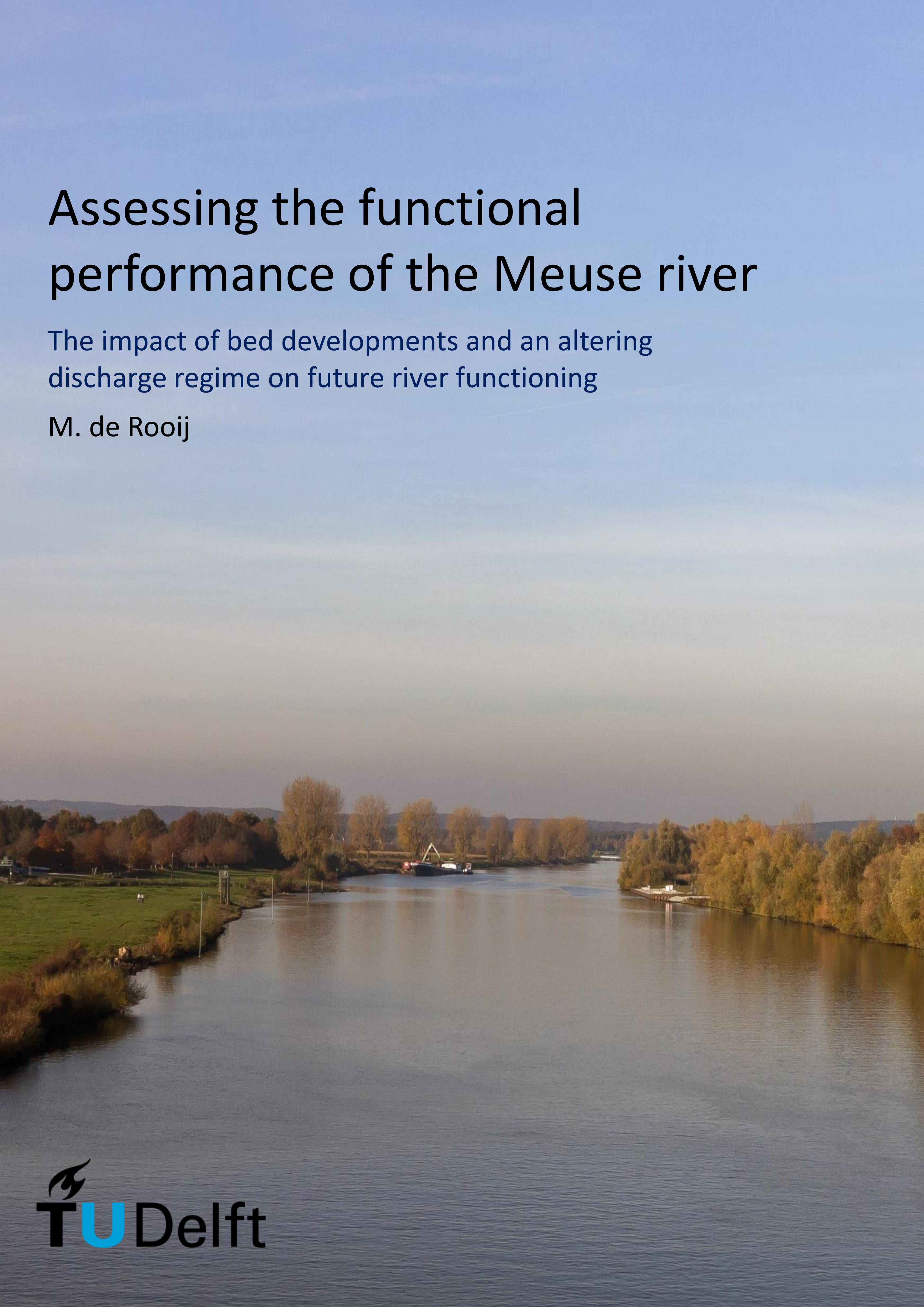
Assessing the functional performance of the Meuse river

The impact of bed developments and an altering discharge regime on future river functioning

M. de Rooij



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Summary

The Meuse river is the second largest river in the Netherlands. Like other rivers worldwide, the Meuse river provides a variety of socio-economical functions such as navigation, drinking water supply, flood safety, ecology and leisure. The Meuse is a rain-fed river, which causes large and quick fluctuations in river discharge. In the early 20th century, weir-lock complexes and canals running parallel to the main stream were constructed, causing water levels to be relatively constant at most of the river's stretches.

The Meuse river discharge regime is expected to alter as a result of global warming induced climate change. At the same time, the construction of dams and weirs in combination with intensive dredging, river normalisation works and river bend cut-offs have caused the Meuse riverbed to degrade over the past 100 years. This has caused the bed levels to decrease with about one to three meters, depending on the river stretch. This bed degradation is expected to continue for the future decades.

The aim of the study is to determine the effects of a changing discharge regime and large scale bed level changes on the functional performance of the Meuse river until the year 2050. The functional performance is assessed for the river functions navigation and flood safety.

Methodology

The methodology consists of six steps that are taken consecutively. Figure 0.1 presents these steps.

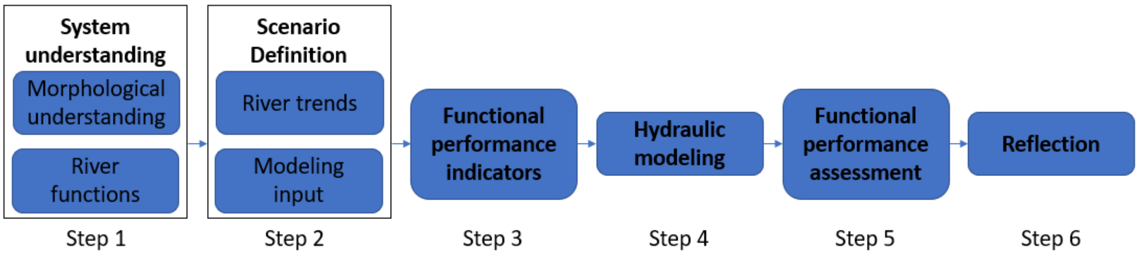

Fig. 0.1.: The research methodology steps.

The first step focuses on understanding morphologic mechanisms in the Meuse river and elaborates on the understanding of river functions. In step 2 the scenarios are determined. With regard to bed level developments, a reference scenario, and two future bed degradation scenarios are defined. To represent the current and future spread of possible discharge regimes, a reference, wet and dry discharge regime are defined.

The third step encompasses the definition of functional performance indicators. The water levels at bottleneck sills and discharges available for bottleneck locks determine the river functioning regarding navigation. Both bed degradation and lower discharges in summer and fall can impact the shape of backwater curves and with it the depth above sills in the river.

For flood safety, the maximum water levels at levees resulting from representative discharge waves determine the functioning of the Meuse river. Changes in representative water levels lead to changes in levee berm width and crest height demands. Bed degradation decreases the representative water levels while higher representative discharge magnitudes have the opposite effect.

In the next step reference and future river characteristics are obtained from a 1D hydraulic model. The defined scenarios are imposed in the hydraulic model by adjusting the upstream boundary condition (representing the discharge regimes) and by changing the bed levels in the river's main stream.

In step five, the output of the hydraulic model (water levels, discharges) is used to assess the current and future functional performance indicator scores. When the indicators are translated into draft limitations and waiting times (navigation) and changed levee dimension demands (flood safety), the current and future functional performance of the Meuse river is quantified.

In the last step, the functional performance assessment is reflected on from a water manager's perspective.

Results

If weirs can maintain their Controlled Water Levels (CWL), water levels depend on the discharge and bed level to a very limited extent. Water levels near sills in the river that limit the draft of ships will experience some change due to the imposed river bed trends, but the impact on navigation efficiency is limited to a few percent. In free-flowing stretches, however, the water level depends on the bed level a lot more. Lower discharges due to climate change can potentially multiply extra waiting times for ships with a factor of 2 or 3.

During extreme discharge events, the Meuse river transforms to a free flowing river. In these periods, the impact of bed degradation on the water levels is more pronounced. Locally, the water level decrease is about two third of the imposed bed degradation. Higher extreme discharge magnitudes caused by climate change are expected to overrule this decrease in water level.

Conclusions

Decreasing water levels and discharges during periods of low flow will emphasize the vulnerability of bottlenecks for optimal river functioning. Increasing flood discharges will demand higher and stronger levees, while bed degradation is expected to compensate for this only to a limited extent. Increasing buffer capacity in Dutch stretches of the Meuse river and elsewhere in the catchment could mitigate the negative impact of reduced discharges due to climate change. Furthermore, bed level developments should be closely monitored in order to include the effects in future decision making issues. On top of that, it is advised to assess whether it is legitimate to assume that weirs can sustain their CWL at all time.

Preface

This graduation thesis is the final challenge of my Master of Science program in Hydraulic Engineering and Water Management at Delft University of Technology. As a graduate intern, I spent a lot of time at the Arcadis offices in Amersfoort and Rotterdam. The atmosphere, contacts and facilities Arcadis offered were of great help to my thesis work. To be able to work in a new, professional environment was very refreshing and stimulating. Especially the colleagues and fellow graduate students made it a pleasure working at the office every day again. I would like to thank Harm Albert Zanting and Floris Groenendijk for letting me have this great experience.

This research would not have been possible without the guidance, mentoring and supervision of my graduation committee. Thank you all for your feedback, insights and patience during this thesis process. I have experienced the committee meetings as intense, challenging and sometimes confronting, but also fruitful and educational moments. Thank you all for that!
On top of that, I would like to thank some people in person. First of all, my daily supervisor and fellow Arcadian Wout van Dijk. Whenever I got lost in my thesis work, you could help me out with a few sharp statements. Thanks as well for being as flexible and approachable as you were. Thank you as well, Saskia van Vuren. The chance of letting me do this research is very valuable to me. The personal meetings we had, but also the large number of people you connected me to within and outside Rijkswaterstaat have given me a lot of energy to bring this project to a good end. Astrid Blom, thank you for the sometimes short but insightful meetings we had. In a few short sentences you were always able to get me back on track.
Special thanks go to my parents and Frank, Thijs and Doret for their compassion, inspiration and confidence during my time as a student in Delft. Lisette, thanks a lot for your love, support and necessary distraction during my student life and the last months of my thesis work in particular.
Finally, I would like to thank the close friends and roommates I met in Delft, you made my student life unforgettable. Besides, I had never thought I would have to spend so much time with Bart, Max and Zhouxin in lock-down, but the pleasure was all mine guys!

I am looking forward to finalize my graduation with a presentation and defense, enabling me to start my life as a professional engineer. I am very happy to start this new phase with the experience of doing this research work in my back pocket.

Marijn de Rooij
Rotterdam, June 2020

Contents

Introduction

1

1.1 Background

Apart from conveying water, sediments and ice (Janssen et al., 1979), nutrients (Yindong et al., 2015) and plastic (Schmidt et al., 2017), rivers also provide socio-economical functions like navigation, drinking water supply, mining activities and hydropower. These functions are enabled by the range of hydraulic and morphological properties that characterize (sections of) rivers, including the discharge, water level, bed level, flow speed and river width. Functions provided by the river are at stress because of global warming and the river response to human interventions in the river.

Global warming results in a changing climate, which affects the flow conditions in the river. In general, this climate change is expected to cause more frequent and more severe flood peaks and lower and more persistent annual flows. The severity of global warming is uncertain. The global trend, however, is quite straightforward: the more global warming, the more future river discharges tend towards the extremes (Arnell and Gosling, 2013).

Interventions in a river generally cause altering sediment carrying capacities and a change in upstream sediment input. Engineering interventions like the construction of dams and weirs cause a reduced sediment load for downstream branches and interventions like bed protections and canalizations increase the flow speed and the sediment carrying capacity.

Both a reduced sediment input load and an increased sediment carrying capacity, cause the river to find a new equilibrium profile, which is found in a trend towards a reduced slope. The slope reduction can be visualized by tilting the bed around a hinge point typically close to the river mouth. Between the hinge point and the river mouth, aggradation occurs, while degradation causes the river to incise upstream from the hinge point. This trend towards the new equilibrium state is a long-term, persistent and uncertain process (Galay, 1983; De Vriend, 2015). Bed degradation is a challenge faced in numerous rivers worldwide (Habersack et al., 2016; Blom, 2016; Zheng et al., 2018).

In the Netherlands, Rijkswaterstaat is responsible for the major rivers and other primary waterways to fulfill their functionalities. In order to make this possible for the future, the ministries IenW and LNV, Rijkswaterstaat, provinces, water boards and municipalities, jointly initiated the Integrated River Management (IRM) program. The goal of IRM is to manage a future proof water system that succesfully fulfills numerous socio-economic and environmental functions. The rivers Rhine and Meuse are among the main parts of the Dutch water system and therefore get focus within IRM. The integrated approach that is aimed for, means that different local and national stakeholders are represented, but also that river management is executed in such way that it suits the hydraulic and morphologic mechanisms in the river system. For IRM a quickscan for riverbed management was executed. In this study, effects of altering discharge regimes and bedlevel changes on the river functions are studied. Also, it considers management strategies that aim to improve the river's

performance for the different functions.
In the light of the IRM program, a preliminary study assessing the functional performance of the Dutch Rhine, including river dynamics and exogenous trends was done by Hiemstra (2019). In this study, effects of global warming and human river interventions were translated to changes in water levels in order to assess the river's functional performance. Also, the cost-effectiveness of sediment nourishments was evaluated. As the responsibilities of IRM are not limited to the Rhine catchment, there is need for focus on the Meuse river as well.

