic duration' parameters in the flood protection sub-model were excluded from the sensitivity analysis for the same reason as the lookups; they are known to be uncertain, but they have a limited effect on other parts of the model.

Again, an important note is that some small mistakes in the model were found and solved during the sensitivity analysis. This has slightly altered model behaviour, and therefore the base run can only be compared to runs within each test (per variable) and not between tests. The model documentation in chapter 8 contains information about the latest model version, and therefore the correct model.

Table F9: Input variables for the sensitivity test and their outcomes of interest

Variable	Unit	Why this variable?	Base value	Lower value	Upper value	Outcome of interest 1	Outcome of interest 2	Outcome of interest 3	Outcome of interest 4
Erosion sedimentation multiplier	Dmnl	Lookup function	*Figure F19a*	*Figure F19b*	*Figure F19c*	Reeds set-back	% reeds	Vegetation roughness	Flooding in m³/s
Vegetation effect on current speed floodplain	Dmnl	Lookup function	*Figure F20a*	*Figure F20b*	*Figure F20c*	Current speed floodplain	Flooding in m³/s		
Water level effect on side channel inflow	Dmnl	Lookup function	*Figure F21a*	*Figure F21b*	*Figure F21c*	Water level side channel above NAP	Water level main channel above NAP	Water level difference	
Water volume effect on current speed floodplain	Dmnl	Lookup function	*Figure F22a*	*Figure F22b*	*Figure F22c*	Flooding in m³/s	Water in floodplain	Current speed floodplain	
Width effect on current speed side channel	Dmnl	Lookup function	*Figure F23a*	*Figure F23b*	*Figure F23c*	Water in side channel	Water in floodplain	Water level difference	
Cargo capacity adjustment time	Day	Time variable	2	0.25	30	Cargo capacity			
Delay time pioneering	Day	Time variable	730	365	1460	% grass	Floodplain vegetation roughness		
Delay time succession reeds to scrub	Day	Time variable	16790	7665	25915	% reeds	% scrub	Floodplain vegetation roughness	
Delay time succession scrub to forest	Day	Time variable	18250	25915	36500	% scrub	% forest	Floodplain vegetation roughness	
Delay time succession grass to reeds	Day	Time variable	730	365	1460	% grass	% reeds	Floodplain vegetation roughness	
Time floodplain to channel	day	Time variable	0.020 833	0.010416 667	0.04166 6667	Water main channel to floodplain	Water side channel to floodplain		
Time channel to floodplain	day	Time variable	0.0041 67	0.00416 7	0.02083 3333	Water main channel to floodplain	Water side channel to floodplain	Water in main channel	Water in side channel
Vegetation removal time	day	Time variable	14	5	30	% grass	% reeds	% scrub	Vegetation roughness

Erosion sedimentation multiplier

The erosion sedimentation multiplier takes the duration of inundation of the floodplain as input and returns a value between 0 and 1 that is multiplied with the erosion rate of the different vegetation classes. In the model, the relation between duration of inundation and the multiplier is assumed as in *figure F19a*. If the floodplain is inundated less than 15 days, the erosion rate will be lowered from its normal value. *Figure F19b* shows a lower value of the multiplier; only if the duration of inundation is 22.5 days will the multiplier be set to 1. *Figure F19c* indicates that the multiplier is already set to 1 after 5 days of floodplain inundation, which is the higher value of the multiplier.

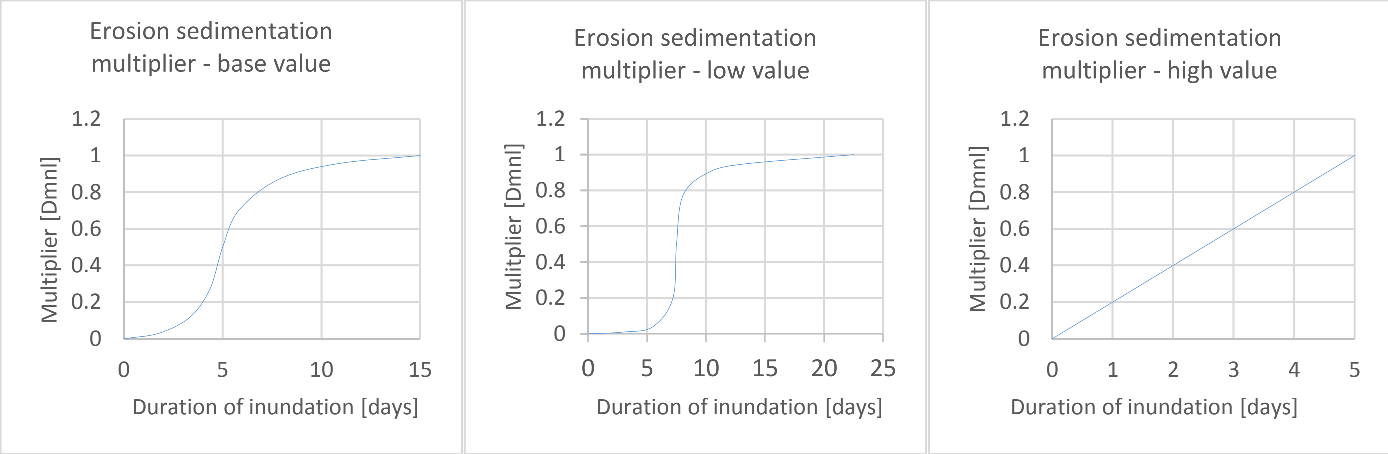


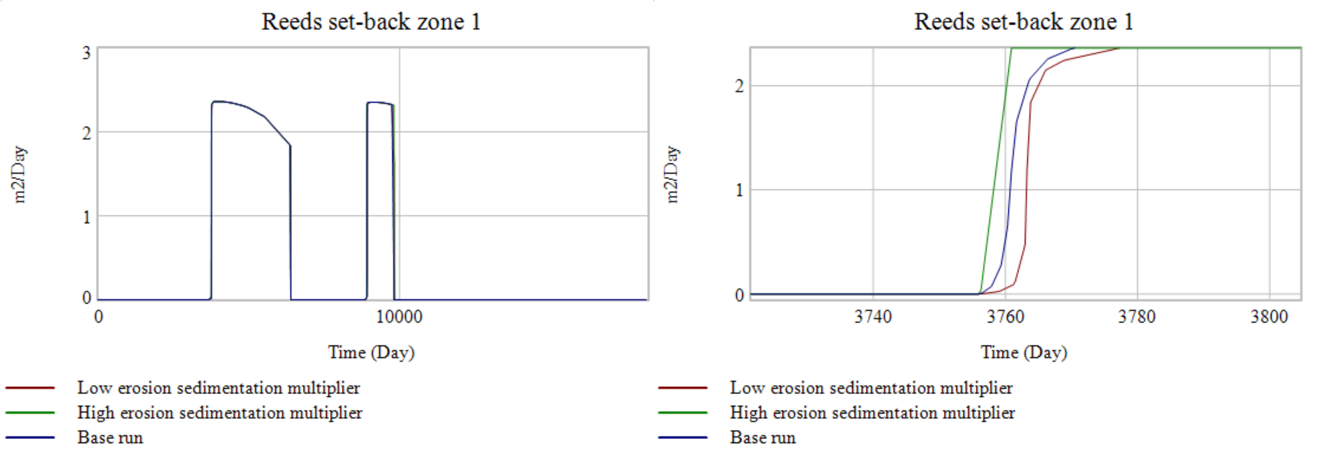
Figure F19: Lookup graphs erosion sedimentation multiplier

Dynamic hypothesis

The erosion sedimentation multiplier only affects erosion and sedimentation processes at the start of a floodplain inundation period. If the duration is longer than 15 days (in the base run), the erosion sedimentation multiplier no longer has any effect. The base run contains only two relatively long periods of floodplain inundation, and therefore it was expected that changing the erosion sedimentation multiplier would have limited effect. If the base run would contain many short periods of floodplain inundation, the effect would be larger.

Sensitivity results

Figure F20 and *table F10* indeed show that the erosion sedimentation multiplier does not significantly change the model behaviour. Only if the graph of *Reeds set-back zone 1* is zoomed in to a time interval of 20 days, can differences between the runs with different lookups be observed.



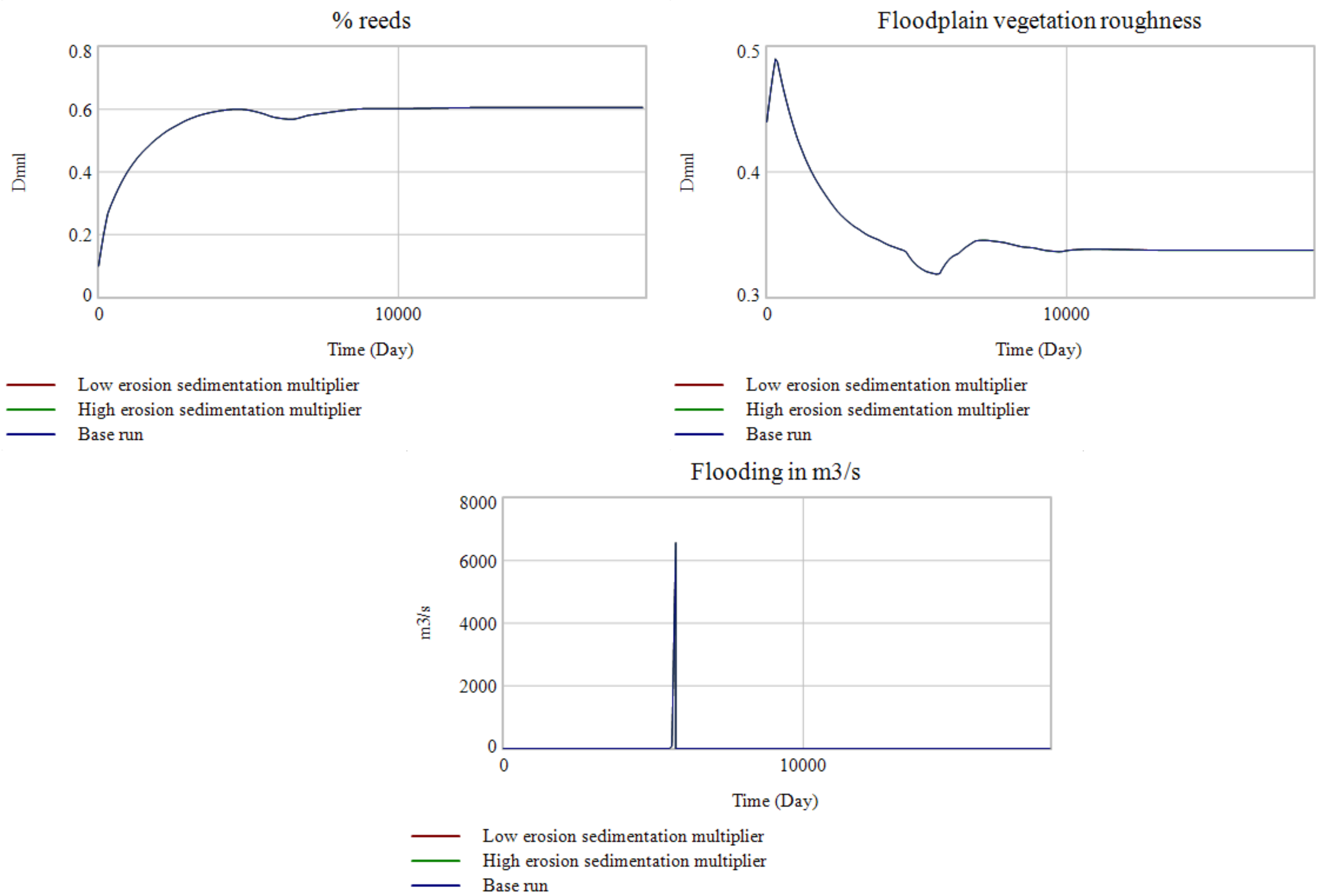


Figure F20: Sensitivity results for erosion sedimentation multiplier

Table F10: Sensitivity results for erosion sedimentation multiplier

	Erosion sedimentation multiplier [Dmnl]	**Total flooding [m³]**	**Area under % reeds graph [Dmnl]**
Base value	*Figure F19a*	3.94E+10	9820
Lower extreme value	*Figure F19b*	3.94E+10	9823
Upper extreme value	*Figure F19c*	3.94E+10	9815

Conclusion

Although the results of this sensitivity test show that changing the erosion sedimentation multiplier does not have a significant effect on the model behaviour, it could have more significant effect if many short periods of floodplain inundation were to occur.

