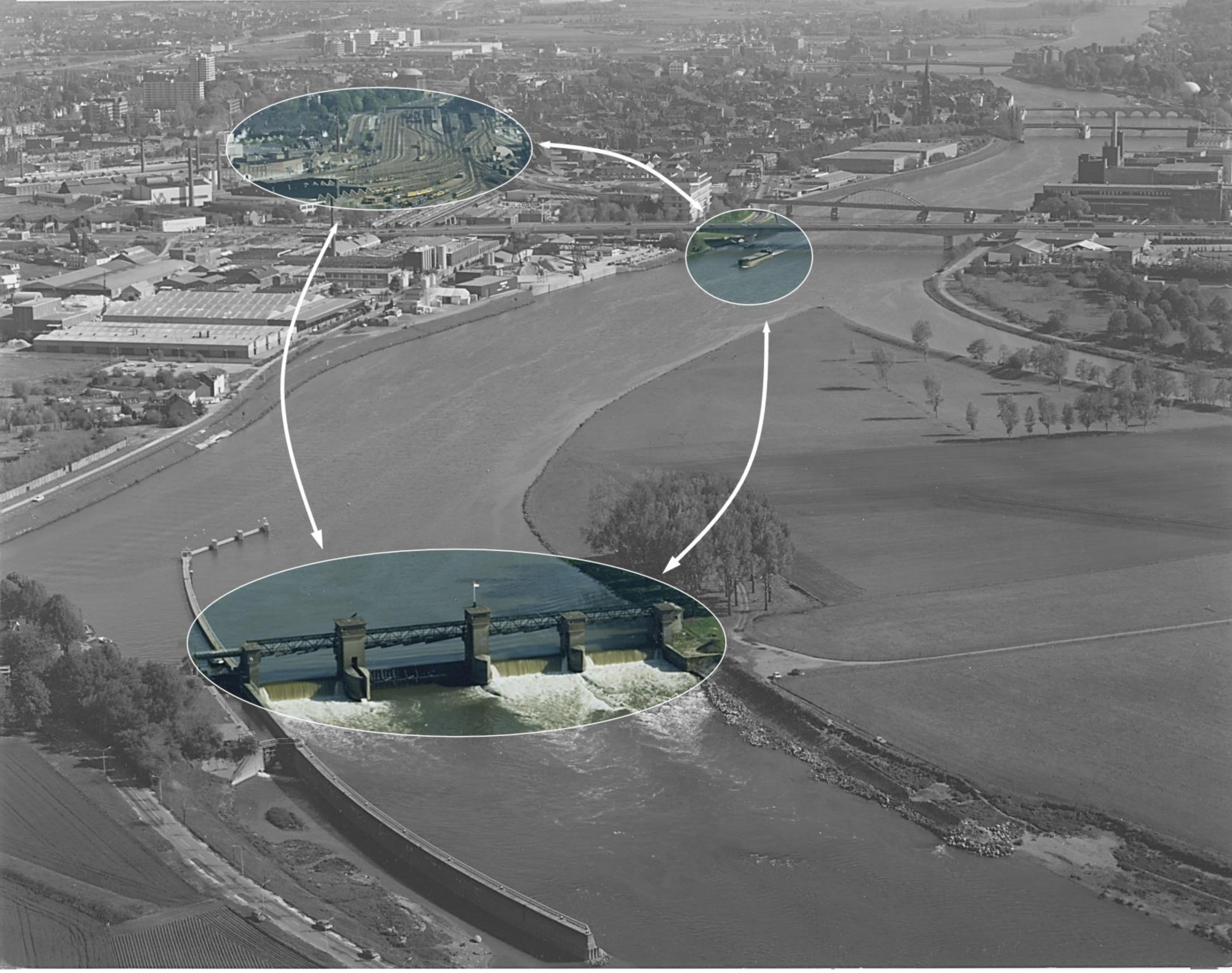

System-based replacement of hydraulic structures

A study to replace the weirs in the river Meuse

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System-based replacement of hydraulic structures

A study to replace the weirs in the river Meuse

By

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At Delft University of Technology (TU Delft)
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Abstract

For centuries humanity has been engineering the second largest river system in the Netherlands, the river Meuse system. This resulted in improvements for the shipping and water safety functions, but simultaneously has had a negative impact on other functions of the river Meuse system. Nature and water quality, for example, degraded due to the construction of dikes, weirs, locks, bend cut-offs, summer bed mining and floodplain reduction. Additionally, climate change is affecting the fresh water availability due to low river discharges in combination with little precipitation in dry periods. On top of that, weir leakage and levelling of ships lead to water loss, which amplifies the fresh water availability problems even more. What the future might bring is deeply uncertain, however, the current problems are expected to grow larger due to influence of climate change and socio-economic developments.

With the upcoming task to replace the hydraulic structures (weirs and locks) in the Meuse river, a unique opportunity arises to improve the problems that the river Meuse system experiences and prepare it for future developments. Replacement strategies need to be developed and tested on the system. Traditionally separate models will be constructed to simulate shipping, nature, water quality and hydraulics. They tend to be complex and computationally heavy and more often than not, these models make predictions based on a small set of the most probable scenarios. However, in the rapidly changing times of today, these scenarios are often not sufficient enough to account for the highly uncertain future. Therefore, in this thesis, one model is constructed containing the multi-functionality of the river Meuse system which is tested on a broad range of future scenarios to test replacement strategies for the hydraulic structures.

Methodology

Robust Decision Making (RDM) is used to explore replacement strategies from a multifunctional perspective and evaluate them based on their robustness. RDM is a method which helps making decisions that lead to the construction of a robust system without making predictions and a system is robust if the applied strategy performs satisfactory under a wide variety of future conditions. RDM works with four steps, first the river Meuse system is modelled in the system dynamics software Vensim. This Meuse Model consists of submodels that simulate: the flow of water, the flow of shipping and the performance of the functions water quality, fresh water availability and the shipping load on the locks. All functions are therefore assessed in one model. The second step explores the behaviour of the current system by analysing the performance of the functions under future scenarios (i.e., combinations of future uncertainties). To cope with the deep uncertainty of the future, the probability of occurrence for each scenario is assumed to be uniformly distributed. Thirdly, design options are developed based on the vulnerabilities of the current system and combinations of design options form replacement strategies. In the fourth and last step, the replacement strategies are applied to the system in a policy analysis, after which the design options are evaluated based on their robustness.

Exploration of the current system

Exploring the current system behaviour over a variability of plausible futures demonstrates that in some scenarios problems arise for the functioning of the system. The performance of the fresh water availability is in general robust. The river Meuse system is designed to maintain a specific water level to provide for shipping. However, especially in weir section Grave, which contains outflow to the river Waal and a relatively large leakage of the weir at Grave, fresh water availability problems occurred during extreme drought events. In approximately 18% of the runs, the fresh water availability was smaller than full capacity. A scenario discovery revealed that several uncertainties have crucial impact on the undesired performance of the fresh water availability. It is found that leakage of the weirs and certain dry discharge years are influential uncertain input variables that cause problems for the fresh water availability.

The water quality in the weir sections of the river Meuse reaches for most of the runs risky or undesired behaviour. The weir sections Linne, Grave and Lith are the most vulnerable because the weirs in these weir sections maintain relatively large water depths. This results in low flow velocities and therefore high risk for algal and cyanobacterial blooms and low diffusivity of toxic substances. For the intensity of shipping, two future scenarios are composed under socio-economic developments. The first leads to a slight increase of ship intensity and the second one leads to a slight decrease of ship intensity in the coming decades. Most of the locks seem to be able to cope with this change. Only the lock at Grave might experience issues as it contains the smallest and least amount of lock chambers in the corridor. For approximately 30% of the runs, the intensity to capacity ratio of the lock at Grave took either risky or undesired levels (>0.5).

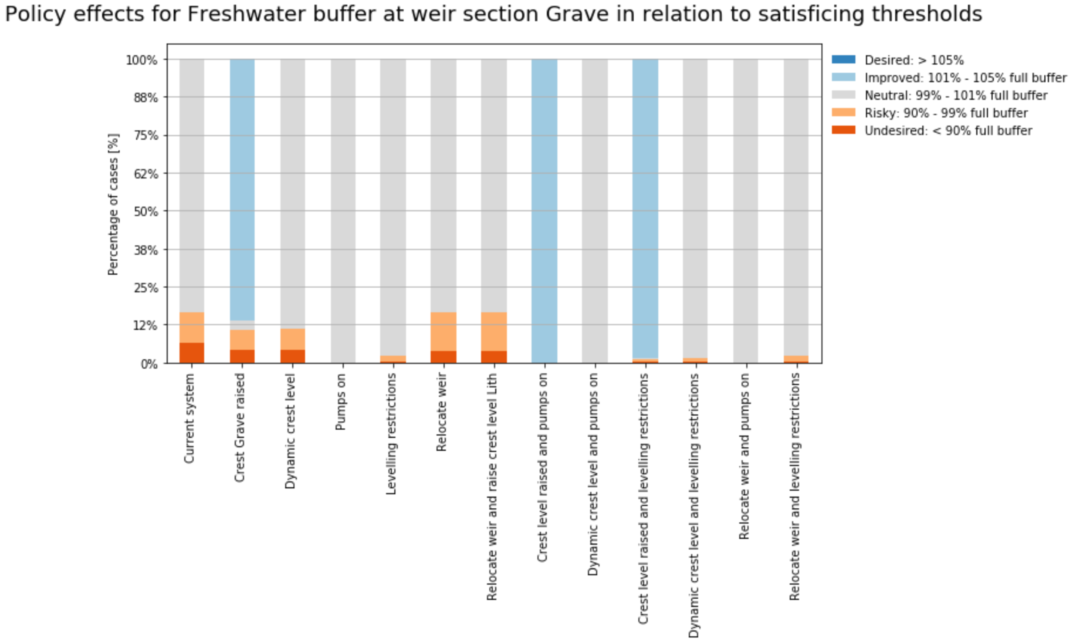
Formulating replacement strategies

Based on these findings, a number of design options are formulated with the main goal to improve the robustness of the fresh water availability. Robustness performance of other functions, however, should not deteriorate, and preferably improve by applying the design options. Weir section Grave is used as main focus for improvement as this weir section is most vulnerable for future scenarios, and improvements will therefore have the largest impact. The design options are:

- Installation of pumps (all weir sections): limit the outflow of water in dry periods
- Heightening crest levels of the weirs at Grave or Lith: increase buffer capacity
- Relocating the weir at Grave in upstream direction: increase the average water depth
- Dynamic crest level (all weir sections): temporarily increase buffer capacity in drought periods
- Efficient locking (all locks): limit the daily outflow of water in dry periods by imposing a minimum amount of ships that need to enter the lock chamber before starting the locking cycle

Analysing the replacement strategies

Combinations of design options are made to form replacement strategies, which are now applied to the system. All design options lead to improvement of the fresh water availability for weir section Grave (see below figure). By introducing efficient locking, however, the intensity/capacity value of the lock at Grave increases compared to the current system for more than 80% of the runs. Raising the crest level of the weir at Grave leads to a decrease of flow velocity, and therefore water quality, for approximately 80% of the runs. Changing this to a dynamic crest level results in a decrease in flow velocity for approximately 25% of the runs, which is significantly less. By relocating the weir at Grave, the robustness of the fresh water availability in weir section Lith is slightly reduced and the ship draught downstream of the weir at Grave is at risk. To increase the water depth and remove the risk of insufficient ship draught, the crest level of the weir at Lith is raised. However, an increase in water depth leads to a decrease in flow velocity and therefore water quality. Installing pumps creates the largest robustness for freshwater availability, does not induce any deterioration for the other functions and is therefore seen as best performing replacement strategy.



Conclusion

The research implemented a general robust decision making method to analyse complex systems and applied it to the replacement of hydraulic structures in rivers. Thereby it has shown how various design options can be evaluated for multiple functions and under uncertain future scenarios. This approach can be used to select design strategies that perform well under a broad scope of future uncertainties and thus make the system more robust. However, the model and tools used in this thesis also know many limitations. Costs, for example, are left outside of the scope of this thesis but is expected to have a large impact on the decision making process. Furthermore, potentially better fitting methods such as Many Objective Robust Decision Making or Dynamic Pathways are available to analyse replacement strategies. Because of these limitations, the results from this study can be seen as a first interpretation and setup for further research.

Acknowledgements

This thesis brings my journey of the Master of Science program in Hydraulic Engineering at Delft University of Technology to an end. This study has been conducted in collaboration with Rijkswaterstaat. I am grateful for the opportunity to work on such a complex and substantial subject and to be part of Rijkswaterstaat for a short time. Being able to contact colleagues at Rijkswaterstaat and attend meetings was not only very helpful but also felt like a great addition to my thesis time.

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I want to thank my friends from hydraulic engineering who were the perfect group of friends. You helped me with study related things but more importantly, you made the times that we were not studying incredible. I truly enjoy being with the lot of you and I hope we get to hang out for many years to come.

Above all, I want to show gratitude to my family. Many thanks to my parents, who always supported me no matter what the situation was. Your effortlessly love and interest was a motivation that kept me going for so many years. My sister Jolie, thank you for being there to give advice, comment on my report but most importantly for your listening ear. My girlfriend Anna, thank you for your love and support. You always want to help and were always able to calm me down. I am coming your way now.

Douwe Willems
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Nomenclature

Abbreviations

EMA	Exploratory Modelling and Analysis
HVWN	Main navigation network
HWN	Main road network
HWS	Main water system
RDM	Robust Decision Making
RWS	Rijkswaterstaat
R&R	Replacement and Renovation (Dutch: Vervanging en Renovatie, V&R)
XLRM	External uncertainties (X), Levers (L), Relations (R), Performance Metrics (M)

Terminology

System	Group of related and interacting elements, such as the river Meuse
Element	Part of a system, such as weir
Component	Part of an element, such as the gate is a part of a weir
Weir section	Part of the river between two weirs
Scenario	Combination of uncertainties
Design option	A specific measure to mitigate certain events in the system
Policy/replacement strategy	Combination of design options (levers), also a replacement strategy
Experiment	Combination of scenario and policy
Hydraulic complex	Combination of hydraulic structures at one location (e.g. lock and weir)
External influence	Uncertainty coming from outside of the system
Vensim	System Dynamics modelling software
Model	System Dynamics representation of reality
Submodel	Part of the model
Sample size	Amount of scenarios simulated
Uncertainty space	The space created by the set of uncertainties
Robust	The applied strategy performs satisfactory under a wide variety of future conditions
Deep uncertainty	Various parties to a decision do not know or cannot agree on the system, its boundaries, the outcomes of interest and the probability distribution for uncertain inputs to the system

1 Introduction

Water has always had an unique role in Dutch history, shaping its cities and landscapes. But besides creating a beautiful environment, it also creates economical and technical challenges. Too much water is a problem and at the same, too little water is a problem as well (Bentveld & Lassche, 2021). To protect against flooding and enable navigation, the Dutch developed their hydraulic system. For centuries engineers have been designing and redesigning, and they will continue to do so in the future. Part of the Dutch hydraulic system is the river Meuse, the second largest river in the Netherlands. In this man-made system, two main functions have always been of the highest priority: to prevent the hinterland from flooding and to make navigation possible (van Hengel, 2017). Over the last decades, however, the prioritization of functions has been changing. Nowadays the multifunctionality of the river system has become more and more important, as improvements have to be made regarding ecology, nature and fresh water supply (Asselman et al., 2018; "Maasverdrag," 2002). Furthermore, developments such as climate change and socio-economic growth impose pressure on the fresh water availability of the river Meuse system. Leakage of water at the hydraulic structures increases the pressure even more. As the hydraulic structures in the Meuse system are growing older, the question remains how they can be replaced in order to serve all the functions and create a robust system.

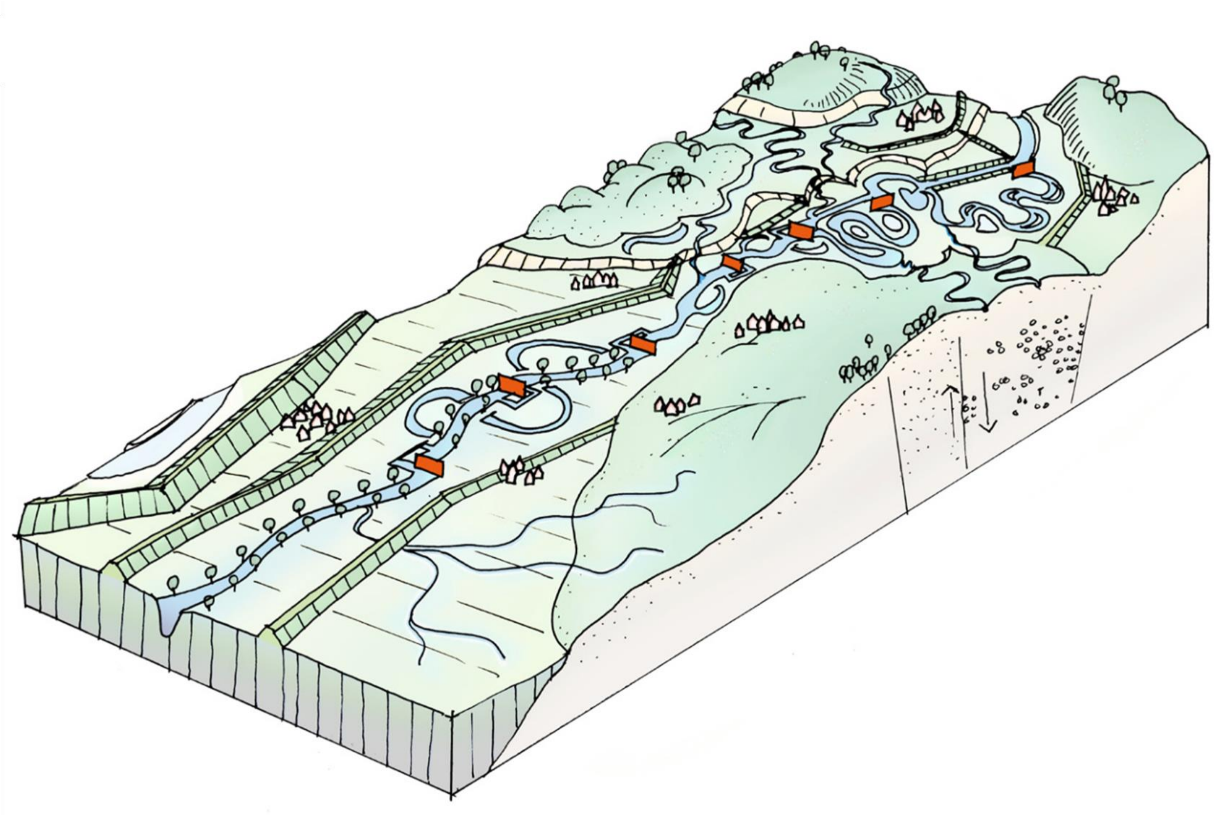


Figure 1 Sketch showing the fundamentals of the man-made river Meuse. The sketch shows the weirs highlighted in red, the dikes along the river, the normalization of the river and sand mining spots at the beginning of the river. Source: (Asselman, Barneveld, Klijn, & van Winden, 2018)

1.1 Water Network of the Netherlands

Three networks shape the Dutch water system: The main water system (Dutch: Hoofdwatersysteem, HWS), the main navigation network (Dutch: Hoofdvaarwegennetwerk, HVWN) and the main road network (Dutch: Hoofdwegennetwerk, HWN). Spread out over these three network systems, 650 hydraulic structures are situated and essential to the Dutch water system as it is today. Many of the structures that are built in the previous century, reach the end of their lifetime in the coming decades and therefore need to be replaced (Rijkswaterstaat, 2015d, 2020), resulting in an imposing replacement project. This gives the opportunity to improve neglected functions and design a future minded system. Multiple adaptations can be proposed in order to facilitate multifunctional use (van Hengel, 2017).

The replacement project is called: the national program of replacement and renovation (R&R) and is carried out by the Dutch ministry of infrastructure and water management, represented by Rijkswaterstaat (RWS). The challenge is of such large magnitude that RWS has to strive for an economic and timewise smart approach in order to finish successfully (Rijkswaterstaat, 2015d).

1.2 Hydraulic structures in the Netherlands

A Hydraulic structure is a structure which is built in a wet environment such as a river, a lake or the sea. They are always part of the larger system and therefore must be designed, built and maintained in an integral fashion (TU-Delft). Examples of hydraulic structures are weirs, locks, storm surge barriers, bridges and pumping stations.

These hydraulic structures play an essential role in the general water management of the deltaic region called the Netherlands. Most of the hydraulic structures in the HWS, HVWN and HWN are built in the first half of the previous century, see *Figure 2*. Which means that they need to be replaced in the coming decades (Rijkswaterstaat, 2015d).

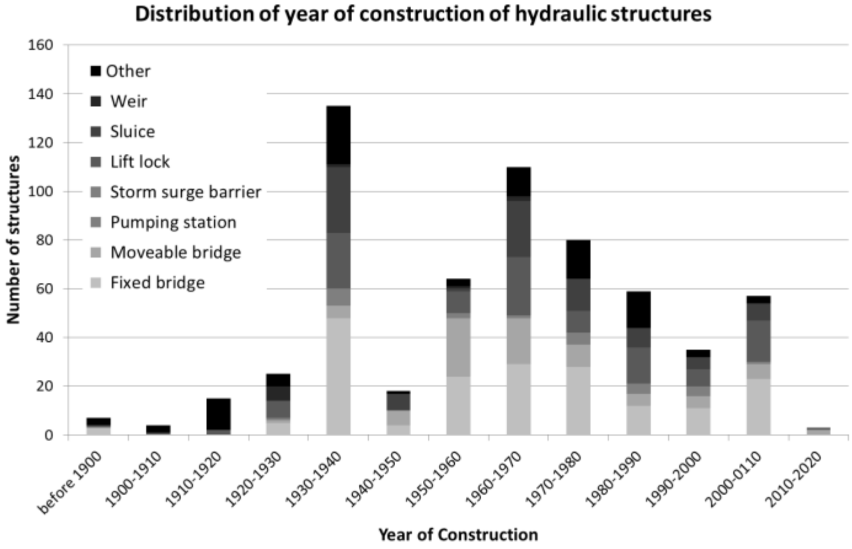


Figure 2 Overview hydraulic structures built dates (van Vuren et al., 2017).

About 60% of the Dutch population lives below sea level, 70% of the gross national product is earned in this man-made part of the country and 45% of the transport is via water. This is possible because of the network of hydraulic structures which provide safety, clean and sufficient fresh water and a thriving navigational network (Bernardini et al., 2014). The table below gives a rough overview concerning the impact of the hydraulic structures discussed in this study, on the functionalities of the river system.

Function **Hydraulic Structure**	**Flood safety**	**Fresh water availability**	**Efficient shipping**	**Nature, Ecology and water quality**
Weir	Water management (1)	Maintain a water level in the weir section (1)	Guarantee certain draught (1)	Blocking throughput of sediment, nutrients and organisms, influences flow velocity (3)
Lock	Water management (2)	Maintain a water level in the weir section (2)	Transport ships between different water levels (1)	Blocking throughput of sediment, nutrients and organisms, influences flow velocity (3)

Table 1 Types of hydraulic structures and their impact on the main functionalities of the river. A hydraulic structure can serve a function in three ways: (1) it has a primary a goal to serve for a certain function, (2) as a secondary goal to serve for a function or (3) negatively affects a function. Based on: (Nicolai, van Vuren, Markus, & van der Wiel, 2014)

Hydraulic structures such as weirs and locks are built to regulate the upstream water level. This is done to facilitate for multiple functions of the river, as for example, guaranteeing a certain draught for ships sailing in the navigation channel and creating a water buffer upstream of the weir.

Incident illustrating the vulnerability of the river Meuse system.

An event in 2016 made clear that the Meuse system nowadays is built upon- and relies heavily on the hydraulic structures. Due to ship collision with the weir at Grave, the water level in a part of the river Meuse was not maintainable and dropped significantly. Which resulted in major consequences for navigation, the flood protection system and nature. No navigation was possible between Lith and Sambeek, this led to an enormous detour and costs of approximately up to 2.5 million euros per week, according to VNO-NCW. Companies in this region that used to transport by water, now needed to transport by road. Furthermore houseboats dropped to the bottom of the river and damage to banks and hydraulic structures became an issue (Joustra, Muller, & van Asselt, 2018; Zanten, van der Reijden, Slot, Kamphorst, & Duvekot, 2017).

Figure 3 Aftermath of ship collision with the weir at Grave. Source: Rijkswaterstaat

1.3 A Hydraulic structures' end of lifetime

The fact that many hydraulic structures reach the end of their lifetime in a short period of time, results in a major challenge for RWS. This challenge is addressed in the program R&R (Rijkswaterstaat, 2015d). Preparation is key in this concept and therefore research projects have been, and will be, performed.

Hydraulic structures are renovated or replaced based on their end of lifetime. The end of lifetime of a structure can be reached in two ways:

- *Technical end of lifetime;*
- *Functional end of lifetime.*

Technical end of lifetime is reached when the structure cannot fulfil the original requirements in a cost-efficient way anymore. It is simply worn out or chances of breaking are high. Terms representing the technical end of lifetime would be reliability, availability, maintainability and safety (Rijkswaterstaat, 2015b).

Another scenario would be that circumstances have changed and therefore the original functional requirements. For example, due to climate change different water levels might be the new loads on a structure or shipping intensity in a certain corridor might have changed. In these cases, the *Functional end of lifetime* is reached and the structure does not meet the requirements anymore. Events that result in different functional requirements could be climate change, socio-economical change, innovations and change in norms (Rijkswaterstaat, 2015b).

The current state of hydraulic structures is mostly based on technical end of lifetime (Rijkswaterstaat, 2020). This means that active measures are taken when the technical end of lifetime of a structure becomes critical. It might as well be the case, however, that a structures' functioning is simply below the standard for one or more functions.

One of the projects related to V&R was the Replacement Assignment Hydraulic Structures (Dutch: Vervangingsopgave Natte Kunstwerken, VONK). VONK ultimately discusses three ways to determine the end of lifetime of a hydraulic structure. The first method adds the design lifetime to the building date, for example, a structure with 80 years design lifetime and built in 1920 has to be replaced by the year 2000. This is called the *basic method*. An overview for the Dutch hydraulic structures, using the basic method, is shown in *Figure 4*. Illustrated in the graph is a large quantity of structures which are up for replacement before the year 2040, implying that it is necessary to formulate an efficient replacement strategy for this period.

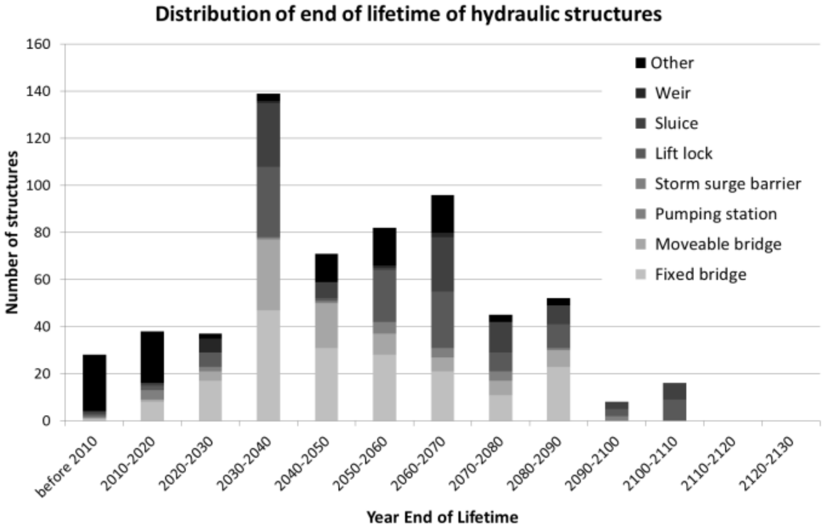


Figure 4 Overview tipping point hydraulic structures based on basic method (van Vuren et al., 2017). For each type of structure, a specific lifetime is considered. The design lifetime is 80-100 years, depending on the type of structure.

The second way to determine end of lifetime is based on *Technical requirements:* a probability distribution for technical lifetime duration is determined within this method. The probabilistic model shows the uncertainty in technical lifetime of a specific hydraulic structure and contains one, or multiple unknown parameters. These parameters must be estimated based on the available data from the Bayesian statistics. Estimation of these parameters leads to an end of lifetime timeframe, see *Figure 6* (Nicolai et al., 2014; Rijkswaterstaat, 2015b).

A last method is to determine end of lifetime based on *Functional requirements:* A hydraulic structure has reached end of functional lifetime when it cannot fulfil one of its functional requirements. The model then determines the actual functional requirements until a specific date in the future and makes a comparison with the original functional requirements of the structure. When the actual functional requirement is more than what the structure has to offer, then the structure has reached end of lifetime (Nicolai et al., 2014), see *Figure 6*. The actual functional requirements are determined based on future scenarios which include economic growth and climate change (Rijkswaterstaat, 2015b). In this study, emphasis is placed on functional end of lifetime.

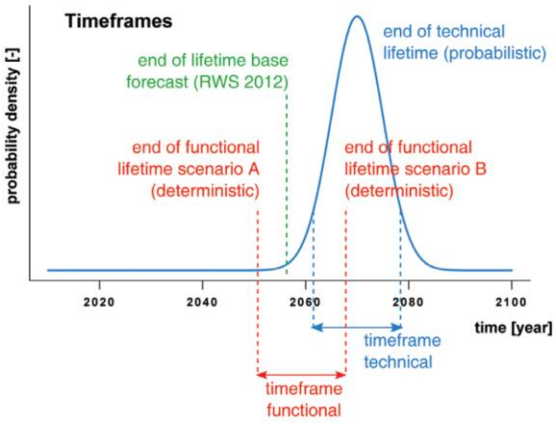


Figure 6 Graphical representation of Technical and Functional end of lifetime (Kallen et al., 2014)

Example functional end of lifetime, based on (Kallen et al., 2014).

A lock is used to transport ships from high water levels to lower water levels and vice versa. Due to increasing ship sizes or ship traffic scenarios, a reduction in performance might occur as the lock becomes too small or/and waiting time increases. A functional end of lifetime is then determined based on multiple future scenarios as shown in the figure below. Each scenario represents a different combination of uncertainties such as climate change and socio-economic developments.

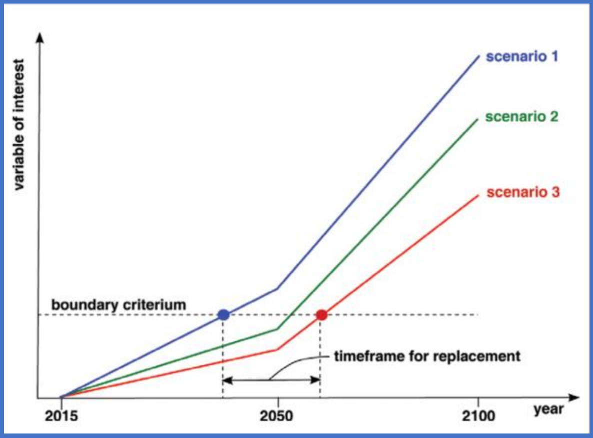


Figure 5 Example of Functional end of lifetime timeframe (Kallen et al., 2014)

1.4 Previous research and opportunities

The impact of the replacement of hydraulic structures in the Netherlands is significant for both costs and planning. Therefore, a lot of attention goes to thoughtfully setting up a plan. This makes the replacement of hydraulic structures a thoroughly researched and well-discussed topic (deBouwcampus, 2016-2017). In *Table 2* an overview is presented with studies and their topics in the same field of interest. Noticeable is the few studies regarding the last two columns and thus by combining these topics the topics of this research is created.

A multi-functional system considers multiple functions alongside the main functions shipping and water safety. With a multi-functional system-based replacement strategy, all functions, elements and their interactions in the system are considered to create a system which is most beneficial for all functions and elements. A traditional replacement strategy focusses solely on a single structure or a small part of the system.

Interest / **Paper**	**Replacement strategy**	**Technical lifetime**	**Functional lifetime**	**Multi-functional system**	**System-based replacement strategy**
Integrative Framework for long term reinvestment planning for the replacement of hydraulic structures (Bernardini et al., 2014)	X	X			
Functional and technical end-of-service estimates for hydraulic structures (Kallen et al., 2014)		X	X		
Dealing with aging of hydraulic infrastructure: an approach for redesign water infrastructure Networks (van Vuren, Konings, Jansen, van der Vlist, & Smet, 2015)	X				
Towards a new approach to estimate the functional end of life time of hydraulic infrastructures (van Vuren et al., 2017)			X		
A system approach for replacement strategy of hydraulic structures (van der Wiel et al., 2017)					X
Kunstwerken in Netwerkmodellen (Weiler & Berger, 2019)					[X]
Functionele levensduur; inventarisatie relevante projecten (de Groot-Wallast & van Twuiver, 2019)			X		
Functionele levensduur; Case Julianakanaal-Grensmaas (Breedeveld, Kramer, & van Twuiver, 2019)			X		[X]

Table 2 Overview research topics previously performed, X = main research focus, [X] = secondary research focus or partly true. The green box highlights the research focus of this study.

1.5 Problem statement

The replacement of hydraulic structures in the Netherlands is a complex challenge. Consequently, plenty of research has been done regarding this topic, as seen in *Table 2*. As elaborated in chapter *1.4*, this study intents to fill the following gaps:

System-based and multi-functional approach

The river Meuse system as it is today, is constructed in the previous century under different circumstances and with different intentions. Over the past decades the quality of the functions of the river Meuse have changed. Today, the river Meuse is out of balance and its functioning is a threat to this multifunctional system (van Vuren & Leushuis, 2020). Not all functions are served well, and some suffer because other thrive, for example, shipping and flood safety was improved at the expense of nature and water quality (Asselman et al., 2018). Also external factors threaten the river Meuse system. Climate change, for example, induces problems for the fresh water availability in the system and socio-economic developments might amplify these problems by increasing the demand for fresh water (de Wit et al., 2001; Elling & Alferink, 2017). If the goal is to strive for a multifunctional river Meuse system, then a system-based strategy is needed (van der Vlist, Barneveld, Breedeveld, van Doorn, & Luyten, 2019).
With the upcoming task to replace the hydraulic structures, an opportunity arises to redesign and reconsider the river Meuse system (van Hengel, 2017). Therefore it is of value to analyse the system as a whole as the interactions and coherence between the structures are taken into account (van Vuren & Wojciechowska, 2015).

The replacement of hydraulic structures in the Meuse will be performed somewhere between two extremes, on one hand a one-on-one replacement with the intention to maintain the current system. On the other hand, a complex replacement intended to change the system and its functions (van der Vlist et al., 2019). A hydraulic structure, for example, could receive additional functions, the functions of the network could get optimized, and the layout of the system could be altered.