The Meuse (see Figure 1.1) is, after the Rhine, the second largest river in the Netherlands. Its spring is located at the Langres Plateau in France. From there it flows via Belgium to the North Sea in the Netherlands. It has a total length of about 900 km. The Meuse enters the Netherlands in the south of Limburg near Eijsden (rkm 0). From Borgharen (rkm 16) onwards, it forms the border between Belgium and the Netherlands. This part is called the Common Meuse (Dutch: Grensmaas). The Common Meuse is a relatively steep (slope of $5{\cdot}10^{-4}$), free flowing, dynamic gravel bed river that is not suited for navigational purposes. From Maastricht to Roermond navigation is possible through the Julianakanaal. After the river passes the weir at Linne, the water level in the river is controlled by weirs that divide the river in separate basins. Because of this weirs the river is navigable. In between Linne and Roermond, the bed slope decreases relatively quickly to approximately one fifth of the slope in the Common Meuse. Downstream from Roermond, the Meuse has a predominantly sandy riverbed (Murillo-Muñoz, 1998; Asselman et al., 2018) and has therefore very different characteristics compared to the upstream reaches. From Lith onwards, the North Sea tide influences the hydro- and morphodynamics, altering the river characteristics once again.
The Meuse river is characterized as a rain-fed river system, including large fluctuations in river discharge, responding rather quickly to changes in upstream parts of the river basin. Moreover, the water level in the Meuse is controlled by several weirs, essentially differentiating the Meuse from the Rhine. The riverbed sediment contains coarse sediment (gravel) in the upper layer and fine sediments (fine sand) beneath, which makes it challenging to accurately foresee and anticipate on future riverbed developments in the Meuse river (see Section 2.2.1) (Murillo-Muñoz and Klaassen, 2006; Asselman et al., 2018).

Fig. 1.1.: The Meuse river catchment and its major tributaries (Internationale Maascommissie, 2013).

It is expected that the Meuse river discharge regime will alter as a result of global warming (Sperna Weiland et al., 2015). Like other rivers, also in the Meuse river the peak discharges will become higher and more frequent, while the low-flows during late summer and fall will become even lower and more persistent. Depending on the global warming scenario (developed by Van den Hurk et al. (2014)), the peak discharges (return period of 1250 years) will increase by 8 to 27% in 2050, while the annual mean 7 day minimum flow will decrease by 0 to 44% (Hegnauer et al., 2014; Sperna Weiland et al., 2015).

Like other rivers, the Meuse experienced a degrading bed level trend in the 20^{th} century. The trends vary per river stretch, which is given in Table 1.1. The bed level measurements can be distorted by dredging activities. To see the response of the river without this distortion, the timeframes without dredging activities are given as well. Measurements on Meuse riverbed levels are available for the period 2007-2017 as well. The analysis of these more recent measurements is presented in Section 2.2.3.

Tab. 1.1.: The speed of bedlevel changes (m/year). Adjusted from Van Dongen and Meijer (2008).

Trajectory		Maximum timeframe		No dredging impact		1995-2007	
		Period	Average	Period	Average	Period	Average
Bovenmaas	(rkm 5 - 15)	1995-2007	-0.010	1995-2007	-0.010	1995-2007	-0.010
Grensmaas	(rkm 16 - 53)	1921-2007	-0.032	1970-2007	-0.015	1995-2007	-0.033
Plassenmaas	(rkm 69 - 87)	1916-2007	-0.025	1970-2007	-0.010	1995-2007	-0.028
Peelhorstmaas	(rkm 87 - 121)	1916-2007	-0.010	1942-2007	-0.007	1995-2007	-0.025
Venloslenk	(rkm 121 - 155)	1916-2007	-0.012	1942-2007	-0.006	1995-2007	-0.025
Benedenmaas	(rkm 164 - 200)	1937-2007	-0.019	1942-1995	-0.004	1995-2007	-0.062
Getijdenmaas	(rkm 201 - 226)	1936-2007	-0.024	1942-1984	-0.006	1995-2007	-0.045

From a water manager's perspective, an increasing pressure on river functions is undesirable. In the IRM program, appropriate management options will be found in order to cope with the increasing pressure put on river functions. Management strategies concern soft measures like sediment nourishments, hard measures like the construction of longitudinal dams, but also river widening and secondary channels are considered. Before decisions on river management options are made, an understanding of the functioning and its response to morphologic and hydraulic developments is required.

1.2 Problem definition

Until 2050, the effects of global warming and human river interventions are expected to put increasing pressure on the functional performance of the Meuse river. The way the hydraulic and morphological conditions will alter in the future are uncertain as well as the interaction between the two. Because of global warming discharge peaks will be more frequent and more severe, while the annual period of low-flows will take longer with lower discharges. In the last century, bed degradation has been omnipresent in the Dutch reaches of the Meuse. The degradation rates vary from reach to reach, but the overall trend until 2007 was straightforward (Table 1.1). More recent bed level trends are still unknown and so is the future development of bed levels in the Meuse river.

Moreover, there is a need for insight in the effects of a changed discharge regime and large-scale morphological processes on the performance of the Meuse river on important river functions. At this moment, it is unknown whether these developments urge for future mitigating measures.

1.3 Research objective and research questions

The aim of the study is to determine the effects of a changing discharge regime and large scale bed level changes on the functional performance of the Meuse river until the year 2050.

The research questions that will be answered in order to achieve the research objective are:

1. What mechanisms determine the response of the Meuse riverbed to human interventions in the river system?
2. What indicators determine the current performance of the Meuse river regarding the functions navigation and flood safety?
3. How will water levels and discharges in the Meuse river change taking the altering discharge regime and large scale bed level changes into account?
4. What is the impact of the expected change of water levels and discharges on the functional performance indicators in both regulated and free flowing Meuse river stretches?
5. Reflecting on these results, what recommendations can be given for water managers responsible for the Meuse river?

1.4 Methodology

The problem definition above describes the problem in a very broad perspective. To ensure the feasibility of this study, regarding the limited time span, important limitations are set to the research scope. The most important limitations are the number of river functions that is included, the simplification of the numerical modeling that is going to be used and the type of measures that will be considered.

From the numerous functions that the Meuse river enables (Section 2.3), only navigation and flood safety are included in this study. The function of drinking water supply was initially considered as well and information regarding that function is presented in Appendix A.

In this study, only hydrodynamics will be modeled numerically. Morphologic changes will be imposed on this hydraulic model in order to keep the modeling work relatively simple and feasible. Using a morphologic model would take too much effort, which would make it impossible to execute the functional assessments in the available time frame. The influence of an altering discharge regime on the bed level change in the Meuse river falls not within the scope of this study. Figure 1.2 presents the considered steps taken in this research.

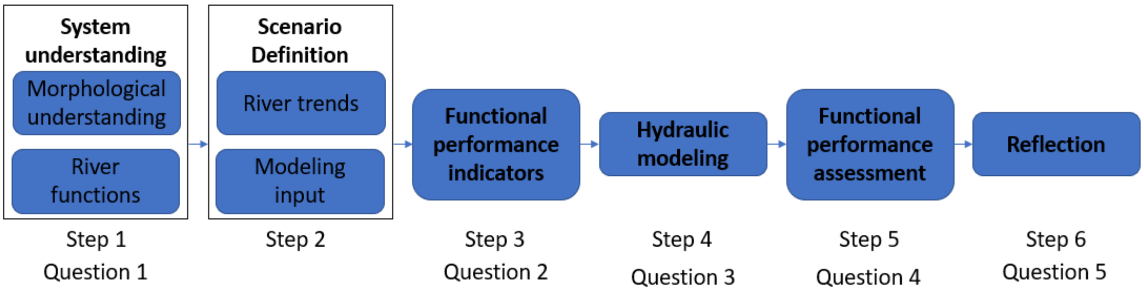

Fig. 1.2.: The research steps and linked research questions.

The research work starts with understanding the river system in step 1. Next the functionality of the Meuse river is addressed. In this step, the effects of a changing discharge regime and water level are translated to a change in functional performance. This functional performance is quantified with the use of indicators that will be defined in this step. When it is clear what indicators determine the functional performance of the river, the future river state is estimated. This step (step 3) encompasses the definition of different future scenarios, using several scenarios for a changing discharge regime and bed level changes. These scenarios define the changes that are implemented for the bed levels and boundary conditions of the hydraulic model that is ran in step 4. At the end of step 4, the water levels and discharges that result from the defined scenarios become clear. These data is used in step 5, in which the actual functional performance is assessed, using the assessment indicators from step 2. Based on the functional performance assessment results, reflection on the future river state from a water management perspective will encompass step 6.

1.5 Thesis outline

This section explains the structure of this thesis report. The report consists of 6 chapters. Chapters 2, 4 and 5 answer the research questions presented in Section 1.3. The outline is summarized below:

- Chapter 2 provides an overview of the Meuse river system, addressing its hydrologic, morphologic and functional characteristics. In Section 2.2 the first research question is addressed.

- Chapter 3 describes the way river development scenarios are defined. The developments regarding the future discharge regime are based on existing studies, while for the bed level developments rough estimations are necessary. On top of that, this chapter describes the hydraulic model set-up.

- Chapter 4 provides insight in the river functions navigation and flood safety, leading to definition of the indicators determining the current functional performance of the Meuse river system. Furthermore, the functional performance assessment is explained. Also, the results of the hydraulic modeling and functional performance assessments are presented (Sections 4.1.4 and 4.2.4). At last, an global estimate of the costs attached to altering river functioning is given. This chapter provides the answers to the second, third and fourth research questions.

- Chapter 5 discusses the way assumptions and other choices made in this research influence the outcome. Moreover, it deals with the applicability of this study to other river systems, also comparing this research work to the work by Hiemstra (2019). Furthermore, the way this research work can be used for water managers is addressed in Section 5.3.

- In Chapter 6 the main conclusions of this research are presented, addressing answers to each separate research question. Next, recommendations for further research is presented.

2

Area description

In order to obtain insight in the relationship between river functioning and future developments in the river, an overview of the Meuse river is needed. General information is presented in Section 2.1 and an overview of the different functions the Meuse river facilitates is given in Section 2.3.
In Section 2.2, morphology of the Meuse river is addressed, among others dealing with the following research question:

What mechanisms determine the response of the Meuse riverbed to human interventions in the river system?

In Figure 2.1, the positioning of this chapter in the research process is summarized.

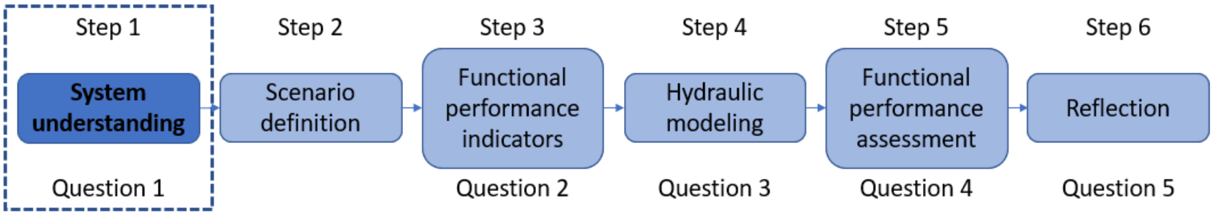

Fig. 2.1.: Summary of research steps. The current chapter deals with step 1.

2.1 Introduction

The Meuse river catchment is located in France, Belgium, Germany and the Netherlands, draining a total area of about 33,000 km^2. The Meuse river headwaters are located at the Langres Plateau in France, from which the river flows towards the north past the city of Sedan. It passes the French-Belgian border at Hastière. In Belgium, the Meuse flows past Namur and Liège after which it enters the Netherlands near Eijsden. Past Maastricht, near the village of Borgharen (rkm 15), the Meuse forms the border between Belgium and the Netherlands until rkm 55. The stretch betweeen rkm 15 and rkm 55 is not available for navigation. Upstream from Borgharen the Meuse water level is controlled by the weir at Borgharen and therefore navigable. Parallel to the common Meuse lies the Julianakanaal, which facilitates navigation between Maastricht and Maasbracht. The weir at Linne facilitates navigability until the Julianakanaal entrance at Maasbracht. Between Linne and Roermond, the Meuse is meandering heavily and in between the meanders large sand/gravel mining pits are present. This stretch is navigable due to the weir at Roermond. The biggest share of navigation on this traject, however, follows the channel parallel to the Meuse from Heel to Buggenum. For an overview, see Figure 2.2. Downstream from Roermond, the Meuse river is a lowland river with a dominantly sandy riverbed. Thanks to weirs at Belfeld, Sambeek, Grave and Lith the Meuse is navigable from Roermond to the North Sea. Downstream from Lith, the Meuse is a freeflowing river. The tidal range at Lith is about 30 cm, increasing in downstream direction.