Vegetation effect on current speed floodplain

The vegetation effect on the current speed in the floodplain takes the roughness of the vegetation in the floodplain as input and returns a value between 0 and 1 to be multiplied with the current speed of the floodplain. In the model, the relation between vegetation roughness and current speed is supposed to be linear, as depicted in *figure F21a*. An important assumption is that the current speed will never be multiplied by 0 but always at least with 0.25, even if the floodplain vegetation roughness is at its maximum value (1). Therefore, the water in the floodplain will never be completely stagnant. When the vegetation roughness has a lower effect, the current speed will only be halved when the floodplain vegetation roughness is at its maximum. When the vegetation roughness has a higher effect, the current speed decreases faster and will reach 0 at a vegetation roughness of 1.

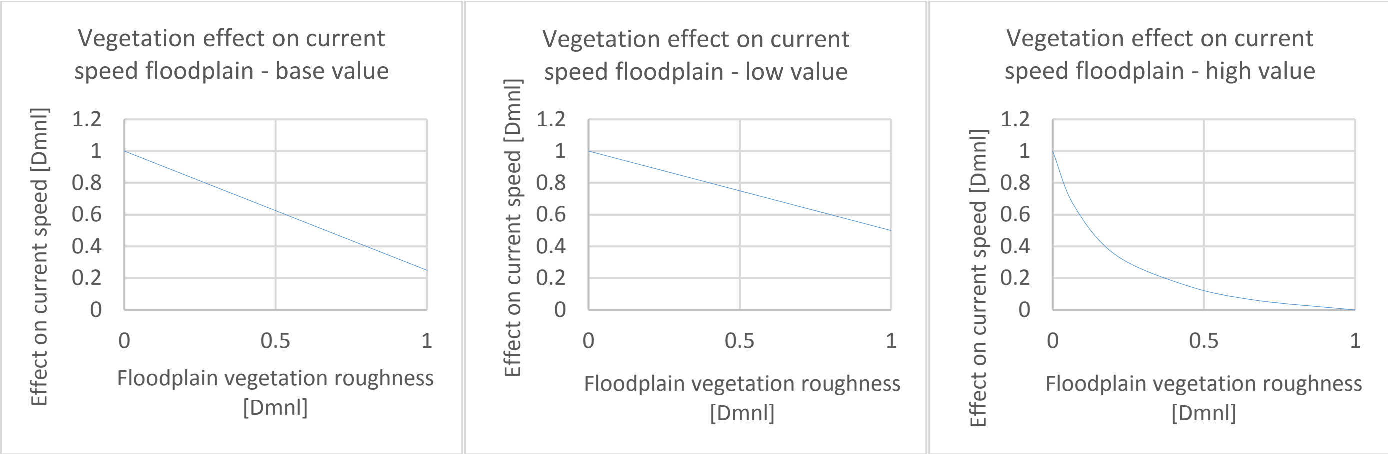


Figure F21: Lookup graphs vegetation effect on current speed floodplain

Dynamic hypothesis
It was expected that lowering the effect of the vegetation roughness on the current speed in the floodplain would cause the current speed to drop and therefore flooding to rise. The opposite was expected for increasing the vegetation effect.

Sensitivity results
A stronger effect of the vegetation roughness indeed led to a decrease of the current speed in the floodplain, and therefore to an increase in flooding (see *figure F22* and *table F11*).

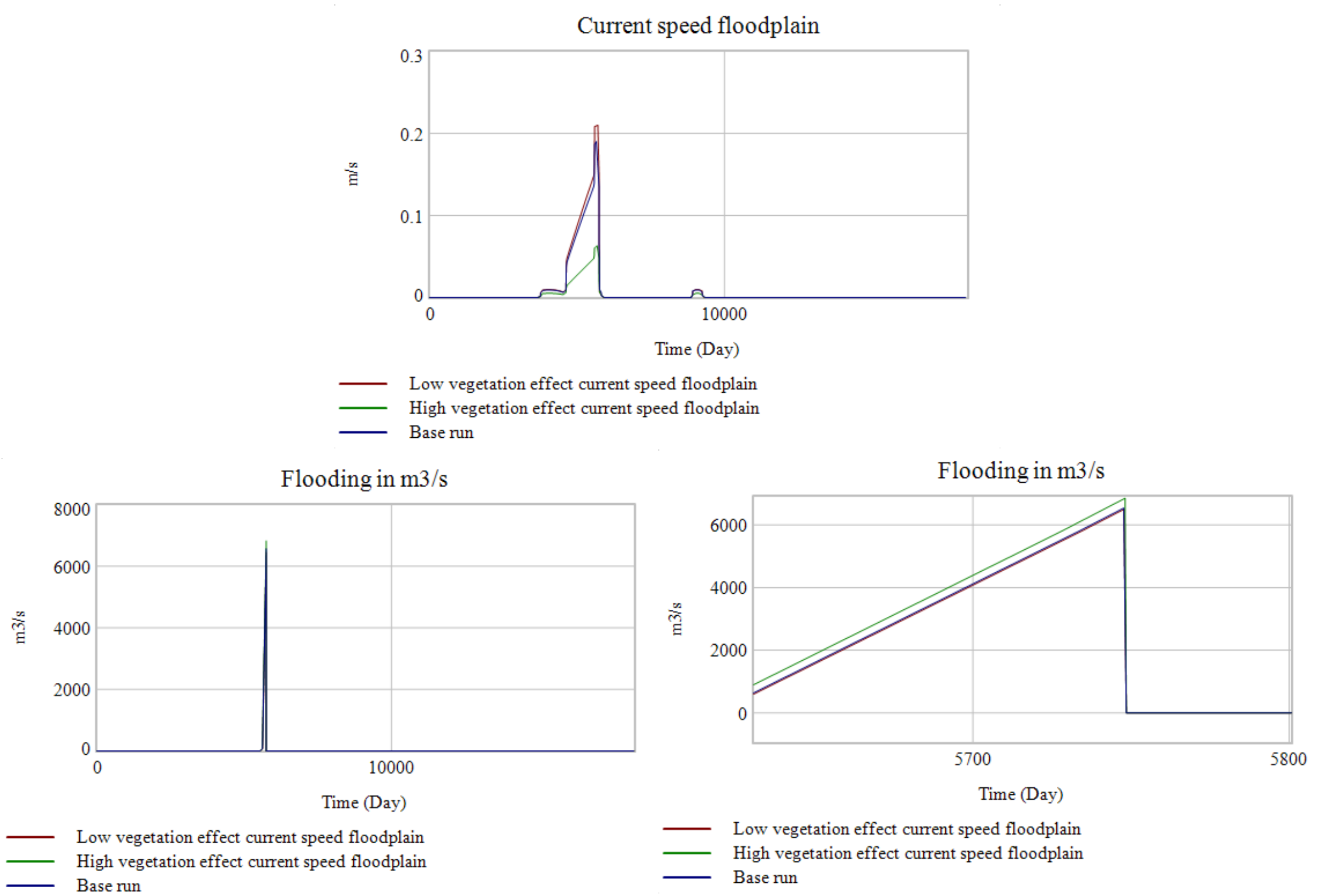


Figure F22: Sensitivity results for vegetation effect on current speed floodplain

Table F11: Sensitivity results for vegetation effect on current speed floodplain

	Vegetation effect on current speed floodplain [Dmnl]	Total flooding [m³]
Base value	*Figure F21a*	3.94E+10
Lower extreme value	*Figure F21b*	3.89E+10
Upper extreme value	*Figure F21c*	4.27E+10

Conclusion
The sensitivity test for this variable indicated that it is important to choose the relationship between the floodplain vegetation roughness and the current speed in the floodplain correctly. For now, the relationship that was chosen initially is considered the best option, because floodplain vegetation does have a significant effect on the current speed, but stagnant water in the floodplain should be avoided.

Water level effect on side channel inflow
The water level effect on side channel inflow is meant to level the water level in the main channel with the water level in the side channel, since in real river systems the water levels of these two channels should be the same. It therefore takes the water level difference between the side channel and the main channel (side – main) as input, and returns a correction factor for the inflow into the side channel. If the difference is below 0, more water should flow into the side channel, and if the difference is above 0, less water flow is required. *Figure F23a* shows the lookup as implemented in the model. *Figure F23b* shows a lower effect of the water level difference, and *figure F23c* a higher effect.

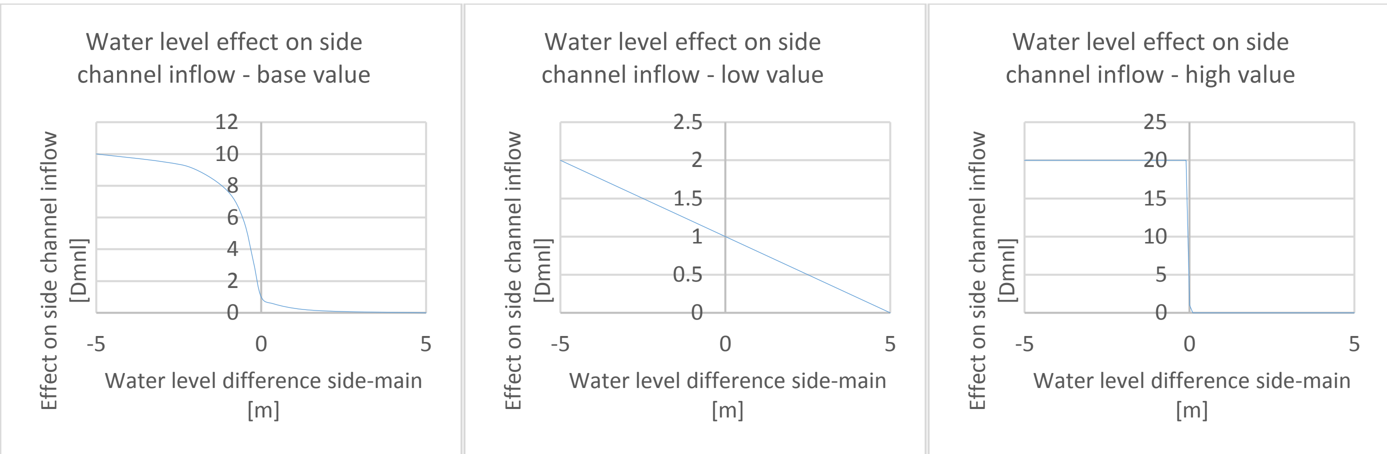


Figure F23: Lookup graphs water level effect on side channel inflow

Dynamic hypothesis
It was expected that the lower effect of the water level difference on the side channel inflow would result in a larger difference between the water level in the main channel and the water level in the side channel, because less correction would take place. On the other hand, a stronger effect of the water level difference will lead to almost 0 meters difference between the two water levels.