On top of this, a system analysis might lead to more insights about a hydraulic structures' affect towards its functions, for example the adhesive behaviour towards ecology and fresh water supply. This can lead to a generic approach for all the hydraulic structures in the system. For the river Meuse, studies containing the above are yet to be performed (van der Vlist et al., 2019).

Deep uncertainty of future scenarios

Change in circumstances has been thoroughly studied (Bernardini et al., 2014; *MIRT - onderzoek goederenvervoercorridors*, 2017; Orgelist & de Vries, 2012; van Tilburg, 2015). However, how these circumstances subsequently and simultaneously will affect the system in the future all together is less known. A clear overview of functional requirements is needed together with an analysis of how the system will react to all of these possible scenarios. Uncertainties in the system can be understood in two ways:

- Endogenous uncertainties, uncertainties that come from within the system. For example the leakage of a weir, which is influenced by the amount of debris between the weir gates.
- Exogeneous uncertainties, uncertainties that come from outside of the system. The system is constantly influenced by external factors such as the climate and socio-economics.

By considering all these uncertainties, possible future scenarios can be composed and consequently assumptions about the robustness of the system can be made.

1.6 Objective and research questions

Because the hydraulic structures in the river Meuse should be replaced in the coming years (Rijkswaterstaat, 2017c; van Hengel, 2017), this study performs a system-based based replacement approach, considering multiple functions. The river Meuse system will be designed for the coming 100 years and therefore external influences such as climate change and socio-economical change should be simulated for this period. The aim is to test different replacement strategies on the deeply uncertain future scenarios for the coming century and select the replacement strategy which results in the most robust river Meuse system. A system is robust if the applied strategy performs satisfactory under a wide variety of future conditions (Walker, Haasnoot, & Kwakkel, 2013). This should show if a one-on-one replacement approach or a more complex approach (i.e. redesigning the system) is preferred.

In general, the hydraulic structures in the Meuse fulfil more than one function. The most important functions are water quality, shipping, freshwater availability and societal functions such as nature, agriculture and drinking water (see chapter *2.3*). The end of functional lifetime is therefore based on more than one criterion. In *Figure 7* the framework to determine end of lifetime for hydraulic structures is presented. Each hydraulic structure needs to fulfil certain functions. These functions are influenced by criteria. These criteria can determine if the functional requirement is met and when this is not the case, a structure might have reached end of lifetime and the system might consequently not be robust.

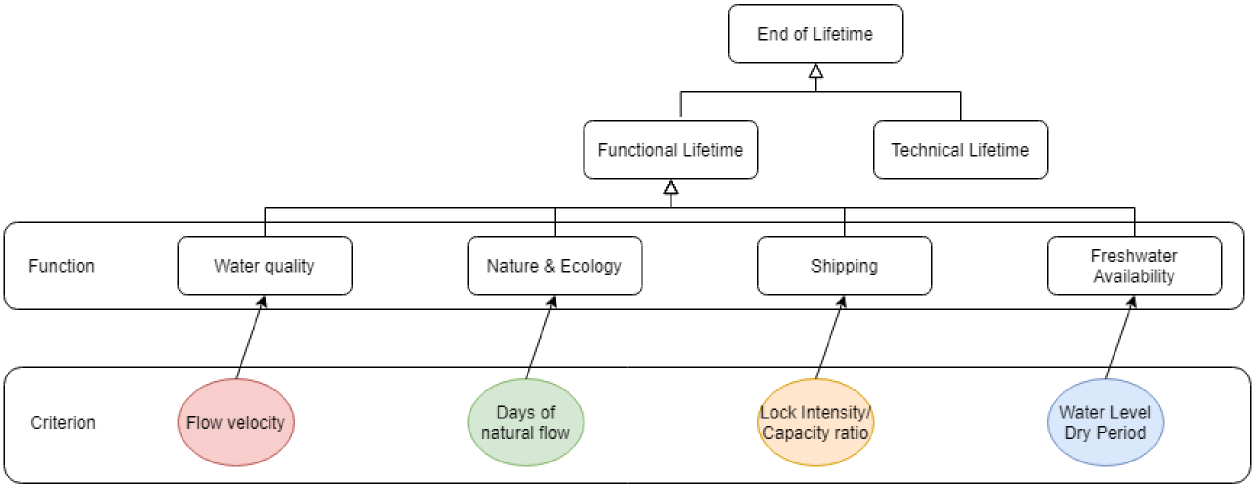


Figure 7 General End of Lifetime framework for Hydraulic Structures

This research considers the functional end of lifetime based on the response of the system towards the external influences and the design options of hydraulic structures in the system. The system reaches end of functional lifetime if the functional requirements cannot be maintained.

As guidance through this study, research questions are constructed. The main research question is an overarching goal for this study, at the end of the study an answer to this question is presented.

"What does a system-based replacement strategy look like for the river Meuse system and does this have added value compared to a conventional strategy?"

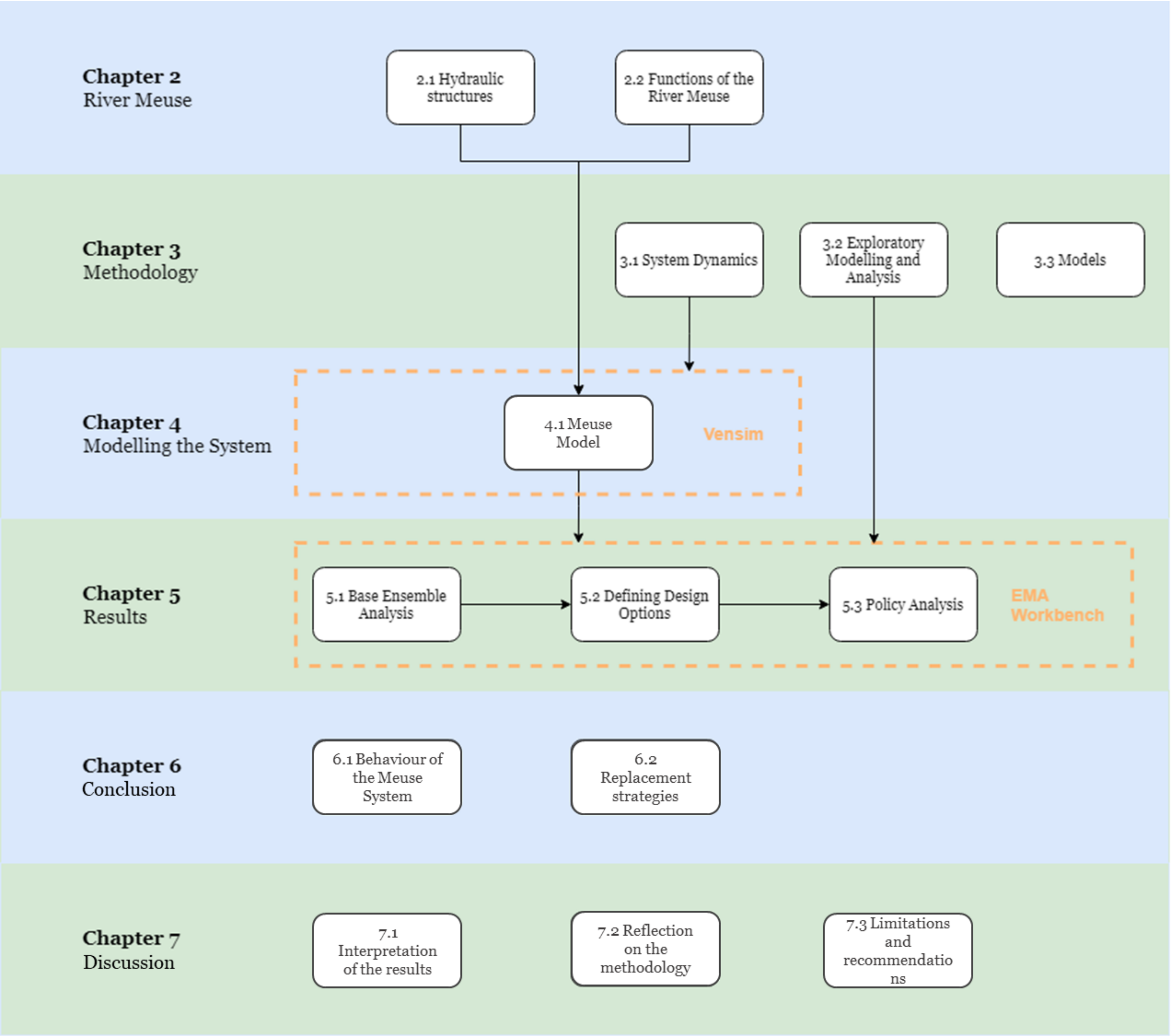
To answer this main research question, sub-questions are composed. These questions are meant for guidance during the research. The sub-questions are in chronological order and are as follows:

1. What functions are important for the river Meuse system?
2. What uncertainties have impact on the Meuse system for the coming 100 years and how does the river Meuse system behave under these uncertainties?
3. How can the river Meuse system be modelled for the coming century and how can a system-based multi-functional analysis be performed?
4. What design options can be formulated for the river Meuse system?
5. What design options can be recommended for the river Meuse system?

1.7 Thesis outline

Firstly, chapter *2* gives insight in the river Meuse system. Subsequently the methodology is explained in chapter *3*. The Meuse Model is constructed in Chapter *4* and analysed in chapter *5*. The last two chapters consist of the conclusion in chapter *6* and discussion in chapter *7*.

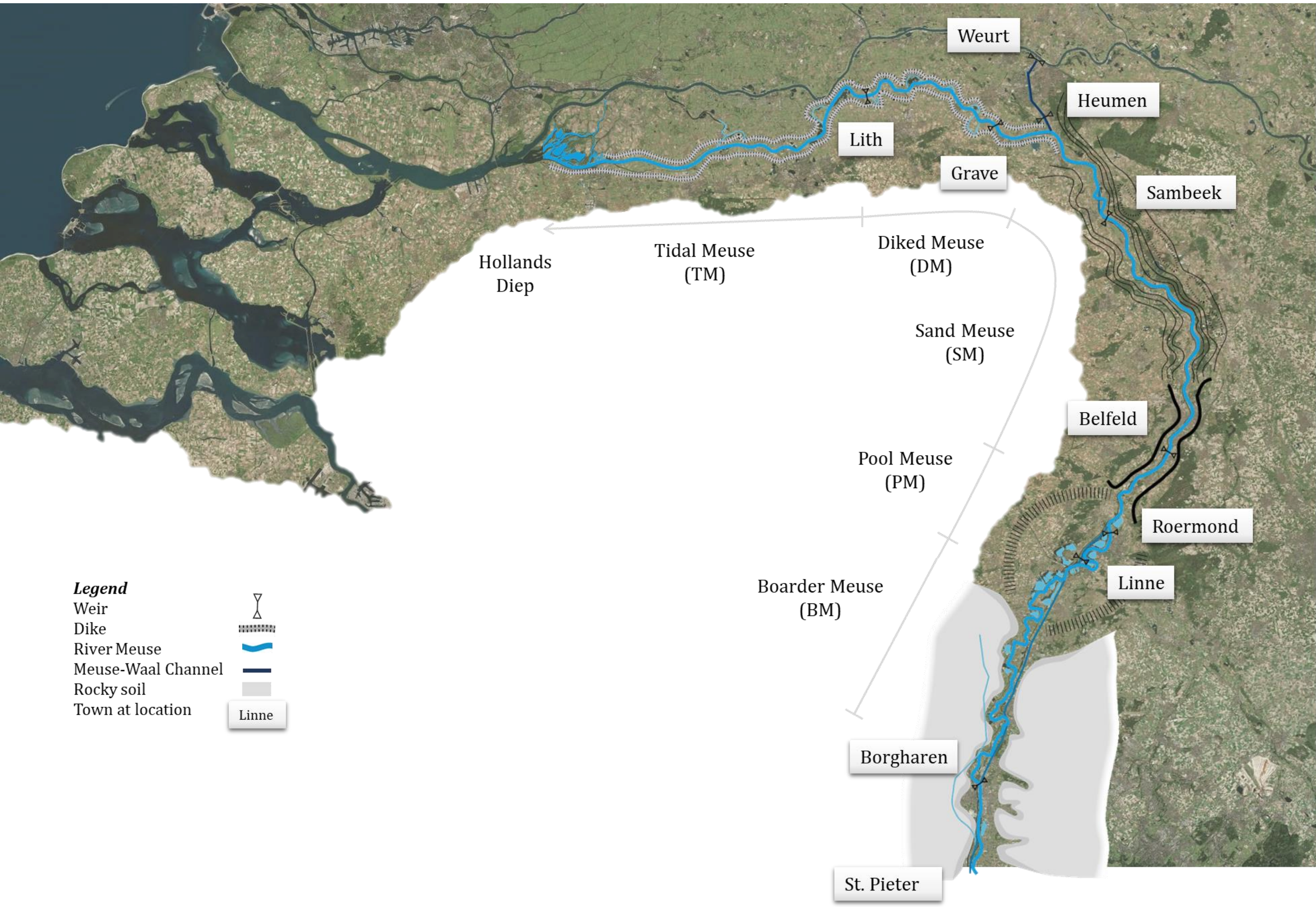
Figure 8 Thesis outline schematized



2. River Meuse

Protection against flooding has always been a main occupation in the Netherlands. This was no different for the river Meuse (Nienhuis, 2008). On top of that, the coal mining in the province of Limburg developed during the first world war and needed to be shipped further inland (Asselman et al., 2018). All of this resulted in building the Meuse river system of today. The river Meuse has a length of approximately 900km from origin to outflow. It has a catchment area of 35 thousand km^2 and 9 million inhabitants (Asselman et al., 2018). While crossing the three countries; France, Belgium and the Netherlands, the Meuse is fed by multiple tributaries. In the Netherlands, the most important tributaries are the Rur, the Niers and the Schwalm (van Hengel, 2017).

Figure 9 River Meuse in the Netherlands



The river Meuse enters the Netherlands at St. Pieter and travels through multiple provinces to end up in the Hollands Diep estuary as seen in *Figure 9*. There are seven weirs situated in the Dutch Meuse. All are maintained by RWS and have the goal to guarantee a certain minimum water depth in the corresponding weir reach. At the Belgian-Dutch boarder, the river Meuse has multiple bifurcation points, *Figure 10*. An agreement has been made for the discharge distribution at those locations ("Maasverdrag," 2002; van Hengel, 2017).

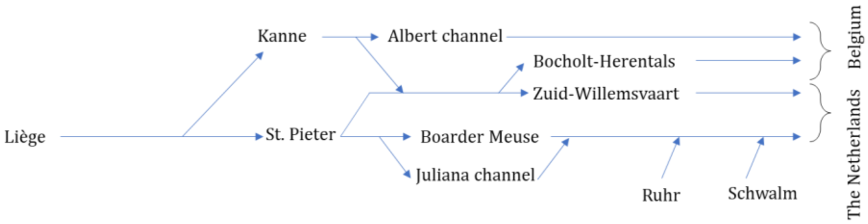


Figure 10 Meuse river network at the border between Belgium and the Netherlands. Based on:(van Hengel, 2017)

The most downstream section of the Meuse is called the Tidal Meuse. No weirs are constructed in this section and the tide is influential. The two upstream sections are respectively: Diked Meuse (DM), from Lith until approximately Grave and Sand Meuse (SM), from Grave until Roermond, see *Figure 9*. These sections are considered in this study.

The Meuse is a rain river, which means that its discharge is directly influenced by precipitation. The difference in precipitation between wet periods and dry periods can be significant. This can also be seen in the discharge pattern of the Meuse river.

Throughout the past ages, humanity has been altering the course and the landscape of the river Meuse (Nienhuis, 2008). Nonetheless, floods were still a common occurrence in the Netherlands until approximately 1930 when plan Lely was carried out (Asselman et al., 2018). This plan was established to create a more stable river. Bends were cut-off, dikes with a high level of protection were built and additionally the river became regulated. As a result, the length and width of the river reduced significantly. In the last couple of decennia this strategy has been changing and a more natural river is preferred (Asselman et al., 2018).

The desired condition regarding ecology and water quality has not yet been reached (Asselman et al., 2018). Therefore, active measures must be taken to guarantee improvements in the future. For the coming years, plans and policies, such as “Programma Aanpak Grote Wateren” and “Integraal Rivieren Management”, have been designed to stimulate this progress (BouwplaatsIRM, 2019; Dotinga, van Ruiten, Schreuders, Fischer, & van Swieten, 2021).

2.1 Hydraulic Structures in the Meuse

The 7 weirs in the river Meuse regulate the water level to be able to make navigation possible throughout the year. A minimum water depth in the navigation channel of 4.9m is maintained (Breedeveld et al., 2019). In the parallel flow river the Waal, for example, small water depths could be possible as it is generally a weir free river. A lock is needed to transport ships past the weirs, such that at every weir position, one or more locks are situated.

In Table 3 an overview of weirs and locks and their characteristics is given for the river Meuse. RWS has determined that the steel construction of the weir at Grave (which accounts for more than 90% of the total construction) reaches end of technical lifetime before 2028. The weir at Grave would be the first to reach end of lifetime in the river Meuse. For the weirs at Linne, Roermond, Belfeld and Sambeek the poirée parts need replacement in 2030-2040 (van Hengel, 2017).

The replacement of these hydraulic structures is part of the R&R program of RWS. This program contains the large task associated with multiple hydraulic structures in the Netherlands reaching end of lifetime in the coming decades. By replacing one of these hydraulic structures, the design of the whole system is partly determined. The replacement of the complex at Grave might therefore steer the design of the "new" river Meuse system in a certain direction. This emphasizes the importance of designing a well thought through plan regarding the replacement of the weir complex at Grave.

The weir at Grave is part of a complex which, among others, includes two locks. Due to the end of lifetime of the weir, reorganization of the whole complex becomes an option. Questions like "Is the weir still necessary?" and "Does the design of the hydraulic structures need to be altered or do the structures just need to be renewed?" can be asked to determine the future of the complex.

Complex	Weir	Lock chamber 1	Lock chamber 2	Lock chamber 3	Info
Linne	BD = 1925	BD = 1925 Size = Large			Weir crest level: 20.85m +NAP Sill lvl: 16.1m +NAP
Roermond	BD = 1926	BD = 1926 Size = Large			Weir crest level: 16.85m +NAP Sill lvl: 11.0m +NAP
Belfeld	BD = 1926	BD = Size = Small	BD = Size = Small	BD = Size = Large	Weir crest level: 14.1m +NAP Sill lvl: 8.45m +NAP
Sambeek	BD = 1925 EL≈2030-2040	BD = 1925 EL = 2025 Size = Small	BD = 1967 EL = 2067 Size = Small	BD = 1967 EL = 2067 Size= Large	Weir crest level: 11.1m +NAP Sill lvl: 4m +NAP
Grave	BD = 1926 EL ≈ 2028	BD = 1974 EL = 2074 Size = Small			Weir crest level: 7.9m +NAP Sill lvl: 1m +NAP
Lith	BD = 1936 EL≈2030-2040	BD = 1936 EL = 2036 Size =Small	BD = 1997 EL = 2097 Size = Middle		Weir crest level: 5.4m +NAP Sill lvl: -0.25m +NAP

Table 3 Overview of operational hydraulic structures in research area, BD = Build Date, EL= expected End Lifetime based on given dates for the weirs (van Hengel, 2017) and the basic method for the locks (Nicolai et al., 2014), Size = length of lock chamber, the width of the lock chambers is generally 18m.

2.2 Impact of hydraulic structures on river dynamics

The Meuse is a rainfed river and is therefore, in its natural state, dependent on seasonality. By constructing weirs, the natural flow regime is altered by maintaining a constant high water level such that the throughflow is blocked and seasonality is gone. This has had a drastic impact on the nature and ecology in the Meuse catchment area (Admiraal, van der Velde, Smit, & Gazemier, 1993; Asselman et al., 2018; Nienhuis, 2008).

The weirs only influence the river flow, however, when the discharge through the river Meuse is small enough. At a certain discharge, the weirs are lifted. From this point onward the weirs do not affect the flow until the discharge reaches a certain value such that the weirs are once more positioned in the river. For very high discharge magnitudes, the floodplains are inundated, and the river flows around the hydraulic structures. The impact of the hydraulic structures on the flow of the river then becomes negligible and the weirs do not influence the flooding probability (Vergouwe, 2014), see *Figure 11*.

Figure 11 Weir structure during high flow, source: Rijkswaterstaat

2.3 Functions of the River Meuse

RWS makes a clear distinction between the types of functions (Rijkswaterstaat, 2015a; van Hengel, 2017):

- Main functions: water safety, sufficient freshwater availability and water quality;
- Shipping;
- Societal functions.

Van Hengel (2017) states that shipping is a societal function with a rather special position within the set of tasks of RWS. Mobility within the system must be guaranteed and is therefore an important function as seen by RWS.

The Meuse system was designed with a focus on the functions water safety and shipping (van Tilburg, 2015). The system as it is today, is domiciling more functions than water safety and shipping alone (Asselman et al., 2018). Functions such as freshwater availability, water quality and societal functions are next to water safety and shipping of interest (Asselman et al., 2018). Nowadays, the Meuse system contains a broad variety of functions and therefore became a multifunctional river system. Functions of the river Meuse considered in this study are shipping, water quality, fresh water availability and societal functions. The weirs do not significantly affect the flood safety functionality of the river Meuse (Vergouwe, 2014), as seen in the previous chapter, and this function is therefore left outside of the scope of this study.

Shipping

To allow for shipping, a certain water depth needs to be provided. In order to guarantee this throughout the year, weirs are constructed in the river to create an artificial backwater curve. At each weir a lock complex is situated such that ships can surpass the weirs. The quality of these locks is measured based on the Intensity/Capacity ratio which is a measure of overload of the lock. A higher lock overload leads to longer waiting times which might lead to unwanted circumstances (Rijkswaterstaat, 2017d). An I/C value of 0.5 is said to be risky and requires RWS to start an investigation and an I/C value larger than 0.6 is unwanted and must be prevented (Rijkswaterstaat, 2017d). The southern corridor does not experience any problems during the low water period, however, when low water occurs on the river Waal, ships might sail via the northern Meuse corridor and the intensity increases. Currently, the lock complex at Grave contains the smallest- and least amount of lock chambers (see *Table 3*) and thus the lowest capacity. This has led to unwanted circumstances in the past, waiting times at Grave even exceeded 6 hours (Volker, Rook, & Volker, 2017).

For the coming decades, the size of the ships sailing through the Meuse are expected to grow (*MIRT - onderzoek goederenvervoercorridors*, 2017). Predictions for the number of ships sailing via the Meuse end up between a slight increase and a slight decline for the coming decades (De Jong, 2020). Under the influence of climate change, however, an increase in low water levels on the river Waal is expected such that shipping might choose to sail via the river Meuse instead (Orgelist & de Vries, 2012). All of this contributes to changes in shipping intensity. To be able to cope with the intensity, the capacity of the river Meuse system has to be matched accordingly.

Water Quality

When the water quality satisfies the standards, prosperous conditions develop for the users and environment. A good quality of water is for example, an important condition for recreational activities and ecology. The most important standards regarding the water quality is the European Standards for Water (European_parlement, 2000). Because of these standards, many improvements have been made in the previous decades. Compared to the 70's, when the water literally smelled, water quality in the river Meuse has improved drastically. However, after these initial improvements, a further push for improvements has come to a halt (Reeze, Buijse, & Liefveld, 2005). In some years incidents even occurred, and because of that the risk for toxic effects on most of the species in the Boarder Meuse increased in the early 2000's (Reeze et al., 2005).

Water quality is influenced by the concentration of toxic substances originating from industry and agriculture (Liefveld & Jesse, 2006). The weirs do not influence the amount of toxic substances entering the river Meuse, but do influence the diffusion of these substances in the river. The discharge (and therefore flow velocity) through the river determines the amount of diffusion of these substances. The lower the flow velocity, the less easily spontaneous high concentrations of toxic substances can be diffused.

On top of that, water quality might reduce due to a combination of low flow velocities and high temperatures. This leads to the development of low oxygen concentrations and algal growth, which leads to even less nutrients and oxygen (Liefveld & Jesse, 2006). The algal produce oxygen during the day but use it in the night, which can result in extremely low oxygen concentrations in the morning. At low flow spots, oxygen sensitive organisms can end up in a problematic situation (Liefveld & Jesse, 2006).

The average flow velocity in the river Meuse is approximately 0.12m/s during average discharges (230 m^3/s) and in the Boarder Meuse this increases to 1.2 m/s, as this part of the river Meuse is characterised by a natural flow regime (Liefveld & Jesse, 2006). However, the water quality in the weir sections of the river Meuse is the most vulnerable during low flow conditions, as diffusion is smallest in this situation. How the function water quality is measured in this study is explained in *Water Quality Submodel*.

Fresh water availability

Fresh water availability is about the balance between demand and supply of water. After all, many utilizations are depending on the availability of fresh water (see *Appendix B*). A division can be made between users and consumers. Water consumers situated in the river Meuse are extracting water from the river Meuse system without return, such as for drink water and agriculture. Approximately 4 million people in the Netherlands are provided with fresh water originated from the river Meuse (RIWA, 2019). The extraction points are in weir section Linne and just after weir section Lith. Agriculture consumes water from the river Meuse to water the crops. Especially during dry periods the need for watering crops is high as crops are not self-sustainable anymore due to low groundwater levels. The amount of water used in these periods is hard to estimate, because this consumption is simply not tracked. Agricultural consumption of river Meuse water during drought periods is expected to grow in the coming years because irrigation cannons grow larger and climate change is expected to result in longer periods of drought (Bentveld & Lassche, 2021). During long lasting dry periods, a certain order is proposed in which the water supply for the water consumers is stopped (Rijkswaterstaat, 2015c). By optimising the river Meuse system, the usage frequency of this ranking order might be positively influenced.

Shipping is an example of a user in the river Meuse system, as it is dependent on the available water depth but does not consume it. When water depths become too shallow to sail, ships are forced to delay or circumnavigate, resulting in high costs. On top of that, the water level needs to be maintained for nature and structures, such as houses and bridges, because it is simply used and built to it. A change in water level might for example lead to extinction of certain flora and fauna in the river Meuse catchment area, because they need the water level to be as it is today to survive. Structures have been built based on the current water level and a lower water level would mean that foundations could be exposed or effective loads increase which might lead to decrease in stability and possible collapse.

The availability of fresh water is depending on the precipitation surplus in the river catchment and the throughflow of water towards the sea. Especially in dry periods, the input of water in the river Meuse is scarce and problems occur (van Hengel, 2017). Rijkswaterstaat then has to come up with temporary solutions to prevent the problem from growing worse, as seen in *Figure 12*.

Example of improvised solution by RWS to heighten the water level upstream of the weir.

During dry periods, a water level higher than the current retaining level is preferred. In this way it is prevented that the water level in the weir reach, under natural conditions, ends up under the required water level. Contemporary, RWS places beams on top of weirs in an improvisational manner.

Figure 12 Improvised beam on top of weir Sambeek, source Rijkswaterstaat Henry Veugelers

Societal Functions

Examples of societal functions are (van Hengel, 2017):

- Drinking water, weir dependent and subjected to the functions water quality and availability
- Water sports (swimming), weir dependent and subjected to water quality
- Industry, weir dependent and subjected to water quality
- Agriculture, weir dependent and subjected to water availability
- Nature, weir dependent and subjected to water quality. The quality of nature in the Boarder Meuse is determined by the variation in flow velocity. Due to, for example, the release of water from reservoirs in Belgium, peak flow velocities can develop which are able to wash away eggs and macrofauna or cover them with sediment or debris (Liefveld & Jesse, 2006). Weirs in the Netherlands cannot alter these peak flows much. However, the Dutch weirs do affect the low flow velocity, and the lower the low flow velocity, the more severe effect peak velocities will have on nature in the river (Liefveld & Jesse, 2006). On top of that is nature vulnerable for high concentrations of toxic substances in the river, which is also depending on the low flow velocities. Lastly, migration of fish declines when fresh water availability is too low for a fully function fishway. Therefore, minimum flow velocities and fresh water availability is used to measure the quality of nature in the river Meuse, which is part of the water quality and fresh water availability function.
- Recreation, independent to weirs
- Culture, independent to weirs

However, removing the weirs is outside of the scope of this study. Furthermore, because the quality of the societal functions in the river Meuse is measured based on the availability and quality of water, the societal functions are not assessed on its own.

Conclusion

The functions of the river Meuse system currently experience stress. Intensity/Capacity ratios of the lock at Grave can reach risky levels and due to future developments a worsening of the situation might be expected (Koenraadt, Frielink, & Tretjakova, 2018). Due to climate change the fresh water availability might become threatened (Asselman et al., 2018; Elling & Alferink, 2017). Low discharge periods in combination with leakages and a large demand might lead to problems in the future. The water quality experiences problems as well, due to low velocities the water quality can become risky (CBS, PBL, RIVM, & WUR, 2019). Under the current system, these functions have been experiencing problems. Future scenarios under influence of for example climate change and socio-economic growth, might worsen the functioning of the current river Meuse system.

Figure 13 Water scarcity during dry periods in the Netherlands. Source: (Rijkswaterstaat, 2015c)

3. Methodology

This chapter elaborates on the methods used in this study. A combination of System Dynamics (**SD**) with Exploratory Modelling and Analysis (**EMA**) will be applied. This combination of methods is known as Exploratory System Dynamics Modelling and Analysis (**ESDMA**) (Kwakkel & Pruyt, 2013).

The appliance of these tools and programs are explained based on the **XLRM** framework, which is a framework used to structure the modelling setup (Robert J. Lempert, Popper, & Bankes, 2003). It contains four categories which each represent a certain stage in the modelling process (see *Figure 14*). The first category contains the uncertain factors or exogenous (X) that are defining the future scenarios. Input in terms of design options or levers (L) are to shape the strategies. The model and relationships (R) are describing the system itself and its behaviour. The output is given by performance metrics (M) and analyse the outcomes. In this framework, the SD model is the R in *Figure 14*, as it describes the complex system. EMA is used to explore deep uncertainty by combining X and L and it analyses the robustness of the system (M). EMA is thus controlling the arrows in the figure and can therefore be seen as a wrapper around the SD model. In the next sections these techniques and why they are applied will be further explained.

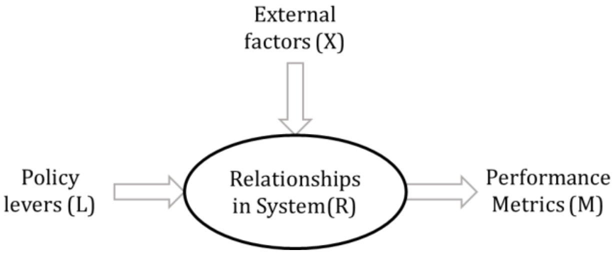


Figure 14 The XLRM framework

3.1 System Dynamics

The river Meuse is a complex system. This means that its outcomes cannot be predicted even though the starting values are known. With the same starting values, a complex system can produce different outcomes over time, as the interactions within the system might vary (Kamensky, 2011). An example related to the Meuse system would be that however the layout and characteristics of the hydraulic structures are known, the intensity of shipping, availability of freshwater and other functions in the system can vary due to uncertainties in the system.

System dynamics (SD) is a modelling method which is used to model the elements in a complex system and the interactions between these elements (Forrester, 1958; System-Dynamics-Society). It helps to understand the processes of the system. SD is used in this study because all the functions of the Meuse system can be combined in one single model, including interactions between the functions. In contrast to conventional methods that are generally limited in functionality, such as Sobek for hydraulics and Bivas/Sivak for shipping. By using SD an understanding of the processes within the complex system is ought to be achieved. SD uses differential equations to model the system. These are visualised by, among other, stocks and flows. Stocks are elements or variables in the system that have in- and outflows and are defined by integral equations. The model also contains other parameters such as constants and auxiliary variables. Between the parameters negative or positive feedbacks can occur. Vensim (Vensim, 2020) is the SD modelling software used to model the complex system of this study.

3.2 Exploratory Modelling and Analysis

Hydraulic structures in the Meuse system are to be designed to last until the next century (Rijkswaterstaat, 2015d). Due to the length of this period, the Meuse system may experience changes due to, for example, climate change and socio-economical change. These are examples of unavoidable uncertainties when redesigning such a system for the long term future. The designer therefore has to make decisions under deep uncertainty (Kwakkel, 2017; Robert J. Lempert, Groves, Popper, & Bankes, 2006).

Deep uncertainty means that the various parties to a decision do not know or cannot agree on the system, its boundaries, the outcomes of interest and the prior probability distribution for uncertain inputs to the system (Robert J. Lempert et al., 2003; Walker et al., 2013). It is then impossible to predict the exact future behaviour of the system. An approach which makes it possible to cope with these uncertainties, however, is Exploratory Modelling and Analysis (EMA). With EMA, a wide range of plausible future scenarios is explored and tested on the system by doing many experiments (Bankes, 1993; Bankes, Walker, & Kwakkel, 2013; Kwakkel & Pruyt, 2013). The EMA technique is therefore interesting for developing replacement strategies and understanding the behaviour of the Meuse system in this study. Each uncertainty is taken into account in the analysis by assuming a uniform distribution for its occurrence. In this way all possible scenarios are explored, even the most extreme ones. EMA is found to be a fitting approach to deal with the uncertainties in this study. The EMA workbench (Kwakkel, 2017) is an open source Python library and is used to perform EMA.

A strategy that results in satisfactory outcomes for most of the future scenarios, should be able to persist in real life. This is the description of a robust solution (Walker et al., 2013). This is not the same as an optimal strategy, which performs best (or at lowest cost) for a fixed set of assumptions. As the ability to predict long-term conditions is limited, it is therefore nearly impossible to find the optimal strategy (Groves et al., 2014).

Robust decision making (**RDM**) is applied to formulate robust strategies (Kasprzyk, 2015; Robert J. Lempert et al., 2006; Walker et al., 2013). RDM is a method to make decisions for a deep uncertain future, it is designed to analyse complex systems by stress testing policies on multiple possible futures rather than using models and data as a predictive tool (Robert J. Lempert et al., 2013). The RDM method generally consists of certain steps. First, the current system and its uncertainties is modelled, followed by a so called base ensemble exploration in which the current system is exposed to multiple future scenarios (Kwakkel, Walker, & Haasnoot, 2016). Hereafter, multiple alternative strategies are designed and applied to the system (Bankes et al., 2013). Then, the results of the strategies are analysed and trade-offs are studied in a policy analysis (Bryant & Lempert, 2009). Then at last, after all strategies have been assessed and exposed to multiple states of the world, it can be determined which strategies are most robust (Kwakkel, Walker, et al., 2016).