Between 1911 and 2014, the average Meuse river discharge at Monsin (12 km upstream from Belgian-Dutch border at Eijsden) is 273 m^3/s (Sperna Weiland et al., 2015). Because of the big dependency of the Meuse discharge to rain, the absence of glaciers in the catchment area and the relatively small size of the catchment area, the average discharge varies heavily per year and even per month. Discharge data reaching from 1911 to 2014, for instance, report yearly averages ranging from 406.6 m^3/s (1966) to 74.5 m^3/s (1976). In Figure 2.3 the flow duration

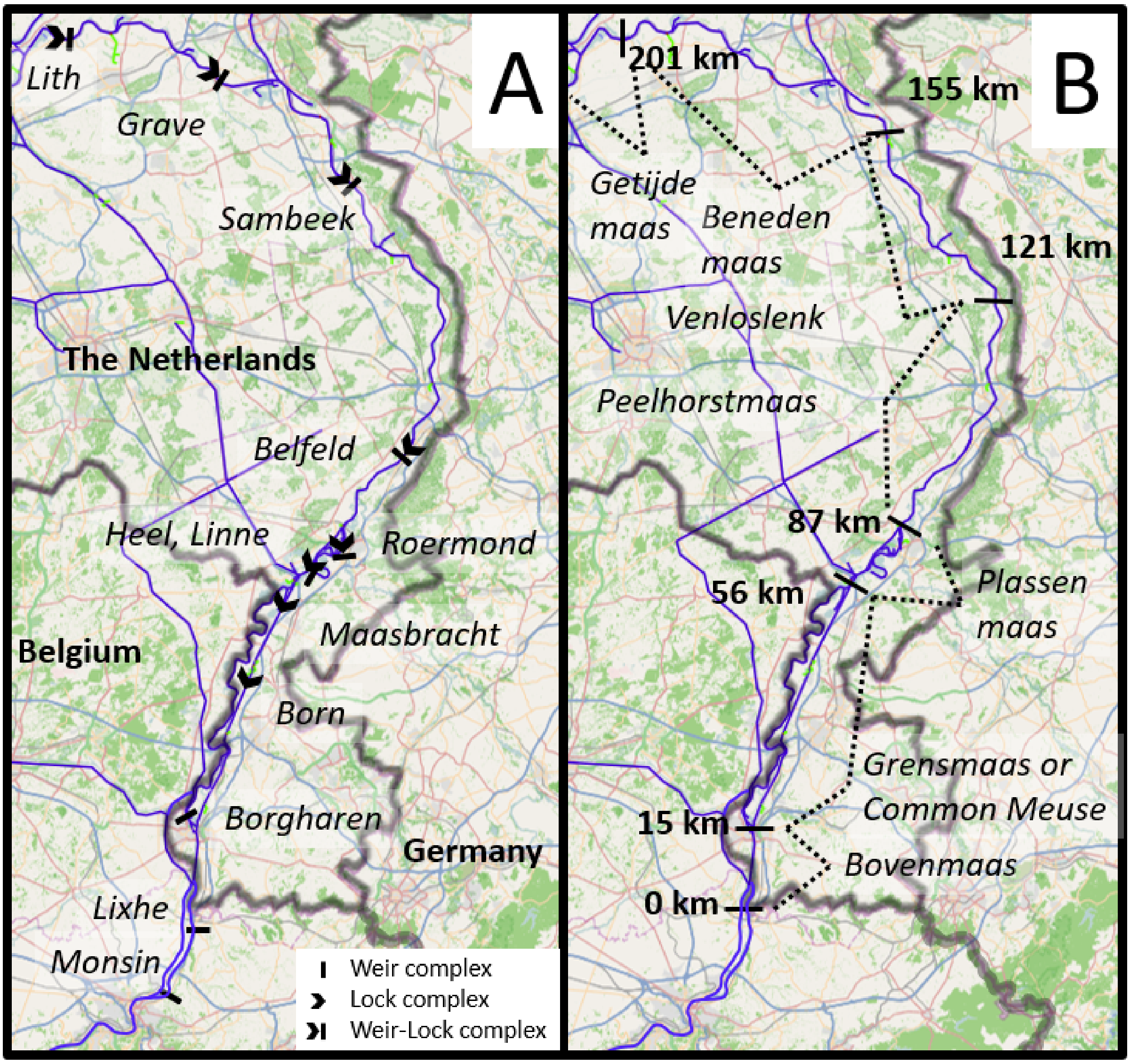

Fig. 2.2.: The Dutch Meuse, its most downstream weir-lock complexes (A) and named river trajectories (B). In map A, one lock is pictured for both lock complex Heel and Linne although the complexes are in reality separate. Lock Heel provides a connection between the Lateraalkanaal and the Meuse river, while lock Linne provides a connection between the Meuse river basin upstream from weir Linne and downstream from weir Linne (OpenStreetMap Nederland, n.d. Rijkswaterstaat, 2020d).

curve is presented. From Figure 2.4 it becomes clear that both the inter annual and intra-annual variations in discharge are big. This variability causes the Meuse river to be unpredictable. It can be imagined that unpredictable river conditions form a challenging context for user functions that are performed on the Meuse river.

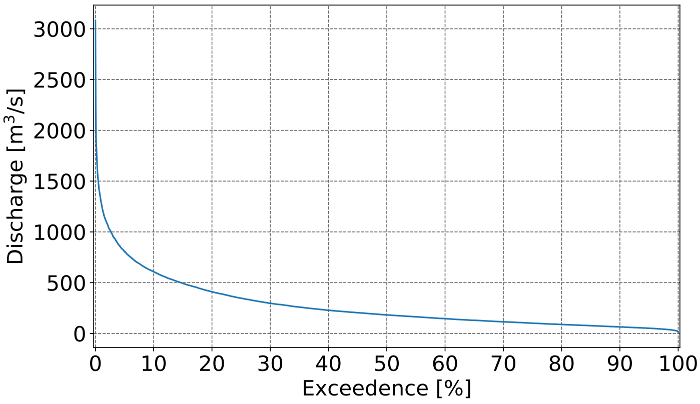

Fig. 2.3.: Flow duration curve at Monsin for the period 1911-2014. Adjusted from Sperna Weiland et al. (2015).

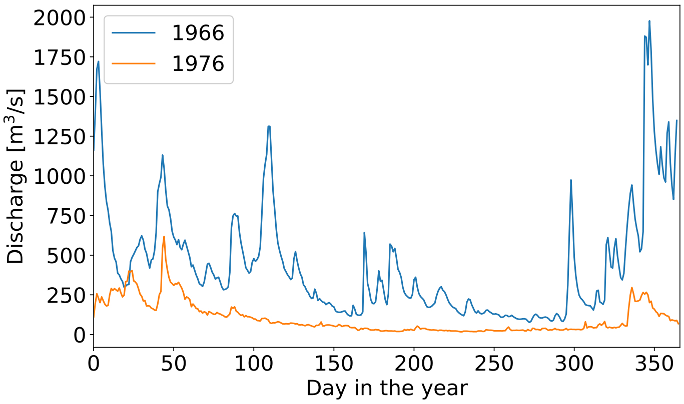

Fig. 2.4.: Daily discharges at Monsin in 1966 and 1976.

Also on a decadal scale, the Meuse river is still highly variable. This means that research on developments during the last decade in which the hydraulic conditions are important, is still highly influenced by the discharge regime of that particular decade. The variability of the inter annual discharge distributions does not even out at a decadal scale. When analyzing, for instance, bed level developments, this is something that should be dealt with. Drawing conclusions based on analysis of a decade of data is not reliable. This implies that the accuracy of forecasts for the coming decades is highly dependent on random variability as well.

The Dutch stretches of the Meuse river cross geological active areas, where stretches of uplifting blocks and subsiding blocks alternate each other (Figure 2.5). This tectonic movements all have an order of magnitude of a few centimeter (2-3) per century. According to Van den Berg et al. (1994), the reaches upstream from Grevenbricht (rkm 45) until the border (rkm 0) flow over uplifting tectonic blocks. In between Grevenbricht and Tegelen (rkm 102.5) the area is subsiding. From Tegelen to Velden (rkm 112) a slight uplift was measured again, while downstream from Velden the area is subsiding. In the uplifting stretches, the Meuse is incided in the landscape, resulting in terraces in the river valley. In the subsiding areas, the river has more room, resulting in a typical lowland river with space for meandering.

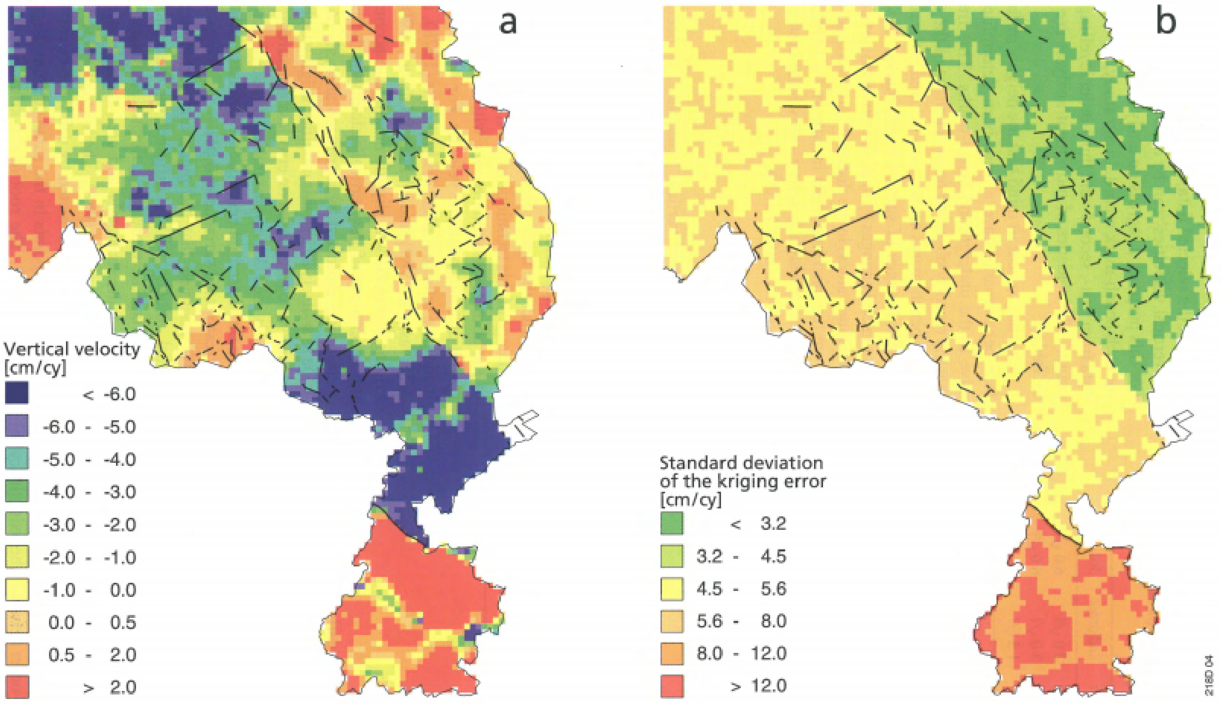

Fig. 2.5.: Vertical tectonic movement rates (cm/cy) in the area surrounding the Meuse river in the Netherlands (Van den Berg et al., 1994).

During the 30's of the 20^{th} century, weirs were constructed in the Meuse river to guarantee a certain minimal water level throughout the year. The weirs were combined with ship locks to make sure the river was navigable in between the several weir stretches. The weirs are located at Borgharen, Linne/Heel, Roermond, Belfeld, Sambeek, Grave and Lith. The effects of a weir on the water levels are explained in Figure 2.6, Figure 2.7 and Figure 2.8.

Most of the time, the water level at a weir determines the upstream water level of each weir stretch. In times of low flow, the water level increase in upstream direction is very small (See Figure 2.6). When discharge increases, however, a backwater curve forms upstream from the weir, increasing the water level in upstream direction (See Figure 2.7). When the backwater curve increases, the water level at the downstream side of the next weir upstream almost equals the controlled water level of this weir. At this moment, the weir gets obsolete and is opened. At this

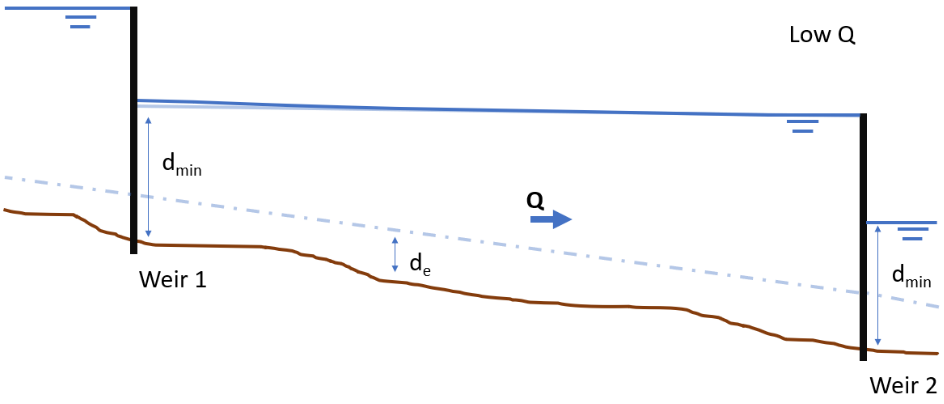

Fig. 2.6.: Water levels during low flows. The dashed line represents the equilibrium water level when no weirs would be present.