Sensitivity results
Figure F24 shows that a lower effect of the water level difference indeed led to a larger difference in water level between the two channels. The graph of the run with the higher effect could not be loaded, so its effect could not be analysed. The explanation for this is that that the required

numerical accuracy could not be obtained and the graph could not be produced. This is caused by the fact that the water level in the side channel, the water level in the main channel, and the water flow from the main channel to the side channel became so interdependent when the right lookup graph was implemented, that valid results could no longer be obtained with System Dynamics. Other methods, such as hydrodynamic process models that are fit for solving the relevant partial differential equations, would be required.

This test results indicates a limit of applicability of the model if continuity in water levels between the main channel and the side channel is to be preserved.

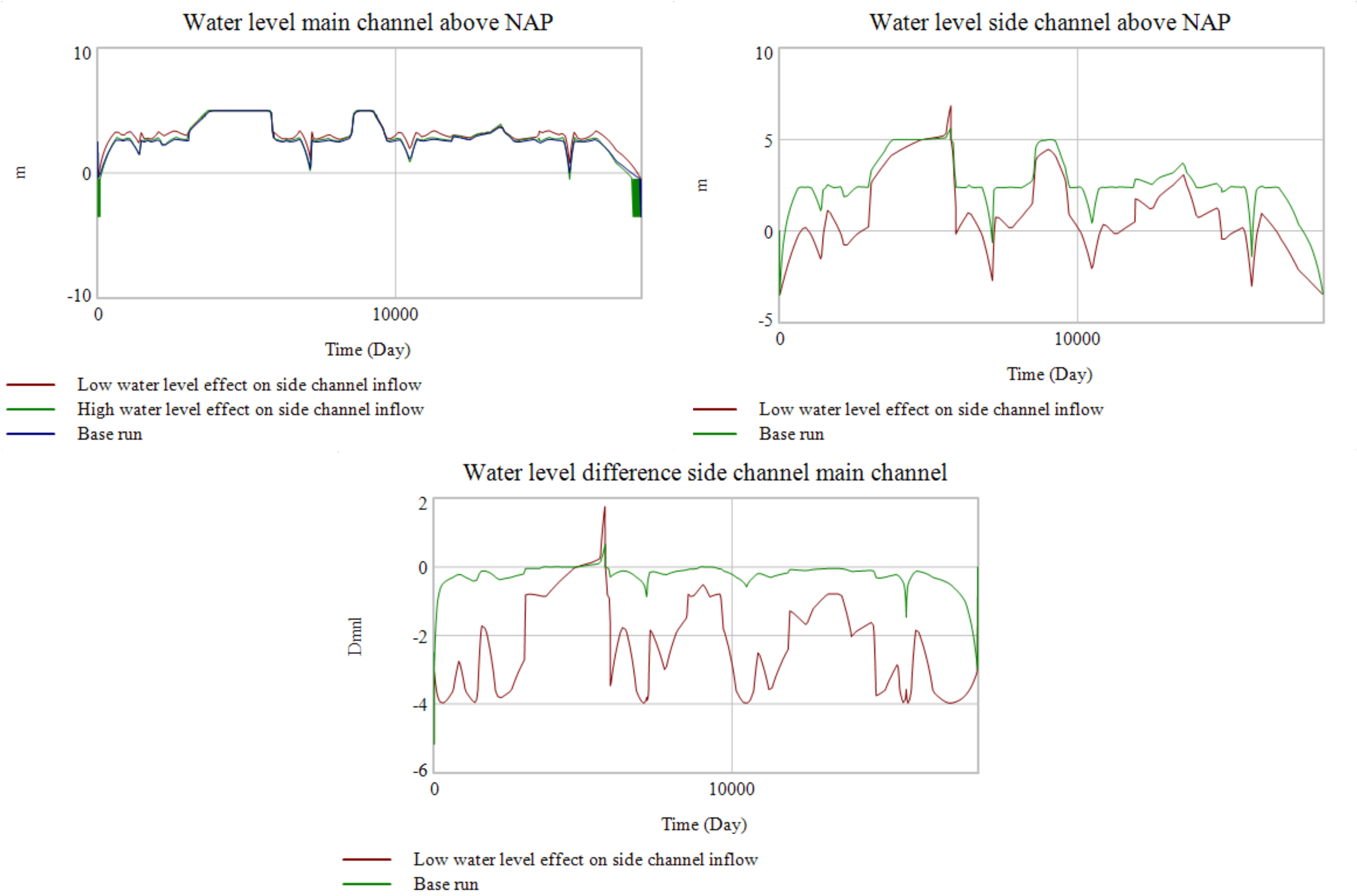


Figure F24: Sensitivity results for water level effect on side channel inflow

Conclusion

The original graph of the water level effect on side channel inflow behaves as expected and shows the most promising behaviour. The graph should not be steeper (as is the high value), because that would cause too strong a coupling and highly non-linear, unstable behaviour. On the other hand, the graph should also not be less steep because then the water level difference between the main and the side channel increases, which is unrealistic in a continuous system.

Water volume effect on current speed floodplain

Instead of basing the current speed on the water inflow (as is the case for the main and side channel), the current speed in the floodplain is based on the water volume in the floodplain. If there is more water in the floodplain, its current speed will be closer to its maximum value. *Figure F25a* shows the relation between the water volume and the current speed multiplier for the base situation. At a water volume of 5 million m^3 (the floodplain capacity is around 7 million

m^3), the current speed is at its maximum. If the effect is lower, the current speed will reach its maximum at a value of 50 million m^3, and the relation is exponential (*figure F25b*). A higher effect of the current speed leads to a maximum current speed at 500000 m^3 water volume (*figure F25c*).

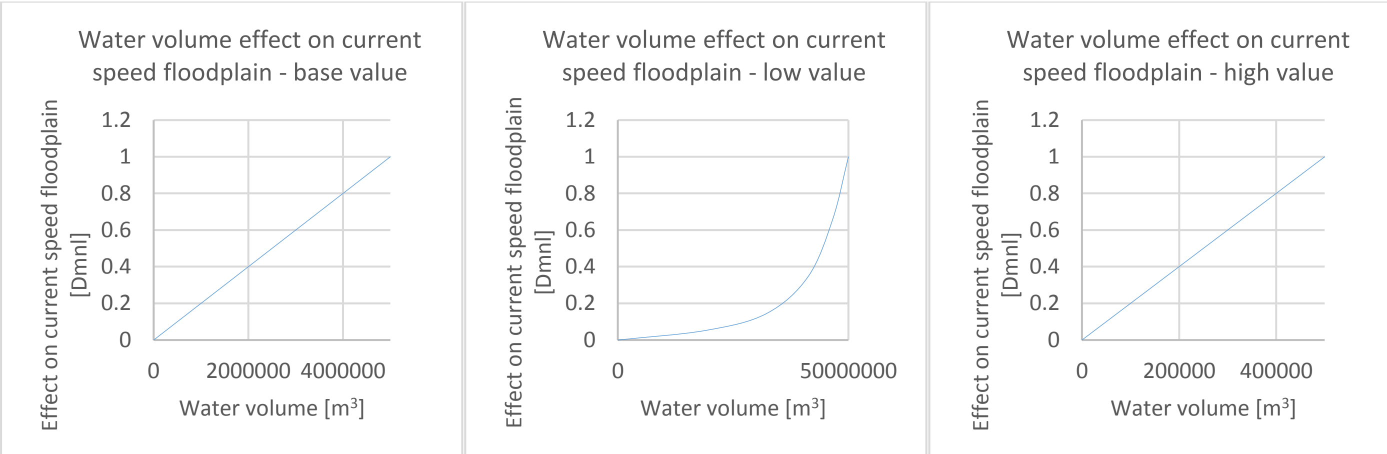
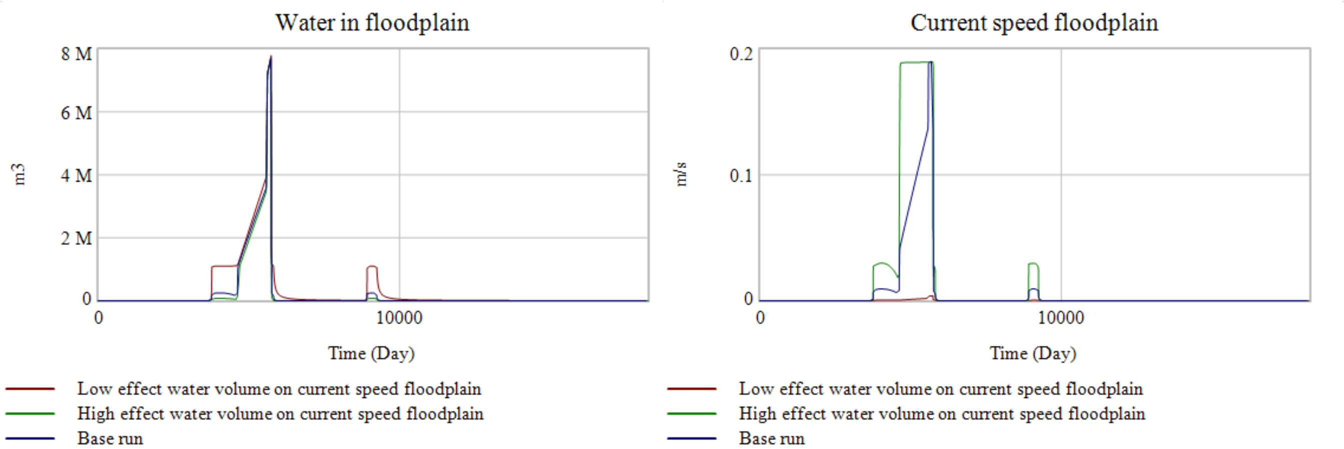


Figure F25: Lookup graphs water volume effect on current speed floodplain

Dynamic hypothesis
Since a decrease in the effect of the water volume on the current speed leads to a lower current speed, it was expected that flooding would increase. An increase in the effect of water volume on the current speed was expected to lead to a decrease in flooding.

Sensitivity results
Figure F26 and *table F12* indicate that flooding indeed increased as the effect of water volume on current speed decreased. When the effect was increased, however, flooding did not decrease as was expected. This was probably caused by the fact that at the time of flooding, the current speed multiplier was 1 for the base lookup function as well as for the high lookup function. Therefore, no difference existed between these runs with regard to flooding.



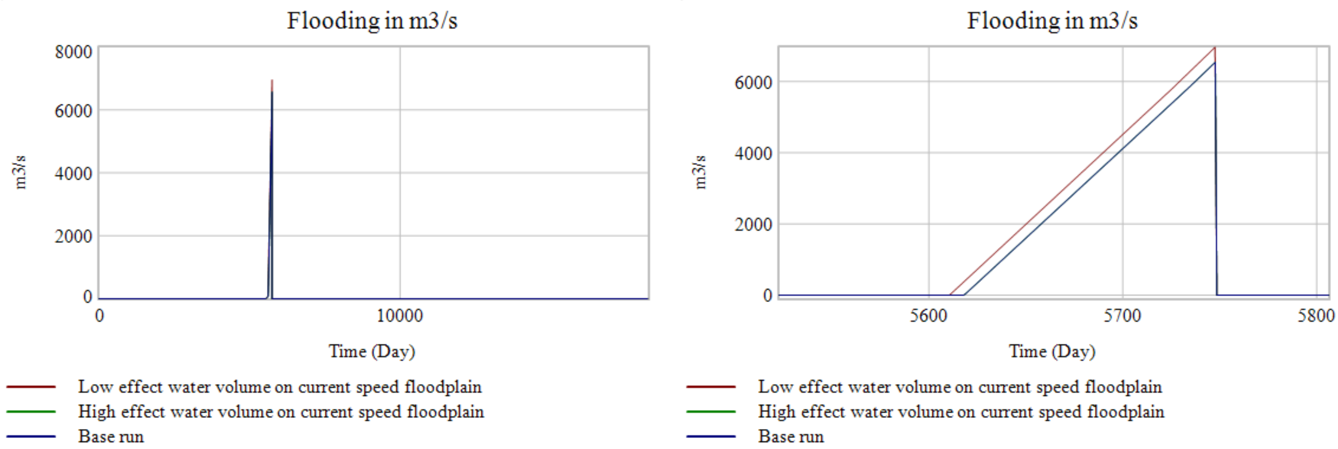


Figure F26: Sensitivity results for water volume effect on current speed floodplain

Table F12: Sensitivity results for water volume effect on current speed floodplain

	Water volume effect on current speed floodplain [Dmnl]	**Total flooding [m³]**
Base value	*Figure F25a*	3.94E+10
Lower extreme value	*Figure F25b*	4.43E+10
Upper extreme value	*Figure F25c*	3.94E+10

Conclusion

The choice of the relation between water volume and current speed in the floodplain is important to choose correctly since it has a big influence on the behaviour of water in the floodplain. For now, the base relationship is assumed to be correct, since the current speed will reach its maximum at a volume of 5 million m^3, and the maximum capacity of the floodplain is around 7 million m^3.