3.2.1 Base ensemble analysis

The model used in this study has consolidative characteristics, it is based on consolidating known facts which are bundled into a single package (Bankes et al., 2013; Hodges, 1991). It is, however, used in an exploratory fashion by implementing uncertainties and design options and exploring plausible future states of the world. Exploration is done by selecting combinations of uncertainties which result in a scenario. Selecting values for these uncertainties is performed by the Latin Hypercube Sampling (LHS) method.

LHS relies on its probability density function over each uncertain dimension but has better space filling properties compared to for example Monte Carlo sampling (see Figure 15). The difference between LHS and Monte Carlo is that Monte Carlo samples randomly over the probability density curve and LHS samples randomly within each bin. The distribution of the samples over the complete uncertainty space is therefore much more spread compared to Monte Carlo sampling, see *Figure 15*. Furthermore, the EMA workbench uses uniform distribution types. As the purpose of EM is to get an understanding of how the system behaves across the entire space of uncertainties. A combination of a uniform distribution and LHS leads to insight in the entire space because of its evenly sampled set of samples, as is shown for two uncertainties with 5 samples in *Figure 16*. The bins have equal dimensions stating that uniform distributions are used. LHS constructs a highly dependent joint probability density function for the random variables in the problem, which allows good accuracy in the response parameters using only a small number of samples. Therefore, LHS in combination with uniform distributions is used in this study. However, no assumptions regarding likelihood can be made.

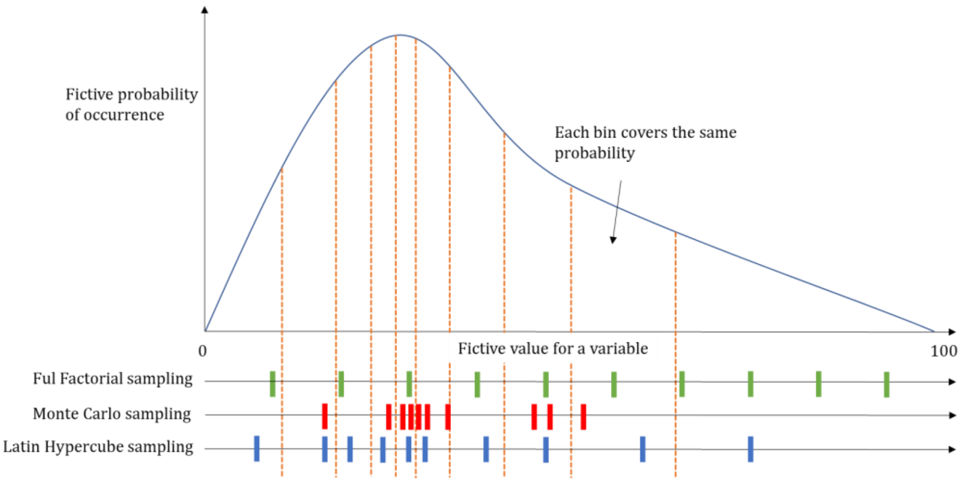


Figure 15 Example of sampling methods. This study, however, uses uniform distribution types.

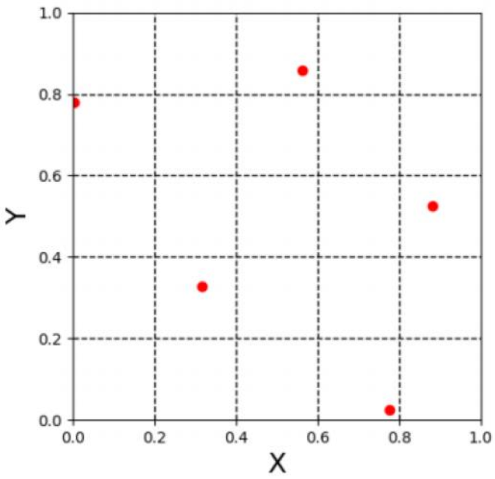


Figure 16 Example of a 2D LHS (van der Scheer, 2021)

Exploration

The first analysis used is an exploration of the outcomes by using robustness plots. Robustness metrics help analyse the outcomes. Two robustness metrics are used in this study: 1) satisficing robustness 2) regret based robustness. The satisficing robustness plots contain thresholds to which the results have to satisfy to, such as a minimum flow velocity. The plot shows the amount of runs that reach a certain threshold and therefore the general behaviour of the system. Regret based robustness is used to compare the policies to the one-on-one replacement strategy in the policy analysis. Robustness metrics are further explained in Chapter *4.5*.

The second analysis is scenario discovery. Scenario discovery is used to identify the uncertain factors that are the cause of the outcomes reaching a certain threshold (for example, a certain volume of freshwater buffer). The Patient Rule Induction Method (PRIM) algorithm is used to perform scenario discovery, it uses a technique called peeling to make an optimal selection of the outcomes of interest (Friedman & Fischer, 1999; Kwakkel & Jaxa-Rozen, 2016). In the peeling process, a box is placed around the outcomes of interest. This box is made smaller multiple times with the goal to create the best trade-off between coverage and density. Coverage is the fraction of cases of interest within the box and density is the fraction of cases in the box which is of interest. The PRIM tool will be further explained in Chapter *5.1.1*.

3.2.2 Replacement Strategies

The influential uncertainties of the system are now known and can be anticipated on by developing design options. The design options are constructed with the goal to improve the outcomes of one or more functions of the river Meuse system. Combinations of these design options are called replacement strategies.

3.2.3 Policy Analysis

In the policy analysis the results of the replacement strategies are studied. The first analysis to study these results is a sensitivity analysis by using feature scoring from the EMA workbench. Feature scoring looks for the most influential influence factors such as uncertainties and replacement strategies. The effect of the input variable on the output variable is measured. The feature scoring of the base ensemble is compared to the feature scoring of the simulations including the replacement strategies. In this comparison the contribution of the replacement strategies can be analysed.

The next tool used in this analysis is the satisficing and regret based robustness plots, as explained in the base ensemble analysis. The robustness of the policies can be analysed in these plots by using robustness metrics, and potential trade-offs between functions of the river Meuse might be observed. In this way a robust replacement strategy can be selected.

Lastly longitudinal graphs are presented showing the bed level and minimum water levels of the current system and policies. These plots show if the smallest water level which is generated by the system, is positively influenced by applying the design options.

3.3 Models and methodology overview

In *Figure 17* an overview is given regarding the methodology of this study.

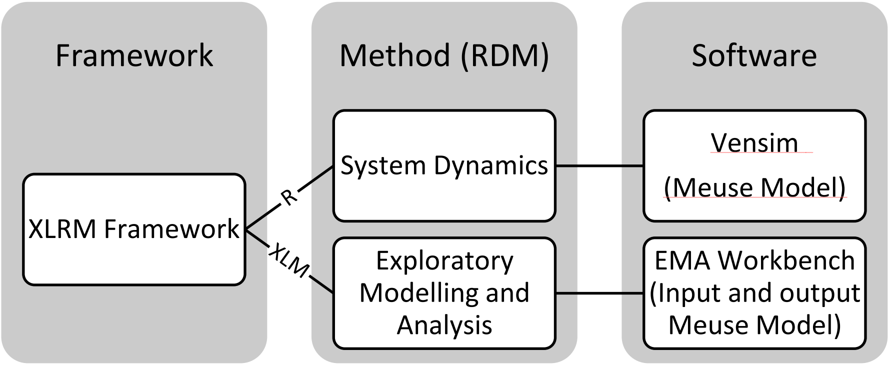


Figure 17 Framework, Method and Software used in this study summarised. The XLRM framework is performed by using the RDM method, which consists of a system dynamics part and Exploratory Modelling and analysis part. For the system dynamics part the Vensim software is used. For the EMA part the EMA workbench is used.

4. Modelling the System

This chapter describes the SD models and EMA workbench setup for the Meuse Model. First the SD model of the Meuse system, the Meuse Model, is introduced. Then the uncertainties in the Meuse system are explained. Hereafter, the Meuse Model is validated and lastly the system metrics are explained.

The area of interest in this study is the river Meuse from Borgharen to Lith and in particular its hydraulic structures. Chapter *River Meuse* gave insight in the river Meuse system. At Borgharen the most upstream weir in the Dutch Meuse river is situated, it is positioned at the bifurcation point: Boarder Meuse-Juliana canal (see *Figure 18*). This weir divides the available discharge between the Juliana canal and the Boarder Meuse and its position and crest height are therefore assumed to be fixed in this study. The weir at Lith, the most downstream situated weir and the weir at Borgharen are both not expected to be replaced in the coming 50 years (van Hengel, 2017). This makes both weirs perfect as boundaries for the Meuse System Model (MS Model).

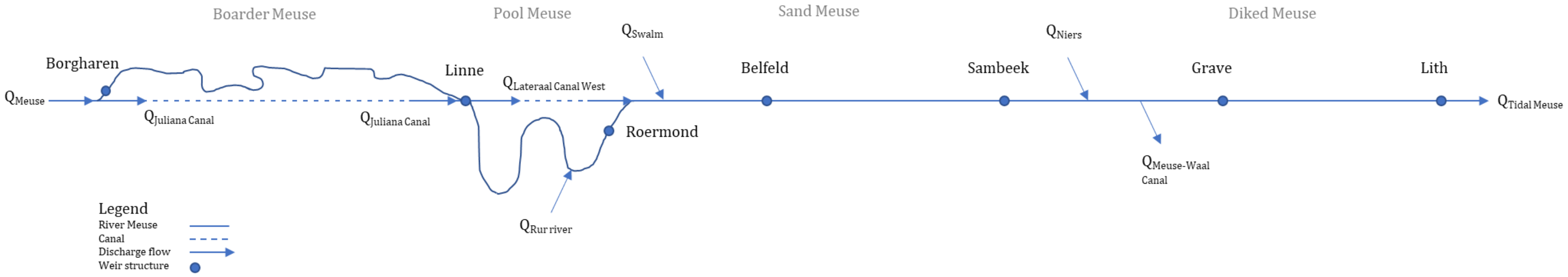


Figure 18 River section considered in the Meuse Model with in- and outflows. The dotted lines represent canals. The meandering lines represent parts of the river Meuse which are still naturally meandering. The Boarder Meuse is for a large part a natural flowing river.

4.1 Meuse Model Set-Up

The Meuse system (MS) is a complex system containing interactions, uncertainties and is constantly adapting. Such a system is a typical example of a dynamic system (Kamensky, 2011). The Meuse System is modelled with the software VENSIM and can be found on https://github.com/DouweW/System-based-replacement-of-hydraulic-structures. The MS Model is built up from five submodels (see *Figure 19*). Each submodel represents a different function or interest and together they schematize the river Meuse:

1) **Water flow submodel**, general flow of water through the river.
2) **Shipping flow submodel**, general flow of ships through the locks.
3) Fresh water availability submodel
4) Nature and ecology submodel
5) Shipping capacity submodel

The first two submodels are schematizing general flows through the river and are therefore seen as the basis of the Meuse Model. The submodels 3, 4 and 5 are schematizing certain functions of the river and contain the Key Performance Indicators (KPI's), for that specific function.

To keep the computational time short, the model is simulated for one given year. Additionally it is assumed that the hydraulic- and shipping flows of the previous year do not affect the river Meuse system of the current year. At the start of the simulation, one specific year between 2020 and 2100 is selected to simulate the model for. In the next sections the submodels are explained.

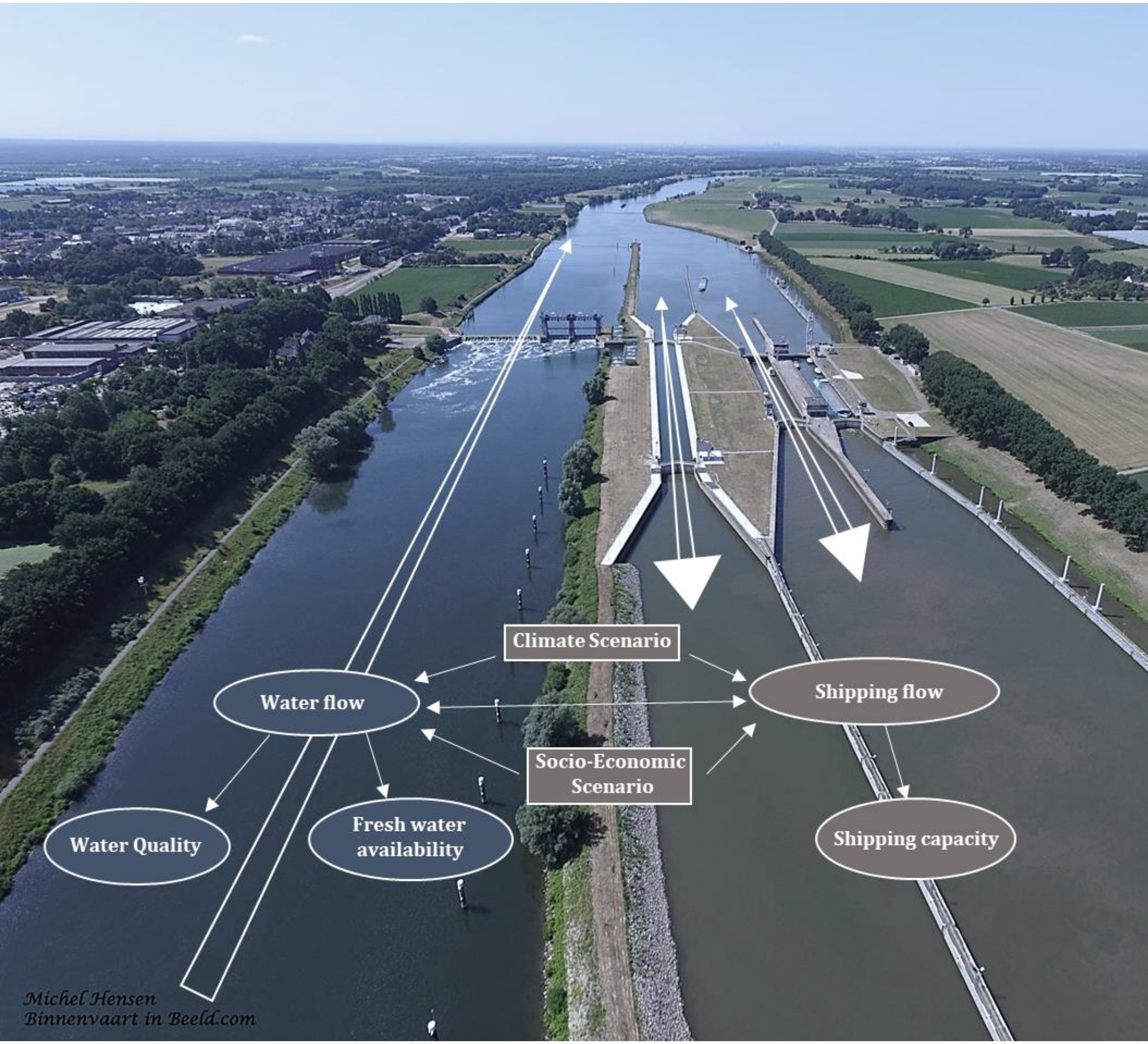


Figure 19 Overview submodels given for the hydraulic complex at Belfeld.
Source: www.binnenvaartinbeeld.com/sites/default/files/styles/watermerk/public/Objecten/Belfeld%20DJI_0293.JPG?itok=LtGMxBBz

4.1.1 Water Flow Submodel

The first submodel discussed is the water flow model which contains the water flow through the river and its hydraulic structures such as weirs. This study focusses on the influence of hydraulic structures on the functions of the river, the water flow model acts as a connection between the weirs and the functions of the river. During low flow and normal periods water is partially blocked such that the water level can be kept at a high level. During high flow periods however, the weirs are lifted and do not affect the river flow (Maheshwari, Walker, & McMahon, 1995). Because weir impact is assessed in this study, the main focus of the model has been the low and normal flow situations. In this model the river Meuse, as schematized in *Figure 18*, is split up in multiple river segments of a thousand meter, as portrayed in the example of *Figure 20*. The river segment length of a thousand meters is chosen based on a trade-off between: being able to accurately represent the river and keeping the simulation time short enough. A thousand meters for the river segment length gave acceptable results for both of these requirements.

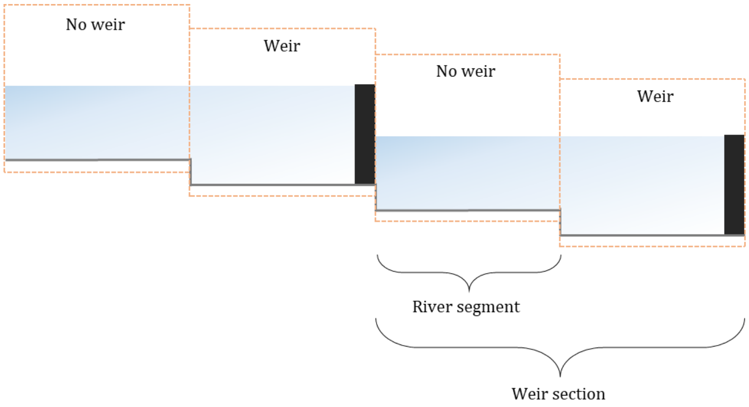


Figure 20 Example of longitudinal river section sketch containing two weir sections and four river segments. The Meuse model contains many river segments of 100m in length per weir section.

Calculating the flow through the river

To model its hydraulic behaviour, the river is divided in river segments. In this way, each river segment represents a controlled water body and therefore can be schematized as a stock flow model, see *Figure 21*. A stock flow model consists of stocks, flows and variables. The flows fill and empty the stock, which works as a volume balance and therefore the following equation can be formulated for each river segment:

$$V_{segment} = V_{Initial} + \int_{t}^{t_1} (Q_{IN} - Q_{OUT})\, dt \tag{1}$$

With:

$V_{segment}$ = *volume of water in river segment [m³]*
$V_{initial}$ = *Volume of water in river segment at previous time step [m³]*
Q_{IN} = *Discharge into the river segment [m³/s]*
Q_{OUT} = *Discharge out of the river segment [m³/s]*

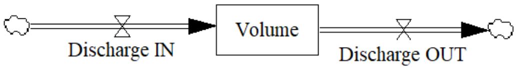


Figure 21 Example of a stock and flows in VENSIM.

Discharge into the river segment is calculated by the previous river segment and therefore the only unknown in the right hand side of equation (1), is the flow out of the river segment. To calculate the flow through unhindered river segments, a difference between flowing and storing cross section is made. During the dammed situation, only part of the river cross section is flowing. The other part of the cross section is storing water, as schematized in *Figure 22*.

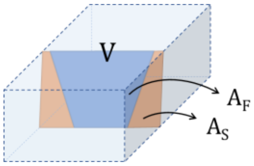


Figure 22 Flow cross section A_F and storage cross section A_S

Three flow situations are considered through this weir section and determine the outflow in the weir segments. 1) no flow situation ($Q = 0m^3/s$), the water level in the weir reach is horizontal. 2) a low flow situation ($0m^3/s < Q < Q_{opening\_weir}$) and a gradient in the water level develops and 3) a high flow situation ($Q_{opening\_weir} < Q$) in which the weirs are lifted and the river is thus free flowing. These three situations are sketched in *Figure 23*.

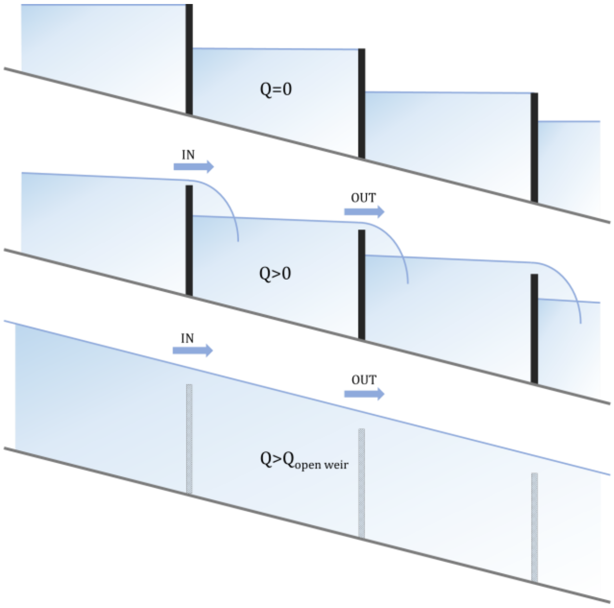


Figure 23 Top: Low flow conditions, bathtub model with successive weir reaches Bottom: High flow conditions, weirs removed.

During 1) and 2) the water depth in the river segments containing a weir is similar to the crest height of the weir. The discharge out of a river segment with a weir is considered to be the same as the discharge coming in to the river segment, plus possible inflows and outflows of water, such as precipitation and evaporation. Only when the leakage of the weir is larger than the inflow in the river segment, the leakage of the weir determines the flow to the next weir section. In river segments without a weir, the discharge to the next river segment is determined by calculating the difference between the water depth in the river segment and the water depth under the backwater curve originating at the weir, as showed in *Appendix A*. The difference in volume is flowing to the next river segment. Moreover, the magnitude of the discharge through the Meuse Model river system is influenced by the discharge entering the boundaries of the river section, the precipitation in the river sections catchment area and the evaporation of the surface water. How the discharge to the next river segment is calculated in the Meuse Model, is presented in a flow chart in *Figure 46* in *Appendix A*.

Furthermore two leakage variables at the end of the weir reach are considered. Firstly the leakage of the weirs is accounted for. Secondly the water loss while levelling ships is taken into account. The latter is influenced by the number of ships passing the lock. As more ships pass the hydraulic complex, more levelling cycles are needed which results in a larger absolute volume of water lost.

River Meuse discharge series

At the upstream boundary of Borgharen, water flows into the river section selected for this study. At the Belgian city of Liège (Monsin), just over the Dutch-Belgian border, discharge timeseries for the years 1911-2015 are known (see *Appendix B*). By using the KNMI climate scenarios the reference discharge series are then transformed to a year of simulation somewhere in the future, as will be explained in chapter *Exogenous uncertainties* and *Appendix B* (Kramer & Mens, 2016). The Monsin discharge series is reduced by the discharge that flows into the canals and results in the discharge at the upstream boundary of Borgharen.

During high flow conditions the weirs are lifted. This is regulated for each weir individually, see Table 4. Until the discharge is lower than the target, such that the weirs can be positioned again, the Meuse is a free flowing river. In this situation the flow is assumed steady and uniform.

Table 4 Opening and closing specifications hydraulic structures. Source: internal email conversation Rijkswaterstaat.

Hydraulic structure	Opening at [m³/s]
Weir at Borgharen	1700
Weir at Linne	1350-1400
Weir at Roermond	1000-1100
Weir at Belfeld	900-1000
Weir at Sambeek	>1300
Weir at Grave	1200-1500
Weir at Lith	1200

Periods of extreme drought might increase in magnitude and duration due to the possibility of increasing potential evaporation and decreasing summer precipitation (KNMI, 2018). To account for these extreme drought events, drought periods and intensities are added as uncertain variables in the model and influence the discharge at the upstream boundary (see *Exogenous uncertainties* and *Appendix B*). In many occasions, the duration of an undershoot of a certain threshold is normative for water scarcity (Korving & Versteeg, 2018).

Calculating water depth in the river segment

The water level in the weir reach is determined by calculating the wet area which is placed into the average cross-section of the weir reach. By means of a with lookup function in VENSIM, the water depth is derived from the cross-sectional area.

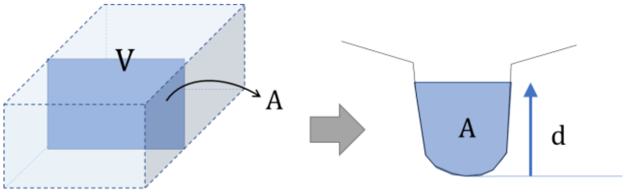
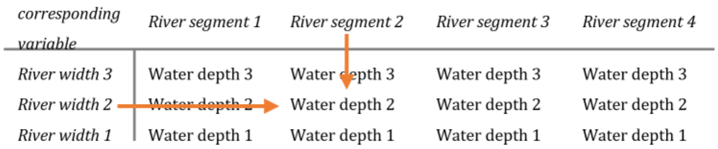


Figure 24 Deriving flow depth free flow situation.

River segment characteristics

Furthermore, each river segment has a unique bottom friction for a given water depth. The bottom gradient is set to 0.0004 [-] for the Boarder Meuse and 0.00014 [-] for the rest of the river. From Sobek file *"Maas-j19_5-v1"*, unique cross sections are retrieved for each river segment. These are implemented in Vensim by means of tabbed arrays. A tabbed array works as a matrix, the rows of this matrix correspond to the river section and the columns of this matrix correspond to a certain variable of that river section. In this way a certain cross sectional characteristic can be selected from the matrix based on the river segment location and the water depth in that river segment. The water depth of a river segment is, for example, selected from the water depth tabbed array with the corresponding variable being the width of the river at that point in time, see *Table 5*. Should the river width end up between river width 1 and river width 2, the water depth will then be an interpolated value between water depth 1 and water depth 2. The width of the river is selected in the same way, but based on the corresponding area and the area is calculated by dividing the volume of the river segment by the length of the river segment.

Table 5 Example of water depth tabbed array. At a certain point in time, the Meuse Model is selecting the water depth of river segment 2 based on the previously selected river width. If the value of the area would fall between area 2 and area 1, the corresponding water depth would be an interpolated value between water depth 1 and water depth 2



corresponding variable	*River segment 1*	*River segment 2*	*River segment 3*	*River segment 4*
River width 3	Water depth 3	Water depth 3	Water depth 3	Water depth 3
River width 2	Water depth 2	Water depth 2	Water depth 2	Water depth 2
River width 1	Water depth 1	Water depth 1	Water depth 1	Water depth 1

At certain river segments bifurcation points or confluences can be found, see *Figure 18*. At the boundary of the river of this study, the discharge from the Meuse is split over the Boarder Meuse and the Juliana Canal. At the mouth of the Juliana canal this discharge is reunited with the discharge of the river Meuse. The same happens at the start and end of the Lateraal Canal. The Meuse-Waal canal allows ships to sail from the river Meuse into the river Waal and vice versa. With this exchange of ships a discharge of water might develop from the river Meuse into the river Waal. This discharge is approximated to 0.8 m^3/s (da Silva & Lokin, 2018). The discharge of the river Rur, the river Schwalm and the river Niers are added to the Meuse river. Certain parts of the river are naturally flowing and are not impacted by the weirs. This is, for example, the case for the Boarder Meuse. Therefore, the influence distance is computed for each weir.

4.1.2 Shipping Flow Submodel

The flow of ships through the system is determined by the locks and their capacity. For a ship to pass a weir, it sails into the adjacent lock, which then lowers its water level according to the water level on the other side of the weir. At this point the ship can sail out of the lock and continue its journey along the river. Crossing a weir, by means of a lock, delays the total transportation time. This is, however, accepted, provided that the capacity of the lock is large enough and no unnecessary waiting time develops. This is measured by the intensity to capacity ratio, which is simply stating how much the lock capacity is stressed. In the next section the intensity and capacity of the locks in the Meuse Model is explained.

Intensity

In comparison to shipping on the Waal, where most shipping routes are towards the German hinterland, the number of short distance trips for the river Meuse is relatively high (De Jong, 2020). This makes tracking of ships complicated and therefore shipping on the Meuse is not modelled as one connected stock flow diagram, such as the previously discussed water flow model, but each lock complex is modelled separately.

The shipping data (see *Appendix B*) is split up in commercial and leisure categories. Both categories are influenced by the socio-economic situation which is affiliated to a certain growth or decline of the number of ships over time. The demand for commercial vessels is initiated by socio-economic growth from the hinterland (Germany/Limburg/Rotterdam) and the shipping availability of the river Waal (De Jong, 2020). The growth in leisure vessels is even so determined by the socio-economic development.

The socio-economic scenario influences the intensity of commercial and leisure ships at each specific lock given the year of simulation. The intensity of commercial ships is additionally influenced by the percentage of transport over water compared to road and rail, and the inflow of ships that are choosing to sail over the regulated river Meuse instead of the free flowing river Waal during periods of drought. This can lead to an increase of intensities on the Diked Meuse up to 50% (De Jong, 2020). Shipping data for the reference year are retrieved from the NIS database from Rijkswaterstaat and (De Jong, 2020) (see *Table 6*). The weekly amount of shipping passages is calculated from the yearly average amount of passages for the years 2011 to 2018. The maximum of these years has been selected to represent the weekly shipping flow, as recommended by (De Jong, 2020). The shipping intensity is then transformed to a year of simulation somewhere in the future by using the socio-economic scenarios, as will be explained in chapter *Exogenous uncertainties* and *Appendix B*.

Table 6 Shipping intensities at the locks. Retrieved from (De Jong, 2020) and NIS database Rijkswaterstaat

Lock	**Commercial [Ship/Week]**	**Leisure [Ship/Week]**
Linne	44	643
Roermond	62	518
Belfeld	439	458
Sambeek	547	498
Grave	289	511
Lith	334	807

In the reference year of 2012, the South-East corridor transported approximately 8% of the goods via rail, 72% via road and 20% via water (*MIRT - onderzoek goederenvervoercorridors*, 2017). Due to innovations or other reasons a modal shift towards shipping might occur (Koenraadt et al., 2018). As a result, the aforementioned percentages might shift. This shift is considered in the form of an uncertainty: shipping transport to total transport ratio.

Capacity

The capacity of the lock is dynamically calculated at each lock and is depending on the maximum number of ships that can pass the lock in a certain amount of time. This corresponds to the number of levelling cycles in an hour multiplied with the number of ships transported in one cycle. First the time needed for one cycle is determined as in equation *(12)* in *Appendix A* (van Dongen, 2018).

To generate the capacity of commercial shipping, the maximum number of ships (n_{max}) is multiplied by the number of chambers, divided by the time needed for one cycle (T_c) and reduced by the relative amount of recreational shipping. To take both directions into account, this number is doubled. As one cycle involves bringing ships from the higher water level to the lower water level and vice versa. The weekly capacity is determined as in equation *(13)* in *Appendix A*.

The sill height in front of the locks prevents ships with a certain draught from sailing through the lock, depending on the available water depth. The ship sizes sailing on the river Meuse is divided into three main categories. These are: CEMT class V, CEMT class IV and CEMT class III and lower. Each category has been given a ship draught. In case the water depth in the river is too small and the ship might hit the sill in front of the lock, the ship will choose not to sail. This will impact the capacity of the Meuse system.

Each lock complex has one or more lock chambers. These lock chambers can be of different size, in this study three sizes are considered: large, medium or small. The amount of ships that fit into the lock and the size of these ships is dependent on the size of the lock chambers. The lock complex of Grave, for example, only counts one small lock chamber. Other lock complexes contain either more than one lock chamber or larger chambers, and therefore the lock at Grave can be seen as a critical point in the corridor. At certain periods in the year the Intensity/Capacity ratio at lock Grave can increase drastically (De Jong, 2020).

4.1.3 Fresh Water Availability Submodel

The fresh water availability model is used to describe the function of availability of water in the Meuse system. This model contains the Key Performance Indicator (KPI) *percentage of fresh water volume* which computes the minimum volume of water compared to a full fresh water buffer for each weir section in the simulated year. A full freshwater buffer can be understood as the volume of water under the backwater curve in when there is no discharge. Only situations when there is a minimal amount of available fresh water volume are of interest as the problems that might occur are expected to be most severe in this situation. It is important that the freshwater buffer does not ends up lower than a full fresh water buffer, because certain functions might be hindered as water saving measures are introduced, as is explained in more detail in chapter *2.3*. The situation is assumed to be critical when the volume of freshwater buffer ends up to be lower than 90% of a full freshwater buffer as this might lead to reduction of shipping, problems for structures and problems and insufficient water for nature. In *Appendix B* the location of the water users is shown and most of the them can be found in weir section Lith, Roermond and Grave. However, shipping industry, structures and nature can be found throughout the whole river Meuse and can be severely by a shortage of water. Therefore all weir sections are considered of equal importance. Further specification on how the freshwater buffer is measured, will be given in Chapter *5.1.1*.

The Fresh water buffer is calculated by performing a volume balance of water for the specific weir section. Inflows are river discharge, precipitation and the inflows from tributaries. Outflows are consisting of the river discharge out of the river section, the evaporation of the water in the river, the leakage of the weirs, the water loss during levelling of the locks and the outflows at bifurcation points, see *Figure 25*. This means that when dry periods occur with only little input of fresh water, a scarcity of fresh water can be prevented by having a large enough freshwater buffer. Hydraulic structures influence the quality and quantity of the freshwater buffer by altering the water level of the specific river section.

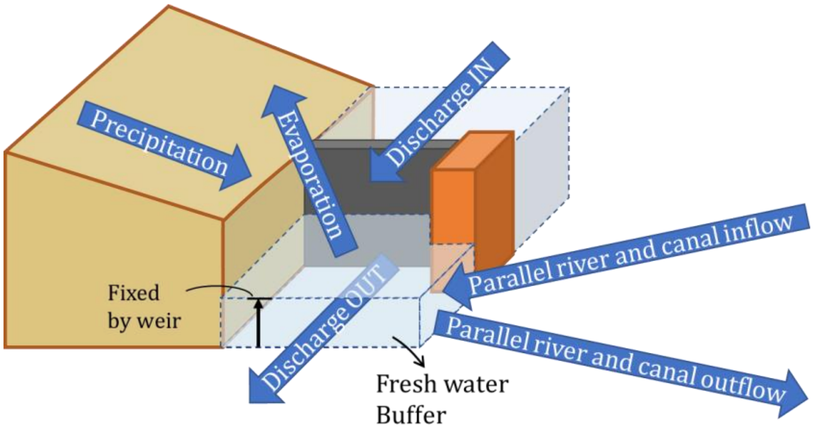


Figure 25 Fresh water buffer volume balance

4.1.4 Water Quality Submodel

By constructing hydraulic structures in the river, it becomes a hybrid river, which means that in certain periods the river is dammed and in other periods the river acts as free flowing. During the dammed situation, the weirs are in place and the flow of the river is reduced significantly. During low discharge periods, the flow in the river can be almost completely non-existent because of the large water depth maintained by the weirs. Especially in these periods, the water quality might end up being problematic. Chapter *2.3* explains that because of low flow velocities, diffusion of toxic substances becomes more difficult which can lead to problems when high concentrations of these substances end up in the river. A second problem created by the low flow velocity is that the residence time of the water increases. This leads to a decrease of oxygen and might lead to algae growth in warm periods (Admiraal et al., 1993). A third problem created with low flow velocities is that when peak discharges occur during these low flow periods, the difference between flow velocities results in washing away fish eggs and macrofauna or covering them in sediment or debris (Liefveld & Jesse, 2006). This is especially problematic in the Boarder Meuse (Liefveld & Jesse, 2006). Thus, minimum flow velocity is preferred to be high.