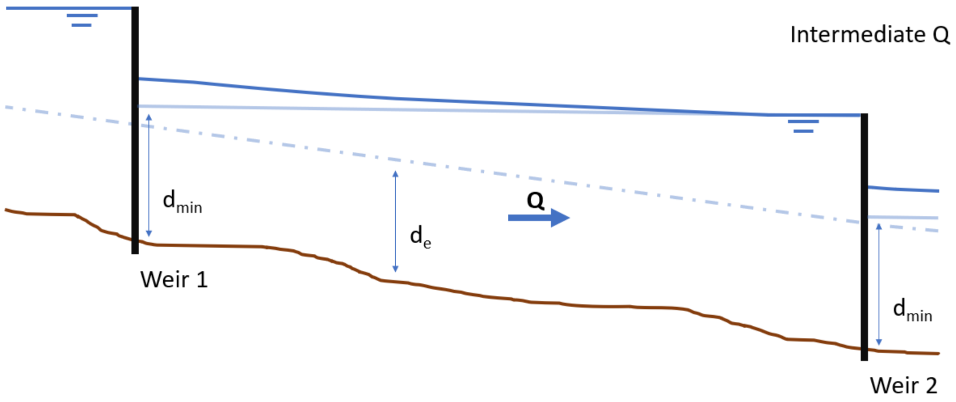

Fig. 2.7.: Water levels during intermediate discharge with backwater curves visible. The dashed line represents the equilibrium water level when no weirs would be present..

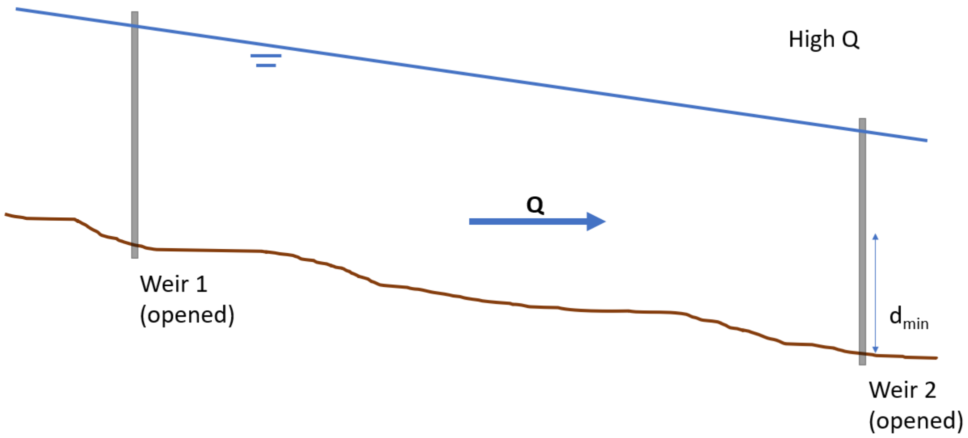

Fig. 2.8.: During high flows, the weirs can be opened and the river is free flowing. The weir piles constrict the opening, which has local effects on the water level that are not included in this sketch.

moment the river transforms to a free flowing river (See Figure 2.8).

2.2 Morphological processes in the Meuse river

Like many other rivers in the world, the Meuse river has been subjected to intensive river engineering. From the end of the 19^{th} century on, people have tried to control the river to make it safer and easier to navigate (Breukel et al., 1992).Thanks to these measures, the Meuse river has become an important navigational route. On the long term, however, a river's response to an engineering intervention can counteract the short term gain in river conditions. The long-term response of rivers is typically slow and very persistent.

2.2.1 Meuse riverbed

The Meuse river bed material was analyzed and described elaborately by Murillo-Muñoz (1998). The following description of the Meuse river bed material is largely based on that thesis. Characteristic grain diameters in the Meuse river vary strongly in longitudinal direction. In the more upstream reaches of the Meuse river, the bed material has a relatively constant value for the d_{50} of about 16mm. A few kilometers downstream from Roermond, the variability in grain size becomes much bigger and also the sand fraction increases. From Venlo onwards, the d_{50} has a value of about 2.6mm, but the variation in grain size is huge. Figure 2.9 shows that between km 90 and 110 the Meuse shifts from a gravel-bed river to a sand-bed river.

In any Meuse river stretch, the bed material behaviour cannot be understood without taking the large variation of grain sizes into account. Especially the influence of static armors is reported to be big on the sediment behaviour throughout the Meuse river (Vermeer, 1990; Sieben, 2008; Asselman et al., 2018; Reeze et al., 2020).

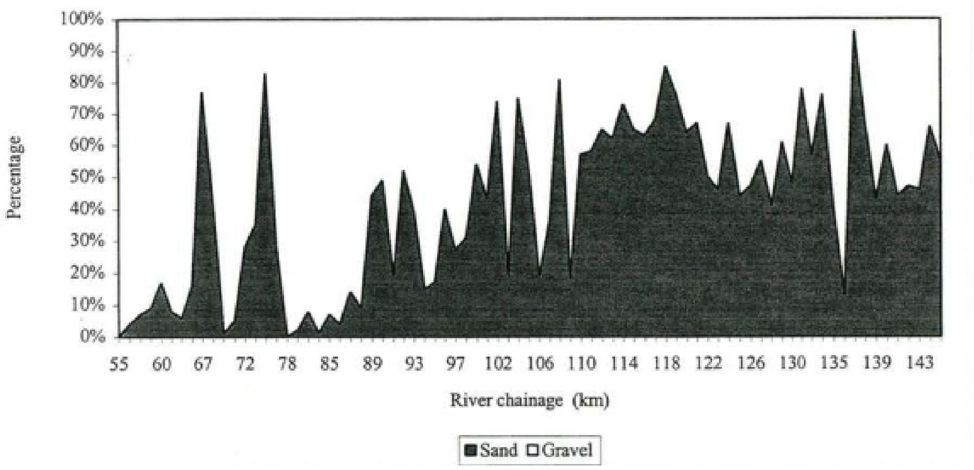

Fig. 2.9.: Gravel and Sand content in the bed surface sediment along the Meuse river Murillo-Muñoz, 1998. The measured data is from 1983.

Static armor

Rivers with a gravel bed typically have a coarse layer on the riverbed surface. This layer is known as the armor layer. According to Hassan et al. (2006) the armor layer typically consists of the grains that belong to the 10% or 16% coarsest grains in the substrate. Conditions under which an armor layer can form are varying. A common condition is that the substrate composition is at least bimodal, meaning the sediment consists of different dominant particle sizes. One mechanism of armoring was found by Parker and Klingeman (1982) and Parker, Dhamotharan, et al. (1982). They noticed that in some rivers, all particle sizes are approximately equally represented in the transported sediment, although the finer particles are set to motion easier than the coarser ones. They explained this by the fact that the coarser particles are overrepresented in the riverbed surface layer. In this way the finer particles shelter under the coarser ones, leading to a similar sediment transport rates of both particle sizes. This type of armoring is referred to in literature as a mobile armor layer (Parker and Sutherland, 1990; Hassan et al., 2006; Orru et al., 2016). In order to sustain the mobile armor, sediment supply from upstream is required. Another type of armor formation occurs when the river flow induced shear stress on the riverbed is such that the finer particles are set to motion, but the coarser particles are not. In this way, selective transport causes the surface layer of the riverbed to be coarser than the average substrate. This type of armoring is referred to as a static armor (Parker and Sutherland, 1990; Hassan et al., 2006; Orru et al., 2016). Figure 2.10 shows a cross section of a riverbed with a fully developed static armor.

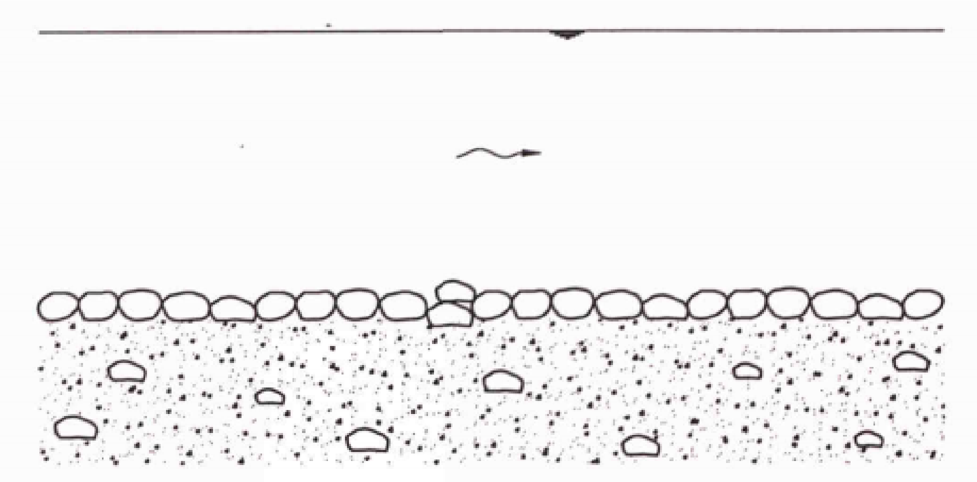

Fig. 2.10.: A fully developed static armor (Waterloopkundig Laboratorium, 1994).

A sediment supply-limited river is more likely to form such a static armor (Parker and Sutherland, 1990; Hassan et al., 2006; Orru et al., 2016). Over time, these rivers run out of fine sediments on the bed surface, leaving behind the coarser grains. A static armor can break up in times of increased shear stress on the riverbed, as a result of increased river discharge. The breakup and reformation of a static armor was studied in different circumstances. Vericat et al. (2006) studied armor break up and reformation in a gravel bed river. This research reported the gravel bed broke up during flood events and reformed only in base flow conditions. Orru et al. (2016) studied the formation and breakup of an armor layer in an experimental flume with a trimodal sand-gravel bed in the upstream reach of the flume, followed by a sandy bed reach. First they allowed a static armor layer to fully develop during 16 hours of constant discharge. After 16 hours, the sediment transport in the flume was almost zero. Next, the discharge was suddenly increased, leading to breakups in the armored stretch. The armor reformed and strengthened during the peak flow conditions. This reformation was possible due to grain mobilization in the upstream reaches of the flume. Due to armor breakup in upstream reaches, there was sediment supply for the more downstream reaches. It is stressed that the armor reformation was a dynamic one. Because the coarse static armor was set to motion, the gravel front forming the transition from gravel-sand bed to sand bed had moved in downstream direction.

There are similarities between the experiment by Orru et al. (2016) and the reported conditions n the Meuse river. Micha and Borlee (1989), Asselman (2019), and Reeze et al. (2020) report the bedload transport at the Belgian-Dutch border to be close to zero, ruling out the formation of a mobile armor in the Dutch stretches of the Meuse river. Murillo-Muñoz (1998) report the Meuse river bed to be multimodal, whereas Figure 2.9 shows that the gravel content of the substrate decreases in downstream direction. Although the presented measurements are not as up to date as would be desirable, it gives some basic understanding in the morphologic system of the Meuse river. More recent information on grain size distribution is not available. A difference is that in the experiment breakup of the armor layer inevitably leads to a lower overall bed level, while in the Meuse river sediment could be picked up from the riverbanks as well. Another big difference is formed by the flow conditions. In the experiment the discharge was increased instantly, while this would take some time in the Meuse river. This might have impact on the armor breakup.
For the morphodynamics of the Meuse river, the development of static armors is important. They cause the bedload in the Meuse river to be flood dominated (Waterloopkundig Laboratorium, 1994; Murillo-Muñoz, 1998; Sieben, 2008; Sloff et al., 2011). Asselman (2019) reports that bedload transport in the lower Meuse stretches becomes nonzero at discharges of about 500 m^3/s. However, recent insights on the current Meuse riverbed and its morphologic behavior are not available. This combination makes the morphodynamic behavior of the Meuse river rather complicated to predict.