Width effect on current speed side channel

The relation between discharge and current speed for the main channel is taken as a basis for the relation between discharge and current speed of the side channel. However, since the side channel is usually narrower, its current speed is higher for the same discharge. Therefore, a correction factor is calculated based on the ratio of the width of the main channel and of the side channel:

$$\frac{\dfrac{Width\ main\ channel}{Height\ main\ channel}}{\dfrac{Width\ side\ channel}{Height\ side\ channel}}$$

The normal value for this lookup graph is given in *figure F27a*. The graph for a lower width effect is given in *figure F27b*, and the graph for a higher width effect in *figure F27c*.

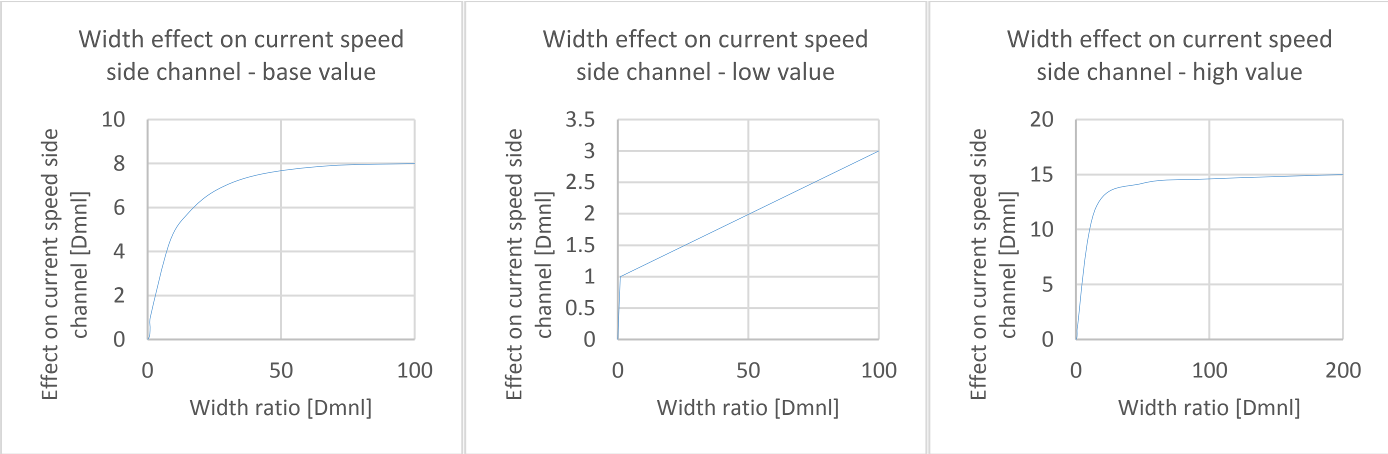


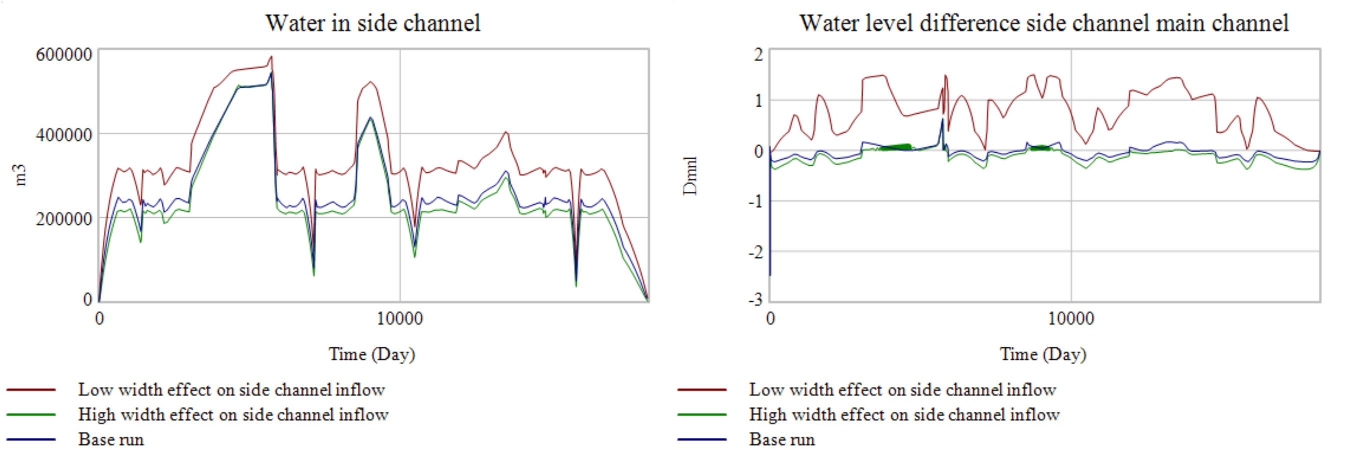
Figure F27: Lookup graphs width effect on current speed side channel

Dynamic hypothesis

The current speed in the side channel decreases if the effect of the width ratio is decreased. Therefore, it was expected that the water level in the side channel would rise, resulting in more water in the floodplain. In first instance, an increase in the water level difference between the main and side channel would be expected, because the water level in the side channel rises, while the water level in the main channel is lowered. However, this effect would be counteracted by *Water level effect on side channel inflow* that decreases the side channel inflow if the water level difference with the main channel is too high. For a decrease in the effect of the width ratio the opposite effect was expected.

Sensitivity results

As can be seen in *figure F28*, decreasing the effect of the width ratio on the current speed indeed increased the water volume and water level in the side channel. It was increased at such a rate that the maximum capacity of the side channel was exceeded, and more water flowed into the floodplain. The water level difference increased, which indicates that the compensating effect of *Water level effect on side channel inflow* is not that strong. Increasing the effect of the width ratio led to a slight decrease of the water level in the side channel and to an increase in the water level difference (where the water in the main channel was higher than the water in the side channel). Increasing the effect resulted in numerically inaccurate results when the water level difference was around zero. These effects are not ascribable to the width effect itself because it is constant during the whole run-time. Therefore, this indicates a limit of applicability of the model, possibly caused by a combination of this effect and *Water level effect on side channel inflow*.



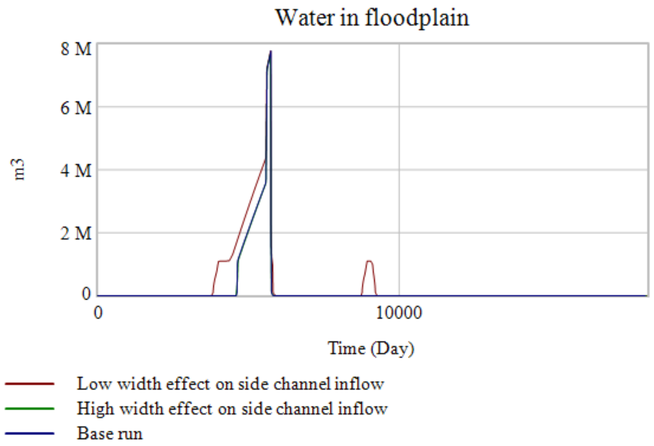


Figure F28: Sensitivity results for width effect on current speed side channel

Conclusion
Altering the lookup function for the effect of channel width on current speed resulted in expected behaviour; when the width ratio had a higher effect, less water flowed into the side channel and therefore the water level was lower. However, the test also showed the importance of the correct definition of this lookup graph. Ideally, the relation between the width of a channel and its current speed is derived from empirical data and implemented without simplifications. Since this is not possible in this model, the base value of the lookup graph is considered to be the upper value of the plausible range of values that this lookup can attain.

Cargo capacity adjustment time
The cargo capacity adjustment time is a time variable that could strongly shift model behaviour in time if it was given a high or low value. Therefore, runs of the model were tested and compared for three values; the base value (2 days), a lower value (0.25 days), and a higher value (30 days).

Dynamic hypothesis
Lowering the adjustment time is expected to result in reaching maximum cargo capacity faster. Increasing the adjustment time, on the other hand, is expected to result in a slower response of the cargo capacity to favourable river channel conditions, and therefore reaching maximum capacity later.

Sensitivity results
Figure F29 shows that a shorter cargo capacity adjustment time led to a short and high peak of cargo capacity increase, while a longer capacity adjustment time led to a longer and lower peak. This also affected the cargo capacity over the whole run, as *table F13* shows.