Measuring water quality is done by means of the KPI *minimum flow velocity* within the weir section. It is assumed that the problems regarding water quality develop over a period of 5 days. Therefore the average of the minimum 5 day flow velocities are assessed for each weir section. At a flow velocity lower than 0.03 m/s, cyanobacterial blooms might occur (Mitrovic, Hardwick, & Dorani, 2011), which shows that the water quality is in bad condition and is therefore undesired. Low flow situations are also lead to risky situations regarding concentrations of toxic substances (RIWA, 2018). An assumption is made that flow velocities below 0.1 m/s lead to these risky situations.

4.1.5 Shipping Capacity Submodel

The shipping capacity model describes the function shipping and contains the KPI which indicate its performance. The KPI used is the *intensity/capacity ratio* and represents the load on the locks and therefore the functioning of the shipping system. The I/C ratio is calculated by dividing the intensity of ships by the capacity of the locks. When the I/C value of a lock reaches values larger than 0.6, the average waiting times for ships is expected to increase exponentially. This could potentially create bottlenecks leading to an undesirable situation (Rijkswaterstaat, 2017a). An I/C value larger than 0.5 is considered risky and when these values are reached, Rijkswaterstaat will start an investigation (Rijkswaterstaat, 2017a). A lock complex might consist of multiple lock chambers, each of a different size and thus having a unique capacity. Therefore, every lock chamber needs to be calculated individually and the sum of the lock chambers represents the capacity of the lock complex. The capacity of the lock complex can be increased by constructing more and/or bigger lock chambers.

4.2 Key Uncertainties in the Meuse Model

The Meuse Model uses a number of uncertainties and combinations of uncertainties form a scenario, which is a “guess of how the world works”. To be able to form and explore most of these scenarios, exploratory modelling is utilized (Bankes, 1993; Bankes et al., 2013; Kwakkel & Pruyt, 2013).

Two types of uncertainties can be distinguished. 1) Exogeneous uncertainties, these uncertainties are generated outside of the system and influence variables within the model, for example climate change. 2) Endogenous uncertainties, these uncertainties are generated within the system and are represented by variables. For example the uncertainty: leakage of the weir, which is caused by the amount of debris stuck between the weir gate and its frame and is thus an uncertainty coming from within the system.

4.2.1 Exogenous uncertainties

The **Climate scenario** can vary between a lower bound and an upper bound. In the case study climate change impacts the intensity of the average seasonal discharges, the discharge during a drought period, the precipitation and the evaporation in the river catchment area (see *Appendix B*). The lower bound climate change (G_L) combines moderate change in temperature, the upper bound climate change ($W_{H,dry}$) includes a more drastic change in temperature and leads to especially dry summers and a moderately dry spring (KNMI, 2014). Climate change is expected to have a significant influence on the future scenarios of the Meuse system. It specifically has a great influence on the discharge regime of the Meuse (de Wit et al., 2001). In general a trend can be seen towards an increase of the average discharge during the wet periods, in winter and the beginning of spring, and a decrease of the average discharge during the dry periods, in autumn (de Wit et al., 2001). This means that the average high discharges increase, and the average low discharges decrease.

In (Kramer & Mens, 2016), two climate scenarios are used. One scenario describes moderate climate change (G_L) and the second scenario describes severe climate change ($W_{h,dry}$). The moderate climate change scenario contains a moderate decrease of low discharges but result in an increase of high discharges until the year 2050 and after slightly decrease again. The severe climate change scenario ($W_{h,dry}$) contains a severe decrease of low discharges and a moderate increase of the high discharges. Based on these scenarios, discharge series for the river Meuse are generated from historical discharge series by applying a transformation formula (Hegnauer, Beersma, van den Boogaard, Buishand, & Passchier, 2014; Kramer & Mens, 2016). This is done for the years 2050 and 2085 (see for example *Figure 26*). In the Meuse Model one of the 105 historical discharge years can be selected in combination with a climate scenario and a simulation year. The model will then generate a discharge timeseries which is transformed to the simulation year based on the climate scenario and use it as input. The transformation to the simulation year is done by interpolating or extrapolating between the available discharge series (i.e. the discharge series from (Kramer & Mens, 2016) for the reference year 2014, the year 2050 and the year 2085). This same technique has been done for the discharge series of the tributaries Rur, Schwalm and Niers and for the surface precipitation and evaporation. Thus many future discharge scenarios can be created ($2\ scenarios \cdot 105\ years = 210\ future\ discharge\ scenarios$).

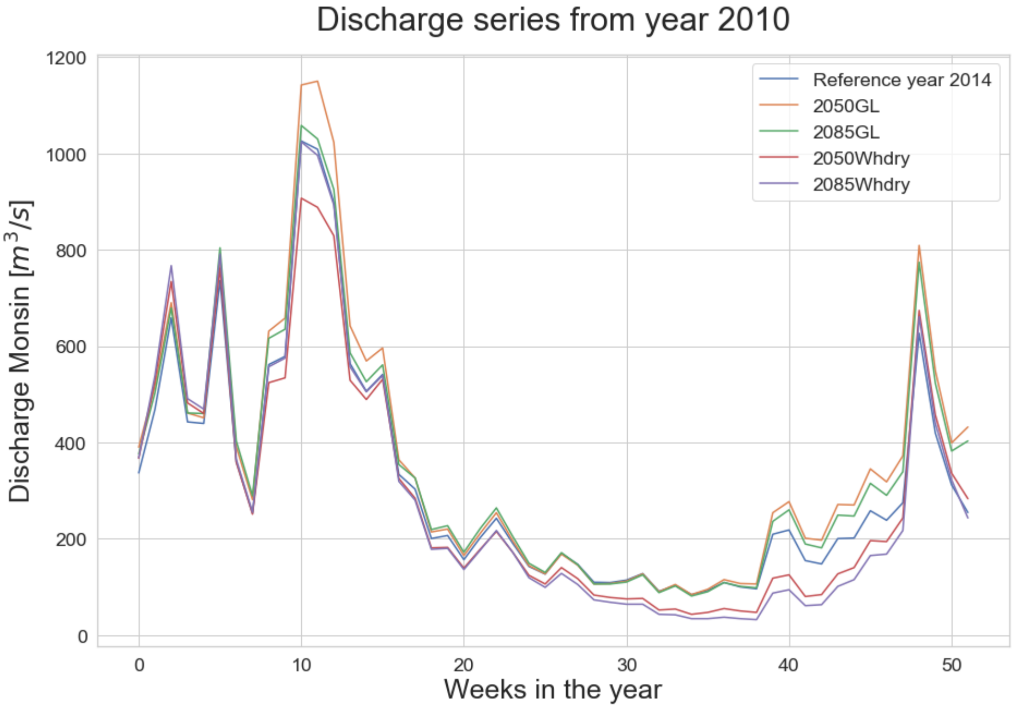


Figure 26 Historical discharge series from the year 2010 transformed to the years 2050 and 2085 by using climate scenarios GL and Whdry

Climate change is even so affecting the seawater level. The DM and the VS are, however, located too far from the sea to be affected by the increase in seawater level. Furthermore, the water level in the river Meuse is interrupted by multiple hydraulic structures such as weirs and locks, with the result that during normal water levels the sea has a marginal influence on the river behind these structures.

Socio-economic developments vary between a lower bound and an upper bound (see *Appendix B*). The lower bound socio economic development (WLO_L) consists of low technological progress and a declining population resulting in a limited economic growth (CPB/PBL, 2015). The upper bound socio-economic development (WLO_H) consists of rapid technological growth and a growing population resulting in a strongly growing economy (CPB/PBL, 2015). A summery is given in *Table 7*.

The river Meuse is used as a logistical system. Goods are transported to companies connected to the Meuse. In case of socio-economic growth, the demand of transport over the Meuse will increase. The opposite holds for a socio-economic decline. Shipping is therefore influenced by a change in the socio-economical perspective (Orgelist & de Vries, 2012).

The **percentage of transport via water** is influenced by multiple exogenous uncertainties (see *Appendix B*). Just like transport via road or rail, the transport via water takes on a certain percentage of the total transport (*MIRT - onderzoek goederenvervoercorridors*, 2017). The amount of containers at Rotterdam and Antwerp is expected to double in the coming decennia (Elling & Alferink, 2017) and due to expansion limitations in other sectors, navigation might be the solution (Orgelist & de Vries, 2012). Other factors which can influence the percentage of transport via water are, for example, decisions by governments and innovations. The current market share of transport via water is 20%. For the coming 100 years this is assumed to change to with ±10% (*MIRT - onderzoek goederenvervoercorridors*, 2017).

Table 7 Overview of exogenous uncertainties for the Meuse Model

Exogenous uncertainty	**Unit**	**Lower bound**	**Upper bound**	**Source**
Climate scenario	-	G_L	$W_{H,dry}$	KNMI
Socio-economic scenario	-	WLO_L	WLO_H	PBL & CPB
Percentage of transport via water	%	10	30	(*MIRT - onderzoek goederenvervoercorridors*, 2017)
Corresponding variable				
Climate scenario				
Discharge series,	-	G_L	$W_{H,dry}$	(Kramer & Mens, 2016; Sperna Weiland, Hegnauer, Bouaziz, & Beersma, 2015)
Discharge series tributaries,	-			
Evaporation series,	-			
Precipitation series	-			
Socio-economic scenario				
Commercial shipping growth	%/Year	- 0.17	+ 0.33	(Rijkswaterstaat, 2017b)
Leisure shipping growth	%/Year	- 1.1	- 0.6	(Rijkswaterstaat, 2017b)

4.2.2 Endogenous uncertainties

Some important endogenous uncertainties are drought period intensity and length, which can take any value between the upper and the lower bound in *Table 8*. The drought period and intensity is a period of extreme drought that is added to the discharge series to stress-test the system (see *Appendix B*). This extreme drought is implemented to take extreme and unforeseen events into account, such as the extreme high water period in the summer of 2021. During this drought period, the discharge that enters the boundaries of the river cannot grow larger than a certain intensity for a certain period of weeks. For the drought period intensity the lower bound is based on the discharge of 1/50 years (Korving & Versteeg, 2018; Rijkswaterstaat, 2018). For the upper bound of the drought period discharge it was checked what discharge the discharge series would generally reach, this was approximated at 45m^3/s. The duration of the discharge series was set to 4 to 16 weeks. The lower bounds indicates when a event is long enough to be seen as a drought period (Korving & Versteeg, 2018) and the upper bound simply indicates when the period of drought is expected to be finished. Another uncertainty which requires some explanation is the "year from discharge series". In each run a random year from 1911-2015 year discharge series is selected to be transformed to the simulation year by means of climate scenario. Needless to say, each year has a unique discharge pattern for the duration of one year.

Table 8 Overview of endogenous uncertainties for the Meuse Model

Endogenous uncertainties	Unit	Lower bound	Upper bound	Source
Drought intensity	m^3/s	45	20	(Korving & Versteeg, 2018)
Drought period	Week	4	16	(Korving & Versteeg, 2018)
Leakage weir Lith	m^3/s	3.5	13	assumed
Leakage weir Grave	m^3/s	5	15	(Rijkswaterstaat, 2021)
Leakage weir Sambeek	m^3/s	5	15	assumed
Leakage weir Belfeld	m^3/s	1.5	9	assumed
Leakage weir Roermond	m^3/s	1.5	9	assumed
Leakage weir Linne	m^3/s	2	10	(Rijkswaterstaat, 2008)
Water loss one levelling cycle	m^3/cycle	6000	12000	based on (De Jong, 2020)
Number of ships per levelling cycle Grave	Ship/cycle	3	5	(De Jong, 2020)
Number of ships per levelling cycle Lith	Ship/cycle	5	10	(De Jong, 2020)
Extra shipping intensity Diked Meuse	%	20	50	(De Jong, 2020)
Extra shipping: period length	Weeks	4	16	Assumed
Percentage of class IV ships	%	20	30	(De Jong, 2020)
Percentage of class V ships	%	40	50	(De Jong, 2020)
Year from discharge series	Year	1911	2015	(Kramer & Mens, 2016)

4.3 Verification and Validation of the Meuse Model

Verification and validation are needed to generate a useful model. Verification says something about whether the implementation of the model has been done correctly. Validation is the task of determining if the model represents the underlying real system accurately enough. The latter therefore determines if the model can be used to analyse the river Meuse system in this study.

With the water flow and shipping flow submodels an endeavour is made to adequately model the Meuse system and its interactions. These submodels have been constructed based on expert knowledge and literature. In this chapter the model is verified and validated which concludes in whether or not the model is useful for this study. Verification checks if the calculations in the model work accordingly and validation checks if the model represents the underlying real system accurately enough. In the validation process the limits of the model validity come to light. Limits do not necessarily mean that a model is not good enough, but they do show where the model is useful and where it is not. On top of that it should be taken into account that during the model construction a trade-off occurred between modelling the system realistically and the simulation time.

Verification

The model was verified in VENSIM by means of a unit check and a model check, and it was made sure that no errors were shown before running the simulations. For the integration method, VENSIM offers the Euler and the Runge-Kutta (RK) method. As the model uses quite some discrete functions, Euler is used. Euler only uses derivative information at the beginning of the interval and is therefore better at handling abrupt changes coming from the discrete functions compared to the more sophisticated RK method. The RK method uses either two (second-order RK) or four (fourth-order RK) evaluation points in its calculation (Press, Teukolsky, Vetterling, & Flannery, 1992).

In the Meuse Model, the velocity is calculated in an analytical way as the calculation contains the water depth in the current river segment only. The CFL condition, which has to be applied when using numerical calculations, does not have to be applied (see *Appendix C*) which makes it possible to select a relatively large time step. Larger time steps lead to shorter simulation times, and that is why this calculation method is used in the Meuse model. However, time step is still supposed to be small enough for the model not to produce errors. Another argument to keep the time step as small as possible is that a smaller time step leads to a higher accuracy as the variables in the model are calculated on more occasions. A negative effect, however, is that with a smaller time step, the model becomes computationally more heavy resulting in a larger simulation time. As the RDM works with many simulations, the simulation time is ought to be kept as small as possible. These pros and cons result in a trade off when choosing the time step. Determining the time step is now done by step doubling (Press et al., 1992), in which the previously checked time step is halved to find out if performance is improved. In *Figure 49* in *Appendix C*, a time step of 0.0625 is found to be sufficient for the Meuse Model.

Validation

The model was validated by performing multiple model structure and model behaviour tests (Forrester & Senge, 1979). To examine how well the model-generated behaviour matches the observed behaviour of the real system, multiple behaviour-reproduction tests are performed for the water flow model. Locations where these tests are performed are shown in *Figure 27*. In *Figure 28* the behaviour reproduction test for the location Neer is presented. Behaviour reproduction tests for the other locations indicated in *Figure 27* can be found in *Appendix C*. Another test examining the water flow submodel is an extreme-condition test. The Meuse model is fed with zero discharge input and it is checked if the model shows reasonable results. This is shown in *Figure 29*. Furthermore, the shipping flow submodel is based on literature. The shipping flow model is mainly validated based on literature such as (De Jong, 2020), (Koenraadt et al., 2018) and (van Dongen, 2018). In these studies the vulnerability and robustness of the locks in the river Meuse are assessed. For example I/C values

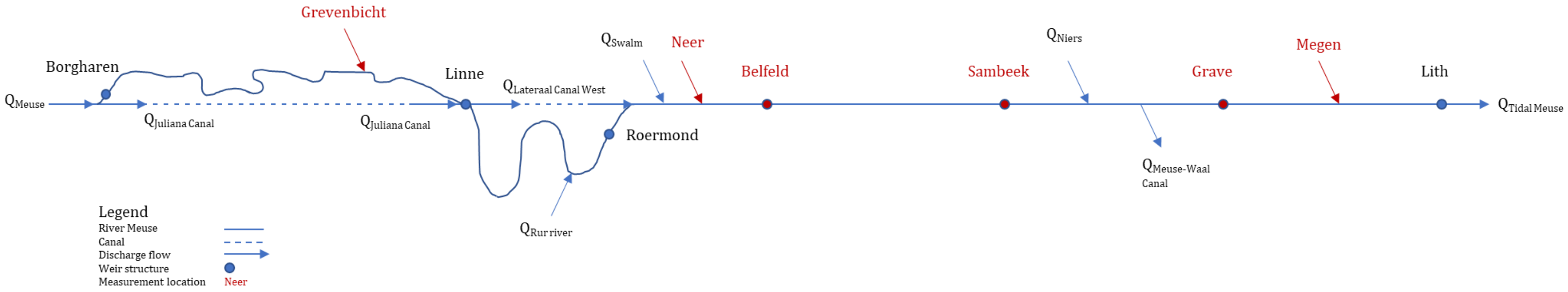


Figure 27 Locations of the performed behaviour reproduction tests of the Vensim model

The discharge series for the year 2016 is used and the computed water depths in Vensim are compared to the measured water depths in real life. From the graph it can be seen that the shape of the water depth timeseries generated by Vensim seems to mimic the shape of the water depth timeseries of the real world data. During high peaks, however, the modelled timeseries does not seem to represent the peaks well enough. This can be explained by the fact that Vensim uses daily average discharges to compute the water depth. The real world water depth is measured at one (or a few) point in time which might lead to higher peaks. Furthermore, the goal of the model is to simulate the lower region of the water depths as low water depths are being analysed in this study. The lower regions seem to be simulated in a good enough manner. Lastly, the simulations will be performed with a weekly timestep aiming at weekly averaged water levels. The extreme condition test, shown in *Figure 29*, shows the water depth at Neer if the river Meuse would have no discharge input for one whole year. An asymptotic curve can be seen as the water exits the river. This can be plausible as the leakage through the weirs decreases when the water depth in the weir section decreases as well.

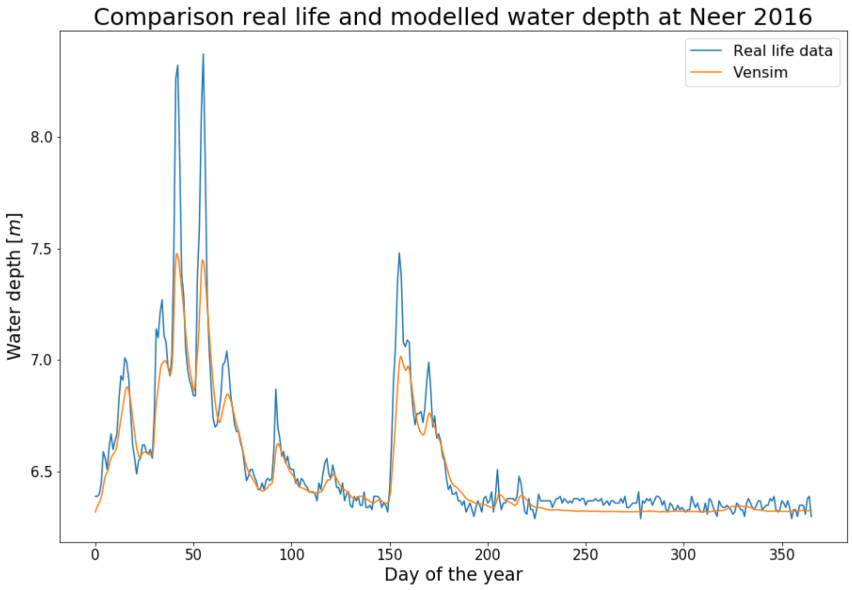


Figure 28 Behaviour reproduction test for the river segment at Neer.

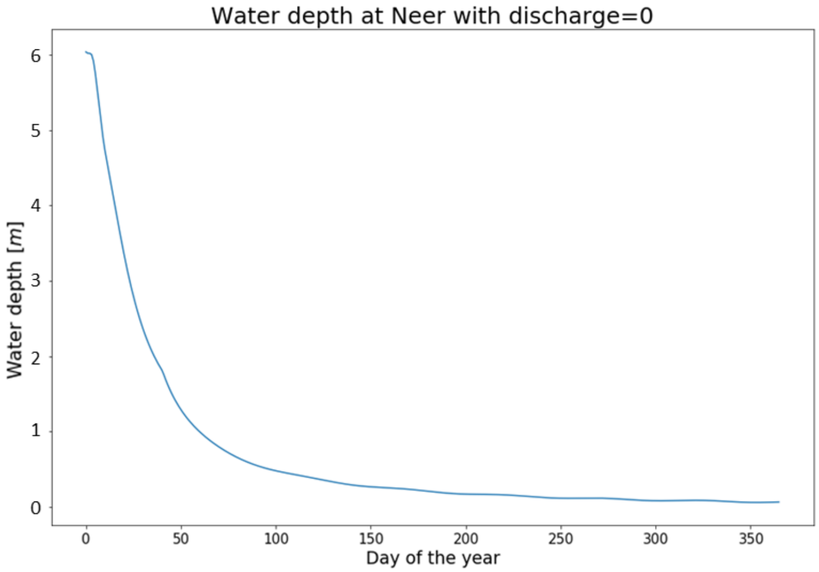


Figure 29 Extreme condition test by setting the discharge into the model to zero.

4.4 EMA Workbench Settings of the Meuse Model

The VENSIM model is controlled by the EMA workbench, such that automatically multiple experiments can be simulated. The LHS sampling method is used to compose these experiments, explained in Chapter *3.2*. The sample size needs to be large enough to describe the whole uncertainty space well enough. To check which sample size is sufficiently large, the minimum values of the fresh water buffer outcomes are plotted for multiple sample sizes. By increasing the sample size, the minimum value of the fresh water buffer should converge to a stable value. The smallest sample size that converges well enough is applied in the simulations as a larger sample size would mean unnecessarily large computation times.

As a starting value the minimum sample size required for the sensitivity analysis is used. The sensitivity analysis technique used is random forests as this technique is reasonable fast, accurate and the standard option in the EMA workbench. As a rule of thumb for the sample size when using random forests, equation (2) applies. The equation states that the sample size should be larger than 100 times the number of uncertainties 'k'.

$$Sample\ size > 100k = 100 \cdot 25 = 2500\ scenarios \qquad (2)$$

Figure 30 shows that convergence of the minimum value of the fresh water buffer is reached at a sample size of approximately 8000 scenarios. With a simulation time of 1.1 seconds, the total duration of simulating the base ensemble amounts to:

$$8000\ simulations * \ 1.1\ seconds\ per\ simulation \ = \ 8800\ sec \ \approx \ 2.5\ hours$$

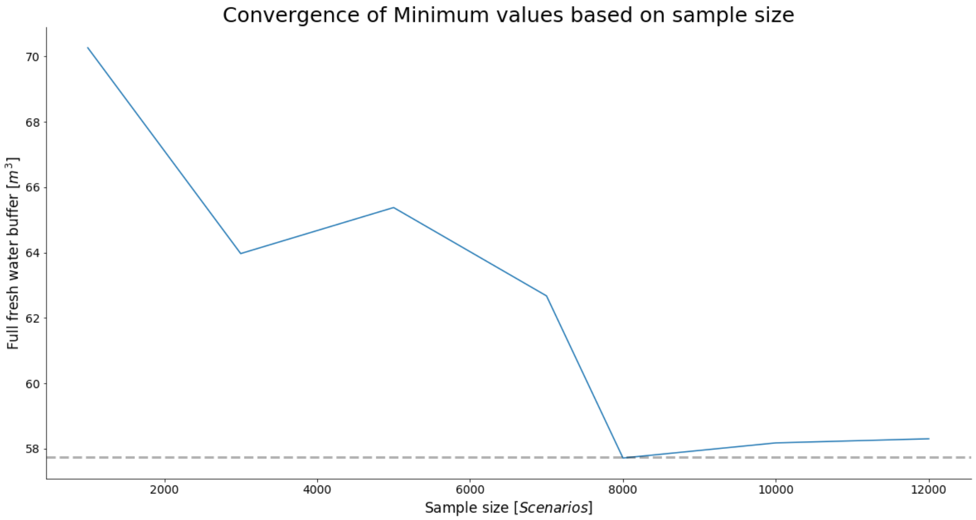


Figure 30 Convergence of the minimum measured fresh water buffer based on the number of simulations

With the reasoning that it is not important what happened to the system in the years prior to a specific simulation year, the simulation period is set to one year with weeks as unit of time. A year between the years 2020 and 2100 is selected to run the simulation for. The setup for the VENSIM model is summarized in *Table 9*.

Table 9 VENSIM and EMA workbench settings overview

Setting	**Value**
VENSIM settings	
Time unit	Week
Simulation period	One year
First year	2020
Final year	2100
Time step	0.0625
Integration method	Euler
EMA Workbench settings	
Number of scenarios	8000
Sampling method	Latin Hypercube

4.5 Key Performance Indicators and Robustness Metrics

Key Performance Indicators

To be able to monitor and track the performance of the system, multiple key performance indicators (KPI) are formulated. These KPI's represent the outcomes that are to be assessed in the robust decision-making process. Each important function or aspect of the river section is therefore to be represented by one or more KPI's.

Three KPI's are composed. These are:

- Percentage of full fresh water buffer: The minimum volume of freshwater buffer in a simulation year in relation to the volume of a full freshwater buffer. A full freshwater buffer represents the volume of water under the backwater curve in a specific weir section.
- Minimum velocity through weir section.
- Intensity/Capacity value at lock.

The KPI for the function freshwater availability is assumed to be most important as a river with little water leads to underperformance for all functionalities. Too little water in the system will cause problems for consumers and users, which require a certain minimum water depth, therefore the minimum amount of available water is of interest. The KPI "Percentage of full freshwater buffer" stores the value of the smallest freshwater buffer measured in a run and compares it to a full buffer. The fresh water availability is becoming less and less self-evident and looking to the future, severe problems might occur when this issue is not addressed. Therefore, the main goal of the Deltaprogram regarding fresh water, is to have a fresh water resilient system for the Netherlands by 2050 ("Deltaprogramma," 2021). In this study it is considered that there are no freshwater availability problems when the freshwater buffer is full. This means that the weirs can maintain the required water level in the weir reach and no severe "dips" in the freshwater buffer are encountered.

The minimum velocity through each weir section says something about the amount of diffusion of toxic substances and prevention of algal and cyanobacteria bloom as discussed in Chapter *Water Quality*. Flow velocities below 0.03 m/s promote the possibility of algal an cyanobacterial bloom (Mitrovic et al., 2011). This velocity threshold is considered an absolutely undesired situation as the risk for problems becomes quite large. A flow velocity below 0.1 m/s is assumed cause problems regarding diffusivity of toxic substances and is therefore set as a threshold initiating risky situations. However, this value is an assumption made for this study to be able to provide a clear judgement, and reality might differ.

The Intensity/Capacity value at the lock is a measure of overload on the lock. An I/C value above 0.5 is found to be risky and an I/C value above 0.6 is found to be problematic (Rijkswaterstaat, 2017d) as explained in section *Shipping Capacity Submodel*.

Robustness Metrics

The assessment of the policies is based on its robustness towards the KPI's. Robustness can be understood in two ways: 1) By reducing the uncertainty around the expected values of a certain KPI. So no matter what the future situation will be, the policy will perform in a narrow bandwidth. 2) By minimizing the undesirable outcomes and thus improving the outcomes for the worst scenarios (Kwakkel, Eker, & Pruyt, 2016).

The robustness of these KPI's is evaluated by means of robustness metrics. Multiple robustness metrics are available, each measuring different types of robustness. The KPI's might have a different type of outcomes and therefore a specific robustness metric might be applicable. In this study regret based robustness metrics and satisficing robustness metrics are used.

A **regret based robustness metric** compares the policy results to the base situation which is in this study a one-on-one replacement of the current system. This metric is applied when the extreme outcomes of a certain KPI need to be improved. The **satisficing metrics** is a combination of the words satisfy and suffice and aim at maximizing the number of scenarios, which meet a minimum performance threshold. Both metrics can easily be represented visually and are therefore applied in this study.

5. Results

In this section the most important decision making insights regarding the river Meuse replacement strategies are presented. First the base ensemble (i.e., one-on-one replacement) is analysed without any policies in chapter *5.1*. Hereafter, design options are developed in chapter *5.2* and explored in chapter *5.3*. The EMA workbench is used in Python to generate and simulate the experiments as explained in chapter *3.2.1*. The python scripts used in this study can be found on https://github.com/DouweW/System-based-replacement-of-hydraulic-structures.

5.1 Base Ensemble Analysis

The base ensemble addresses the one-on-one replacement strategy. In this strategy the structures in the river Meuse are replaced with exact copies of the current structures. The river Meuse system, therefore, will not experience any changes. The goal of the base ensemble analysis is to find out how the current system (i.e., one-on-one replacement) will behave in the future after being exposed to changes in external uncertainties such as climate change and socio-economic developments. The XLRM-framework is applied to the base ensemble (see *Figure 31*) and the system is analysed by exploring the outcomes and the uncertainties.

The base ensemble is explored with two tools from the EMA workbench. First the general behaviour of the outcomes is explored with a satisficing robustness plot and thereafter scenario discovery is used, by applying the Patient Rule Induction Method (PRIM) algorithm. PRIM shows what combinations of inputs cause certain outputs and can therefore be used to find scenarios of interest and is further explained when applying the tool in the next section. This will be helpful when formulating design options.

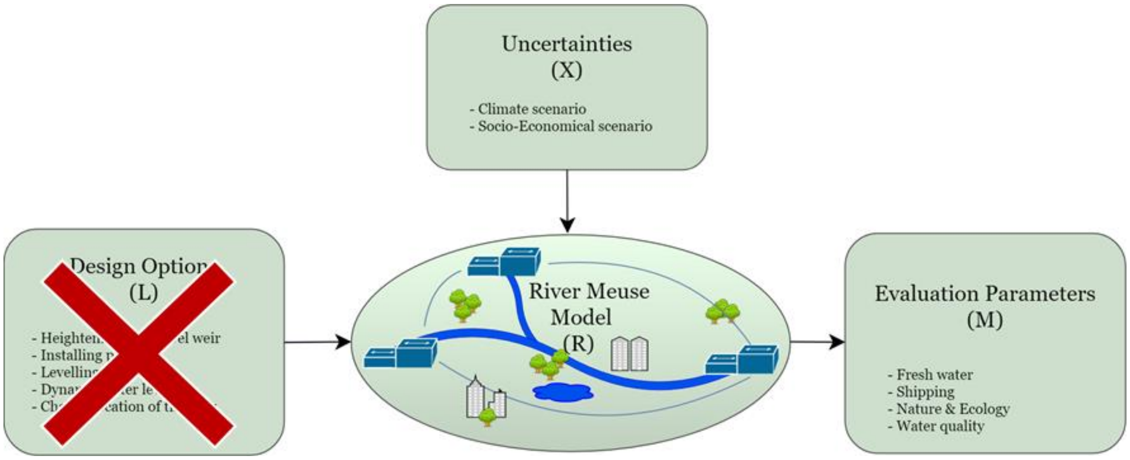


Figure 31 XLRM framework base ensemble analysis. Design options (L) are left out of the equation. The system and its uncertainties is explored.

5.1.1 Exploration of the Outcomes

This section explores the outcomes of the base ensemble. In *Figure 32* the satisficing robustness metric is plotted for the freshwater buffer. The satisficing robustness plot shows the number of runs that reach a certain threshold and the outcomes are grouped on weir section. To be able to test the performance of the outcomes, four categories are composed. Firstly the preferred outcome category where the minimum freshwater buffer in a run is larger than a (101%) full freshwater buffer. Secondly a neutral category, where the buffer volume is approximately the same as a full buffer. Thirdly a risky category, where the buffer volume is in between a full freshwater buffer and 90% capacity and lastly an undesired category where the buffer volume ends up lower than 90% of a full freshwater buffer. The neutral category in *Figure 32* is the largest category in all of the weir sections, and in weir section Sambeek roughly all of the cases end up in this category. This indicates that the fresh water availability of the river Meuse is quite robust by nature, which is logical as the fresh water availability in the river Meuse system is designed to be at least at the capacity of a full buffer throughout the year, as many problems will arise whenever fresh water scarcities might occur. For example, shipping hinder, agricultural problems and drinking water problems.

From *Figure 32* it seems that weir section Grave and weir section Lith are most vulnerable for a reduction of fresh water volume as they contain the most runs in the risky and undesired category. The weir at Grave is assumed to have the largest leakage and additionally the leakage at the lock of Weurt to the river Waal at the bifurcation point of Mook, result in high vulnerability for future scenarios. Weir section Grave is therefore used for further analysis, as it is expected that in this weir section the largest improvements can be made. Weir section Lith experiences risky and undesired behaviour as well, because in situations of low water depth in weir section Grave, less water might be leaked to weir section Lith which might result in a smaller volume entering weir section Lith compared to the volume exiting. However, the outcomes of weir section Grave are more critical compared to weir section Lith. Notable is that for weir section Linne a small portion of runs end up in the preferred an undesired categories. This can be explained by the fact that the Juliana canal remerges with the river Meuse in weir section Linne. In the model, water is pumped back into the Juliana canal during dry periods to make up for the water loss at the locks. On the other hand, discharge is added to weir section Linne when such a drought period does not occur. Therefore the volume of water in weir section Linne can vary more compared to other weir sections.

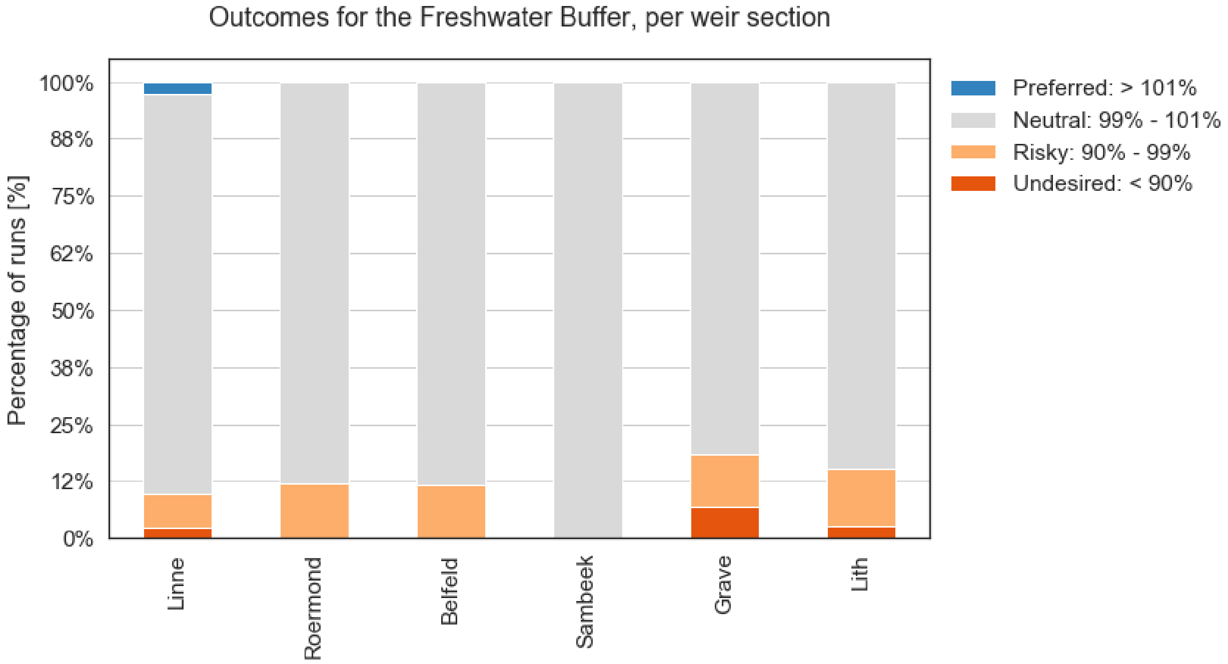


Figure 32 Outcomes for the fresh water buffer based on satisficing thresholds and grouped on weir section. The percentages in the legend are relative to a full freshwater buffer, which represents the volume of water under the backwater curve in equilibrium conditions.