2.2.2 Human impact on morphology

During the last century, lots of human interventions in the river have taken place. The effects of these measures are addressed one by one in Appendix B. In this section, two factors are of main importance. First, the fact that the upstream sediment input in the Meuse river is reported to be zero (Micha and Borlee, 1989; Asselman, 2019; Reeze et al., 2020). The main reason for this is the construction of weirs and dams in Belgium and France. This lack of input means that any sediment leaving the system is not replaced. Sediments leave the system during flood waves and because of dredging activities. All in all, this means the sediment balance is not closed, leading inevitably to a degradation of the riverbed. Appendix B explains that next to dredging and the construction of weirs and dams, other human interventions have increased the overall sediment carrying capacity of the Meuse river. Especially normalization works and river bend cut-offs have had a big impact on this.

2.2.3 Bed level measurements

All in all, a degrading trend in the Meuse riverbed during the past decades is expected. The mechanisms behind the bed level developments are the lack of sediment supply and an increase of the sediment carrying capacity on the one hand and the formation of static armors on the other hand. Dams, weirs and excavations in the French, Belgian and Dutch stretches of the Meuse river trap sediments leading to a tendency of erosion of the river stretches downstream from the interventions. The formation of static armors counteract this mechanism by protecting smaller sediment particles from being picked up by the stream. The protection of static armors only breaks up during periods of above average flow velocities. The interplay between these mechanisms mainly determine the response of the Meuse riverbed to human interventions in the river.
The measurements handled in the report of Van Dongen and Meijer (2008) run from 1889 until 2007 and are summarized in Table 1.1. In the table, several time frames are considered. The maximum time frame reflects all measurements that are available for a specific river stretch.

After 2007, Rijkswaterstaat has continued to measure the bed levels in the Meuse river. With these data, it is checked whether the trends from Van Dongen and Meijer (2008) continue to more recent days. Table 2.1 presents the bedlevel trends for the stretches downstream from the Common Meuse (starting with Plassenmaas), between 2007 and 2017.
Using the same averaging method as in Van Dongen and Meijer (2008), results in different bedlevel change than presented in Table 1.1. The degrading trends observed in the 20^{th} century, tend to stabilize or even turn into aggradation for the measurements past 2007. For the Peelhorstmaas and Benedenmaas, no conclusions can be drawn as the measurements are influenced drastically by the dredging activities that occurred in these reaches.

Tab. 2.1.: The speed of bedlevel changes (m/year). Data obtained from Rijkswaterstaat. The bedlevel trends marked with * are influenced because dredging activities has occurred in the mentioned river stretch.

Trajectory		Period	Average
Plassenmaas	(rkm 57 - 87)	2007-2017	0.000
Peelhorstmaas	(rkm 88 - 121)	2007-2017	-0.066*
Venloslenk	(rkm 122 - 155)	2007-2017	-0.001
Benedenmaas	(rkm 156 - 200)	2007-2017	-0.047*
Getijdenmaas	(rkm 201 - 222)	2007-2017	0.003

2.3 Functions of the Meuse

In this research two functions of the Meuse river are addressed: Navigation and flood safety. The function of drinking water supply is addressed in Appendix A.

2.3.1 Navigation

The Meuse consists of two important navigation routes: the Meuse route that connects the Waal river at Weurt with the Belgian hinterland and the West route that runs from the Hollands Diep to Cuijk, where it connects to the Meuse route (Figure 2.11). Of these two routes, the Meuse route transports the most goods. Over the Meuse route about 14 mln tonnes of dry bulk was transported in 2018, which is about 3 times the transported load transported over the West route. For both routes counts that wet bulk and containers represent a minor share of the transported goods: together 20% of the total transport in terms of tonnage.

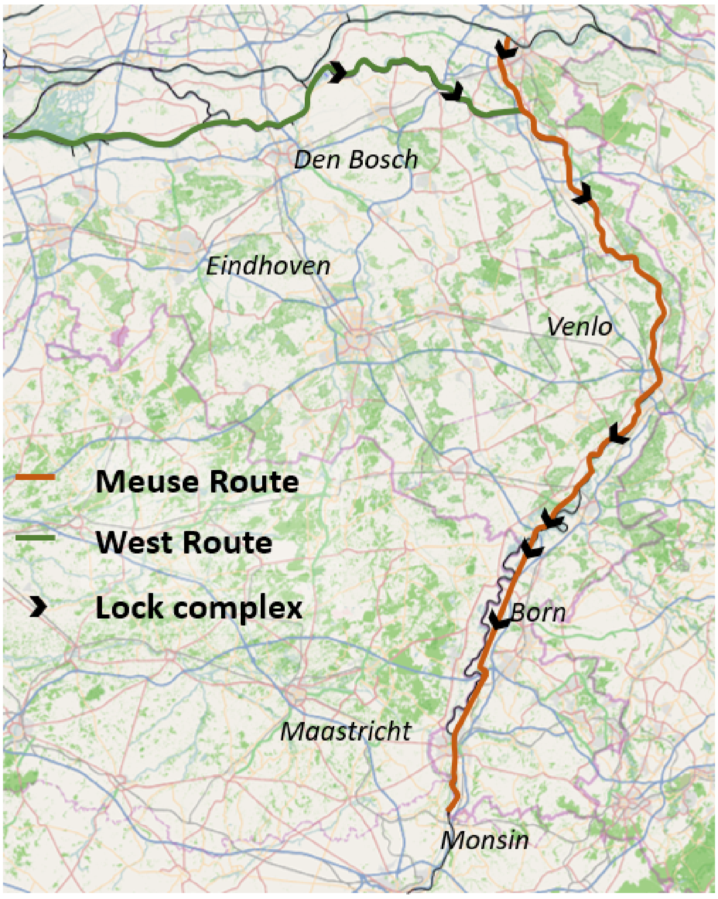

Fig. 2.11.: Main navigation routes in the Dutch Meuse river. North-south Meuse route is in terms of tonnage, number of ships and average size of ships way more important than the West Meuse route.

In Europe, the maximum dimensions (and related tonnages) of ships allowed on a certain navigation trajectory are expressed in so-called CEMT classes, ranging from class 0 to class VII (Rijkswaterstaat, 2017b). The West route is of shipping class of Va, which allows ships with dimensions of LxWxD = 110x11.4x3.5m, which matches the size of a large Rhine vessel. The Meuse route is of class Vb, which extends the maximum length to 170m. Not all vessels sailing on the Meuse river are designed for a draft of 3.5m. Other ships might be theoretically able to reach a draft of 3.5m, but are not fully loaded which limits the draft. The actual tonnage a ship carries divided by the theoretical maximum tonnage it can carry is called the Load Factor (LF, Equation (2.1)). Figure 2.12 presents the number of ships and the average load factor per river trajectory. Shipping is done optimal when the costs are lowest. Important drivers are the shipping costs per ton · km and the shipping time. The shipping costs per ton · km are optimal in case a ship can fill its hull completely. In this case the LF is equal to 1 (Van Dorsser, 2015). Apart from trip distance and cruise speed, the shipping time depends on the time a ship needs to pass obstacles on its route. In the Meuse river, weirs divide the river into stretches with regulated water levels. To pass these weirs, ship locks are built next to them. Usually it takes about 20 minutes to pass a ship lock (Bediencentrale Maasbracht, personal communication, May 1st, 2020).

$$LF = \frac{\text{Actual tonnage}}{\text{Maximum tonnage}} \tag{2.1}$$

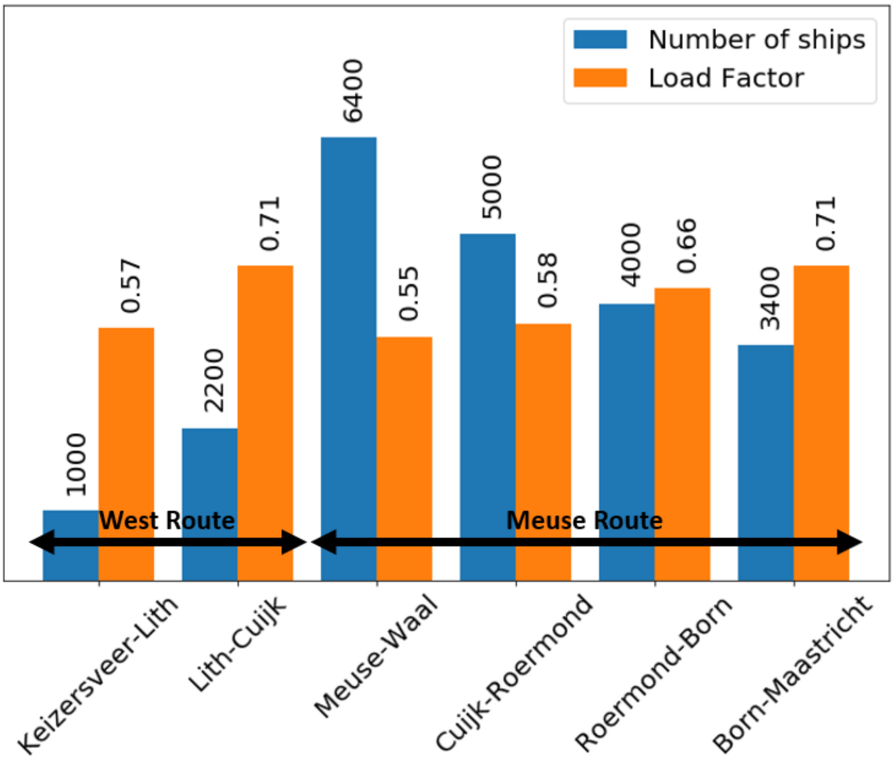

Fig. 2.12.: Number of ships passing with a maximum draft of 3.5m in 2018 for the year 2018 (Rijkswaterstaat, 2019a).

Rijkswaterstaat (2019a) shows that most ships sailing on the Meuse route transport goods between the Julianakanaal or Maastricht area and the Rotterdam or Amsterdam harbour area (± 200 km). Ships on the West route usually make shorter trips between Dordrecht area and Cuijk area (± 110 km). This is based on BIVAS data of 2018. The BIVAS data shows that these routes seem globally representative for shipping on the Meuse route and West route, but on an individual vessel level, large variations are expected.

Optimal hydraulic requirements

Both the maximum LF for a ship and average the passage time of a lock depend on the hydraulic conditions at the ship locks. During normal and low flows, the Meuse river can be simplified to a chain of river basins separated by (weir-) lock complexes. Water is transferred from upstream to downstream by the ship locks, by leakage at weirs and by spilling excess water over the weir crests. In order to maintain the CWL at weirs, the outflow of water may not exceed the inflow. When the CWL is not maintained, this has undesired implications for groundwater tables and water depths. In order to maintain the CWL during periods of river discharge, the locking can be decreased, leading to smaller locking losses. This means that ships must wait before they can pass the lock, leading to an increase in shipping time.

The water depth that is available additional to a ship's draft is called the keel clearance. In this research a keel clearance of 0.5m is taken as a minimum to safely navigate (Bediencentrale Maasbracht, personal communication, May 1st, 2020). A ship with a draft of 3.5m consequently needs a water depth of 4.0m. The smallest water depth on a ships trip determines the maximum draft and consequently the maximum LF. It is necessary to observe the complete trip to determine the requirements for optimal shipping. It was observed already that ships navigating on the Meuse river come from (or go to) the Rotterdam, Amsterdam or Dordrecht area. Rijkswaterstaat (2017b) shows that shipping classes of routes to these areas are bigger or equal to the shipping class of the West and Meuse route. This research therefore assumes that the determining draft limitation for ships passing the Meuse river are always located on the West or Meuse route.

From a shipping perspective, the Meuse river is a chain of obstacles that potentially limit the draft of ships. Except for the sill at Niftrik, concrete sills of ship locks in the Meuse are the most common type of potential draft limitations. Appendix F presents the chain of potential obstacles on both shipping routes. Figure 2.13 shows minimum water depths at different sills in the Meuse river. These depths are acquired by subtracting the sill level (m +NAP) from the minimum water level (m +NAP). The figure shows that sills only limit drafts at the downstream side of locks. If all weirs can maintain the CWL, it becomes clear that at sill Niftrik and downstream from lock Belfeld the available depth is least. Also, at the Waal side of lock Weurt, the draft can be limited.

2.3.2 Flood safety

In 1993 and 1995, very high discharges were observed in the Meuse river (Directoraat-Generaal Rijkswaterstaat, 1994; Directoraat-Generaal Rijkswaterstaat, 1995). The floods peaks were in the order of 3000 m^3/s (Kramer and Mens, 2016). After these extreme events in a relatively short timeframe, the flood safety problems were taken more seriously and the safety standards were raised(Waterwet, 2009). In Figure 2.14 the safety standards of levees along the Meuse river is presented. The safety standards are expressed in a maximum failure probability per year. Until river kilometer 147 (weir and lock complex Sambeek), safety standards are in the order of 1/100 or 1/300 per year with exceptions until 1/1000. Downstream from river kilomter 147, safety standards are in the order of 1/3000 to 1/10000 per year.