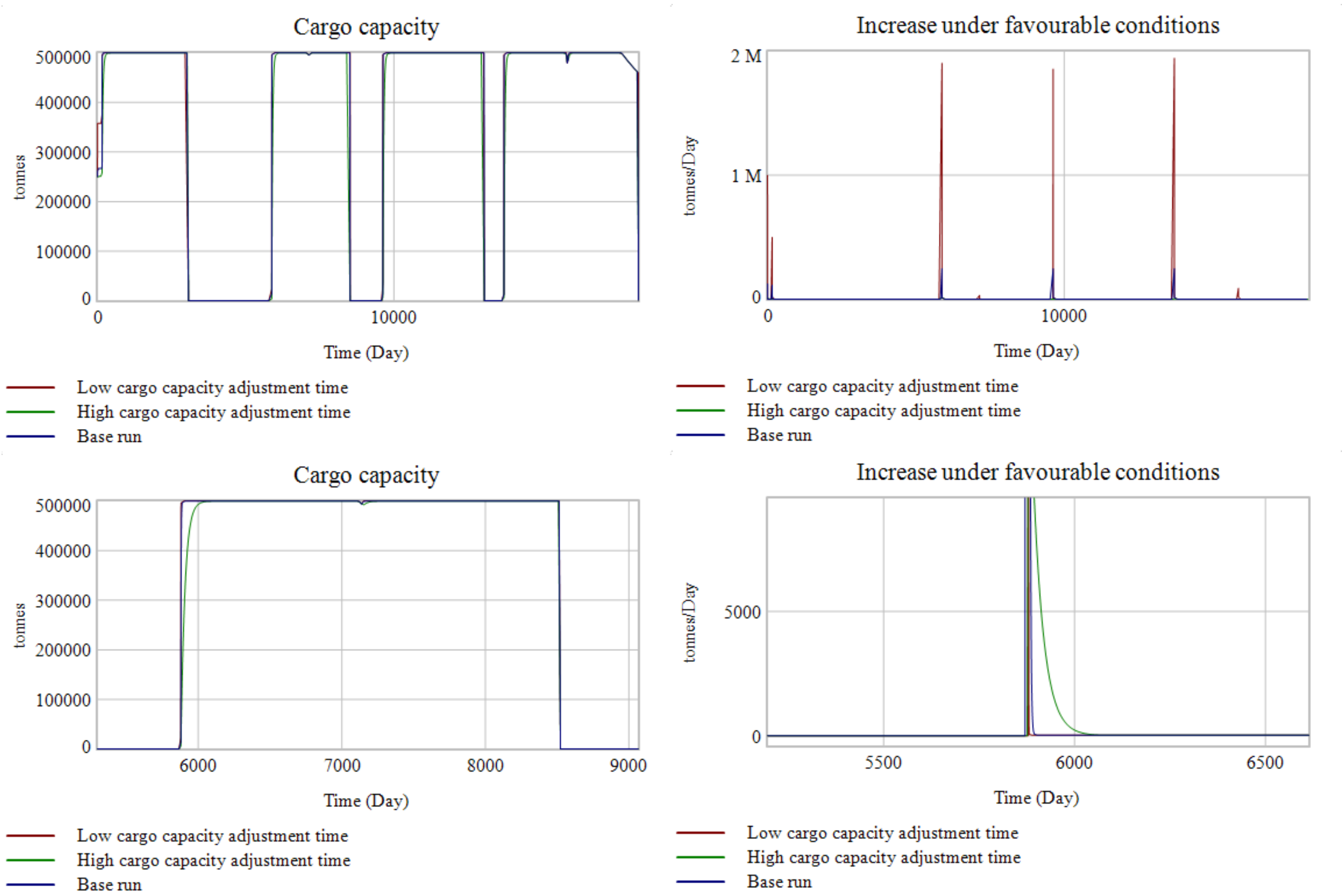


Figure F29: Sensitivity results for cargo capacity adjustment time

Table F13: Sensitivity results for cargo capacity adjustment time

	Cargo capacity adjustment time [day]	Total cargo capacity [tonnes]
Base value	2	6.56E+09
Lower extreme value	0.25	6.57E+09
Upper extreme value	30	6.52E+09

Conclusion

Changing the cargo capacity adjustment time has a significant, but expected, effect on the cargo capacity; an increase in cargo capacity adjustment time leads to a slower increase in the cargo capacity, and therefore in a slightly lower cargo capacity over the whole run.

Delay time pioneering

The delay time pioneering indicates the time it takes (on average) for bare soil to become vegetated with grass. The normal value is 730 days (2 years), its lower value is set to 365 days, and its upper value to 1460 days (4 years).

Dynamic hypothesis

If pioneering of plants requires more time, bare soil will remain bare for a longer period of time, and therefore the amount of vegetation (starting with grass) will increase slower. This results in a smaller share of vegetation in the floodplain, and thus in a lower vegetation roughness (and a higher current speed, et cetera).

Sensitivity results

Figure F30 and *table F14* show that the amount of bare soil indeed increased for a longer pioneering time, and that the amount of grass decreased. However, although it was expected that the amount of vegetation of the other classes would also be lower, this turned out only to be true for reeds. Scrub and forest actually increased due to a longer pioneering delay time. This can be explained by the fact that a lower amount of reeds caused the maximum of the rough vegetation classes to be reached later, and therefore scrub and forest could develop longer before they were removed by human intervention.

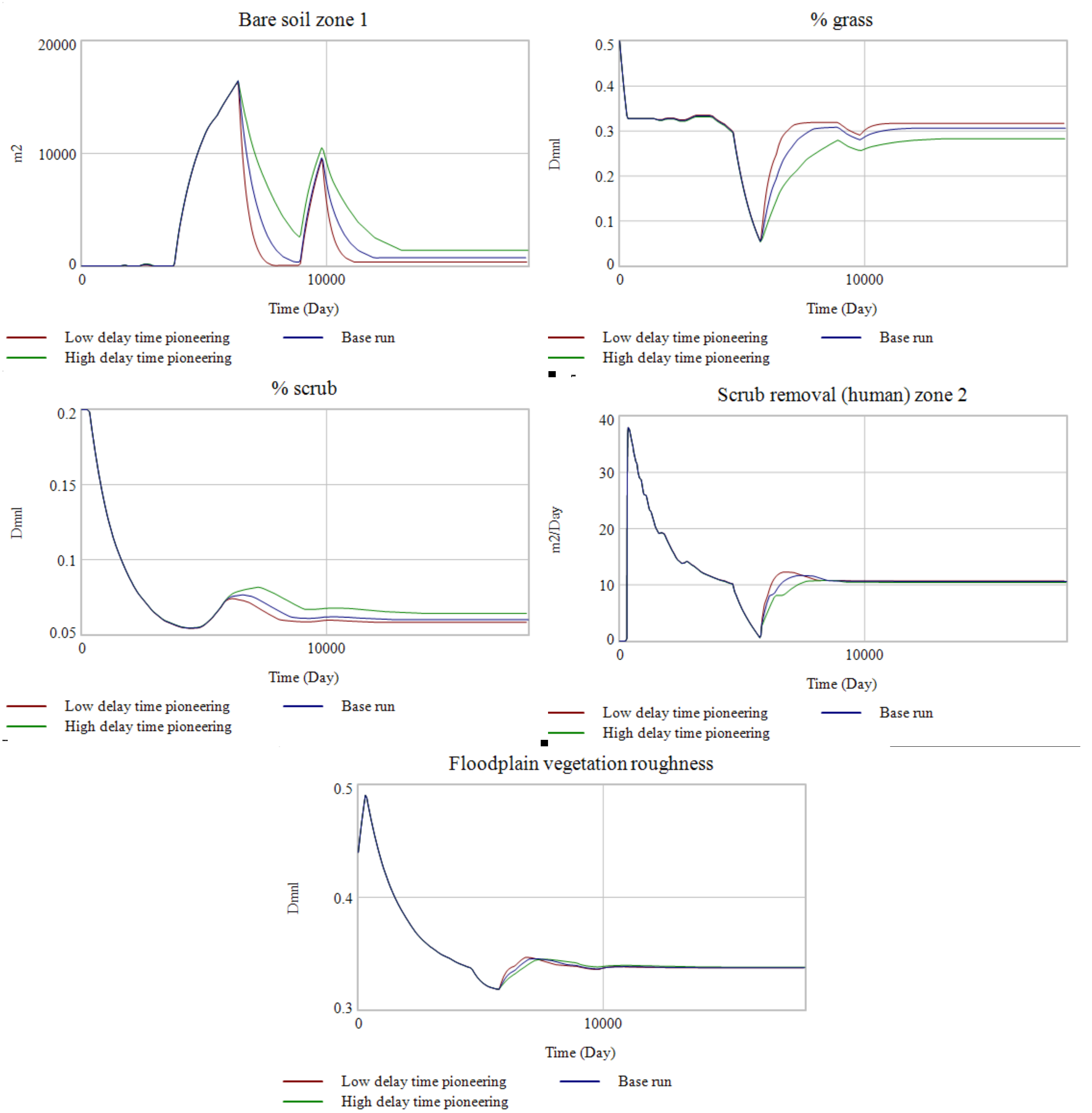


Figure F30: Sensitivity results for delay time pioneering

Table F14: Sensitivity results for delay time pioneering

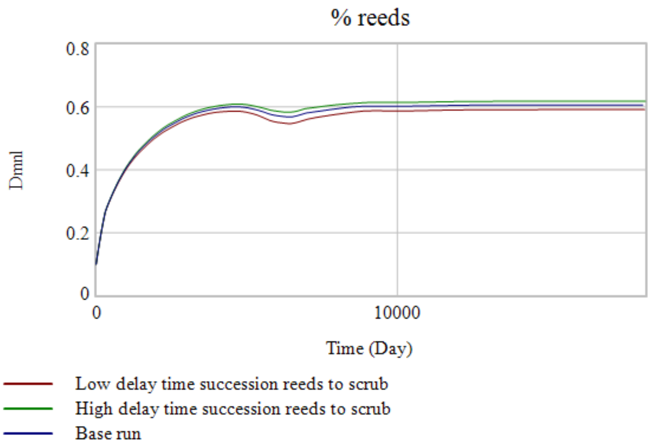
	Delay time pioneering [day]	**Area under % grass graph [Dmnl]**	**Area under % scrub graph [Dmnl]**
Base value	730	5234	1474
Lower extreme value	365	5300	1024
Upper extreme value	1460	5087	1474

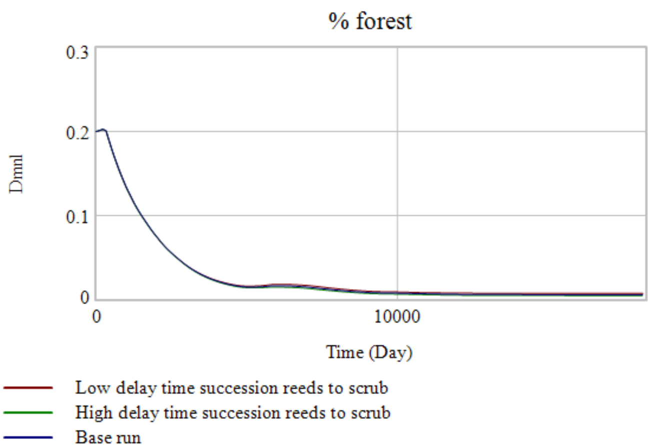
Conclusion
Secondary effects in a stock-flow structure can be strong, as was shown in this test. This led to counterintuitive model behaviour, since only first order effects were expected and included in the dynamic hypothesis. System Dynamics is a useful tool for identifying these secondary effects and showing their effect on system behaviour.

Delay time succession reeds to scrub
The delay time succession reeds to scrub represents the time it takes for reeds to develop into scrub. The normal value for this parameter is 16790 days (46 years), its lower value is set to 13140 days (36 years), and its upper value to 20440 days (56 years).

Dynamic hypothesis
If the time it takes for reeds to develop into scrub increases, there will be relatively more reeds and less scrub in the floodplain. This will result in a lower floodplain vegetation roughness.

Sensitivity results
Figure F31 and *table F15* show that the dynamic hypothesis was indeed correct. The secondary effect via vegetation removal did not occur for changes in this parameter; a higher share of scrub did not lower the share of forest through more vegetation removal.





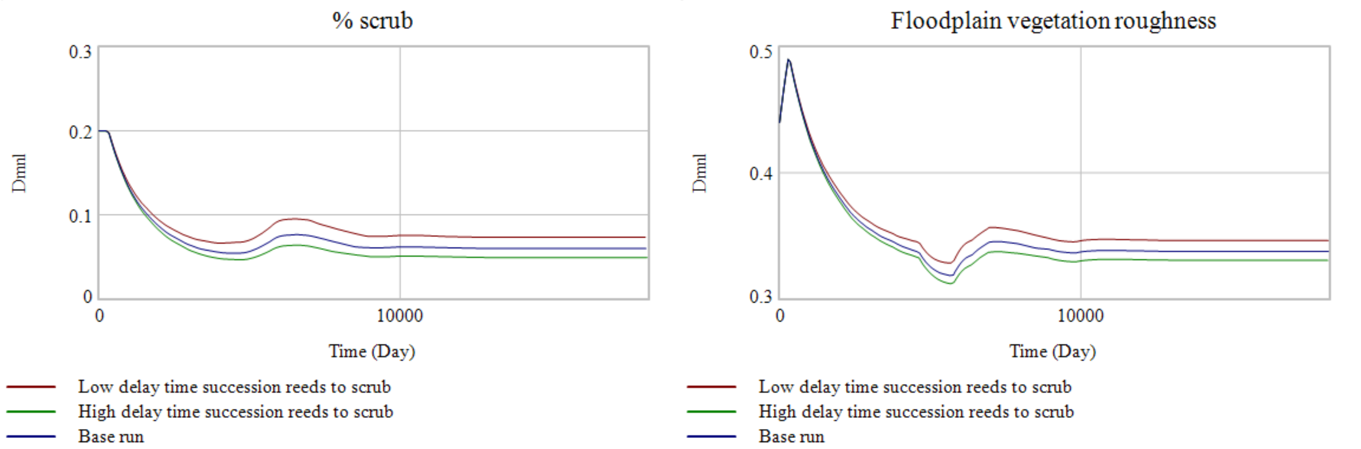


Figure F31: Sensitivity results for delay time succession reeds to scrub

Table F15: Sensitivity results for delay time succession reeds to scrub

	Delay time succession reeds to scrub [day]	**Area under % reeds graph [Dmnl]**	**Area under % scrub graph [Dmnl]**	**Area under % forest graph [Dmnl]**
Base value	16790	9820	1474	464.7
Lower extreme value	13140	9300	1727	479.6
Upper extreme value	20440	10260	1474	417.7

Conclusion
Changes in the delay time succession reeds to scrub resulted in the expected effect on the model behaviour.