Moreover, *Figure 33* shows problematic results regarding the I/C value of the lock at Grave, which confirms the earlier concerns of too little capacity at Grave as it has the smallest- and least amount of locking chambers in the corridor. *Figure 33* shows risky and undesired behaviour for the I/C value at lock Grave (i.e., I/C > 0.5) for approximately 30% of the runs. Locks at other locations experience almost only preferable behaviour. Furthermore, Figure *Figure 34* shows worrying behaviour regarding the minimum flow velocity in the river Meuse. For the weir section Grave, 40% of the outcomes end up in the category risky in which high concentrations of toxic substances are hard to diffuse, and an additional 40% end up in the category undesired leading to situations where algae and cyanobacteria might bloom under the right conditions. The minimum velocity of weir sections Linne, Grave and Lith are the smallest because the water depth under influence of the weirs is the largest for these weir sections, leading to a high risk of poor water quality.

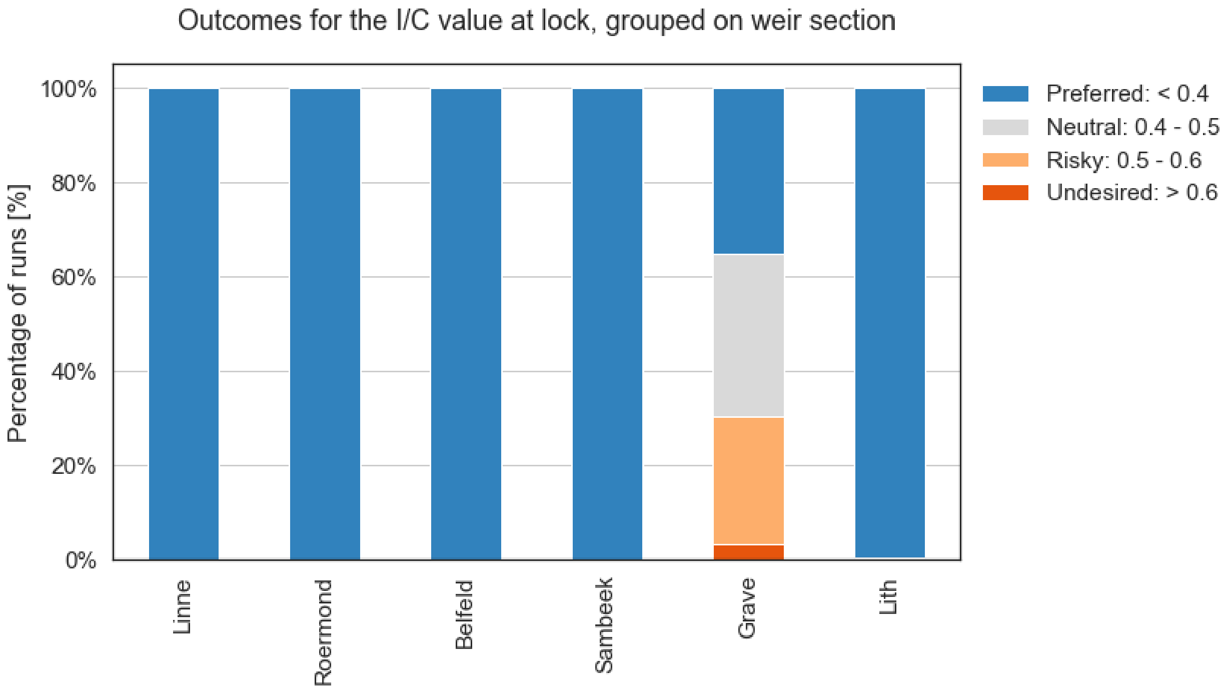


Figure 33 Outcomes of the current system exploration for the Intensity/Capacity ratio at each lock complex

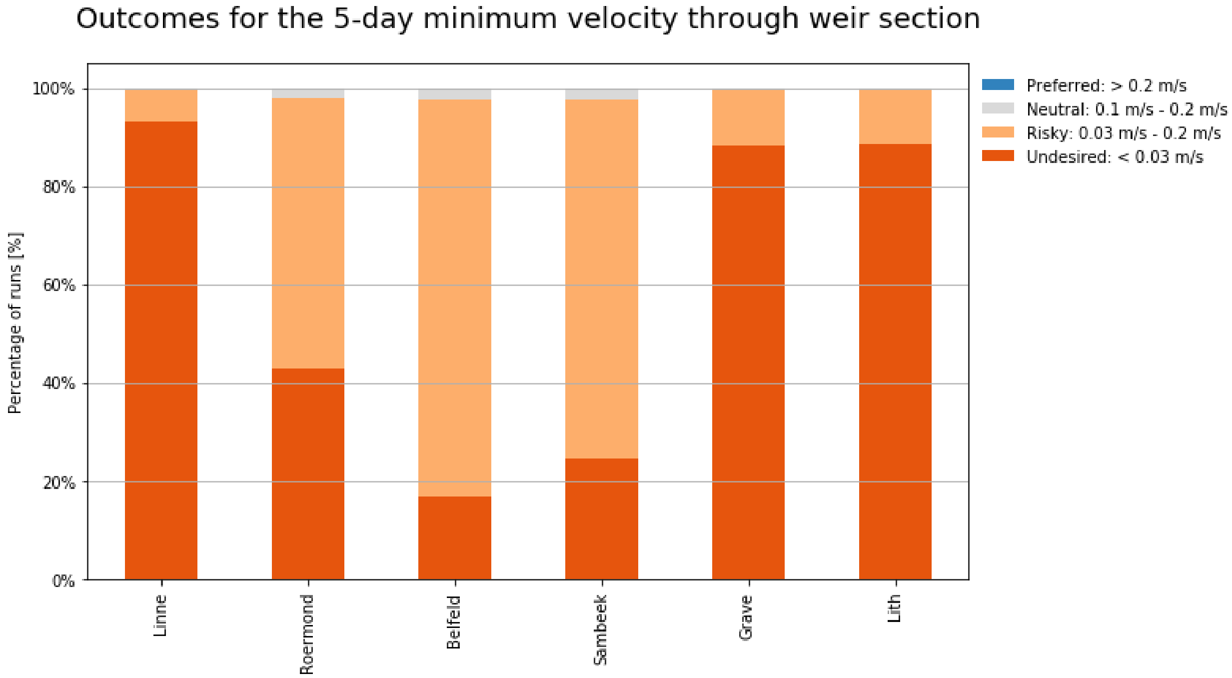


Figure 34 Outcomes of the current system exploration for the 5-day minimum velocity through each weir section

To find out what combination and values of inputs cause these specific output values, scenario discovery is performed. To explain the scenario discovery tool "PRIM", first all the elements from *Figure 35* are discussed. The Patient Rule Induction Method (PRIM) algorithm filters out the most influential uncertainties that cause the outcomes to reach a certain threshold. In *Figure 35*, the KPI "Full fresh water buffer" for weir section Grave is studied because from exploration of the outcomes on the previous pages it became clear that weir section Grave seems to be the most vulnerable as it experiences the most runs in the risky and undesired categories. On the left hand side the uncertainties are shown, followed by the p-value between the brackets. The p-value describes the statistical significance (<0.05) (Kwakkel, 2019). In this plot, all uncertainties have a p-value smaller than 0.05 and can therefore be seen as statistically significant. The grey area in the middle of the plot represents the complete uncertainty space for the uncertainties on the left hand side. In blue the values are shown which result in the outcome to end up under a specific threshold. For example, the climate scenario is statistical significant because it has a p-value of 5.8e-16 (<0.05). Climate scenario W_H has to be selected for the outcome to end up under the threshold. The threshold for the PRIM analysis is set to 75%, meaning that all outcomes which end up under 75% of the full fresh water buffer are considered. In the top right corner the coverage and density is shown. Coverage represents how many of the interesting outcomes are captured in the analysis and density indicates how many of the captured outcomes are actually interesting. A minimum density of 0.8 is chosen for all of the PRIM analysis in this study. The most influential uncertainties that are selected by the PRIM algorithm (see *Figure 35*) are the simulated year, the climate scenario ($W_{H,dry}$), certain years of the discharge series and the leakage of the weir and lock (>10m^3/s). The latter indicates that water loss out of the weir section has a large influence. The first three indicate that a low discharge inflow in combination with low discharges from tributaries and low precipitation values have a large influence on the fresh water buffer. This is a logical result as the discharge inflow and water loss (outflow) are both part of the water balance and are therefore expected to have a large influence on the fresh water buffer.

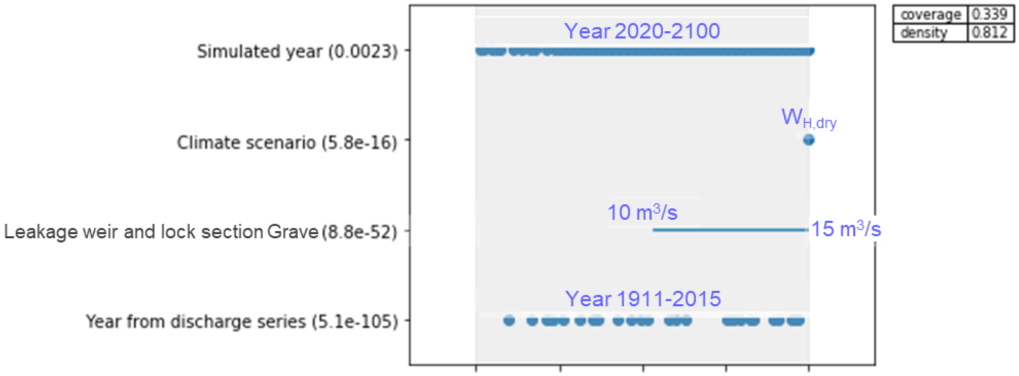


Figure 35 PRIM analysis for the Meuse Model KPI "Full fresh water buffer" for weir section Grave. The threshold is set to 75% meaning that all outcomes that end up under 75% of the full fresh water buffer will be considered in the PRIM analysis. The most influential uncertainties that lead to this are the simulated year, climate scenario ($W_{H,dry}$), Leakage of the weir and lock (>10m^3/s) and certain dry years of the discharge series.

In *Figure 36* the minimum and maximum water levels for a given year in the future is shown. The upper plot highlights the minimum water levels for the simulation year 2025 and 2100 and the lower plot highlights the maximum water levels for these years in the weir sections Grave and Lith. *Figure 36* shows the influence of climate change for the future years of simulation. The maximum water levels of the year 2100 end up higher compared to the maximum water levels of the year 2020 and the opposite is valid for the minimum water levels, stating that the prediction of more severe extremes is correctly implemented in the model (de Wit et al., 2001). In *Appendix D, D. 1* the minimum and maximum water levels of the whole river section is shown. At Mook, the Meuse-Waal canal is situated and discharge is subtracted from the river Meuse. As seen in *Figure 36*, this might lead to a local reduction in water level. In reality this effect will be much less severe as the weir level at Grave is dynamically steered with the intention to maintain a constant water level at Mook. In contrast to the Meuse model which is steered on the available discharge.

Figure 36 Minimum and maximum water depths for the simulated years 2025 and 2100 weir section Grave and Lith. The figure shows the influence of climate change on the minimum and maximum water levels for the weir sections Grave and Lith.

5.1.2 Conclusion Base Ensemble analysis

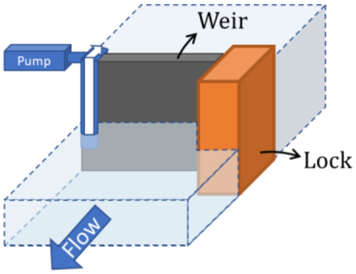
To reduce simulation time, the function fresh water availability is selected as the main improvement focus for the design options because fresh water availability is assumed to be that basis for all other functions. Without enough water, other functions would experience problems such as shipping which is dependent on the water depth. The base ensemble results showed the most problematic outcomes for the freshwater availability of weir section Grave. From the base ensemble analysis the following findings can be summed up:

- The freshwater buffer outcomes in weir section Grave perform the worst compared to other weir sections. Approximately 6% of the outcomes end up under 90% of a full fresh water buffer and 15% end up under a full fresh water buffer.
- The I/C values of lock Grave are for approximately 30% of the outcomes above 0.5 which means a risky situation developed. Other weir sections perform as desired for all runs.
- The minimum velocities found in weir section Linne, Grave and Lith are the lowest because the water depth, under influence of the weirs, is the largest in these weir sections and they therefore risk the poorest water quality. For weir section Grave 40% of the outcomes end up under 0.03m/s which provides a good environment for algae and cyanobacterial bloom and is therefore undesired.
- Weir section Grave performs the worst for all functions and because it is expected that the most improvements can be made in this weir section, Grave is used as main focus to construct design options.
- The PRIM analysis shows the uncertainties that need to be selected in a simulation for the outcomes to reach a certain threshold. For the freshwater buffer a threshold of 70% of a full fresh water buffer is used and it was checked what uncertainties cause the outcomes to end up lower than this threshold. The results of the PRIM analysis showed that uncertainties influencing the in- and outflow in the volume balance lead to large reductions in freshwater buffer. The influential uncertainties are:
    - Climate scenario $W_{h,dry}$. This is the most extreme climate scenario implemented in the model
    - Leakage of the weir and lock at Grave which is larger than $10m^3/s$.
    - Specific dry years from the historical discharge series.
    - Years further in the future, as climate change is expected to influence the discharge more severely and extremely further in the future.

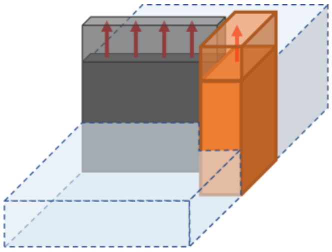
5.2 Defining Design Options

Now that the base ensemble is explored the design options can be defined and consequently replacement strategies can be formed. The amount of replacement strategies is limited by the simulation time. This is caused by that fact that instead of Latin Hypercube sampling, the replacement strategies are Full Factorial sampled. This means that all replacement strategies, that will be composed in this chapter, will be tested equally many times over the uncertainties of the system.

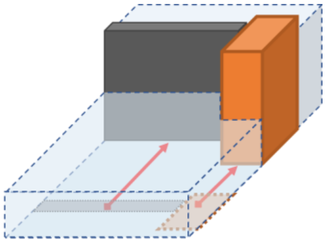
Because of the limited amount of replacement strategies, the design options have to be chosen carefully. The main focus of this study is fresh water availability and the design options will therefore mainly be designed to improve this function of the river Meuse. In the previous chapter it was discovered that the leakage of the weirs, the drought period characteristics and the climate scenario play a major role in the outcome of the fresh water buffer. The following design options can be formulated to make the fresh water buffer more resilient to these uncertainties.



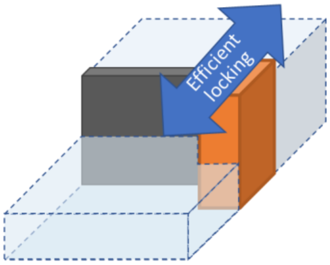
Install pumps, to reduce the loss of water during dry periods. The pump, pumps water from the downstream weir section back into the upstream weir section. In the water flow model, the loss of water due to levelling and leakage of the weir is reduced by the capacity of the pump. It is assumed that the capacity of the pump is equal to the water that is lost through leakage and levelling.



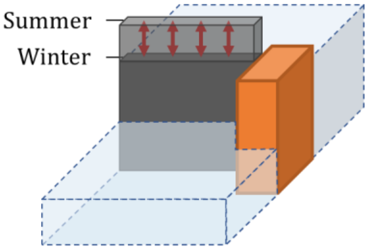
Raise the crest level of the weirs, to increase the water level in the weir section and therefore also the storage capacity. An alternative weir crest height for the weir at Grave and the weir at Lith of 20cm is proposed. An increase of 20cm is found to be large but feasible for the coming decades (Weerts & Beuting, 2019).



Relocate the weir at Grave in upstream direction, to make the weir section smaller such that the average water depth in the weir section is increased and therefore the fresh water buffer volume is increased. Also to check what impacts the relocation of the weir can have on the KPI's. An alternative location for the weir at Grave is also considered by the design team of Rijkswaterstaat, because the weir can simply not be built at the exact same location as the current weir. Possible locations are limited by norms and practicalities (Rijkswaterstaat, 2017d). It is for example found to be not feasible to relocate the weir further downstream as the clearance height under the adjacent bridge might not be sufficient. The hydraulic complex can even so not be moved too close to the bifurcation point at Mook. The new location is therefore chosen at 8km upstream of the current location.



Efficient locking during low discharge periods. By increasing the minimum amount of ships that have to enter the lock to start the levelling cycle, less cycles have to be performed during a day. This also means that a reduction of water loss during levelling can be achieved. According to the available discharge, the minimum amount of ships can be set to three levels: no restrictions, economical levelling and restricted levelling. These restriction levels lead, in the Meuse Model, to a reduction in lock capacity. Economical levelling starts at discharges lower than 44m3/s and leads to a capacity reduction of 10%. Restricted levelling starts at discharges lower than 25m3/s and leads to a capacity reduction of 30%. These capacity reductions are assumptions based on (de Jong & T., 2021).



Dynamic water level, in the low discharge months the crest level of the weirs is raised to be able to store a larger volume of water in the weir sections. In the high discharge months this extra storage is not needed and increases the risk of flooding. The crest level of the weir is therefore reduced to original in the high discharge periods. An increase of 20 cm during low discharge periods is maintained (Weerts & Beuting, 2019).

Other design options that do not include an improvement regarding the freshwater buffer have not been applied due to limitations in simulation time. For example, thought was given to the option of removing a specific weir in the river Meuse. However, from some try-outs in a test case model, it quickly became clear that removing a weir leads to a significant reduction in freshwater buffer which cannot easily be solved with other design options (van den Assem & Gelderland, 2016). As the freshwater buffer being the main goal in this study, the idea of weir removal is disregarded.

Replacement strategies are combinations of design options. A replacement strategy, for example, can be to combine the design options of installing pumps and increasing the crest height of the weir at Grave. However, not all combinations of design options are logical. It is for example not logical to install pumps and mandate efficient locking as the pumps in the model will pump all the lost water back into the previous weir section, resulting in no net water loss and therefore no need for efficient locking. An overview of the replacement strategies can be found in *Table 10*. When the pumps are installed this is stated as pump switch "on". The total number of replacement policies accumulates to thirteen, which results in:

$$8000\ scenarios \cdot 13\ replacement\ strategies = 104\ 000\ experiments.$$

With 1.1 seconds per experiment this amounts to:

$$1.1\ \ seconds \cdot 104\ 000\ experiments = 114400 seconds \approx 32\ hours$$

Table 10 Overview replacement policies. The first row shows the one-on-one replacement strategy (current system) and contains the original values per design decision. In the following rows, the original values are indicated with a "-" to create a clear overview.

Replacement strategy	**Install pumps**	**Crest level weir Grave [m+NAP]**	**Crest level weir Lith [m+NAP]**	**Location weir Grave [km+inlfow]**	**Dynamic crest level [Δm]**	**Efficient locking**
Current system	*No*	*7.9*	*5.5*	*164*	*0*	*No*
Pumps on	Yes	-	-	-	-	-
Crest Grave raised	-	8.1	-	-	-	-
Relocate weir Grave	-	-	-	156	-	-
Dynamic crest lvl	-	-	-	-	+0.2	-
Efficient locking	-	-	-	-	-	Yes
Relocation and raise crest	-	-	5.7	156	-	-
Pumps and raise crest	Yes	8.1	-	-	-	-
Pumps and dynamic crest	Yes	-	-	-	+0.2	-
Efficient locking and raise crest	-	8.1	-	-	-	Yes
Efficient locking and dynamic crest	-	-	-	-	+0.2	Yes
Pumps and relocation	Yes	-	-	156	-	-
Efficient locking and relocation	-	-	-	156	-	Yes

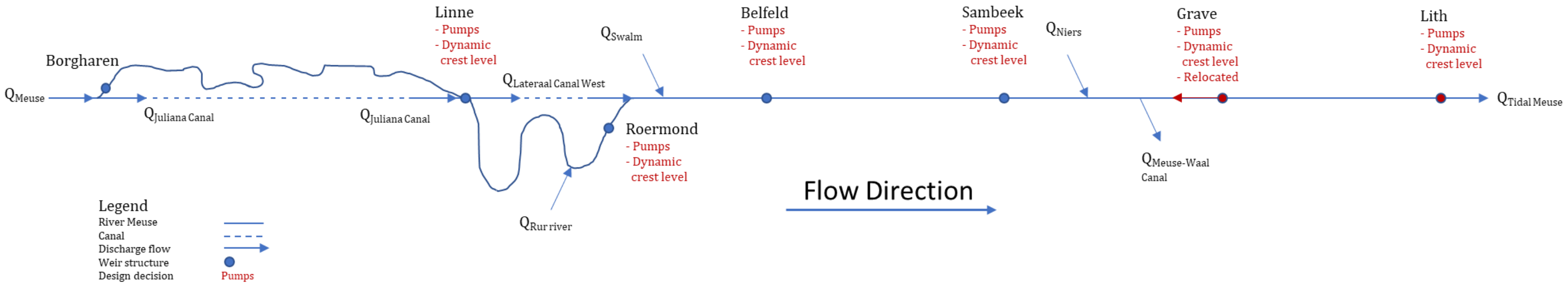


Figure 37 Location of design options (in red)

5.3 Policy Analysis

In this section the performance of the policies is evaluated. This is done by firstly exploring the uncertainties of the system with a sensitivity analysis (Breiman, 2001; Jaxa-Rozen & Kwakkel, 2018). Subsequently the performance of the replacement strategies is evaluated by visually applying the regret and satisficing metrics, as explained in chapter *4.5*. The XLRM framework is again used to control the simulation process, shown in *Figure 38.* This time the design options are added to the framework.

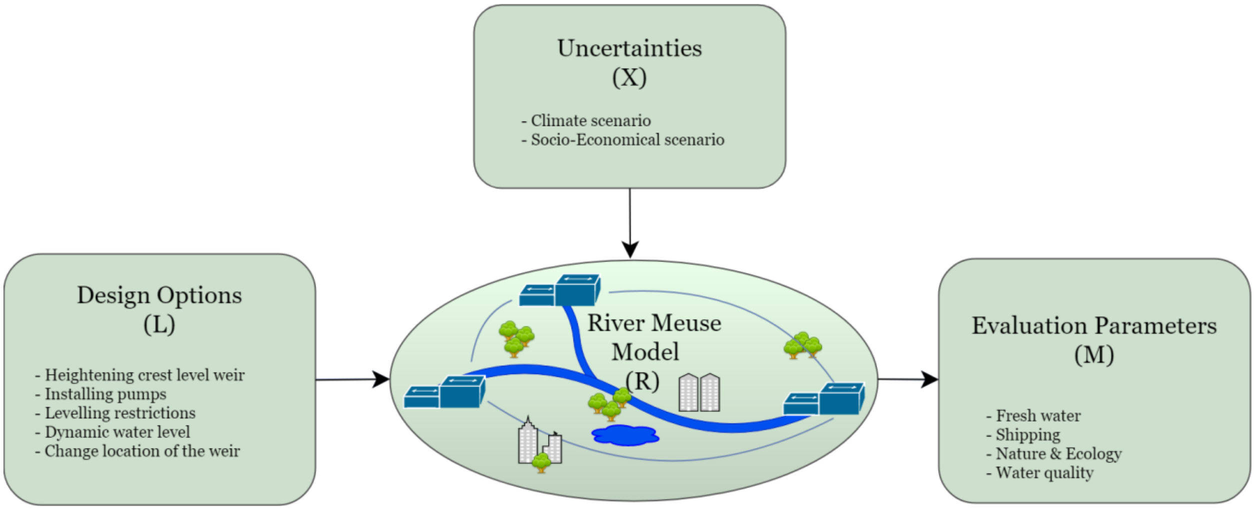


Figure 38 XLRM framework policy analysis

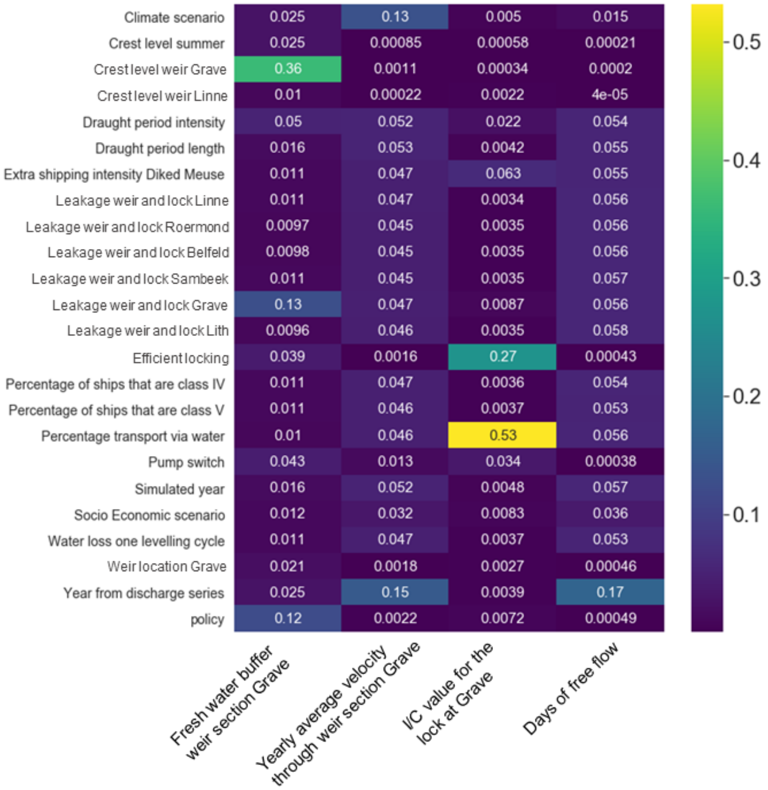
5.3.1 Exploration of the Uncertainties

When trying to understand the behaviour of the system it helps to analyse the most influential uncertainties. A method to study the uncertainties is a sensitivity analysis and in the EMA workbench this is performed by Feature Scoring. In this section the sensitivity analysis of the base ensemble will be compared to the sensitivity analysis including the replacement strategies. The sensitivity plots of weir section Grave are shown on the next page because it performed the worst in the base ensemble analysis and is therefore the most interesting weir section. The most influential uncertainties for the base ensemble (see *Figure 39*) are the leakage of the lock at Grave because it severely influences the fresh water buffer in the weir section Grave. Leakage is part of the outflow out of the weir section which influences the volume balance and is therefore expected to be influential. The year of the discharge series seems influential for all KPIs. This is understandable as the discharge timeseries determines availability of the amount of water in the system. The percentage of transport via water seems to be the most influential uncertainty for the Intensity/Capacity ratio of the locks.

When the replacement strategies are added to the simulations, the sensitivity analysis results in *Figure 40*. It can be seen that the height of the crest level of the weir at Grave has become the most influential variable regarding the fresh water buffer of weir section Grave. By increasing the crest level of the weir at Grave, the volume of the fresh water buffer in the weir section Grave increases as well. It is thus understandable that this variable has a large influence on the KPI. It also shows that certain policies (combinations of design options) influence the fresh water buffer severely. For the Intensity/Capacity ratio of the weir at Grave it is now seen that next to the percentage of transport via water, the design decision “efficient locking” has a large influence on the Intensity/Capacity ratio. In the next section it will be assessed if these design options influence the KPIs in a positive or negative way.

	Fresh water buffer weir section Grave	Yearly average velocity through weir section Grave	I/C value for the lock at Grave	Days of free flow
Climate scenario	0.045	0.039	0.0046	0.033
Draught period intensity	0.11	0.048	0.0054	0.05
Draught period length	0.055	0.053	0.059	0.051
Extra shipping intensity Diked Meuse	0.041	0.04	0.015	0.05
Leakage weir and lock Linne	0.037	0.041	0.0048	0.047
Leakage weir and lock Roermond	0.038	0.041	0.0049	0.046
Leakage weir and lock Belfeld	0.039	0.041	0.005	0.05
Leakage weir and lock Sambeek	0.04	0.041	0.0051	0.048
Leakage weir and lock Grave	0.22	0.042	0.0058	0.05
Leakage weir and lock Lith	0.04	0.041	0.0052	0.046
Percentage of ships that are class IV	0.04	0.041	0.005	0.046
Percentage of ships that are class V	0.036	0.041	0.005	0.048
Percentage of transport via water	0.041	0.04	0.84	0.048
Simulated year	0.048	0.046	0.0065	0.054
Socio-Economic scenario	0.033	0.037	0.015	0.031
Water loss one levelling cycle	0.039	0.041	0.005	0.051
Year from discharge series	0.096	0.33	0.0052	0.25

Figure 39 Feature scoring for the Meuse Model base ensemble. On the left hand side the uncertainties of the system are shown and on the bottom of the graph the KPIs are shown. The numbers and colours in the box represent the influence factor, which has a minimum of 0 and a maximum of 1. With "0" the uncertainty has no influence on the KPI and 1 is maximum influence.



	Fresh water buffer weir section Grave	Yearly average velocity through weir section Grave	I/C value for the lock at Grave	Days of free flow
Climate scenario	0.025	0.13	0.005	0.015
Crest level summer	0.025	0.00085	0.00058	0.00021
Crest level weir Grave	0.36	0.0011	0.00034	0.0002
Crest level weir Linne	0.01	0.00022	0.0022	4e-05
Draught period intensity	0.05	0.052	0.022	0.054
Draught period length	0.016	0.053	0.0042	0.055
Extra shipping intensity Diked Meuse	0.011	0.047	0.063	0.055
Leakage weir and lock Linne	0.011	0.047	0.0034	0.056
Leakage weir and lock Roermond	0.0097	0.045	0.0035	0.056
Leakage weir and lock Belfeld	0.0098	0.045	0.0035	0.056
Leakage weir and lock Sambeek	0.011	0.045	0.0035	0.057
Leakage weir and lock Grave	0.13	0.047	0.0087	0.056
Leakage weir and lock Lith	0.0096	0.046	0.0035	0.058
Efficient locking	0.039	0.0016	0.27	0.00043
Percentage of ships that are class IV	0.011	0.047	0.0036	0.054
Percentage of ships that are class V	0.011	0.046	0.0037	0.053
Percentage transport via water	0.01	0.046	0.53	0.056
Pump switch	0.043	0.013	0.034	0.00038
Simulated year	0.016	0.052	0.0048	0.057
Socio Economic scenario	0.012	0.032	0.0083	0.036
Water loss one levelling cycle	0.011	0.047	0.0037	0.053
Weir location Grave	0.021	0.0018	0.0027	0.00046
Year from discharge series	0.025	0.15	0.0039	0.17
policy	0.12	0.0022	0.0072	0.00049

Figure 40 Feature scoring for the Meuse Model policy simulations. On the left hand side the uncertainties and design options of the Meuse Model system are shown and on the bottom of the graph the interesting KPIs are shown. The numbers and colours in the box represent the influence factor which has a minimum of 0 and a maximum of 1. With "0" the uncertainty or design decision has no influence on the KPI and 1 is maximum influence.

5.3.2 Performance of the replacement strategies

In this section the replacement strategies are evaluated based on their robustness. By presenting the outcomes for all of the KPIs, robustness can be evaluated over multiple functions (R. J. Lempert, 2019). The base ensemble (i.e. current system) is used as a benchmark against the replacement strategies from chapter *5.2*. The outcomes are grouped in five categories based on the thresholds from the Chapter *5.1.1* and relative score in relation to the current system which are underperformance, deterioration, neutral, improvement or outperformance.

In *Figure 41* the policy effects on the KPI freshwater buffer are plotted for weir section Grave in relation to the current system. From this plot it can be seen that all design options perform positively for almost the complete set of scenarios, and thus improvements can be made when applying design options for the freshwater buffer in weir section Grave compared to the current system. By relocating the weir at Grave, approximately 10% of the outcomes is improved in relation to the current system (see *Figure 41*). When looked at *Figure 42*, it can be seen that the amount of outcomes that end up lower than a full freshwater buffer remains the same, but the number of outcomes in the undesired category (lower than 90% of a full freshwater buffer) reduces from approximately 6% to 3% of the runs. The length of the backwater curve becomes shorter and therefore a larger average water depth in the weir section is created (see *D. 2* in *Appendix D*). So by relocating the weir at Grave the desired improvement of reducing the number of outcomes in the undesired category is achieved, albeit that approximately the same number of outcomes end up below a full freshwater buffer. However, when looked at the minimum water depth in weir section Lith (see *D. 7* in *Appendix D*), it can be concluded that relocating the weir at Grave 8 kilometres in upstream direction decreases the minimum water depth below the minimum required water depth. Even by increasing the crest level of the weir at Lith, the minimum required water depth cannot be achieved and because shipping needs to be guaranteed throughout the year, the replacement strategy of removing the weir at Grave does not meet the requirements.

By increasing the crest level of the weir at Grave, either dynamically or permanent, the water depth under the backwater curve is increased, leading to a larger storing capacity and consequently a larger volume available during drought periods. Compared to the current system, the minimum freshwater buffer will be larger when exposed to the same scenarios and is therefore more robust (see *Figure 41*). *Figure 44*, however, shows that a trade-off develops as increasing the water level leads to a reduction of the minimum velocity in the weir section, and has therefore a negative impact on the water quality. Nonetheless, raising the crest level dynamically reduces this negative impact significantly as the crest level is lowered during non-low velocity periods, increasing velocities and reducing water levels (see *Figure 44*).