When assessing the functioning of flood safety on levee stretch scale, an in-depth geotechni-

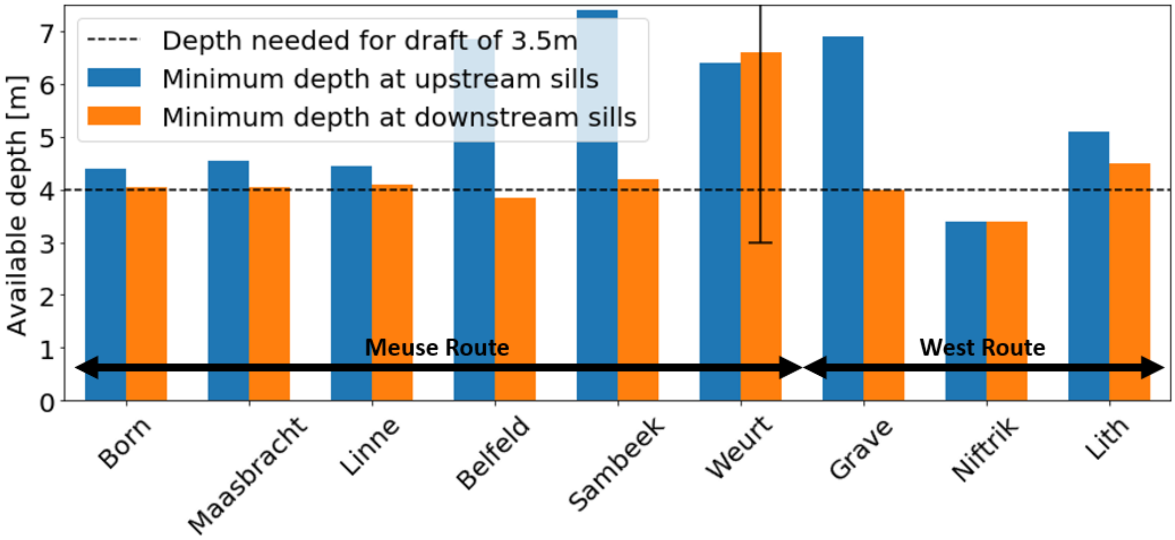

Fig. 2.13.: Minimum depth at sills in the Meuse river. For Weurt the minimum water level during the dry summer of 2018 is depicted as the lower boundary for water levels downstream of lock Weurt.

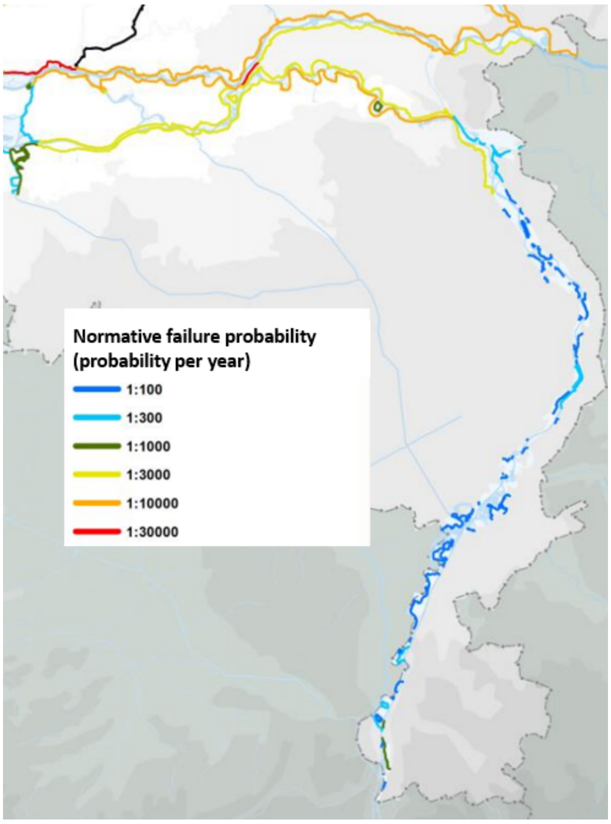

Fig. 2.14.: Safety standards of levees along the Dutch Meuse river (Waterwet, 2009).

cal, hydraulic and meteorological analysis is needed to define the most unfavorable hydraulic conditions and the resulting levee dimensions to withstand the load (Foerster et al., 2012). In this research, however, a more general approach is used in order to allow for a more large scale assessment of the river functioning. The River Engineering Assessment Framework (in Dutch Rivierkundig Beoordelingskader or RBK) provides a starting point for such a large scale approach (Rijkswaterstaat, 2019b). The RBK is composed in order to assess the impact of river engineering interventions in the Dutch main rivers on morphologic, hydraulic and flood safety aspects. For each river section, representative discharges are defined, with which the impact of river interventions on flood safety can be assessed. For the Meuse stretches until (i.e. upstream from) river kilometer 147 the representative discharge is a discharge with a return period of 100 years (currently 3190 m^3/s). For the stretches beyond river kilometer 163, the representative discharge is defined as a discharge with a return period of 3000 years (currently 3950 m^3/s). Between river kilometer 147.8 and 165.3 both return periods are applied, but for simplicity, in this research, only the biggest discharge is applied for this stretch. In this research, river bed developments and an altering discharge regime are assessed as being river engineering interventions. When an altering discharge regime is observed, the discharge magnitudes alter as well, compared to the current magnitudes in the RBK. The impact of altering discharge regimes on these peak discharge magnitudes is presented in Chapter 3.

Figure 2.15 shows that the peak discharge in December 1993 was higher than the peak discharge in February 1995. In 1995 however, flood levels reached higher, as the flood hydrograph was spread over a longer period of time. At the moment the absolute peak reached the Dutch Meuse, virtually all storage capacity in the floodplains was already in use (Directoraat-Generaal Rijkswaterstaat, 1995). This example stretches the need for a deliberate strategy when it comes down to assessing water levels at different discharges. A stationary extreme discharge is not realistic, as the discharge variations in the Meuse river take place on a rather short time scale (see Figure 2.15).

This research assesses the water levels during a synthetic flood wave, using the discharges from the RBK as a peak of the flood wave and construct a representative head and tail of the flood wave. When determining the flood statistics of the Meuse river in the GRADE project, characteristic flood wave shapes were determined as well (Hegnauer et al., 2014). Where the flood peak values are determined quite accurately based on the GRADE analysis, the flood wave shape is less straightforward. For each peak value window, a range of flood wave shapes is presented in the GRADE program. This research uses the mode ($d50$) of the flood wave shape distribution presented in Figure 2.16.

The peak water levels following from representative discharge waves are referred to as representative water levels. A change in representative water levels has impact on the safety level of a levee. When the safety level is to be kept constant, this means the levee dimensions have to change. As there are different failure modes that can result in flooding of the levee hinterland, a change in representative water levels result in a demanded change in levee crest height as well as levee berm width. The crest level determines (among others) the resistance of the levee against failure by overtopping or overflow, while the berm width determines the resistance against piping or macro instability.

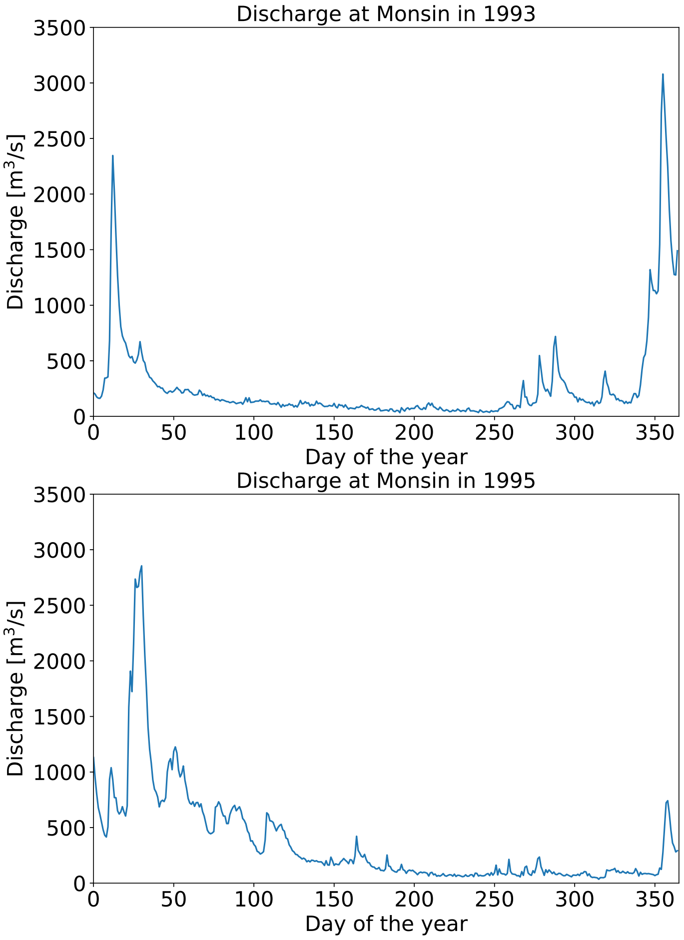

Fig. 2.15.: Flood discharges in winter of 1993/94 and 1994/95 at Monsin (Kramer and Mens, 2016).

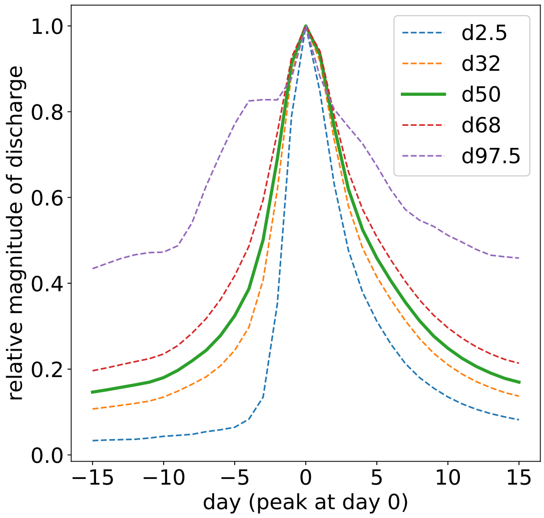

Fig. 2.16.: Range of shapes for flood waves arriving at Monsin, as derived by the GRADE analysis in 2014 (Hegnauer et al., 2014). The green solid line(d50) is the shape used in this reasearch.

3

Future developments in the Meuse river

From Chapter 4 it will become clear how the functional performance of the Meuse river can be assessed using indicators. In order to relate a river's functional performance to river developments, now these developments have to be elaborated on. This study addresses two types of developments, being a changing discharge regime and bed level developments. With regard to the changing discharge regime, sufficient research is available and no further elaboration is needed in this research. This is addressed in Section 3.1. In Section 3.2 essential assumptions on bed level developments are done, based on the mechanisms explained in Section 2.2. In Figure 3.1, the positioning of this chapter in the research process is summarized. In Section 3.3 an overview of the defined scenarios is given.

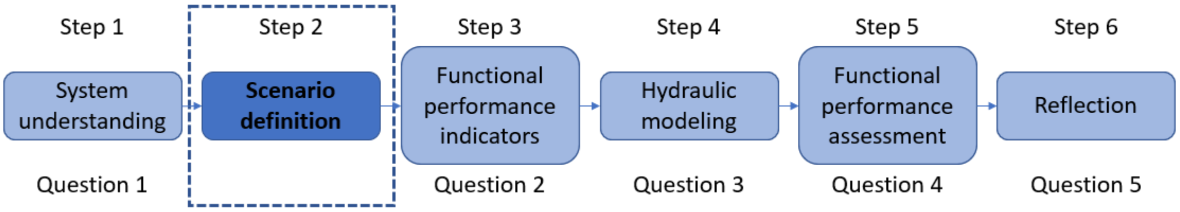

Fig. 3.1.: Summary of research steps. The current chapter deals with step 2.

3.1 Gobal Warming trends

Until 2050, global warming induced climate change will have impact on rainfall and evaporation patterns and causes sea level rise. What this impact looks like is uncertain. The Intergovernmental Panel on Climate Change (IPCC) is the worldwide authority in defining future global warming scenarios. These scenarios are developed in the Coupled Model Intercomparison Project (CMIP). The latest finalized phase was published in 2013 as the 5^{th} Assessment Report (AR5) (IPCC, 2013). The IPCC has a global perspective and defines the consequences on a continental scale. The Royal Dutch Meteorological Institute (KNMI) on its turn, has translated AR5 to the consequences on a national scale for the Netherlands (Van den Hurk et al., 2014). The KNMI used four climate scenarios (Table 3.1) that are identical or very similar to the IPCC scenarios. The scenarios G_L and G_W represent a relatively small global temperature increase, while W_L and W_H represent more severe global warming. For the impacts of climate change on the meteorology, the atmospheric circulation change is important. G_L and W_L refer to a small change in atmospheric circulation, while G_H and W_H represent a more extreme change in atmospheric circulation. In the KNMI report, the implications for the Meuse catchment are already stretched generally.

Tab. 3.1.: KNMI climate change scenarios. Adjusted from Van den Hurk et al. (2014).