Delay time succession scrub to forest
The delay time succession scrub to forest represents the time it takes for scrub to develop into forest. The normal value for this parameter is 18250 days (50 years), its lower value is set to 14600 days (40 years), and its upper value to 21900 days (60 years).

Dynamic hypothesis
If the time it takes for scrub to develop into forest increases, there will be relatively more scrub and less forest in the floodplain. This would result in a higher floodplain vegetation roughness.

Sensitivity results
Increasing the time it takes for scrub to develop into forest led to a slight increase in the share of scrub, and a slight decrease in the share of forest (best visible in *table F16*, not *figure F32*). This in turn slightly increased the vegetation roughness, since scrub is the vegetation class with the highest roughness coefficient. It did not have a significant effect on the share of grass in the total vegetation.

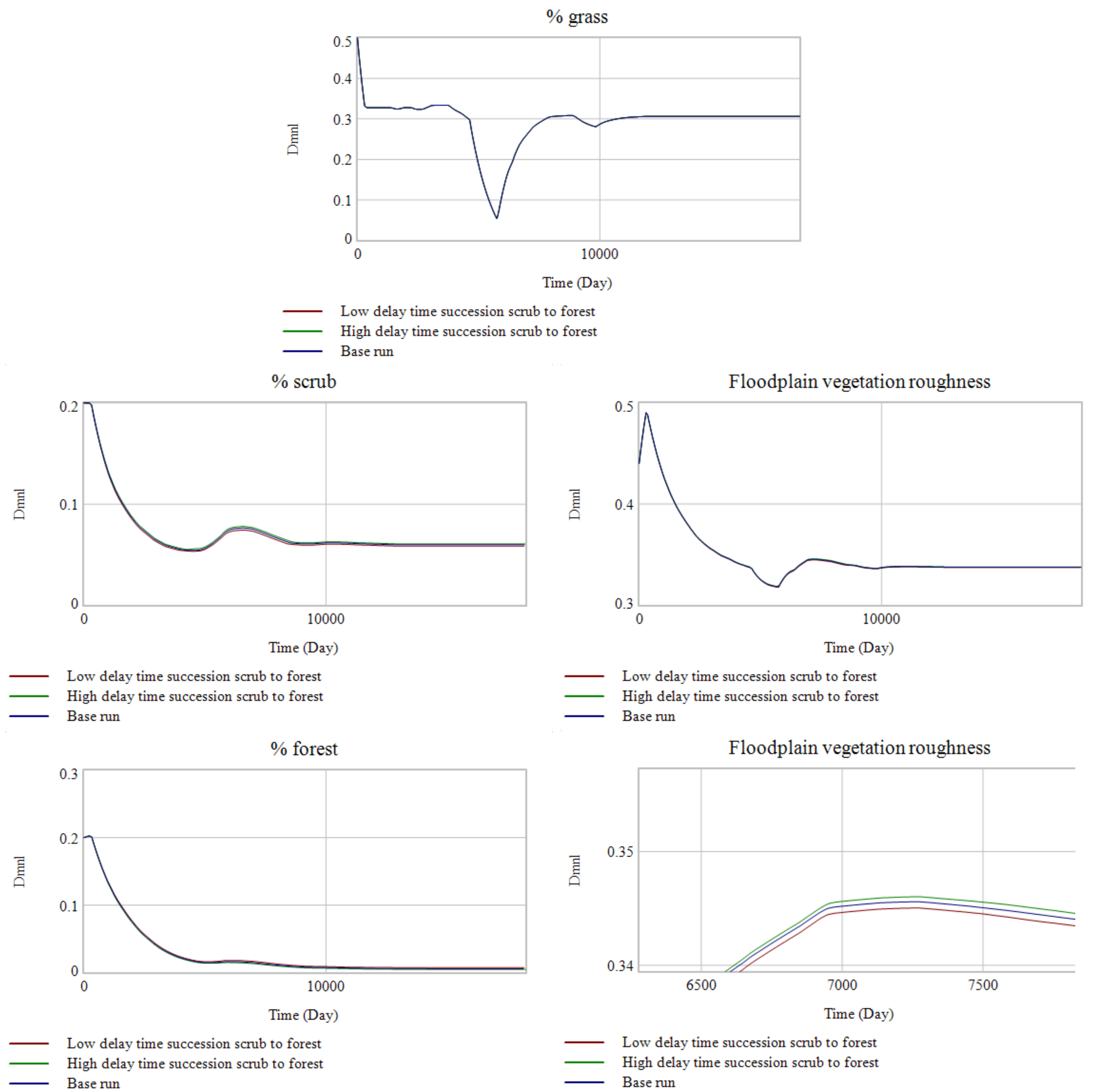


Figure F32: Sensitivity results for delay time succession scrub to forest

Table F16: Sensitivity results for delay time succession scrub to forest

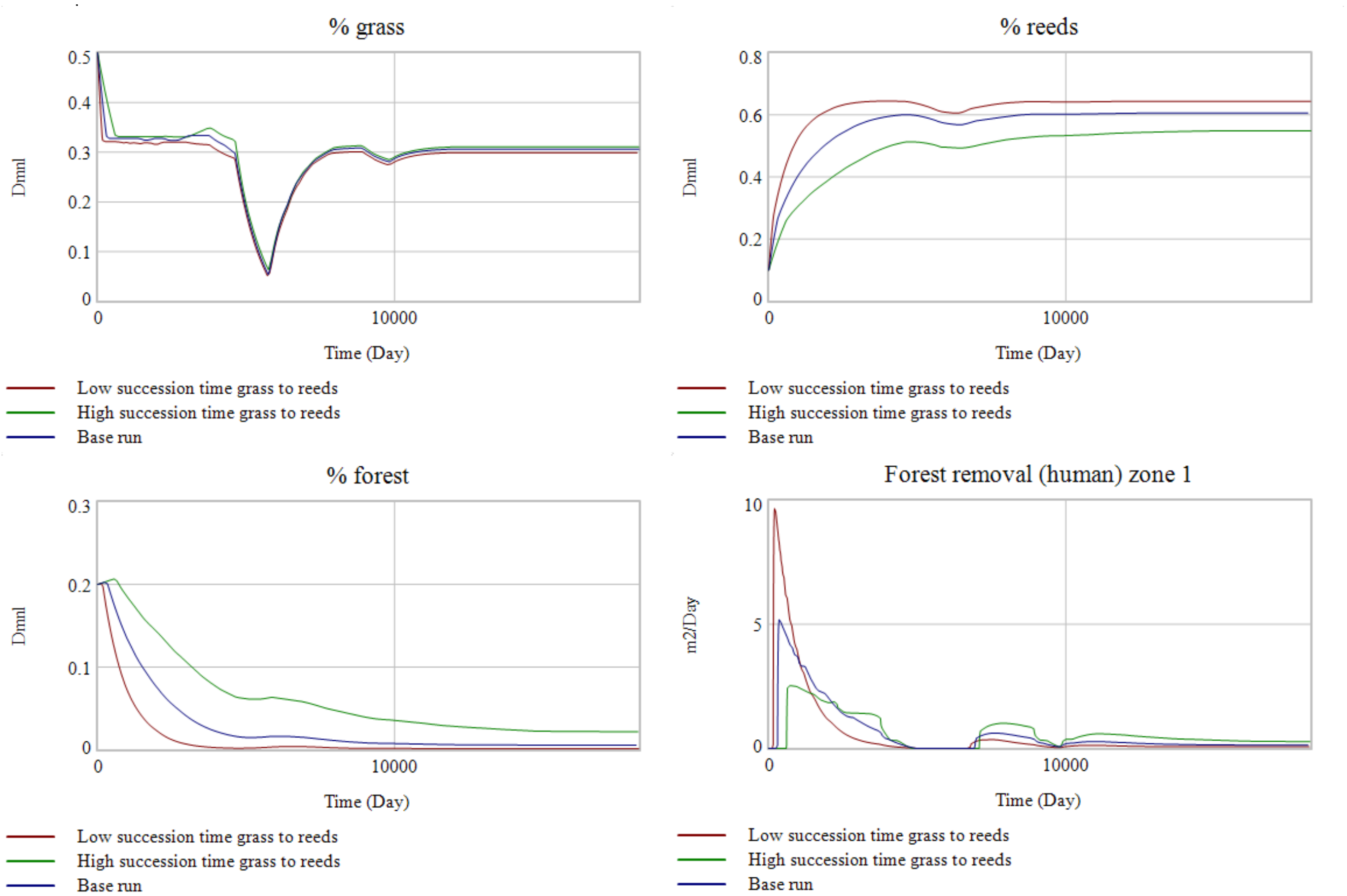
	Delay time succession scrub to forest [day]	**Area under % grass graph [Dmnl]**	**Area under % scrub graph [Dmnl]**	**Area under % forest graph [Dmnl]**
Base value	18250	5234	1474	464.7
Lower extreme value	14600	5236	1464	483.5
Upper extreme value	21900	5235	1480	416.5

Conclusion
Changes in the delay time succession reeds to scrub resulted in the expected effect on the model behaviour.

Delay time succession grass to reeds
The delay time succession grass to reeds represents the time it takes for grass to develop into reeds. The normal value for this parameter is 730 days (2 years), its lower value is set to 365 days (1 year), and its upper value to 1460 days (4 years).

Dynamic hypothesis
If the time it takes for grass to develop into reeds increases, there will be relatively more grass and less reeds in the floodplain. This would result in a lower floodplain vegetation roughness.

Sensitivity results
Figure F33 and *table F17* show that changing the succession time from grass to reeds altered the model behaviour significantly. A shorter delay time led to less grass and more reeds. Counterintuitively, it led to less forest and less vegetation roughness. This can be explained by the fact that more reeds leads to more removal of reeds, scrub, and forest, and therefore to a decrease in forest and vegetation roughness.



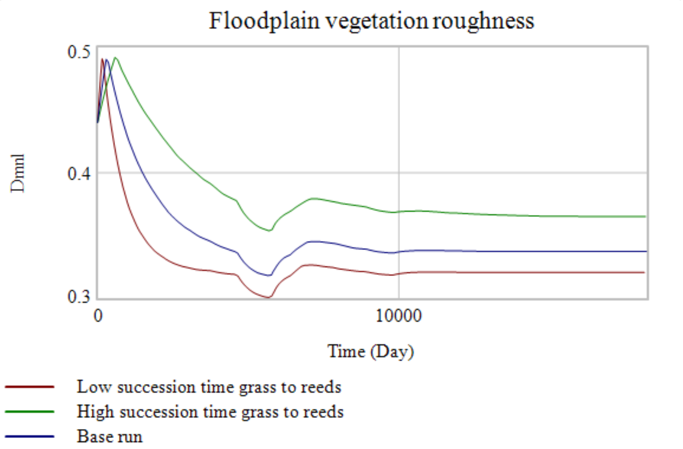


Figure F33: Sensitivity results for delay time succession grass to reeds

Table F17: Sensitivity results for delay time succession grass to reeds

	Delay time succession grass to reeds [day]	**Area under % grass graph [Dmnl]**	**Area under % reeds graph [Dmnl]**	**Area under % forest graph [Dmnl]**
Base value	730	5234	9820	464.7
Lower extreme value	365	4898	10820	194.5
Upper extreme value	1460	5338	8172	1024

Conclusion
Although the dynamic hypothesis was incorrect, the model exhibits correct and intriguing behaviour. In the hypothesis only first order effects of changes were taken into account, while higher order effects play a large role in the behaviour of the floodplain vegetation.