By installing pumps at the weirs, with the goal to pump the lost water back into the weir section, the minimum freshwater buffer is increased significantly to almost full capacity (see *Figure 42*). When the leakage of water in the weir section is countered, no unwanted water loss can occur and the discharge in and out of the weir section can be balanced leading to a stable volume and water level. The only undesired water loss occurs from the flow of ships to the river Waal. *Figure 44* shows an increase of minimum velocity when pumps are installed. This is, however, artificially generated by the model as the velocity calculation point is set at the weir location. By pumping the lost water back to the calculation point, the available discharge will increase and the velocity increases as well. Installing pumps is not expected to lead to a change in minimum velocity in reality.

The last design option in *Figure 41* is efficient locking. When efficient locking is applied, a minimum number of ships have to enter the lock prior to starting the levelling process. Hence, the amount of daily levelling cycles, and therefore water loss, can be reduced. *Figure 43*, however, shows the satisficing robustness metric for the KPI “Maximum I/C”. In this plot it becomes clear that when efficient locking is introduced, a significant increase in maximum I/C value at lock Grave can be expected. Future research should determine if these high Intensity/Capacity values are worth the improvement of the fresh water buffer.

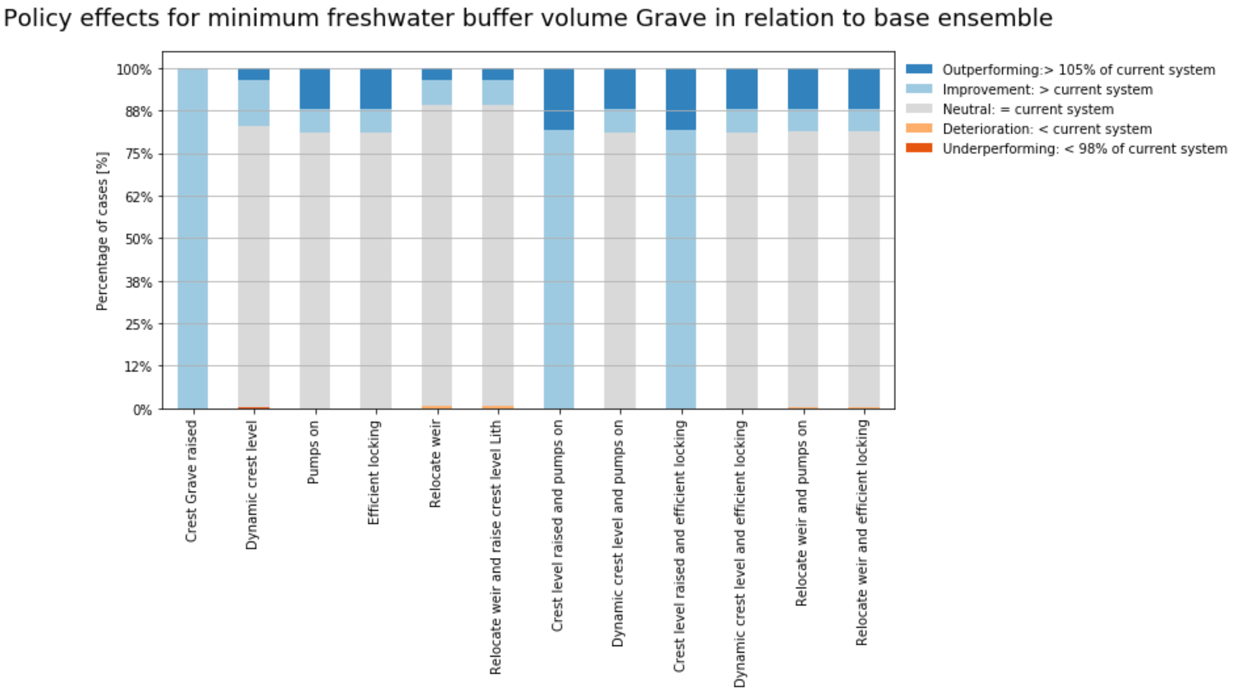


Figure 41 Policy effects for minimum freshwater buffer volume Grave in relation to base ensemble. Each policy scenario is compared to the same base ensemble scenario..

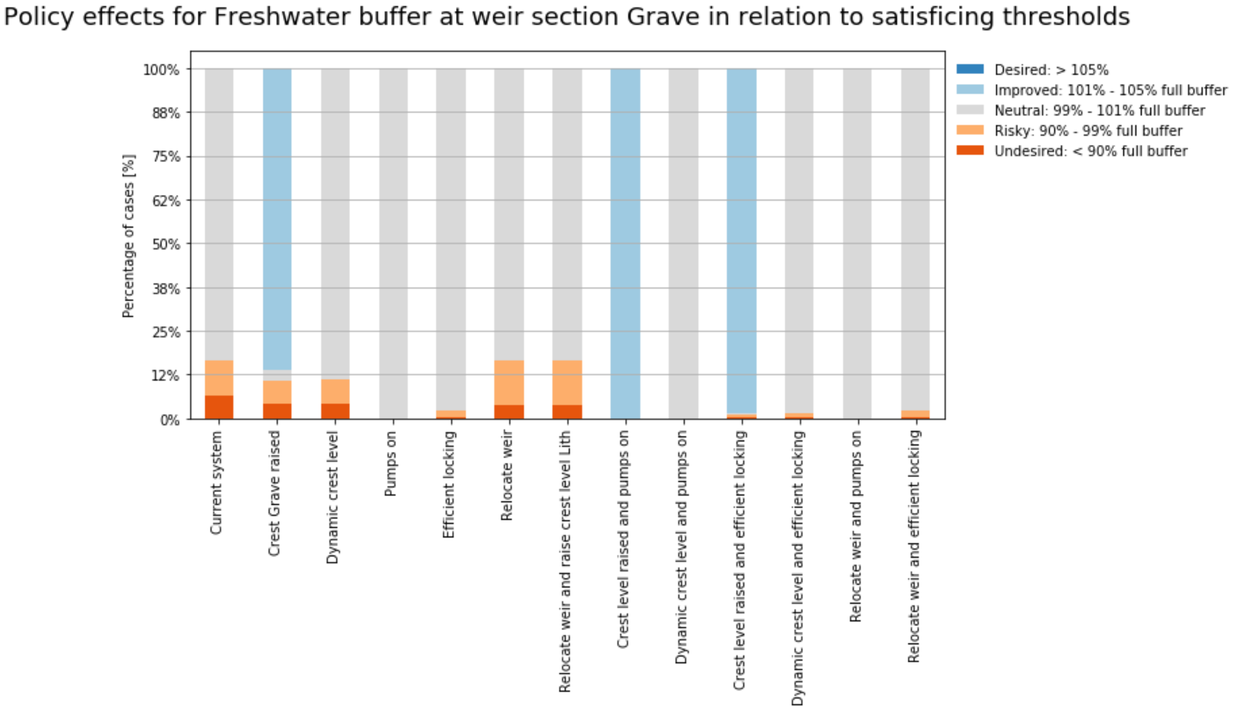


Figure 42 The effects of policies on the satisficing thresholds as set in the base ensemble analysis.

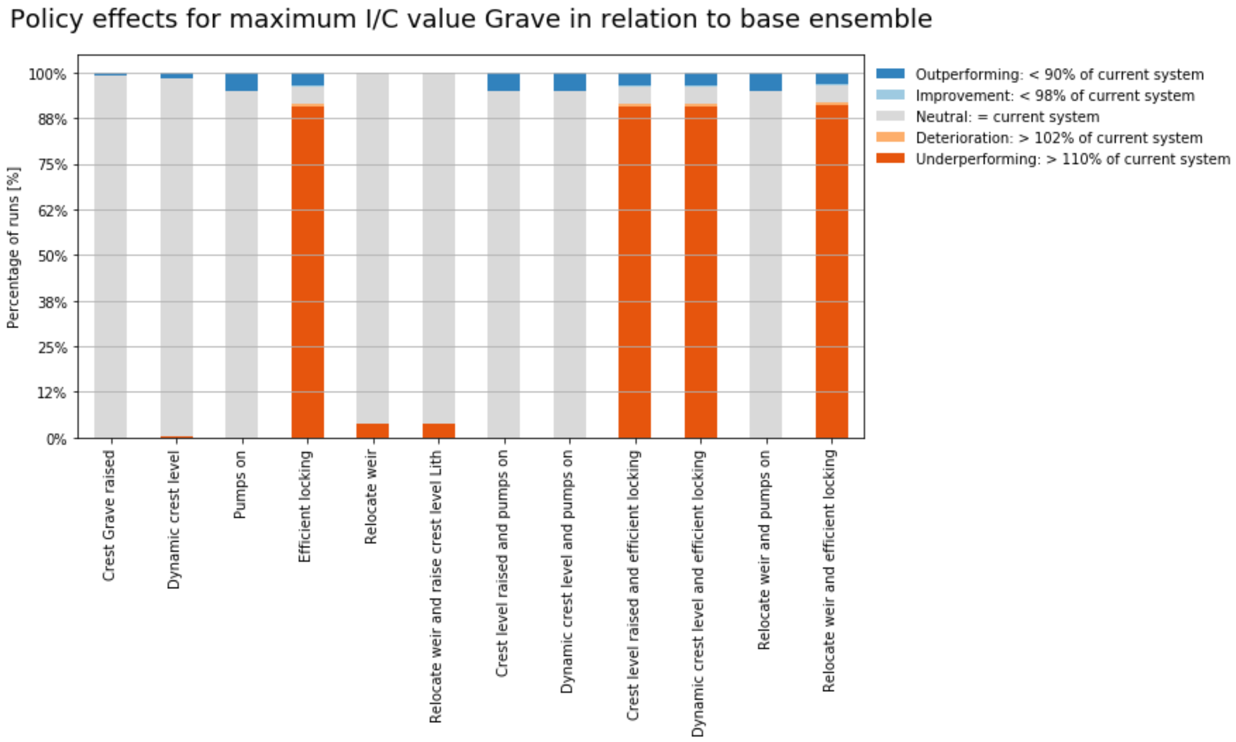


Figure 43 Policy effects for the maximum I/C value at the lock Grave. Each policy scenario is compared to the same base ensemble scenario.

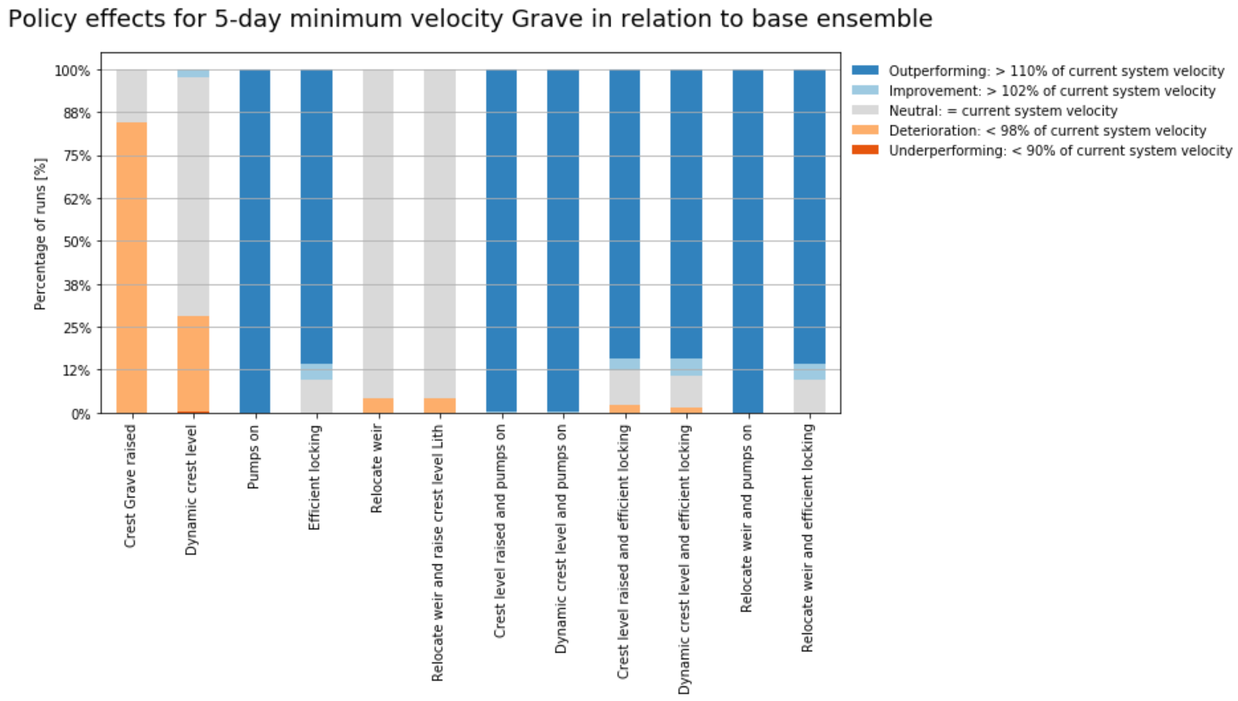


Figure 44 Policy effects for the 5-day minimum velocity in weir section Grave. Each policy scenario is compared to the same base ensemble scenario.

From all of the proposed design options, the design option to install pumps leads to the largest improvements regarding the fresh water buffer and is simultaneously not expected to negatively influence water quality or shipping. In *Figure 45* the effect of the installation of pumps is visualized for the minimum water level in the weir sections Grave and Lith. The pumps are advised to be applied to all weirs as pumping water back into the previous weir section decreases the discharge into the next weir section, which might lead to a reduction of fresh water buffer in the next weir section during dry periods. Ultimately, water loss from all weir sections should be the same, this leads to a stable volume balance for every weir section and therefore should theoretically result in a stable fresh water buffer. From the results in the previous pages it becomes clear that increasing the crest level negatively affects the flow velocity and therefore the water quality in the weir section. By introducing efficient locking the I/C values of the lock at Grave increases with negative effects towards the shipping functionality. Relocating the weir at Grave 8 kilometres in upstream direction leads to risky situations regarding the available ship draught in weir section Lith and raising the crest level in weir section Lith does not prevent that from happening.

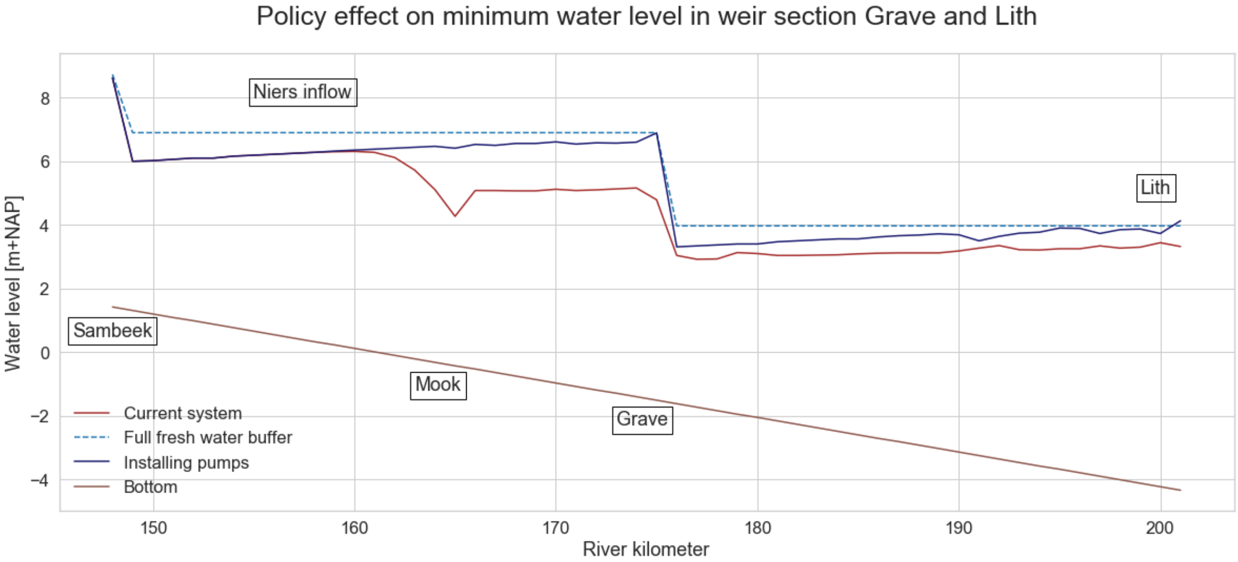


Figure 45 Effect of the policy "installation of pumps" on the minimum water level in longitudinal plot of weir sections Grave and Lith compared to the minimum water level of the current system.

6 Conclusion

The current river Meuse system has mainly been designed to facilitate shipping and flood safety by constructing weirs, locks and dikes (van Tilburg, 2015). However, other functions such as nature and water quality were negatively impacted. But as of today, it is the ambition to improve the river Meuse system in a multi-functional way (van Hengel, 2017). The upcoming replacement of hydraulic structures in the river Meuse creates an opportunity to redevelop the system. Therefore, the question remains if the current system can sufficiently facilitate all functions of the river Meuse system for the years to come, or whether different designs would lead to better functioning. However, the future of the river Meuse system is deeply uncertain due to for example, climate change or socio-economic developments, and the replacement strategy should perform well under all of the future scenarios. Summarised, the replacement strategy for the weirs and locks in the river Meuse has to be able to perform well under the future scenarios, cannot deteriorate any function of the river Meuse and has to perform well for the whole river Meuse system. In this study a method has been applied in order to construct such a replacement strategy by stress-testing potential strategies with a range of future scenarios. The conclusion of the insights are given by answering the research questions.

"*What functions are important for the river Meuse system?*"

The most important functions of the river Meuse system, which are influenced by hydraulic structures are: shipping, fresh water availability, water quality and societal functions such as nature, drinking water and agriculture. The societal functions are dependent on fresh water availability and water quality and are therefore subjugated to these functions. Fresh water availability is set as the main focus of this study as the availability of fresh water is the main driver for the whole river Meuse system, without sufficient water the river system cannot function properly. Developments including climate change could lead to problems regarding fresh water availability and leakages at weirs and locks increase these problems.

The weirs in the river Meuse maintain the water level by manipulating the discharge regime. This directly influences the availability of fresh water in the river Meuse system, but also affects the water quality. By limiting the discharge through the system and increasing the water depth, diffusion of toxic substances becomes more difficult and favourable circumstances arise for algal and cyanobacterial blooms with negative consequences for the water quality (Liefveld & Jesse, 2006). On the other hand, raising the water level and reducing the throughflow increases the availability of fresh water in the system. Furthermore, the ship draught is maintained in the river Meuse by the weirs, allowing fully loaded ships to sail throughout the year. Most weirs and locks in the river Meuse were designed roughly a century ago with the main goal to improve for shipping. The task at hand is therefore, to include the remaining functions in the design of the new weirs and locks.

"How can the river Meuse system be modelled for the coming century and how can a system-based multi-functional analysis be performed?"

In this study the Robust Decision Making (RDM) method was applied. RDM takes deep uncertainty and multiple river functionalities into account when finding robust strategies. Deep uncertainty means that the various parties to a decision do not know or cannot agree on the system, its boundaries, the outcomes of interest and the prior probability distribution for uncertain inputs to the system (Robert J. Lempert et al., 2003; Walker et al., 2013). The RDM method is performed by firstly using a system dynamics software tool to create the Meuse Model, which describes the river Meuse system. System dynamics is a computer-aided approach for strategy and policy design regarding complex, dynamic systems (System-Dynamics-Society). In this system dynamics model the water flow, shipping flow and functionalities, such as water quality, fresh water availability and shipping capacity of the system are modelled. Compared to a conventional method, solely one model is used and additionally this model contains interactions between functions, such as the influence of water availability on shipping. Traditionally complex hydraulic, shipping and water quality models are used separately, such as SOBEK and SIVAK (Deltares, 2019; Rijkswaterstaat, 1998).

Secondly the EMA workbench was used to simulate the system dynamics model for multiple different future scenarios. The future scenarios are composed by uniformly selecting values for uncertain parameters in the system dynamics model to stress-test strategies across a wide range of possible future conditions without making judgements about whether one future is more likely than any other (R. J. Lempert, 2019). Compared to traditional decision making methods, RDM explores a larger, and more extreme set of future scenarios and therefore takes scenarios into account which are not considered in traditional decision making methods. By doing this, a policy which performs well under probable conditions, might be found to perform poor under extreme conditions. Lastly, robustness metrics are used to be able to measure the performance of the system.

6.1 Future behaviour of the current Meuse System

"What uncertainties impact the Meuse system for the coming 100 years and how does the river Meuse system behave under these uncertainties?"

The exploration of the current river Meuse system is achieved by exposing it to possible future scenarios in order to demonstrate its main behaviours. From the base ensemble analysis, the river Meuse system was generally found to perform well for the functionality shipping. Only the lock at Grave would reach risky situations (I/C > 0.5) for approximately 27% of the runs and undesired behaviour (I/C > 0.6) for approximately 3% of the runs. This was in line with the expectations, as the lock complex at Grave contains only one relatively small lock and has therefore the least capacity of the corridor (Koenraadt et al., 2018). An important uncertainty for the function shipping was the percentage of transport that is shipped via water compared to rail and road. This percentage might change in the future under influence of for example governmental decisions or innovations. This could cause a modal shift, which is expected to severely impact shipping intensity.

Water quality, evaluated based on 5-day minimum flow velocities, was found to reach risky or undesired situations for most of the runs, leading to possible problems regarding diffusivity of toxic substances and algal blooms. The flow velocity in the weir sections Linne, Grave and Lith ended up being the lowest as the weirs are maintaining the largest water depth in these weir sections. The water quality was strongly influenced by the selected discharge series as during low discharge situations, the large water depth in the weir section leads to a very low flow velocity and therefore an increase in risk for problems related to water quality.

The river Meuse system has been designed to maintain specific water levels. By analysing the freshwater availability with the Meuse Model, it became clear that the freshwater availability behaved robust by nature as under many future scenarios the freshwater buffer remained at full capacity. However, for weir section Grave approximately 12% of the runs ended up in the risky category (90% to 100% capacity) and approximately 6% of the runs ended up in the undesired category (<90% capacity). Weir section Grave was the worst performing and most vulnerable weir section and was therefore selected as main improvement focus. A scenario discovery analysis discovered that for weir section Grave the most influential uncertainties that lead to low fresh water availability were the leakage of the weir at Grave, the selected climate scenario, the selection of specific dry discharge years and a simulation year further in the future such that climate change has more impact. Therefore, to be able to increase the robustness of the fresh water availability, design options should be created that either increase the storage capacity of the weir section or decrease the loss of water.

6.2 Replacement Strategies

By exploring the current river Meuse system and indicating the most influential uncertainties and vulnerabilities, design options are composed. Due to limitations in calculation time, the number of design options needed to be restricted. Nonetheless, the next research question can be answered.

"What design options can be formulated for the river Meuse system?"

- Installation of pumps: pumping lost water back in dry periods
- Heightening crest levels of the weirs at Grave: increase buffer capacity
- Relocating the weir at Grave in upstream direction: increase average water depth and therefore buffer capacity in the weir section
- Dynamic crest level: temporarily increase buffer capacity

- Efficient locking: limit the loss of water in dry periods by imposing a minimum amount of ships that need to enter the lock chamber before starting the locking cycle

Combinations of these design options can be made to form more replacement strategies. The replacement strategies are added to the system and exposed to similar future scenarios as in the exploration of the current system.

"What design options can be recommended for improving the fresh water availability in a multi-functional river Meuse system?"

The replacement strategies are composed with the main intention to improve the robustness of the freshwater availability in the river Meuse system. Robustness of fresh water availability is measured by how well the system is able to retain full freshwater capacity during future scenarios. From analysing the current system it became apparent that weir section Grave is the worst performing and most vulnerable weir section in the river Meuse system. Therefore it is expected that the largest improvements can be made in weir section Grave, which is why it will be the main focus for improvement. However, the performance of other functionalities and weir sections of the river should not deteriorate and preferable be improved by applying the design option.

All of the designed replacement strategies improved the fresh water availability of weir section Grave and the other weir sections in the river Meuse. The replacement strategy that contains the relocation of the weir at Grave in combination with increasing the crest level of the weir at Lith leads to an improvement of the fresh water buffers in weir sections Grave and Lith for approximately 10% of the runs. The length of weir section Grave is reduced by applying this replacement strategy and therefore the average water level will be higher. However, the minimum required water depth in weir section Lith cannot be guaranteed for all of the runs and therefore the ship draught is at risk. Relocating the weir of Grave thus negatively impacts the function shipping.

Replacement strategies containing efficient locking experience a severe improvement regarding the fresh water availability as almost all of the runs end up at a full fresh water buffer. However, the Intensity/Capacity ratio at the lock of Grave increased severely for 80% of the runs, which makes the overall performance of the replacement strategy insufficient for this study.

Raising the crest level permanently or dynamically leads to an increase of fresh water buffer, however, raising the water depth in the weir section also leads to a reduction of flow velocity and therefore water quality for 80% and 25% of the runs respectively.

The last replacement strategy contains the installation of pumps and this replacement strategy resulted in a significant increase of the minimum fresh water buffer outcomes. Lost water is pumped back into the weir section and because of that, a full freshwater buffer can be maintained for almost all runs. Furthermore the outcomes of the other functions are not worsened by applying this replacement strategy. Installing pumps is therefore found to be the best performing replacement strategy. However, this study has not considered aspects such as costs or sustainability and more research is therefore required. Lastly, the main research question can be answered:

"What does a system-based replacement strategy look like for the river Meuse system and does this have added value compared to a conventional strategy?"

This study has shown that the RDM method is a well suited method to get a general understanding of the system and a first indication of system-based replacement strategies. Complex systems can be modelled without much prior knowledge of variables within the system as these can be taken into account as uncertainties (R. J. Lempert, 2019). A system-based replacement strategy is a strategy which considers all functionalities of the system, considers interactions between elements and is able to perform well in future scenarios (de Groot-Wallast & van Twuiver, 2019). The advantage of such a strategy over a strategy that focusses on one element is a twofold of reasons. First of all, the replacement strategies generated in this study are assessed based on a broad range of future scenarios, preventing unforeseen negative impacts. Secondly, the design options are evaluated based on a system perspective meaning that multiple functions and interactions within the system are considered.

7 Discussion

In this chapter it is firstly explained how the results should be interpreted. Furthermore, it reflects on the methodology. Lastly, it discusses the limitations of the model and recommendations for future studies.

7.1 Interpretation of the results

The findings in this research show that the current river Meuse system is vulnerable for drought on top of its vulnerability for flooding (de Wit et al., 2001). Design options to reduce these vulnerabilities might be at the expense of other functions as the river Meuse system has become a multi-functional system (van Tilburg, 2015). It is therefore recommended to manage the Meuse river in an integral fashion. The RDM approach, explained in chapter *3*, appears to offer such an integral overview of the system and its policies. In this study a first selection of replacement strategies that decrease the vulnerability of the river Meuse system and improve robustness has been made. The results show the impact of these design options on the river Meuse system compared to the one-on-one replacement strategy. The conclusions drawn from this study can contribute to the decision making process for the future river Meuse system design. However, more in depth research is needed to be able to accurately predict the advantages and disadvantages of these replacement strategies. On top of that, more detail in the Meuse Model and extension of performance indicators is required to be able to give a more realistic result, as will be discussed in chapter *7.3*.

The model used in this study is built upon consolidative known facts but is used in an exploratory way, which means that for certain parameters in the model an uncertainty bandwidth is implemented and in each run a value in this uncertainty bandwidth is selected. The uncertainty bandwidth is uniformly distributed such that all values are equally many times selected. This means that the results from the simulations cannot be analysed in a probabilistic way but can rather be seen as stress-testing the system under all possible scenarios.

More information is needed regarding the evaluation of the key performance indicators. In this study it is assumed that if the freshwater buffer is smaller than the full capacity of the freshwater buffer (i.e., filled until the crest of the weir) problems might occur. In reality, however, it is for example not known at what water level problems can occur, which makes it difficult to make constructive evaluations. The same holds for the key performance indicator “water quality”. Only for the key performance indicator “shipping” clear satisficing thresholds were available. The results of this study are therefore meant to give an indication of the state of the key performance indicators but cannot be seen as the absolute truth.

Additionally, more research is required regarding the impact of the replacement strategies on the flood safety of the system. It is expected that alterations to the minimum maintained water level might contribute to a change in flooding probability. For example, when the capacity of the fresh water buffer is increased and a flood occurs, less capacity is available to absorb this flood wave and therefore the probability of flooding might increase. However, as the flooding probability is not considered in this study, no conclusions can be made regarding the performance of the replacement strategies towards flood probability.

7.2 Reflection on the methodology

Firstly, this study has combined multiple functions of the river Meuse system into one model. Hence, a robust decision making (RDM) method could be applied. This study shows that RDM has the potential to find an interesting set of policies within a complex decision arena. The selection of policies in this study, however, is limited by the model as will be discussed in the next section. Therefore, these policies can be seen as an interesting starting point rather than a solution.

Secondly, RDM does not use models and data as a predictive tool, but rather as a way to stress test policies on multiple possible futures (Robert J. Lempert et al., 2013). RDM shows insights in the behaviour of the river Meuse system and as of which, the vulnerabilities of the policies. By exploring a wide variety of possible future scenarios, the modelled system and the applied policies are tested under many different conditions. Along with the most probable scenarios, the less probable scenarios are considered in this selection of possible futures. This adds added value to the research and is found to be necessary to be able to design a robust system. However, no predictions can be made regarding the occurrence of these possible futures.

Also, a wide range of uncertainties causes limitations. By modelling complex systems such as the river Meuse system, calculation time of one run can easily become large. Although it is generally well under the calculation time of conventional models, by performing many runs, the total simulation time can become long. With only a certain amount of time available, choices have to be made which might come at the cost of accuracy and elements that can be included such as functions in the system, design options and uncertainties.

More complex methods could have been used to perform the analysis of the study. For example, the Multi Objective Robust Decision Making (MORDM) method (Kasprzyk, Nataraj, Reed, & Lempert, 2013). This method optimizes the objective to then test it over a set of future scenarios. The method is similar to the RDM method except for an extra step in which it optimizes the selected policies instead of simply testing a set of chosen policies. However, this optimization requires many runs and is therefore computationally very expensive.

Another method fit for the purpose of this study is Dynamic adaptive policy pathways (Haasnoot, Kwakkel, Walker, & ter Maat, 2012). This method uses tipping points, which are the conditions under which an action no longer meets the clearly specified objectives. It then dynamically sets policies in motion with the goal to end up with a robust system that does not underperform. To be able to apply this method, a different setup has to be chosen compared to this study. This study uses one year simulation periods which is generally not long enough to construct hydraulic structures. Therefore a simulation period of at least multiple years is required.

7.3 Limitations and recommendations

The Meuse system is immensely complex and modelling it means that certain aspects or details need to be left out in order to make it computationally feasible and understandable. This section discusses main limitations of the model and adds recommendations for future studies.

First of all, the considered functions of the Meuse system had to be limited to the three functions discussed in the report, fresh water availability, water quality and shipping. In the modelling process it was chosen to focus on these functions in order to limit complexity and time to model the system. Other important functions or decision makers which might be particularly decisive in the decision making process, such as costs, morpho dynamics and flood safety, are not considered in this study. To achieve a complete multi-functional decision, all main functions are recommended to be considered.

Another assumption in the model which, according to the author, might be of big importance is the omission of the groundwater flows. It is expected that in the higher regions with harder soils such as the boarder Meuse, the river has carved deep into the landscape and is therefore generally lower situated than the groundwater level. This causes flows towards the river and will change the perception of the volume balance as has been performed in this study. In the lower areas of the river catchment, the river water level is at approximately the same level as the groundwater level which might lead to leakage towards the groundwater in dry periods. At the point of writing, little is known about these groundwater flows and the soil types along the river Meuse. Therefore it is recommended to do more research on this topic.

Additionally, certain uncertainties have been estimated as no accurate information was available, such as the leakages of the weirs. When more information would be available regarding these uncertainties, more realistic uncertainty bandwidths can be estimated and more uncertainties should be added to the model. Due to limitations in calculation time, it was decided to limit the amount of uncertainties in the model as each new uncertainty requires more runs to be performed.

Moreover, a time unit of one week is used in order to reach reasonable computation times. However, to be able to model the short-time effects, more accuracy is needed. Additionally, analytic formulas are used in the hydraulic model. For more accurate and realistic behaviour, a numerical model is preferred. However, this leads to an increase in computation time.

Furthermore, the study could be expanded by not only including the socio-economic scenarios of the Netherlands but on top of that the socio-economic scenarios of Germany and Belgium. The Meuse is used to transport goods to Germany and Belgium as well as the Netherlands (Koenraadt et al., 2018). A socio-economic scenario in these countries could therefore severely impact the system of the river Meuse. Additionally, it could occur that the river Waal would not suffice for shipping in certain periods of the year because of available water depth. This would lead to a transition of shipping via the river Meuse and therefore an increase in intensity (De Jong, 2020). The possibility of this event is not considered in this study because little is known about this topic yet. Further research is thus recommended.

Limitations are also imposed on the types of hydraulic structures in this study. This study creates replacement strategies for the weirs in the river Meuse specifically. However, replacement of locks, bridges, inlets etcetera is outside of the scope of this research. Also the hydraulic structures in the canals along the river Meuse are left outside of the scope of this research.

Lastly, this study considers a simulation period of one year and assumes that the previous year does not affect the current year. In reality an extremely dry year would presumably affect the functioning of the next year, especially if multiple dry years occur subsequently. In addition to that, no date of replacement added to the simulations. It could for example be interesting to analyse adaptive replacement strategies. Hence, replacement strategies could include the aspect of planning (Walker et al., 2013).

Due to the complexity of the river Meuse system, modelling this system is challenging and time consuming. In order to keep the model understandable but still accurate enough, many limitations have been imposed. However, many of these limitations are expected to be solvable in future research.