Period	Scenario	$\Delta\ T_{global}$ (°C)	Further criteria
2050	G_L	1	Wet spring and dry summer in reference period, reverse in future
	G_H	1	Cold and wet summer in reference period, warm and dry in future
	W_L	2	Wet spring and dry summer in reference period, reverse in future
	W_H	2	Cold and wet summer in reference period, warm and dry in future
2085	G_L	1.5	Wet spring and dry summer in reference period, reverse in future
	G_H	1.5	Cold and wet summer in reference period, warm and dry in future
	W_L	3.5	Wet spring and dry summer in reference period, reverse in future
	W_H	3.5	Cold and wet summer in reference period, warm and dry in future

Hydrological implications

Sperna Weiland et al. (2015) has translated the KNMI '14 climate scenarios to concrete implications for the discharge of the Meuse river. They use the exact same climate scenarios as KNMI did. In order to model the dry years in the dryest scenario W_H, however, it was decided to add a fifth scenario: $W_{H,dry}$. This scenario should be regarded as a twin scenario of W_H. In the W_H scenario, precipitation in winter increases a lot. In that case summer drying is not so much of an issue. In $W_{H,dry}$, the summer drying is more extreme, since the winter precipitation increase is relatively moderate. The global warming and air circulation patterns for both scenarios are the same, but the W_H scenario is the representative for high flows, while the W_H, dry scenario should be observed when considering low flows.

For different scenarios, monthly average discharges for the Meuse river at Borgharen are presented in Figure 3.2. It becomes clear that average summer and fall discharges in the Meuse will decrease in all scenarios, except for the G$_L$ scenario.

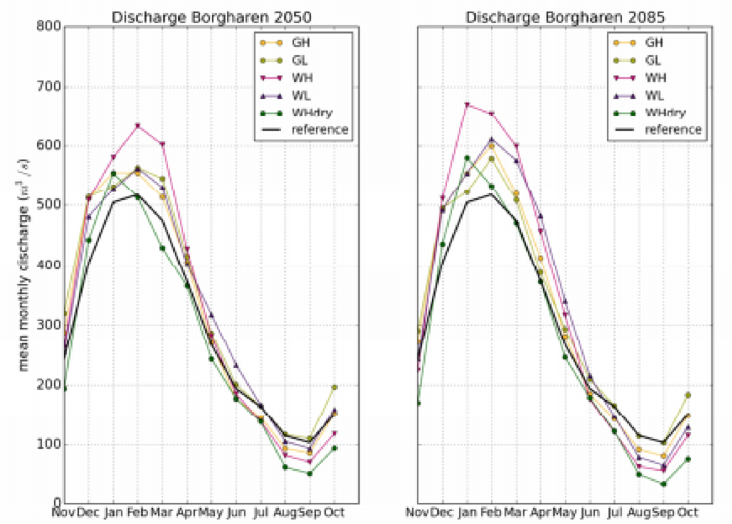

Fig. 3.2.: Discharge scenarios for the Meuse river at Borgharen (Sperna Weiland et al., 2015).

These presented values are monthly averages, which do not represent the inter-annual variability of flows. Kramer and Mens (2016) developed a method to construct 100 year discharge series for the Meuse river at Monsin. In this research, a historical 103 year discharge time series was transformed using the Sperna Weiland et al. (2015) discharge scenarios. With this approach, the real variability of the river is represented in the time series, instead of average values only. In Figure 3.3 daily measured (reference) discharges for a short period of time are presented along with the transformed discharges for each discharge regime scenario.

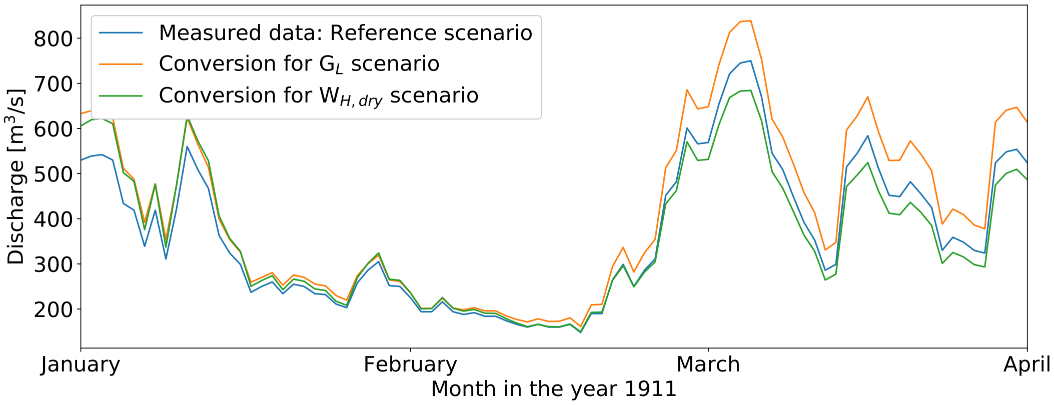

Fig. 3.3.: Daily discharges in the first 3 months of the time series that is used for the low-flow analysis.

The time series constructed by Sperna Weiland et al. (2015) are designed such that they are applicable for low-flow analysis. This means that the high discharges in the time series analysis are not necessarily transformed in a representative way. On top of that, as flood safety standards deal with discharges with very long return periods (up to 3000 years in the Meuse river (Slootjes and Wagenaar, 2016)), a time series of 100 years is not considered sufficiently big to assess the flood safety of the Meuse river. Instead, the outcomes of the GRADE research programme are used for the analysis of flood safety. The GRADE research programme defined discharge magnitudes for a wide range of return periods for different climate change scenarios (Hegnauer et al., 2014). These scenarios are based on the 2006 IPCC scenario, of which two were used in the GRADE programme. The GRADE programme represents the bandwidth of possible climate change impact, as they have used the mildest climate change scenario G and the most severe climate scenario W^+. Although these scenarios have different names than the scenarios used for the low-flow analysis, by choosing these scenarios for the analysis of flood safety, the bandwidth of possible impact of climate change is represented responsibly.

Sea level rise

Due to global warming, the sea level rises on a global scale. This effect reaches the the North Sea as well, be it to a lesser extent. The North sea is the downstream boundary of the Rhine-Meuse Delta. A rise of this downstream boundary condition affects upstream reaches through backwater curves. As the exact rate of sea level rise is unknown, the KNMI developed two scenarios, representing the upper and lower boundary (Figure 3.4).

From Figure 3.4 is becomes clear that in 2050, the sea level rise is probably between 15 and 40 cm. This downstream boundary rise is not easily translated to concrete water level effects in the free flowing stretches of the Meuse river (downstream from Lith). The Rhine-Meuse delta consists of a complicated network of river branches, making it hard to estimate backwater effects

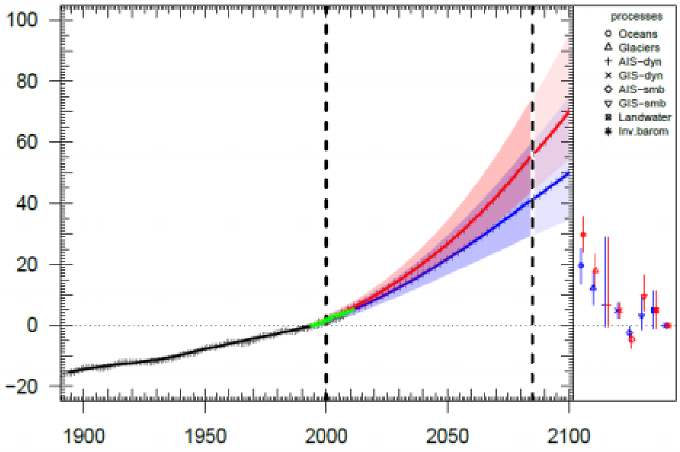

Fig. 3.4.: KNMI scenarios for sea level rise. the shading represents the likely range for each scenario. The vertical axis denotes the 30-year running mean sea-level change in cm, while the horizontal axis denotes time (Van den Hurk et al., 2014).

in the Meuse. It is clear that the weir at Lith forms a hard boundary for the influence of sea level rise. The water level upstream from a closed weir at Lith is not influenced by the water level downstream from the weir. When the weir at Lith is opened, i.e. during high Meuse discharges, backwater effects might affect the water levels further upstream in the Meuse river. According to monitoring in 2018, the actual water level in the North Sea currently lacks behind the lowest sea level rise scenario (Baart et al., 2019). If this trend proceeds, a sea level rise of less than 15 cm is expected in 2050.

As this research aims at quantifying the impact of bed level developments and changing discharge regimes on the functional performance, sea level rise is not incorporated in the analysis. The reasoning is that adding another factor, blurs the effect of other factors having impact.

3.2 Bed level trends

In Section 2.2 the mechanisms behind morphological processes in the Meuse river are explained. Section 2.2.3 elaborates on the measured effects of these mechanisms on the bed levels. In Table 2.1 it becomes clear that extending trends based on between 2007 and 2017 is not possible because the measurements are influenced by dredging activities. Moreover, ten years of bed level measurements is too short to draw clear conclusions with regard to morphological trends. It is essential for this study, however, to determine bed level trends in order to be able to assess the impact of bed level developments on the functioning of the Meuse river. In Section 2.2.2 it is explained that the effects of human interventions in the Meuse river (in the Netherlands and further upstream) have been omnipresent in the river dynamics. For this study, an estimation of the effects of these interventions on future bed level trends has to be made. In order to make a valid assumption, two expertise meetings (in Dutch: kennissessies) were attended in which Dutch river engineering experts discussed on what a reasonable leading assumption for bed level trends would be (personal communication, Kennissessie 1 en 2 project Duurzaam Beheer Rivierbodem, October 10th and October 31st 2019). The agreement on the assumed bed level trend is used in this research as well. Table 3.2 presents the agreed future bed level development assumption until 2050.

Tab. 3.2.: Expected erosion in several Dutch Meuse river trajectories. The different trajectories are picture in Figure 2.2 as well.

Traject name	rkm traject	expected erosion until 2050 [cm]
Upper Meuse	0 - 15	0
Common Meuse	15 - 56	60
Plassenmaas	56 - 87	30
Peelhorst Meuse	87 - 121	20
Venloslenk	121 - 155	30
Lower Meuse	155 - 201	10
Tidal Meuse	201 - 227	0

Comparing Table 3.2 and Table 2.1, it stands out that further bed level erosion is expected in large parts of the Dutch Meuse while the last decade river bed erosion was hardly measured. The overall train of thoughts leading to the assumption is that the mechanisms that lead to erosion are still active in the Meuse river, but that temporary influences may have had a stabilizing effect on the river bed during the last decade. In order to substantiate these expected bed level developments, the considerations have to be elaborated on.

In Section 2.2 it is explained that morphologic developments in the Meuse river take place during periods of high flow particularly, as the armour layer is only mobilized during high discharges of at least 1250 m^3/s. Discharge data show that since 2010, little discharge waves of 1250 m^3/s have taken place, compared to the preceding decades. This is visualized in Figure 3.5. When little extreme flows take place, morphologic trends proceed at a smaller rate. Moreover, armour layers can strengthen when there is no flow deteriorating them. This might be part of the explanation morphologic trends are not expressed clearly in Table 2.1.

Another part of the explanation may be found in the recent developments regarding the Meuse riverbanks. In Section 2.2.2, it is explained that many riverbank were made so-called nature friendly. This implies removing bank protection (gravel, riprap), allowing particles from the riverbank to be picked up by the river flow. Research and monitoring of this process is still going on and until so far unpublished. In general, adding sediments to a river means that the original present sediments are picked up less frequently. This means the nature friendly riverbanks might (temporarily) stabilize the riverbed, explaining the little bed erosion observed during the last decade.

All in all, it has been made clear that accurately determining the expected bed level developments for the Meuse river is practically impossible. Also river engineering experts have agreed on this during the expertise meetings that was referred to earlier on. Recent bed level measurements are

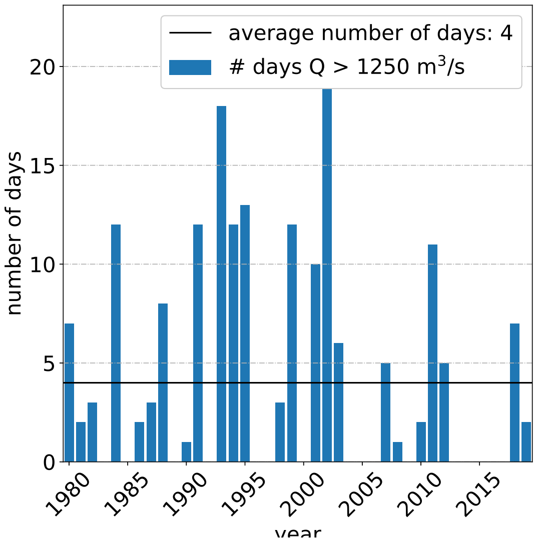

Fig. 3.5.: Number of days per year with discharges bigger than 1250 m^3/s at Monsin/Eijsden between 1990 and 2020.

distorted by dredging activities. On top of that, the hydraulic and morphodynamic conditions during the recent years of frequent measurements (2007-2017) may not have been representative for the Meuse river on a longer time scale.