Time floodplain to channel
In the base run the value for this variable is set to 0.020833 days (30 minutes). However, this value is subject to uncertainty and therefore had to be tested. In the test, its lower value is set to 0.0104167 days (15 minutes) and its upper value to 0.04167 days (1 hour).

Dynamic hypothesis
Lowering this value was expected to increase the water flow from the floodplain to the channels (if this flow is possible), and therefore to a faster decrease of water in the floodplain and an increase in water in the main and side channel. Increasing this value was expected to have the opposite effect.

Sensitivity results
Figure F34 shows no difference between the three runs for different values of *Time floodplain to channel*. The reason for this is that water only flows from the floodplain back to the side channel under three conditions:

- There is water in the floodplain
- The water volume in the channel is below its maximum capacity
- The water level in the floodplain is higher than the summer dike height

In this test, not all of these conditions were met and therefore no water could flow back into the channels.

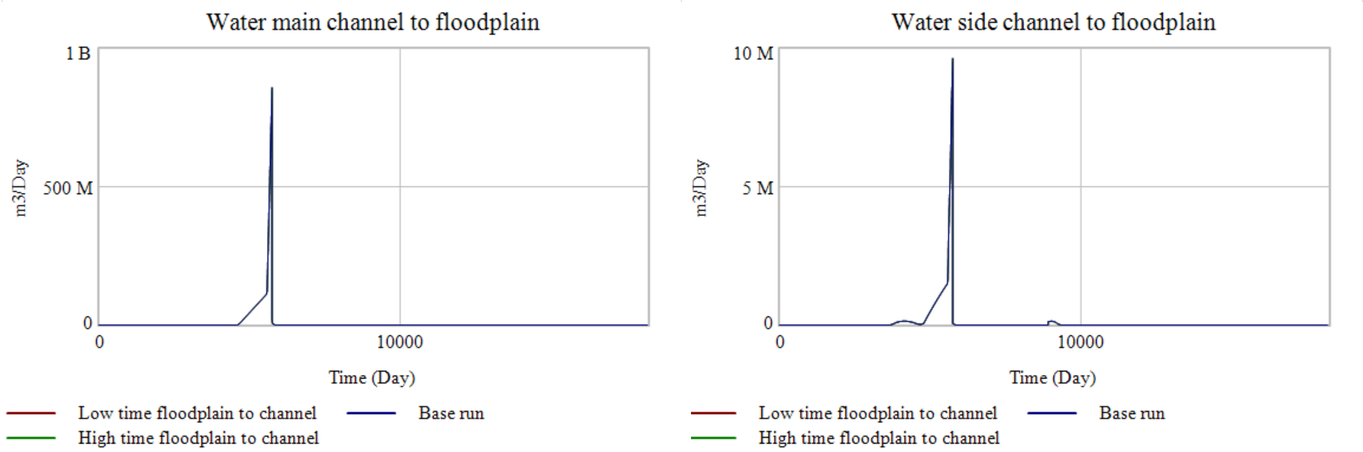


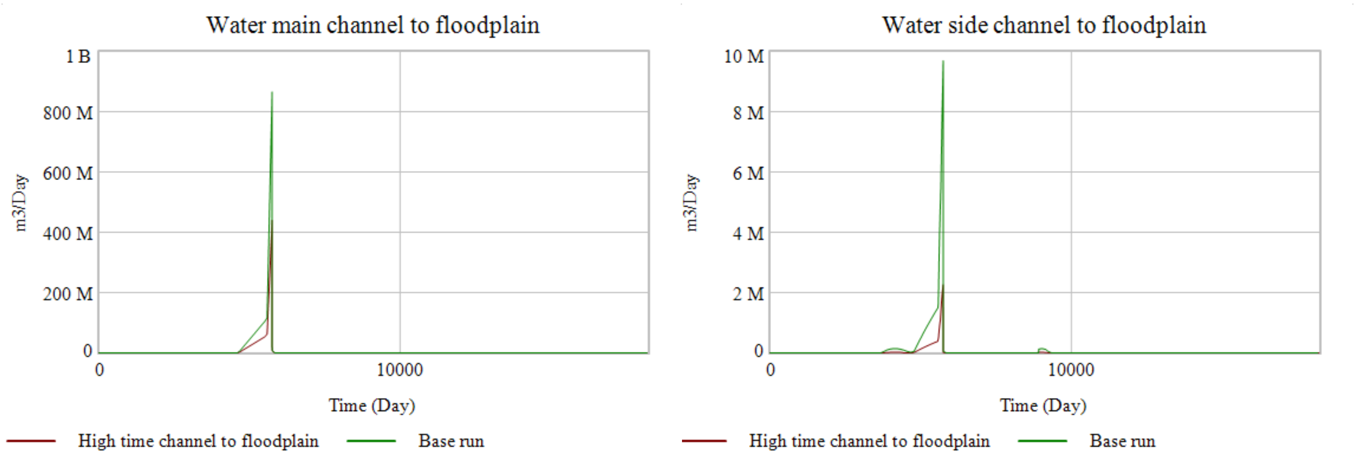
Figure F34: Sensitivity results for time floodplain to channel

Conclusion
No water flow from the floodplain to the side channel is possible if the three conditions above are not all met. In that case, changing the time it takes for water to flow back from the floodplain to the channels does not have any effect on the model behaviour and the sensitivity to this effect cannot be determined under these conditions.

Time channel to floodplain
This variable was already subject to discussion in the verification process; although it should have a very small value, a smaller value than its base value (0.004167 days, 6 minutes) could not be given due to computational constraints. Therefore, to test this variable only a higher value is assigned; 0.020833 days (30 minutes).

Dynamic hypothesis
Increasing this variable was expected to result in less water in the floodplain, and more water in the main and side channel. This would probably result in a water volume in the channels that is above their respective maximum capacities.

Sensitivity results
Figure F35 shows that the dynamic hypothesis was indeed correct.



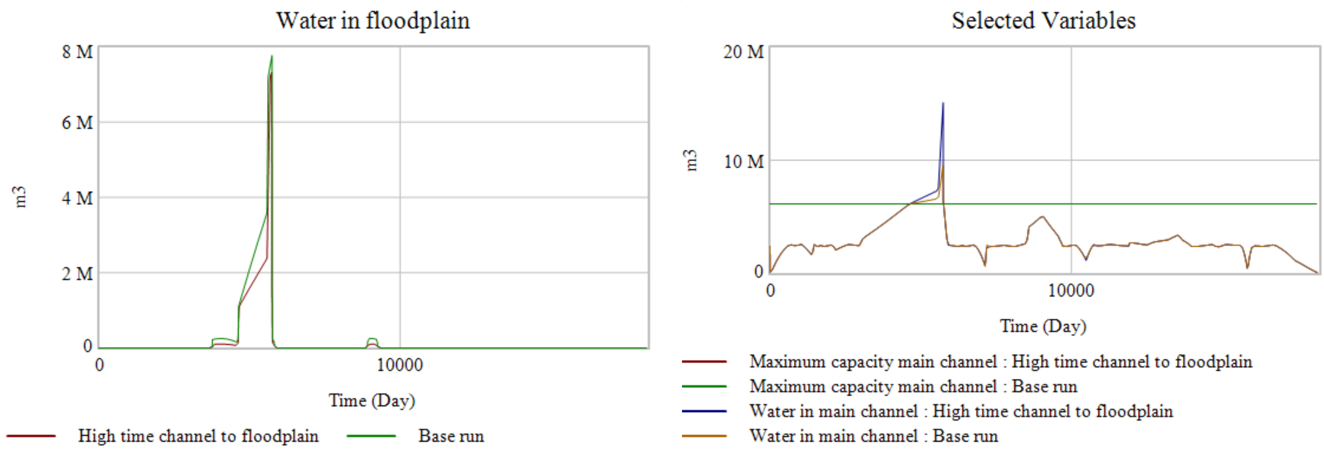


Figure F35: Sensitivity results for time channel to floodplain

Conclusion

Choosing a higher value for *Time channel to floodplain* results in model behaviour that is unlike the real system's behaviour, where there is more water in the main channel than its capacity can accommodate. Choosing a lower value for this variable would be required to model the real system very accurately, but this leads to computational problems. This constraint indicates the limits of the applicability of this model, since it cannot be used for accurate prediction of the water flow into the floodplain at each time interval. Instead, it is able to simulate issues that require an indication of this water flow.

Vegetation removal time

This variable indicates the time human removal of floodplain vegetation takes. Its base value is set to 14 days, its lower value to 5 days, and its upper value to 30 days.

Dynamic hypothesis

It was expected that lowering this variable would lead to an increased peak of vegetation removal, and therefore to a decrease in the three rough vegetation classes. However, in the long term changes in this variable were not expected to have a large effect on the shares of each vegetation class in the total vegetation.

Sensitivity results

Figure F36 and *table F18* show that the dynamic hypothesis was indeed correct. There was a slight increase in reeds and scrub when the vegetation removal time was increased, but overall the model behaviour did not change significantly.