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Appendix A Model Formulas

Water flow submodel

Equation for backwater curve:

$$d_{bc} = d_{crest} - i_b \frac{d_{crest}^3 - d_e^3}{d_{crest}^3 - d_{cr}^3} \tag{3}$$

With:
d_{bc} = Water depth under backwater curve [m]
d_{crest} = Crest height of the weir [m]
i_b = Bottom gradient in river segment [-]
d_e = Equilibrium depth [m]
d_{cr} = Critical depth[m]

Critical depth is calculated with the formula:

$$d_{cr} = \left(\frac{q^2}{g}\right)^{1/3} \tag{4}$$

With:
d_{cr} = Critical depth [m]
q = Discharge per unit width [m^2/s]
g = Gravitational acceleration [m/s^2]

The equilibrium depth is calculated with the formula:

$$d_e = \left(\frac{n^2 q^2}{i_b}\right)^{3/10} \tag{5}$$

With:
d_e = Equilibrium depth [m]
n = Manning's bed friction coefficient [$m^{-1/3}s$]
q = Discharge per unit width [m/s^2]
i_b = Bottom gradient in river segment [-]

and then:

$$\Delta d = d - d_{bc} \tag{6}$$

The discharge out of the river segment is then calculated as follows:

$$Q_{OUT} = Q_{IN} + \Delta dBL \tag{7}$$

With:
Q_{OUT} = Discharge out of the river segment [m^3/s]
Q_{IN} = Discharge in to the river segment [m^3/s]
Δd = Difference between water depth under backwater curve and depth in river segment [m]
B = River flow width [m]
L = Length of river segment [m]

During the third situation, the whole river is free flowing and the flow through all the grid cells is calculated with equations (3), (6) and the following equations for the discharge out of the river segment:

$$\Delta d_{free\_flow} = d - d_e \tag{8}$$

And then:

$$Q_{OUT} = Q_{IN} + \Delta d_{free\_flow} BL \tag{9}$$

Furthermore, the following equations are used to calculate the discharge to the next river segment:

Water depth lower than crest level weir (or backwater curve)	$Q_{IN} - \left(d_{crest(or\ backwater\ curve)} - d\right) * \mathrm{A}$	(10)
Water depth larger than crest	$Q_{IN} - Q_{EVAPORATION} + Q_{PRECIPITATION} * \mathrm{A}$	(11)

With:

A = Surface area in the river segment [m2]
d = Water depth [m]
$Q_{evaporation}$ = Evaporated volume of water per timestep
$Q_{precipitation}$ = Volume of rainwater per timestep

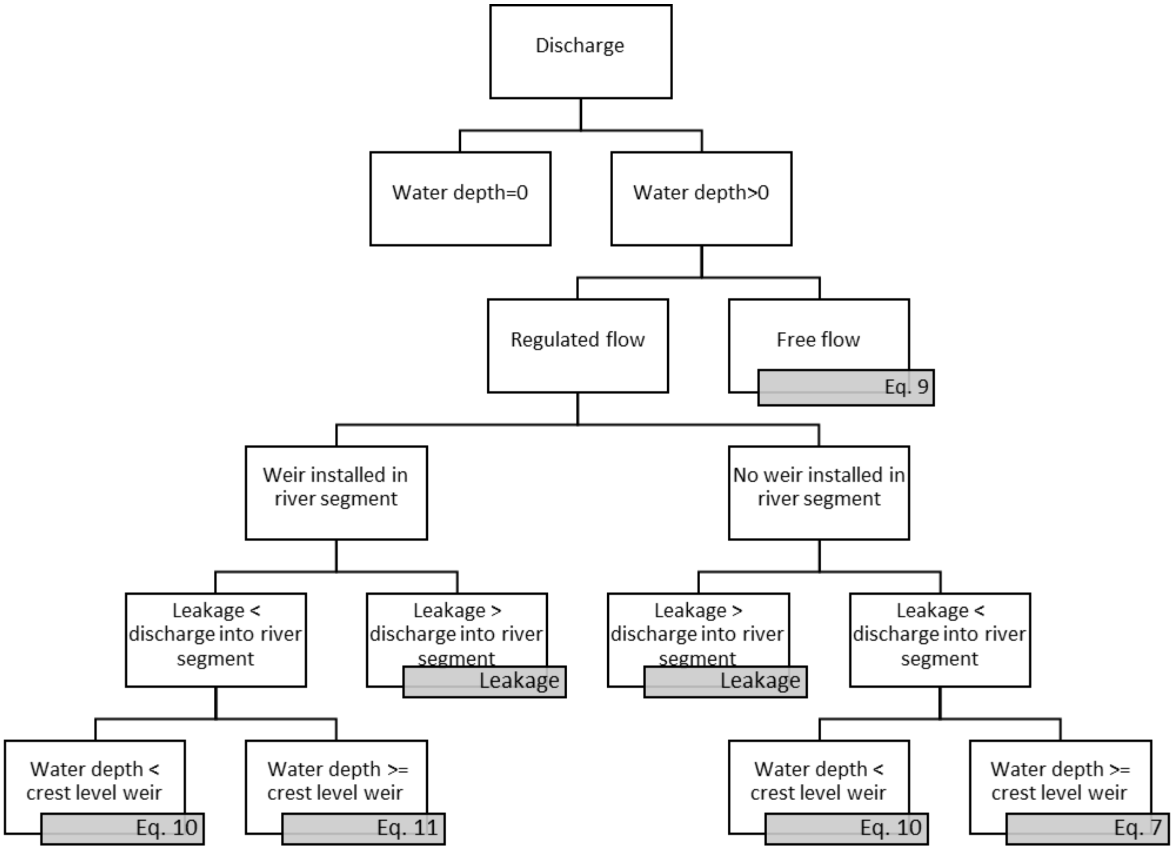


Figure 46 Discharge calculation scheme

Shipping Flow submodel

The time needed for one cycle is determined as follows (van Dongen, 2018):

$$T_c = n_{max} \cdot (t_i + t_u) + t_l - t_i \tag{12}$$

With:
$n_{max} = maximum\ number\ of\ ships\ in\ the\ lock\ chamber\ [ships]$
$t_i = Time\ needed\ to\ sail\ into\ the\ lock\ [min]$
$t_u = Time\ needed\ to\ sail\ out\ of\ the\ lock\ [min]$
$t_l = Time\ needed\ to\ secure\ the\ ships\ to\ the\ wall\ [min]$

The weekly capacity is determined as follows (van Dongen, 2018):

$$C = (7 \cdot 24 \cdot 60) \cdot chambers \cdot (1 - f_{rec}) \cdot directions \cdot n_{max}/T_c \tag{13}$$

With:
$C = Weekly\ capacity\ [ships/week]$
$f_{rec} = Percentage\ recreational\ [\%]$
$chambers = Number\ of\ chambers\ [nr]$
$directions = 2$

Water Quality submodel

The residence time of a water particle in the weir section might be lengthened under influence of a weir as the river depth is heightened, see Equation (14). This might lead to an opportunity for algal growth and a reduction in water quality (Asselman et al., 2018). A natural flow regime with natural flow velocities is therefore preferred.

$$T = \frac{L}{u} = \frac{B \cdot d}{Q} \cdot L \tag{14}$$

With:
$T = Residence\ time$
$u = Velocity$
$L = Length\ of\ the\ weir\ reach$
$Q = Discharge$
$B = Width\ of\ the\ river$
$d = River\ depth$

Appendix B Data

Water users in the river Meuse

The river Meuse knows many water users, this section dives into the type, quantity and location of consumption. The water users in the river Meuse catchment area are:

- Shipping
- Drinking water
- Agriculture
- Industry
- Canals
- Nature

The current ship draught in the river Meuse is at least than 3.0 meters and will be increased to 3.5meters in the future, this translates to a water depth of 4.2 and 4.9 meters respectively (Koenraadt et al., 2018). To be able to provide for shipping and prevent economical damage, these water depths need to be maintained throughout the year as shipping intensity remains relatively constant throughout the year (see "shipping data" in this chapter).

Large drinking water extraction points can be found at Heel, Brakel and the Biesbosch. The extraction point at Heel is situated in weir section Roermond, uses approximately 0.5 m^3/s and delivers to almost 300 000 people (RIWA, 2019; RWS-Zuid-Nederland, 2019). The extraction points at Brakel and the Biesbosch are situated after weir section Lith and combined deliver freshwater to 3.5 million people (RIWA, 2019), see Figure 47. The freshwater that these companies use is extracted from the river Meuse surface water.

Along the river Meuse many agricultural land is situated which uses river Meuse surface water to irrigate crops. The exact amount of extracted river Meuse water is not known as extractions below $100m^3$/hour are not tracked, but it is assumed that during dry periods the farmer will need to irrigate his crops throughout the day.

Large industrial users of the river Meuse freshwater are Chemelot RWE Clauscentrale, Smurfit Kappa, Forfarmers which is situated next to the Julianacanal in weir section Linne and uses approximately $1.5m^3/s$.

The river Meuse is also used to supply the local canals. Before entering the Netherlands, canals bifurcate into the Belgian hinterland towards Antwerp. Just across the Belgian-Dutch boarder, the Julianacanal is situated which also originates from the river Meuse. In the Meuse treaty it was agreed that a minimum of $10m^3/s$ should flow through the river Meuse at all times ("Maasverdrag," 2002). Furthermore, just before the weir at Linne, the Wessem-Nederweert canal is situated and fed by the river Meuse with approximately 6 m^3/s (de Rooij, 2020).

Water that flows into the Zuid-Willemsvaart canal (at Maastricht) flows to the North Brabant and Limburg canal system and to De Groote Peel National Park, which consists of a peat bog. This peat bog needs a water supply during dry periods in order to sustain its ecological value. The water needed to prevent the peat from drying out is at least 3.8 m3/s. Supplying water at a smaller rate means there is a risk of irreversible harm to the ecosystem in De Groote Peel NP (de Rooij, 2020).

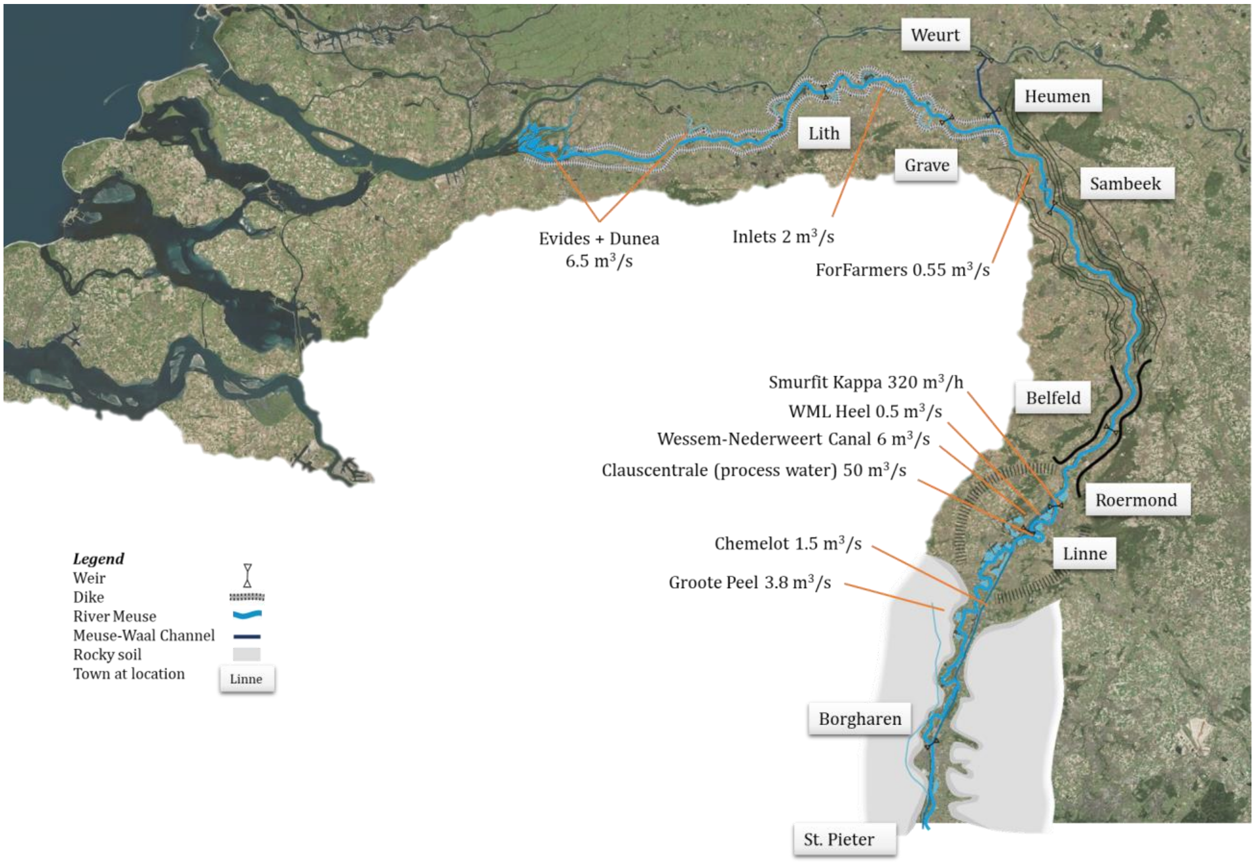


Figure 47 River Meuse water extraction points with quantity and purpose. Retrieved and edited from (de Rooij, 2020)

Future Climate scenarios

The Intergovernmental Panel on Climate Change (IPCC) published the Assessment Report (AR5) containing future global warming scenarios in 2013 (IPCC, 2013). The IPCC is a worldwide institution that focusses on general global trends on a continental scale. The Royal Dutch Meteorological Institute (KNMI) has translated the AR5 consequences to the Netherlands (KNMI, 2014). The KNMI constructed four climate scenarios that are based on- and very similar to the IPCC scenarios:

- G_L: Wet spring and dry summer in reference period, reverse in future
- G_H: Cold and wet summer in reference period, warm and dry in future
- W_L: Wet spring and dry summer in reference period, reverse in future
- W_H: Cold and wet summer in reference period, warm and dry in future

The “G” scenarios represent a relatively small global temperature increase, while the “W” scenarios represent a more severe global warming. The second letter “L” represent a small change in atmospheric circulation, leading to small meteorological change and the second letter “H” represents more extreme change in atmospheric circulation leading to relatively large meteorological change. A fifth scenario was added to the KNMI’14 climate scenarios: $W_{H,dry}$. In this scenario the winter precipitation is decreased such that the summer period will be extra dry (Sperna Weiland et al., 2015). By doing this, the river Meuse system can be tested on dry future scenarios, which is desired in this study.

- $W_{H,dry}$: W_H and additionally moderately dry spring/winter period

Discharge, precipitation and evaporation data

A 100-year historical discharge series is known for the river Meuse at Monsin (Kramer & Mens, 2016). In order to derive future discharge series for the river Meuse, this discharge series is transformed to years in the future by using the climate scenarios G_L and $W_{H,dry}$ from the KNMI'14 climate scenarios (Kramer & Mens, 2016). This was done for the years 2014, 2050 and 2080 and thus historical discharge series were transformed to the reference year 2014 and the future years 2050 and 2085 by using the KNMI'14 scenarios G_l and $W_{H,dry}$.

Result (Kramer & Mens, 2016):

- 100 years of discharge series for the year 2014
- 100 years of discharge series for the year 2050 under influence of climate scenario G_L
- 100 years of discharge series for the year 2050 under influence of climate scenario $W_{H,dry}$
- 100 years of discharge series for the year 2085 under influence of climate scenario G_L
- 100 years of discharge series for the year 2085 under influence of climate scenario $W_{H,dry}$

The same method is applied to the discharge series of the tributaries to the river Meuse, the precipitation series and the evaporation series for the river Meuse.

To stress-test the river Meuse system even more, extreme drought periods are added to the simulations (Korving & Versteeg, 2018). This is done to include the possibility of extreme unforeseen events such as the flooding of summer 2021. Based on historical drought periods and again translated to the future by using the G_L and $W_{H,dry}$ scenarios, drought intensities and drought periods are composed for the river Meuse system. These drought periods and intensities can be combined to create a drought. A drought has typically a degree of occurrence but because this study uses uniform distributions, combinations between all drought periods and drought intensities are made. However, this means that the model outcomes cannot be used as a predictive tool but rather to stress-test the system. The following values are used for the drought period and drought intensity to create droughts which overrule the discharge series of the river Meuse:

- Drought intensity: 20 - 45 m^3/s
- Drought period: 4 - 16 weeks
- No drought

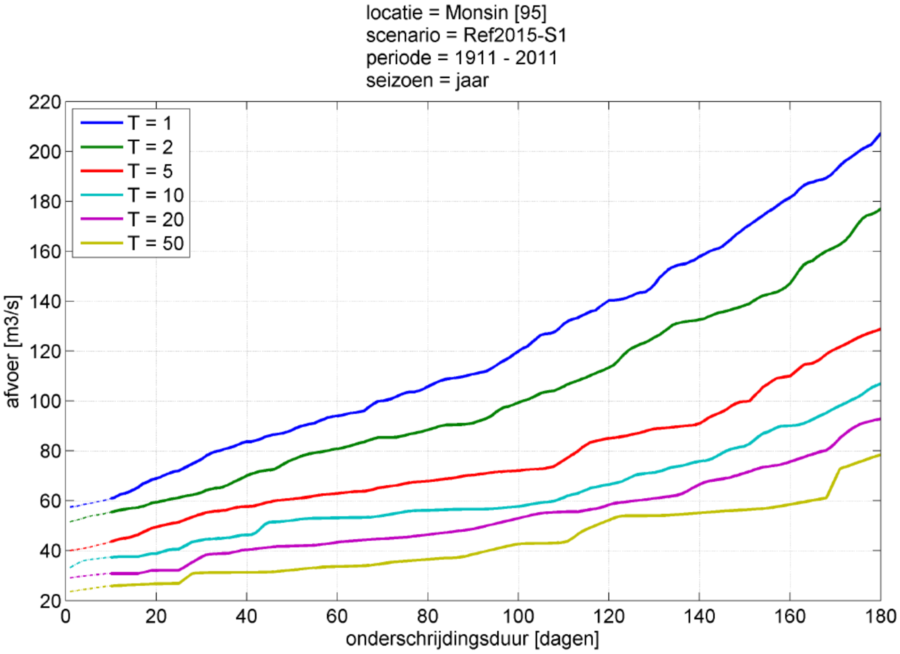


Figure 48 Drought intensities (y-axes) in relation to drought periods (x-axes), retrieved from (Korving & Versteeg, 2018)

Future socio-economic scenarios

The Planning office for Living Environment (Dutch: PBL) in together with Central Planning Agency (Dutch: CPB), constructed two future scenarios for the future of socio-economics, called the WLO-scenarios:

- WLO_H: high increase in population and high economic growth (2% annually)
- WLO_L: limited increase in population and moderate economic growth (1% annually)

Rijkswaterstaat translated these socio-economic scenarios to the shipping on the river Meuse (Rijkswaterstaat, 2017b). This translation is done by looking at the change in transported cargo from and to the regions around the river Meuse and the intensity of ships on the river Meuse. In conclusion this leads to a yearly future development of approximately -0.17% for scenario WLO_L to 0.33% for scenario WLO_H in commercial ship intensity (Rijkswaterstaat, 2017b).

For the leisure shipping intensity Waterrecreatie Advies 2016 constructed future scenarios based on the WLO scenarios (Waterrecreatieadvies, 2016). In general the future trend of ship intensities is declining, however in the province of Limburg, water recreation seems to attract many ships from for example Germany. It is therefore expected that water recreation in Limburg will be more positive compared to the rest of the Netherlands. Therefore in this study a change of recreational ship intensity between -1% to 0% is used.

Shipping data

(De Jong, 2020) collected the weekly average commercial ship passages through the locks in the river Meuse for the years 2011-2018. He chose to take the maximum of these years to construct the ship intensity table below. This was checked with ship passage data from the NIS database of Rijkswaterstaat, which was similar to the results from (De Jong, 2020).

The data of leisure ship passages is retrieved from the NIS database from Rijkswaterstaat. In the summer months the number of leisure ships is typically much higher compared to the number of leisure ship passages in the winter months. Because only the maximum I/C values are calculated in the Meuse Model, the weekly maximum leisure ship passages is retrieved for the years 2019 and 2020. To come to the amount of weekly leisure ship passages used in the Meuse Model, the average of these two years is taken.

Table 11 Weekly ship intensities for the locks in the river Meuse

Lock	Commercial [Ship/Week]	Leisure [Ship/Week]
Linne	44	643
Roermond	62	518
Belfeld	439	458
Sambeek	547	498
Grave	289	511
Lith	334	807

The reference ship intensity data is then transformed to a year in the future by multiplication with a value in between the future shipping growth scenarios (Rijkswaterstaat, 2017b).

Appendix C Model verification

CFL condition:

To prevent numerical errors, the time step and numerical integration method should be chosen accordingly. The CFL condition (Courant, Friedrichs, & Lewy, 1928) is a condition to test the convergence of an explicit numerical integration method (Zijlema, 2011). This condition is only applied to the Test Case as this model calculated the water depth in a numerical fashion. The CFL condition is as follows:

$$|\sigma| = \frac{u\Delta t}{\Delta x} < C$$

With:

u = Characteristic wave speed of the system = Q/A [m/s]
Δt = Time step [week]
Δx = Grid cell length [m]
C = Dimensionless constant and depends on the integration method applied, for Euler C=1. [-]

Then the maximum applicable time step can be calculated:

$$\Delta t < \frac{\Delta x \cdot C}{\frac{Q}{A} \cdot s} = \frac{5000 \cdot 1}{600/2500 \cdot 2628000} \approx 0.035$$

With:

Δt = Timestep [week]
Q = Maximum discharge Through the river system in [m^3/s]
A = Cross section [m^2]
s = Seconds in a week [s/w]

Verification

Time step is supposed to be sufficiently small when the water depth is well enough tracked. This is assumed to be valid for a time step of 0.0625.

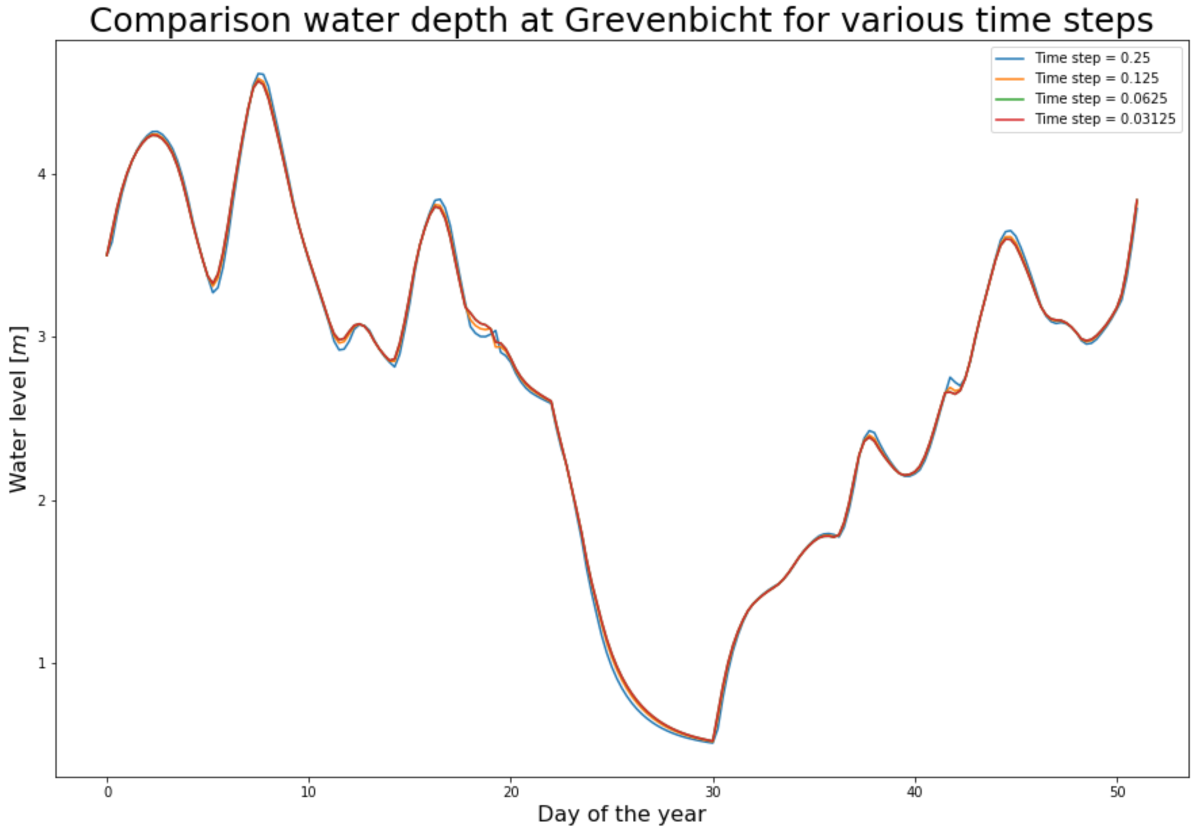


Figure 49 Applying the step doubling method to determine the timestep in the VENSIM model

Validation

Water depths generated by the Meuse model are compared to measured real life data. First the water depth at Grevenbicht is plotted for the year 2016 (see Figure 50). At Grevenbicht the river Meuse is naturally flowing throughout the year. The Vensim data (orange) describes the real life data (blue) mostly accurate enough. Deviations might be caused by inaccuracies in parameters such as roughness, river width, groundwater flows etcetera.

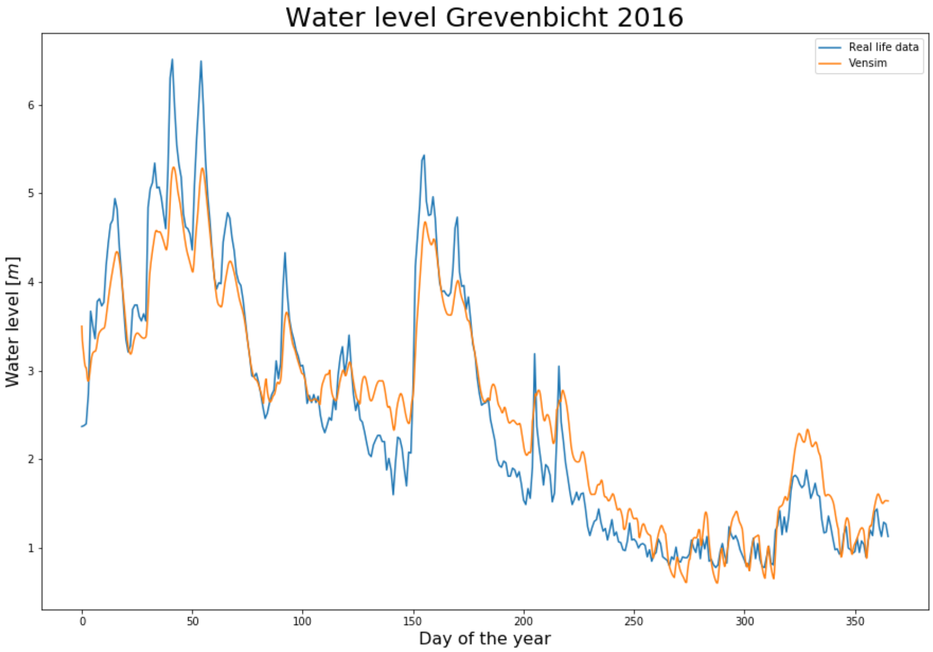


Figure 50 Water depth timeseries at Grevenbicht (Boarder Meuse) for the year 2016. Comparison between real life data (blue) and Modelled data (Orange)

The Vensim data is fitted to the real life data, as can be seen in Figure 51 , and the Vensim data matches well enough with the real life data. Small fluctiations and peaks in the real life data are not seen in the Vensim data which is caused by the discharge series used in the Vensim. This discharge series represents an average of multiple real life measurements at certain points in the day. This leads to smoothing of the data.

The location from Figure 51 is Neer. The water depth at Neer is influenced by the weir at Belfeld, which explains the horizontal parts in the data. Peaks in water depth can either be caused by the removal of the weirs or by a semi natural flow regime when the weirs are still in place. Small deviations in water depth can also be caused by the fact that in real life, the crest height of the weirs is adapted to the desired water level. In the Vensim model a fixed crest level is used. Additionally, some parameters might change under different conditions, for example the bed roughness might change after high discharges as debris and large rocks have been moved to the area. In the Vensim model this is not considered.

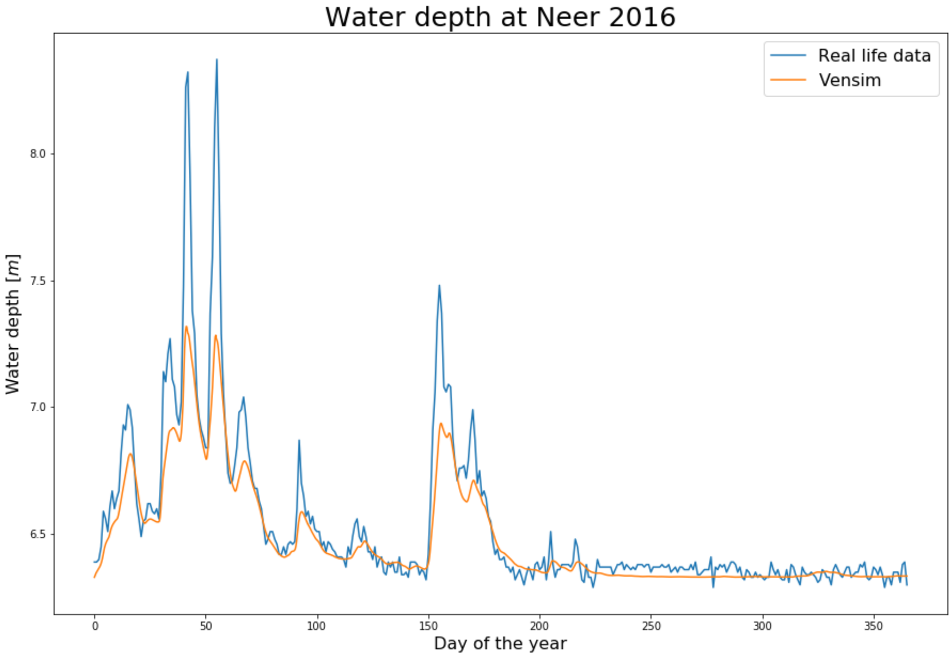


Figure 51 Water depth timeseries at Neer for the year 2016. Fitted comparison between real life data (blue) and Modelled data(Orange)

The next location is just upstream of the weir at Belfeld. The water depth at this location is therefore heavily influenced by the weir. In Figure 52 it can be seen that the water depths from Vensim result in a horizontal line which represents the heigth of the weir. The real life water depth is below the Vensim depth on two occasions. From day 10 to day 70 and from day 150 to day 180. The period from day 10 to day 70 contains a high water period. The reduction in water depth might be explained by the opening of the weirs. This leads to a temporary reduction of the water level if the equilibrium flow depth is lower than the water depth maintained by the weir. In the period from day 150 to day 180 the weirs are still in place but higher discharges are present. Therefore the crest level of the weir has probably been lowered to alow for a higher discharge over the weir. This also leads to a small reduction in the water depth. These dips in water depth are not caused by drought or low discharges and are therefore not necessary to model in this study. In Figure 53, the year 2017 and Figure 54, the year 2018, the same mechanism can be found.

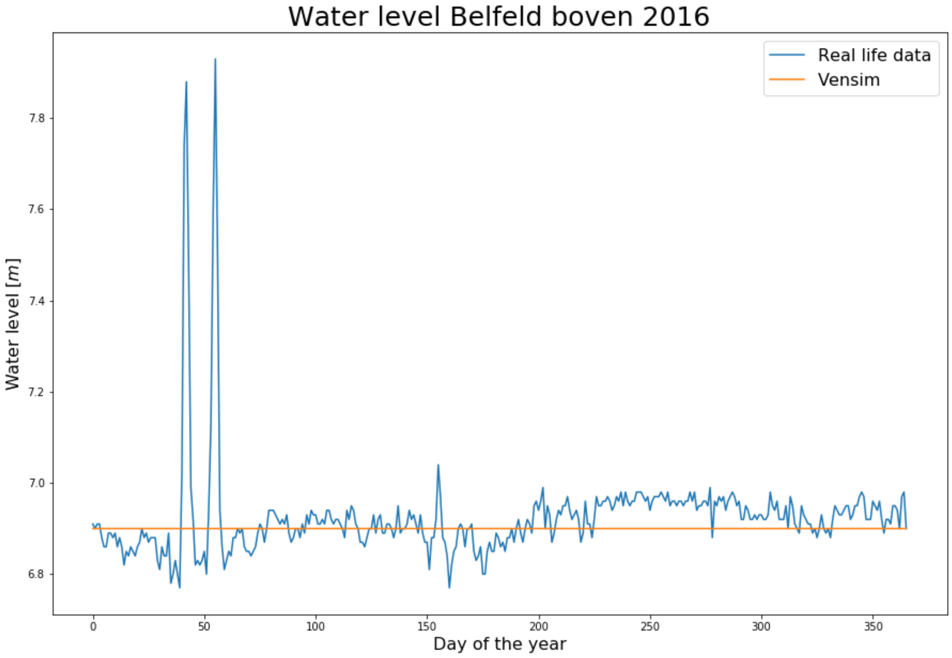


Figure 52 Water depth timeseries at upstream weir Belfeld for the year 2016. Comparison between real life data (blue) and Modelled data(Orange)

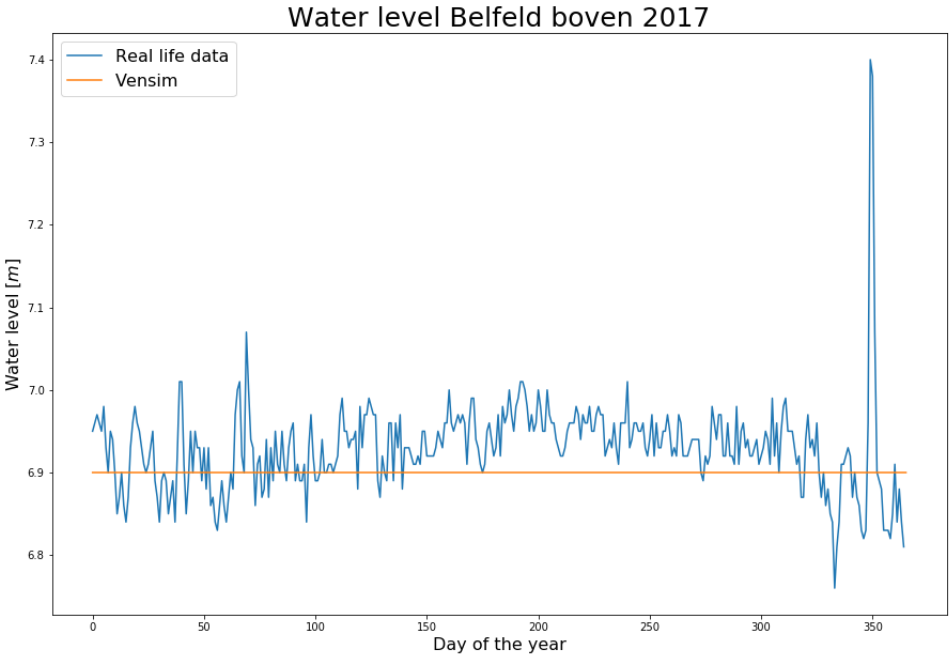


Figure 53 Water depth timeseries at upstream weir Belfeld for the year 2017. Comparison between real life data (blue) and Modelled data(Orange)

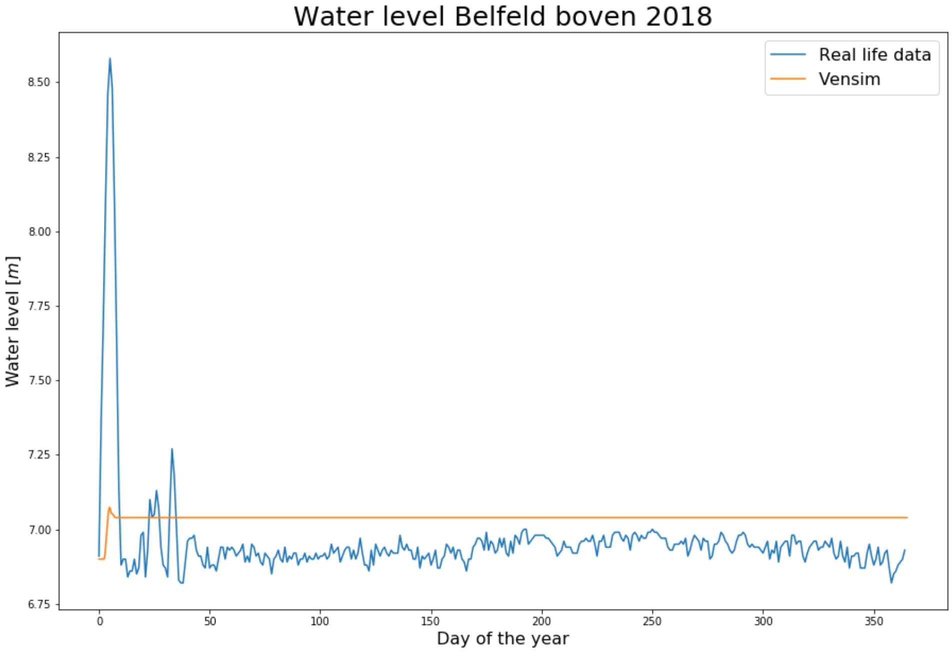


Figure 54 Water depth timeseries at upstream weir Belfeld for the year 2018. Comparison between real life data (blue) and Modelled data(Orange)

Below some more locations are compared with the real life data.

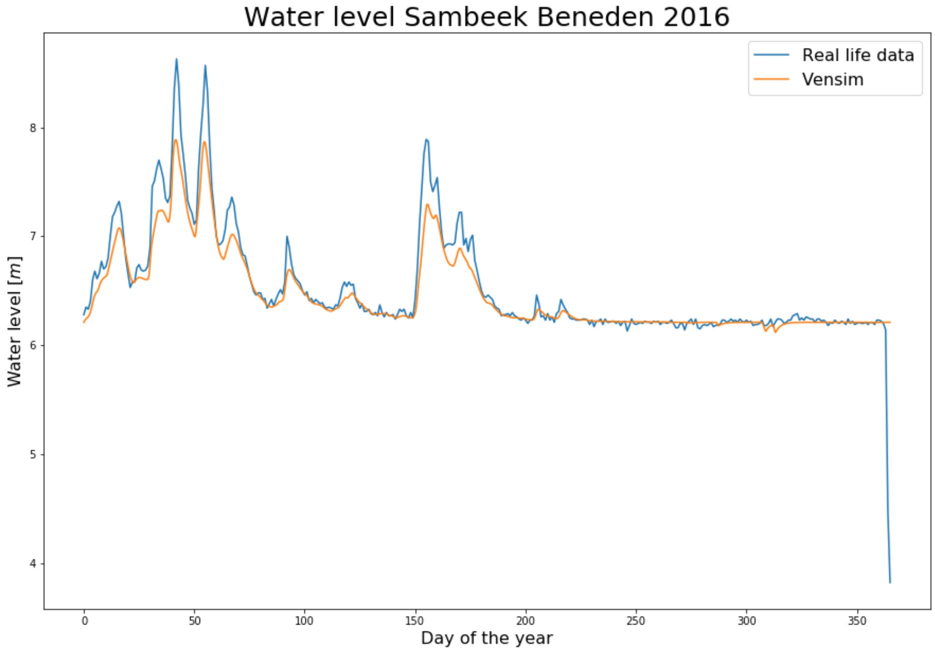


Figure 55 Water depth timeseries at downstream weir Sambeek for the year 2016. Comparison between real life data (blue) and Modelled data(Orange)

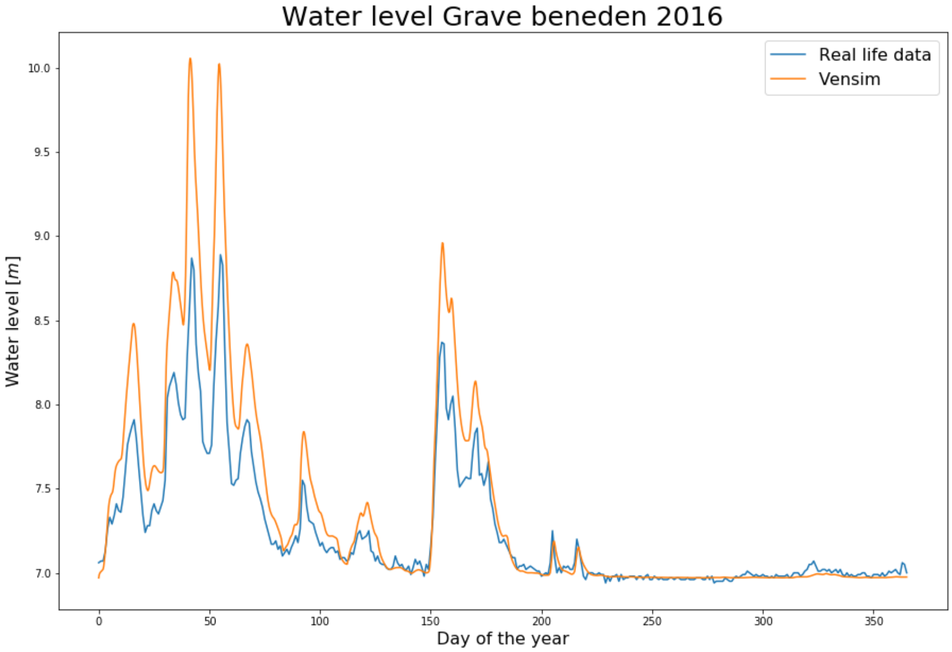


Figure 56 Water depth timeseries at downstream weir Grave for the year 2016. Comparison between real life data (blue) and Modelled data(Orange)

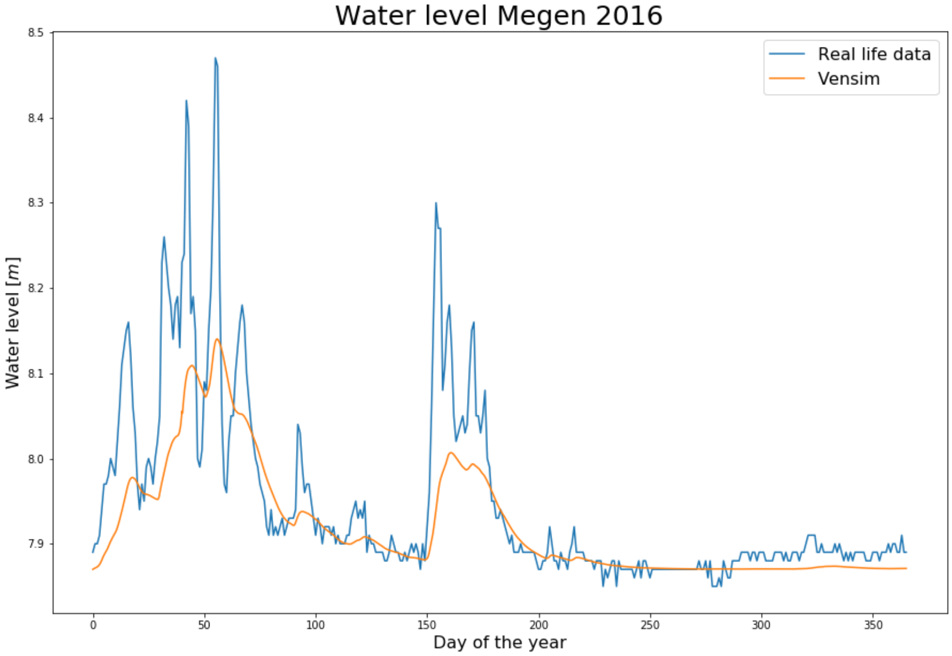
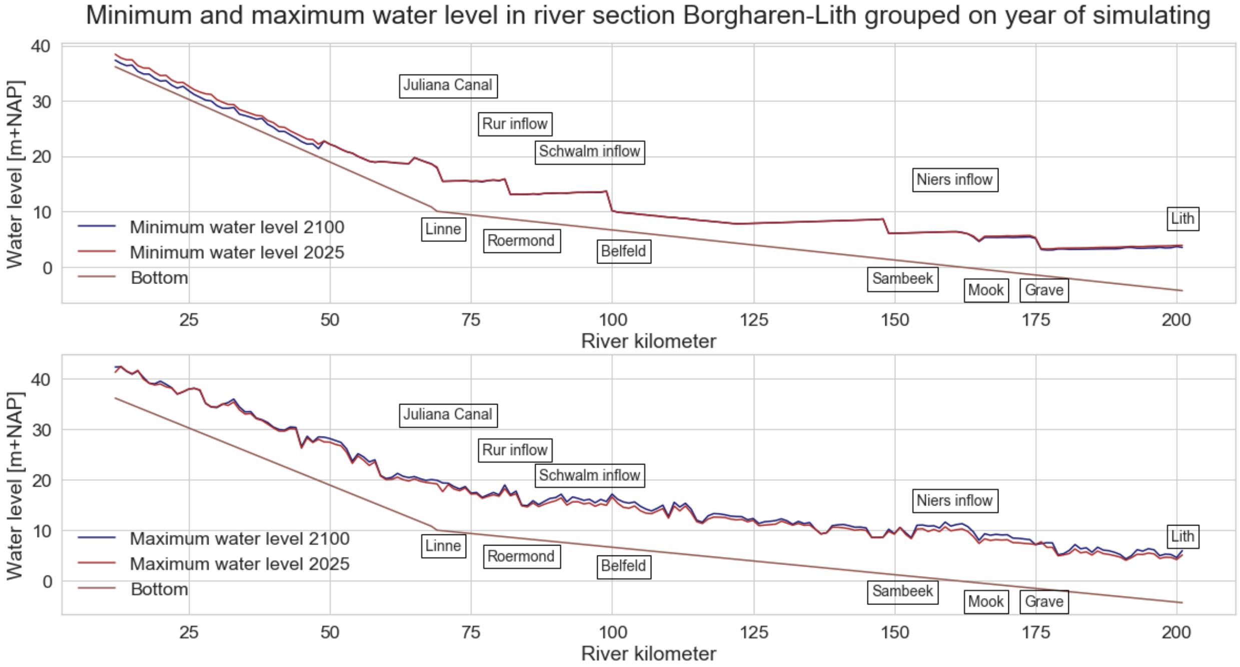
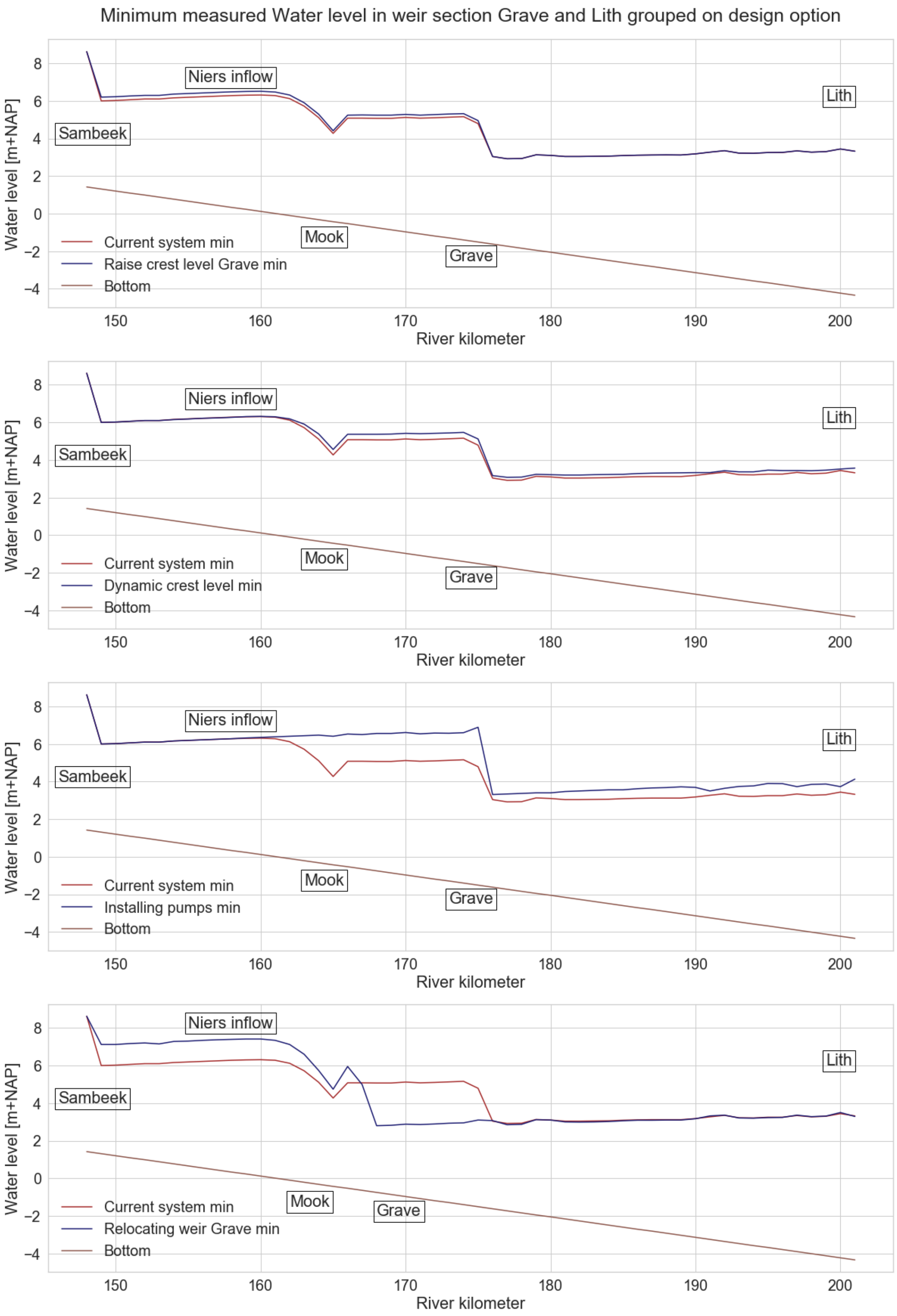


Figure 57 Water depth timeseries at Megen for the year 2016. Comparison between real life data (blue) and Modelled data(Orange)

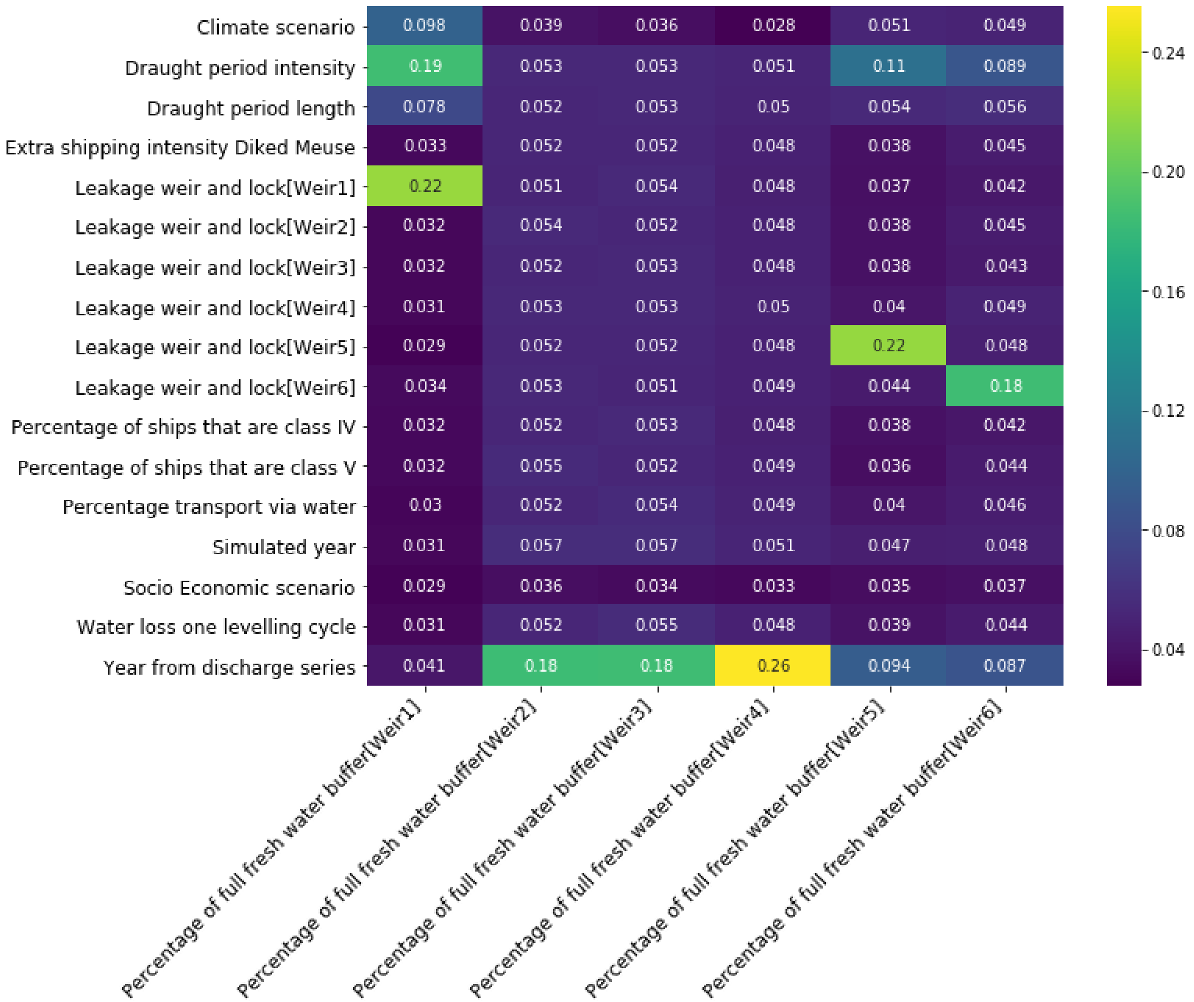
Appendix D Results



D. 1 Water level in river grouped on year of simulating

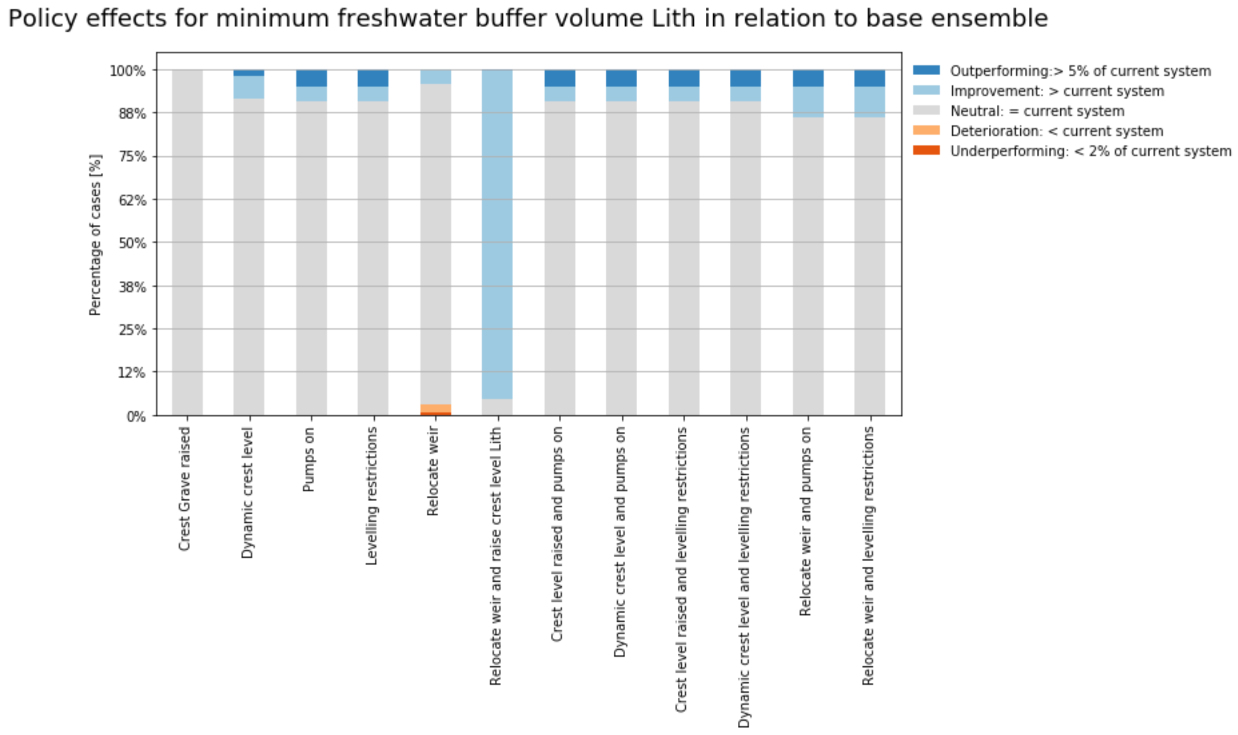


D. 2 Water level in river grouped on policy

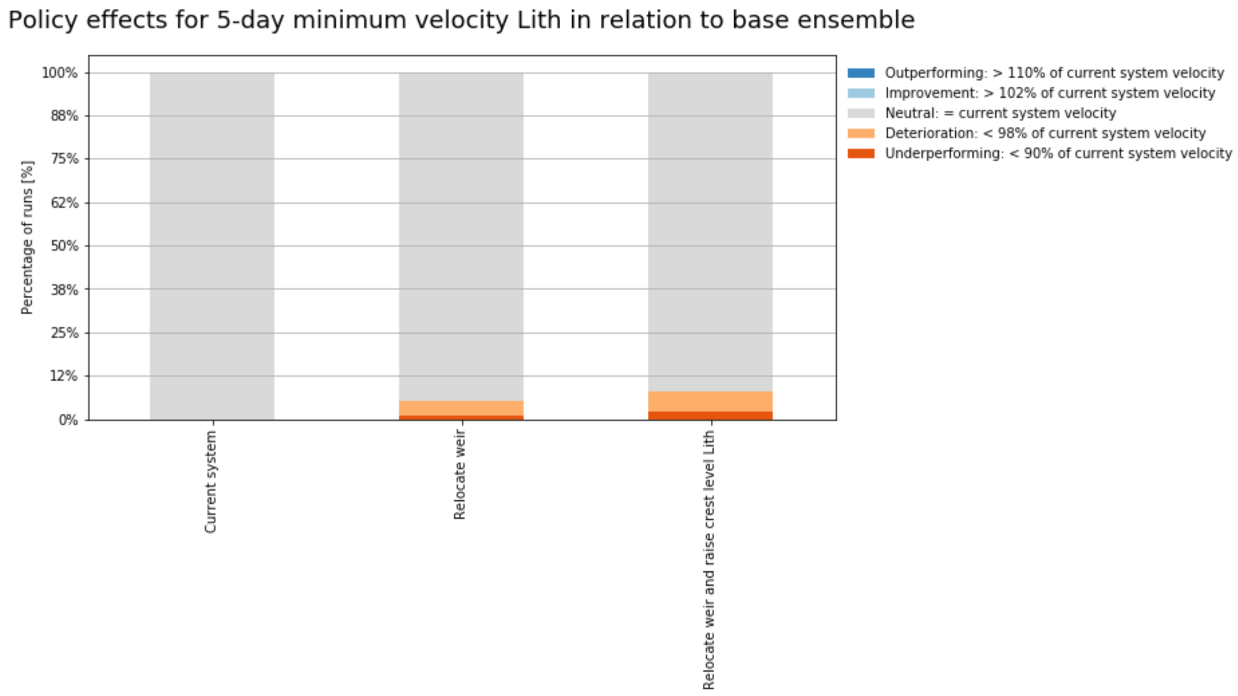


	Percentage of full fresh water buffer[Weir1]	Percentage of full fresh water buffer[Weir2]	Percentage of full fresh water buffer[Weir3]	Percentage of full fresh water buffer[Weir4]	Percentage of full fresh water buffer[Weir5]	Percentage of full fresh water buffer[Weir6]
Climate scenario	0.098	0.039	0.036	0.028	0.051	0.049
Draught period intensity	0.19	0.053	0.053	0.051	0.11	0.089
Draught period length	0.078	0.052	0.053	0.05	0.054	0.056
Extra shipping intensity Diked Meuse	0.033	0.052	0.052	0.048	0.038	0.045
Leakage weir and lock[Weir1]	0.22	0.051	0.054	0.048	0.037	0.042
Leakage weir and lock[Weir2]	0.032	0.054	0.052	0.048	0.038	0.045
Leakage weir and lock[Weir3]	0.032	0.052	0.053	0.048	0.038	0.043
Leakage weir and lock[Weir4]	0.031	0.053	0.053	0.05	0.04	0.049
Leakage weir and lock[Weir5]	0.029	0.052	0.052	0.048	0.22	0.048
Leakage weir and lock[Weir6]	0.034	0.053	0.051	0.049	0.044	0.18
Percentage of ships that are class IV	0.032	0.052	0.053	0.048	0.038	0.042
Percentage of ships that are class V	0.032	0.055	0.052	0.049	0.036	0.044
Percentage transport via water	0.03	0.052	0.054	0.049	0.04	0.046
Simulated year	0.031	0.057	0.057	0.051	0.047	0.048
Socio Economic scenario	0.029	0.036	0.034	0.033	0.035	0.037
Water loss one levelling cycle	0.031	0.052	0.055	0.048	0.039	0.044
Year from discharge series	0.041	0.18	0.18	0.26	0.094	0.087

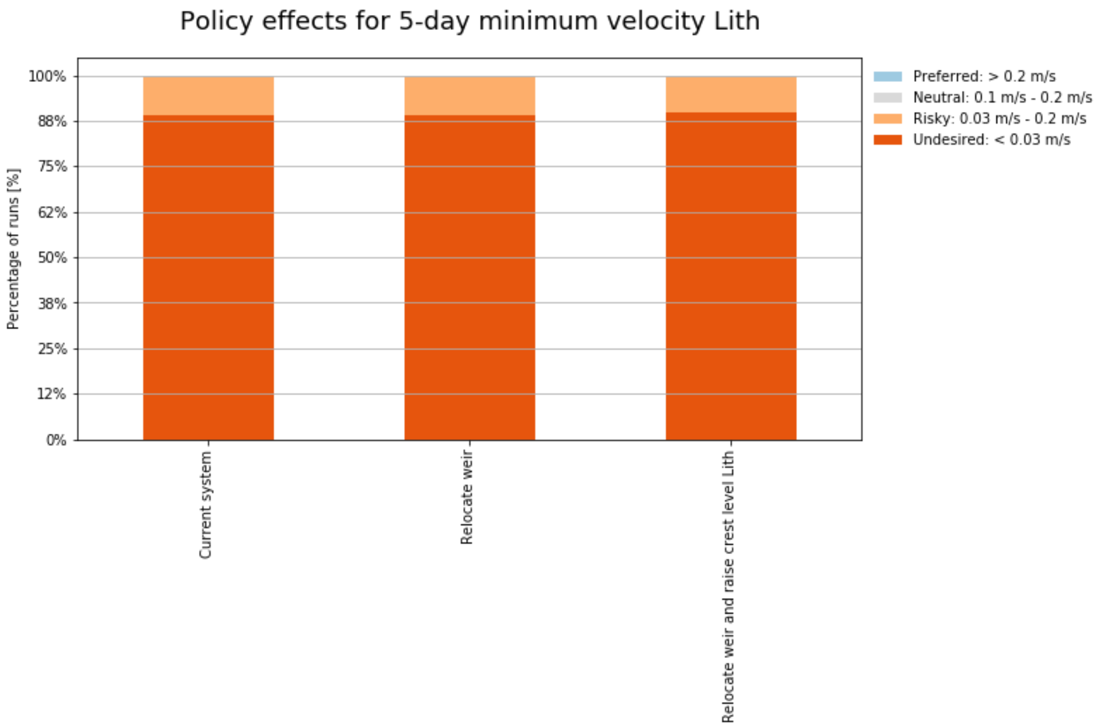
D. 3 Sensitivity analysis base ensemble for the KPI "Percentage of full fresh water buffer



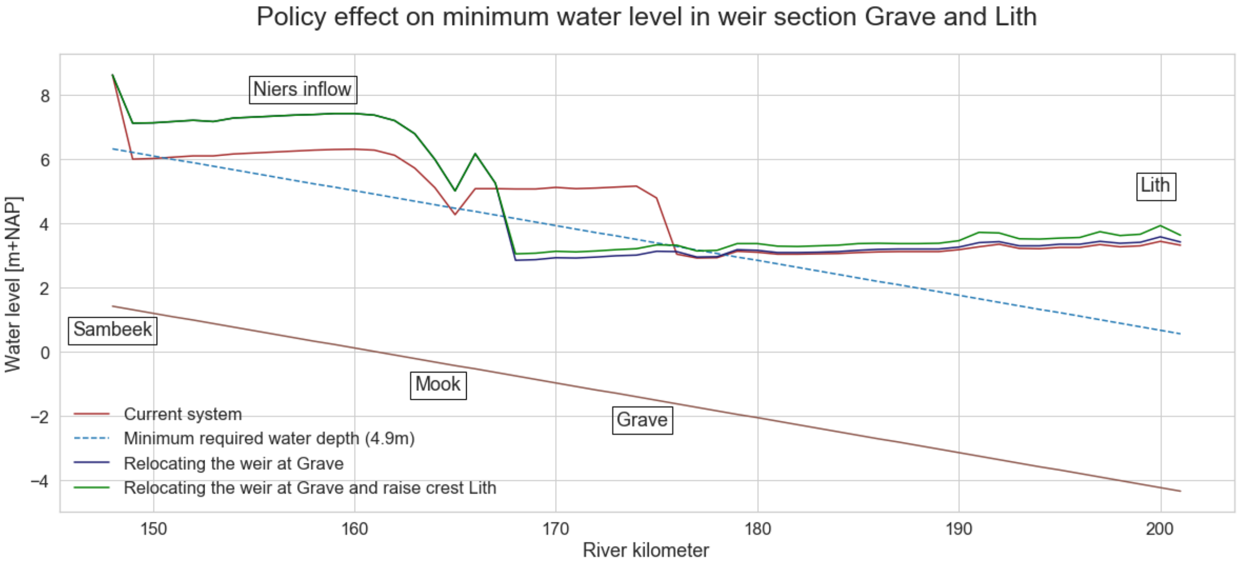
D. 4 Policy effects for freshwater buffer Lith in relation to base ensemble



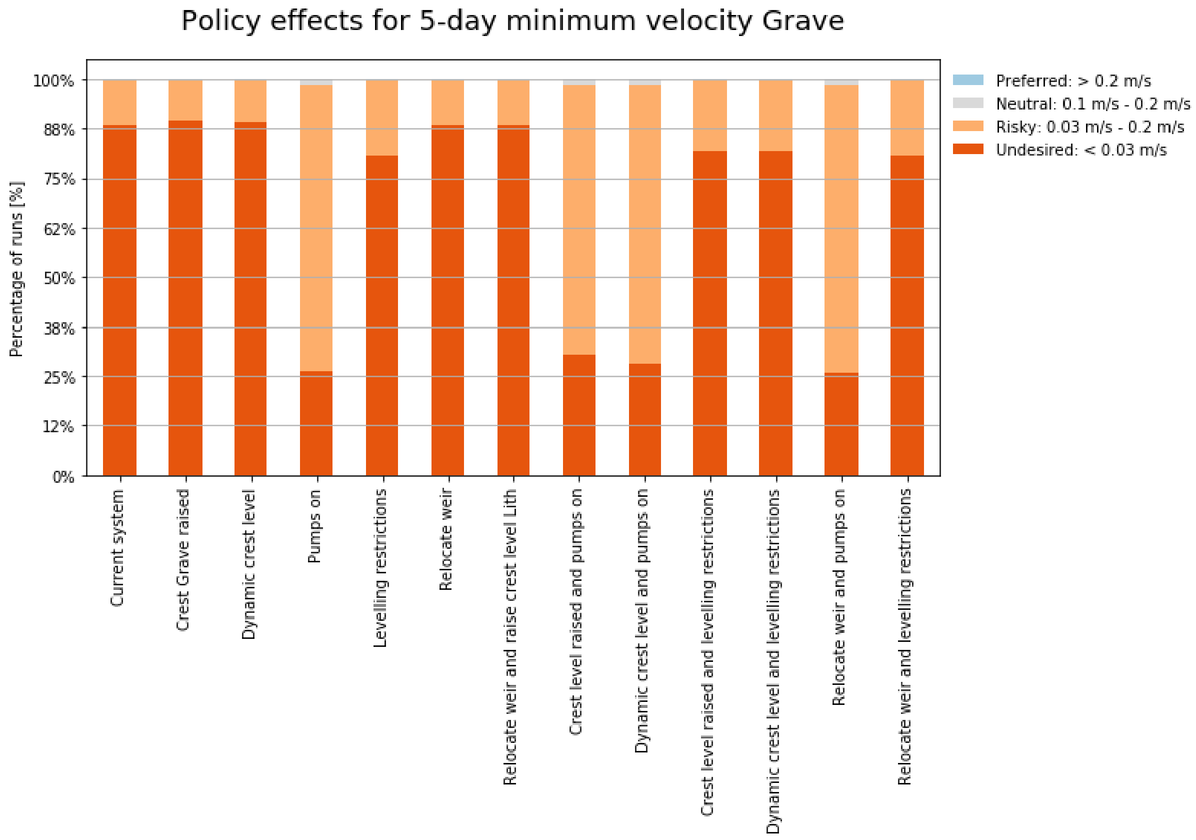
D. 5 Policy effects for 5-day minimum velocity Lith in relation to base ensemble



D. 6 Policy effects for 5-day minimum velocity Lith



D. 7 Effect of relocating the weir at Grave on the minimum water level in longitudinal sketch of weir section Grave and Lith



D. 8 Policy effect on 5-Day minimum velocity in weir section Grave

river Meuse at Maaseik during high and low water. Source: Douwe Willems