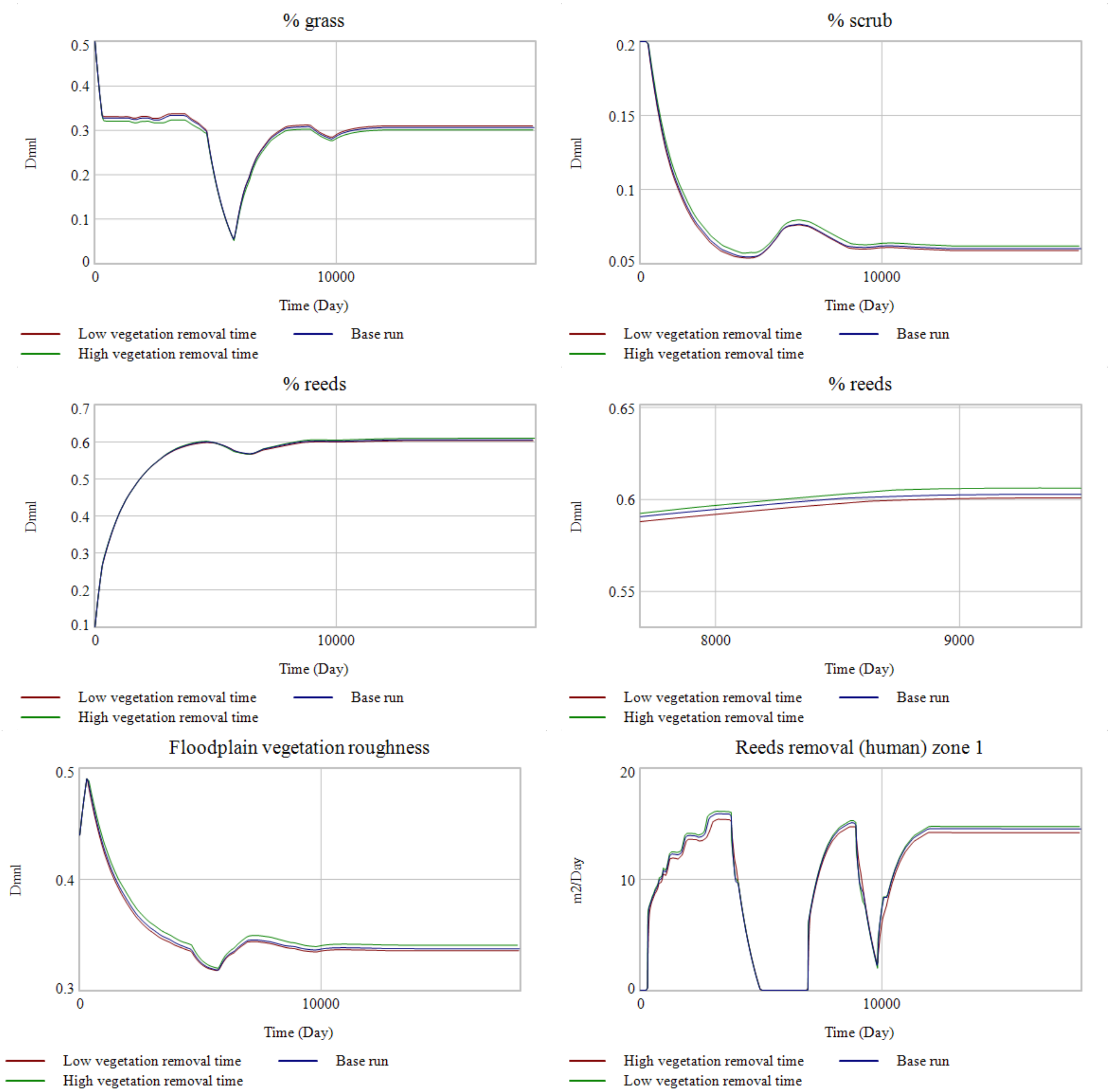


Figure F36: Sensitivity results for vegetation removal time

Table F18: Sensitivity results for vegetation removal time

	Vegetation removal time [day]	**Area under % grass graph [Dmnl]**	**Area under % reeds graph [Dmnl]**	**Area under % scrub graph [Dmnl]**
Base value	14	5234	9820	1474
Lower extreme value	5	5247	9761	1462
Upper extreme value	30	5026	9828	1492

Conclusion

Changing the vegetation removal time does not change the model behaviour significantly.

F4 Validation conclusions

Based on the three validation tests, it is concluded that the model is fit for purpose. It can be used to perform a high level, integrated analysis of the river system and the conflicts that arise between the river uses of environment, navigation, and flood protection. The qualitative validation test indicated that important river processes – such as water level continuity between the main and side channel, water level limits for cargo capacity, and the influence of water discharge and channel width on the current speed – are included in the model. The extreme conditions tests and sensitivity analysis showed that the model responds plausibly to changes in its input and that expected behaviour was obtained.

Of course, there are several issues that need to be taken into account before using the model for policy and conflict analysis. Most importantly, this model cannot reproduce natural succession in the floodplain without human interventions also being present. The time step required to simulate river processes fully is too small in relation to the delay time for succession. When human intervention and erosion and sedimentation processes are present, this problem disappears, so the model is suited to its purpose. Furthermore, the current speed in the model is constant for each river component, while in reality the current speed differs within each component. Another issue is that the model does not allow for a choice in the type of vegetation that is removed when the floodplain vegetation reaches its maximum; all three rough vegetation classes are simply cut back, while in reality a choice can be made. The next issue is also related to the floodplain vegetation; maximum limits for the rough vegetation classes are given as a percentage of the floodplain area, while actually they are determined by the floodplain's discharge capacity and therefore should attain higher values if the floodplain is enlarged. This can be solved by altering the vegetation limits manually when floodplain enlargement is studied. The last issue relates to the limit of model applicability. The model cannot be used for purposes that require very detailed and accurate information regarding the water flows in the river system, since this accuracy cannot be achieved using an approach with ordinary differential equations such as System Dynamics. Other (modelling) methods such as process-based hydrodynamic modelling exist for these purposes.

Another validation result is that several model variables were found to have a large influence on the model behaviour. First of all, the roughness values for the vegetation classes has a large influence on the total vegetation roughness, and their values should therefore be correctly ascertained. Most importantly the order of increasing roughness should be as defined in Ruimte voor Levende Rivieren (2018): grass, reeds, forest, and scrub. Secondly, the time needed for pioneering and the three succession rates can cause significant changes in the model behaviour, both directly and via secondary or higher order effects. Finally, the erosion sedimentation multiplier did not have a large effect on the test runs, but it could have a large effect on the model behaviour if many short periods of floodplain inundation occur. The reason for this is that it only influences the model during the first 15 days of a floodplain inundation period.

Finally, the validation tests showed the importance of correctly defining some lookup graphs. Especially the lookup for *Water level effect on side channel inflow* should be defined correctly; this effect should not be too strong, since that results in high interdependency between the water levels that cannot be solved validly by System Dynamics. On the other hand, the effect should not be too weak, since that results in large water differences between the main and side channel which is unrealistic. In addition, *Vegetation effect on current speed floodplain* and *Water volume effect on current speed floodplain* are important lookup graphs, since they strongly affect the current speed.

Despite simplification choices, the model does contain the essential river, environment, navigation and flood-related processes. The model is sufficiently detailed and shows plausible behaviour for the purpose of comparing several policy and scenario combinations to determine changes in conflicting values between river uses.

Appendix G: Policy and scenario implementation

This appendix provides detail on the experiments that have been performed in this research. Section G1 describes which variables need to be altered when a certain policy is implemented, and how these variables should be altered. Section G2 provides the details related to each of the chosen experiments; which policy and scenario combinations, and what changes in parameters and variables where made.

G1 Policy options and model changes

Table G1 contains a list of the changes that need to be made when implementing a certain policy option. In addition, the range in which these changes should occur is given.

Table G1: Model changes per policy option

Policy	Variables to be altered	How to alter?
Side channel construction	Side channel width	Set to required width; should be >= 0
	Horizontal floodplain width zone 1	Reduce initial value with side channel width
	Horizontal floodplain width zone 2	If side channel width wider than horizontal floodplain width zone 1, also reduce this variable
	Water level floodplain above NAP	This is a lookup based on the floodplain dimensions, so if these change, the volume limits of each floodplain area need to be recalculated
	Side channel bed above NAP	Set to required bed level; should be <= summer dike height
	Side channel threshold	Set to required threshold; should be < (summer dike height above NAP-side channel bed above NAP), otherwise water will only flow into side channel from floodplain; should be >= 0
Increase winter dike height	Winter dike height above NAP	Set to required height; should be >= summer dike height; should be > Maximum height floodplain zone 2 above NAP
	Water level floodplain above NAP	This is a lookup based on the floodplain dimensions, so if these change, the volume limits of each floodplain area need to be recalculated
Increase floodplain width	Horizontal floodplain width zone 1	Set to required width; should be >= 0
	Horizontal floodplain width zone 2	Set to required width; should be >= 0
	Water level floodplain above NAP	This is a lookup based on the floodplain dimensions, so if these change, the volume limits of each floodplain area need to be recalculated
Summer dike removal	Summer dike height above NAP	Set to level of floodplain height above NAP
	Water level floodplain above NAP	This is a lookup based on the floodplain dimensions, so if these change, the volume limits of each floodplain area need to be recalculated

G2 Experiments and variable values

This section provides an overview of the variables that were changed to implement each scenario and what value(s) they were given.

Table G2: Variable values per experiment

Experiment	Side channel width	Horizontal floodplain width zone 1	Horizontal floodplain width zone 2	Water level floodplain above NAP	Side channel bed above NAP	Side channel threshold	Inflow in m³/s	River bed level above NAP (at t=18250)
0 (BAU)	0	50	150	*Figure G1*	5	0	Normal inflow	-3.5
1	40	10	150	*Figure G2*	-3.5	0	Normal inflow	-3.5
2	0	50	150	*Figure G1*	5	0	Extreme inflow	-3.5
3	0	50	150	*Figure G1*	5	0	Normal inflow	-6
4	40	10	150	*Figure G2*	-3.5	0	Low inflow	-3.5
5	40	10	150	*Figure G2*	-3.5	8	Low inflow	-3.5
6	0	50	150	*Figure G1*	5	0	High inflow	-3.5
7	40	10	150	*Figure G2*	-3.5	0	High inflow	-6

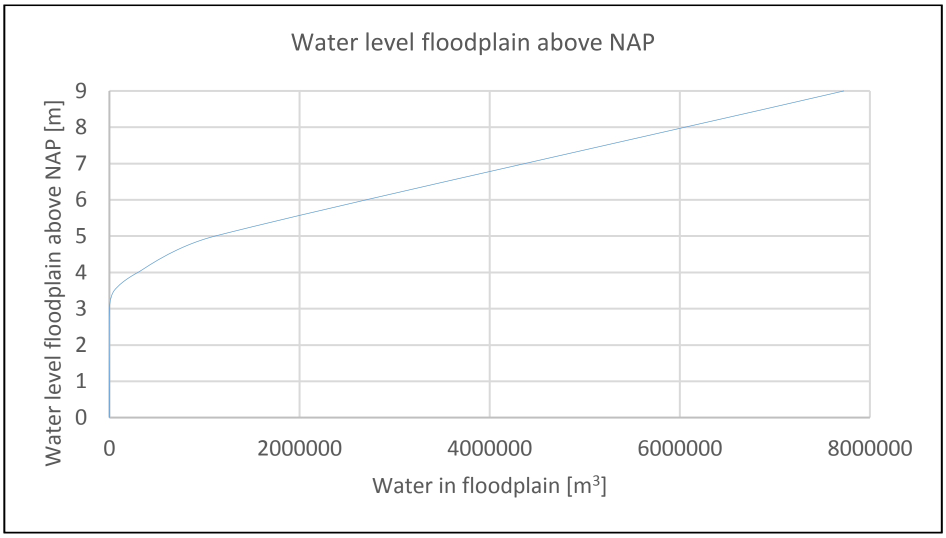


Figure G1: Water level floodplain above NAP – no side channel

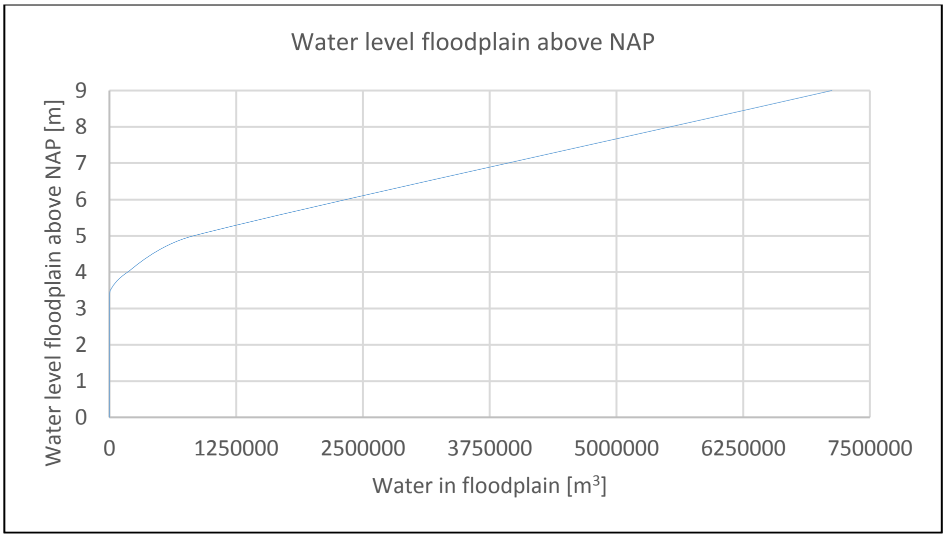


Figure G2: Water level floodplain above NAP – side channel