The overall assumption, acknowledged by Section 2.2 and experts, is that the river Meuse has not reached a equilibrium yet. The logical consequence of this notion is that future bed level trend estimations have to be made in order to assess the effects of future bed level developments on the river functionality. The best guess of expected morphologic developments is presented in Table 3.2. The bed level development estimate is referred to as the expert judgement 2050 bed level

In practice, when monitoring the bed level developments in the coming decades, the probability that the Meuse river follows exactly the estimated bed degradation rates is rather small. In order to be able to compare the impact of different erosion rates, a second bed degradation scenario is considered. This scenario encompasses twice the erosion rates presented in Table 3.2 and will be referred to as the doubled bed erosion scenario. Figure 3.6 presents the bed degradation scenarios per river kilometer.

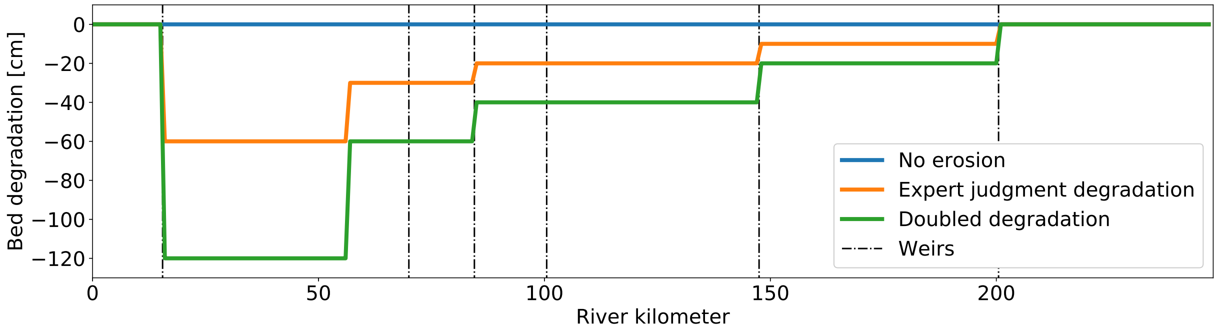

Fig. 3.6.: Imposed bed degradation until 2050 along the Meuse river for the two bed level scenarios. River kilometer 0 is at Eijsden, river kilomter 247 is at Keizersveer.

3.3 Scenario overview

In Table 3.3, an overview of the future development scenarios is presented. The scenarios consist of three discharge regime scenarios and three bed level scenarios.

The three discharge regimes are represented in 103 year daily discharges (from Kramer and Mens (2016)) and by flood wave peak magnitudes (from Hegnauer et al. (2014)). The 103 year time series in the reference discharge regime consist of measured daily discharges at Monsin (near Liège, just upstream from Eijsden) from 1911 until 2014. For the wet climate change scenario G_L (the mildest side of the bandwidth) and for the very dry climate change scenario $W_{H,dry}$ (the most severe side of the bandwidth) these daily measured discharges are transformed to values that comply to these climate change scenarios. The flood peak magnitudes for the reference discharge and climate scenario bandwidth discharge regimes (referred to as mild G and severe W^+) are all reported in the Hegnauer et al. (2014) report.

The bed level scenarios consist of three scenarios: a reference bed level, a bed degradation scenario based on expert judgment and a scenario in which these estimated values are doubled. The reference bed is defined as the bed levels that by default are implemented in the hydraulic model that is used (see Section 3.4). The degraded bed levels are imposed on this model for the main river stream (the flood plains do not change).

Tab. 3.3.: Overview of future developments considered in this research.

Discharge regime	Bed level	Scenario #
Reference	Reference	1
	Expert judgment 2050	2
	Doubled 2050	3
G_L, G	Reference	4
	Expert judgment 2050	5
	Doubled 2050	6
$W_{H,dry}$, W^+	Reference	7
	Expert judgment 2050	8
	Doubled 2050	9

3.4 The hydraulic model

This chapter addresses the methodology of the hydraulic model. Sections 4.1.4 and 4.2.4 present the results of the hydraulic model and the results of the functional performance modeling.
This research uses a Sobek 3 model (also called D-FLOW1D). Sobek 3 consists of 1D hydrodynamic and morphodynamic modeling software. In this research, only hydrodynamics are modeled as morphological developments are imposed on the model. Rijkswaterstaat uses this model and Deltares supported, calibrated and validated the model in order to guarantee it is appropriate for decision making in Dutch river engineering practices. The 1D shallow water equations, or Saint-Venant equations form the base of the model (Deltares, 2020; Stelling and Duinmeijer, 2003). The Saint-Venant equations are given by:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial (hu)}{\partial x} = 0 \tag{3.1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\frac{\partial \zeta}{\partial x} + c_f\frac{u|u|}{h} = 0 \tag{3.2}$$

where u is the flow velocity, ζ the water level above plane of reference, c_f the dimensionless bottom friction coefficient, d the depth below plane of reference and h the total water depth, $h = d + \zeta$. Equations (3.1) and (3.2) are solved numerically, making use of a staggered grid. Stelling and Duinmeijer (2003) provide more explanation on the numerical approch and the staggered grid.
A Sobek 3 model consists of nodes and branches. At a standard node one branch flows in and one branch flows out. At boundary nodes only one branch flows in or out, obliging the node to get an upstream or downstream boundary condition attached. At bifurcation nodes, the water is distributed. In the Sobek 3 model used for this research, the discharge is distributed using discharge time series (Q-t relations) or discharge water level functions (Q-h relations). At confluence nodes, no distribution functions are attached.
The Dutch Meuse river has two canals running parallel to the main stream, the Julianakanaal and Lateraalkanaal. Diversion to the Julianakanaal is imposed by a Q-t relation. The diversion to the Lateraalkanaal is regulated by a Q-h relation. At upstream boundaries of tributary rivers, no discharge is set. In the Meuse river several weirs are located. In the Sobek 3 model, the weirs maintain water levels that comply to the controlled water levels from Rijkswaterstaat (2015) and the weirs open at the discharges that comply to Rijkswaterstaat policies as well (explained in Lob van Gennep (2019)).
The aim of this hydraulic modeling step is to represent the hydraulic conditions in the Meuse river as realistic as possible for the reference scenario. In the other scenarios only bed levels and/or upstream boundary conditions are altered. The upstream boundary condition at node Eijsden is implemented as a discharge time series. For the low flow analysis, these time series consist of 104 years of daily discharges, as explained already in Chapter 3. For the flood analysis, these time

series consist of a discharge wave of 30 days, as explained in Chapter 3 as well.

For the downstream boundary at Keizersveer, a Q-h relation was obtained from Deltares. This boundary condition is maintained throughout all model runs, which means that potential influence of sea level rise (which would alter the Q-h relation) is not regarded in this analysis.

The water division over the the canals in Belgium and Limburg, as explained in Appendix A, is modeled as follows:

- The fraction of Meuse river discharge at Monsin that is allocated for Belgian use according to the Meuse Discharge Treaty, is substracted from the given daily discharges at Monsin. This substraction is not visible in the modeling settings.
- The share of Meuse discharge at Monsin that is allocated to the Common Meuse (according to the Meuse Discharge Treaty) is diverted to the Common Meuse at the bifurcation point near Borgharen, just as in reality.
- The Dutch share of the discharge at Monsin is spread over the Zuid-Willemsvaart and the Julianakanaal according to demands of the freshwater hierarchy and assumptions based on discharge data from Rijkswaterstaat (2020e).
  - When the discharge at Monsin is bigger than 60 m^3/s , 10 m^3/s is diverted to the Zuid-Willemsvaart and 15 m^3/s is diverted to the Julianakanaal.
  - When the discharge at Monsin is between 30 and 60 m^3/s, 6 m^3/s is diverted to the Zuid-Willemsvaart and the residual discharge is diverted to the Julianakanaal.
  - When the discharge at Monsin is below 30 m^3/s, only the absolute minimum discharge of 3.8 m^3/s is diverted into the Zuid-Willemsvaart, while the residual is diverted to the Julianakanaal.
- From discharge data, it turns out that in practice 6 m^3/s is pumped from the Meuse river to the Wessem-Nederweert Canal at Panheel during periods of low flow. This is identically implemented in the hydraulic model.

Tributaries

Along its course in the Netherlands, several smaller streams contribute to the Meuse river discharge. The exact amounts are not monitored consistently and the discharge data on smaller streams is scarcely accessible. Contributions to the Meuse river discharge, however, are measured indirectly at the several monitoring locations along the Meuse. From measurements on the Meuse river, it stays unknown where exactly the water comes from, but as large amounts of data is available, the contributions can be estimated from this data. In the model, the number of tributaries is limited to the three most important ones: the Roer river, Niers river and Dieze river. The contributions of these rivers are based on discharge measurements at Venlo (for the Roer contribution), Megen (for the Niers contribution) and Keizersveer (for the Dieze contribution). The three tributaries combined are assumed to appropriately represent the real contributions. The determination of the contributions of these three rivers is done by plotting weekly averaged discharge measurements of Eijsden to weekly averaged discharge measurements at Venlo, Megen and Keizersveer respectively. The data show very strong correlations that allow for the derivation of discharge relations. These discharge relations are applied to the discharge time series at Eijsden, resulting in contribution time series for each of the three rivers. In this way, the influence of the tributaries on the Meuse river discharge during periods of low flow is recognized in a realistic way. For further details, see Appendix D.

Retention areas

In the Dutch stretches of the Meuse river, several retention areas are located. These retention areas are designed such that they drain water at the peak of design flood waves. The effectiveness of retention areas is very sensitive to the flood wave shape and the peak water level at the retention intake (Huthoff et al., 2014). The intakes in the Sobek 3 model consist of a weir with a fixed crest, leading to an intake discharge governed by the external water level. After comparison with a WAQUA model of the Meuse river, it turns out that the crest levels in the Sobek 3 model do not match the crest levels in the WAQUA model. This rises doubt about the correctness of the implementation of the retention area inlets. Moreover, the presence of retention areas in the Sobek 3 model and the varying effectivity during different scenarios, might blur the effects of the bed level developments and changing discharge regimes. Therefore, in this research all retention areas are removed from the Sobek 3 model. The reasoning for this decision was discussed with Arcadis river engineering specialist Ward Klop (personal communication, May 6th 2020).

Scenario study

Section 1.4 explains that this research addresses several scenarios for for future river states. This comprehends a combination of discharge regime scenarios and bed level scenarios. Given the river functions addressed in this research, both low flow as well as high flow conditions are important for the overall functional performance. The hundred year discharge time series following from Kramer and Mens (2016) are calibrated for especially low flow analysis. The extremely high flows in the time series are not representative for flood risk analysis in the Meuse river. The GRADE research output is suitable for the analysis of flood risk, presenting current discharge magnitudes for a wide range of return periods in the reference scenario as well as future climate scenarios (Hegnauer et al., 2014). Section 3.1 already explained that the research of Kramer and Mens (2016) is based on 2014 climate scenarios G_L and $W_{H,dry}$, while the research of Hegnauer et al. (2014) is based on the 2006 climate scenarios G and W^+. This may give rise to questions about the consistency of the analysis, as this research compares outcomes of different generations of climate scenarios. For the flood safety analysis, however, the scenario outcomes relative to each other are way more important than the absolute outcomes. In this way it is not considered a problem that the climate scenarios used for flood safety assessment are different from and not as up-to-date as the climate scenarios used for the low flow analysis. On top of that, it is important to stress that both low-flow and flood wave climate scenarios represent a bandwidth of potential climate change impact. The G_L and G scenarios represent a relatively mild rate of global warming, while the $W_{H,dry}$ and W^+ scenarios represent a relatively quick rate of global warming
All in all, this research addresses 3 discharge regime scenarios and three bed level scenarios (a reference, an estimated scenario and an extreme scenario), counting up to 9 scenarios in total.

As for each scenario a low flow and flood wave time series is used, a total of 18 models is run. Table 3.3 provides an overview of the scenarios.

4

Functional performance assessment

Chapter 3 defined river trends of which the implications on the river functioning are assessed in this chapter. For each river function, the potential impact of bed degradation on the functioning is qualitatively assessed first. This qualitative assessment concludes in hypotheses that are verified in the results sections (Sections 4.1.4 and 4.2.4). The further contents of this chapter are best explained with help of Figure 4.1.

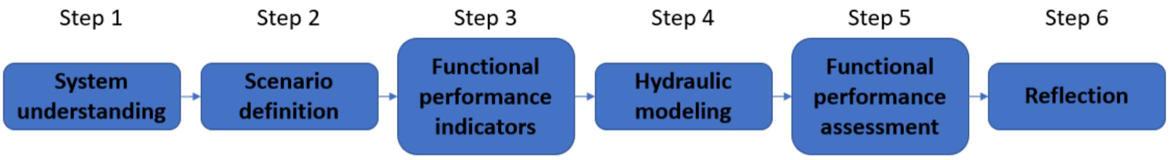

Fig. 4.1.: Summary of research steps. The current chapter addresses steps 3, 4 and 5.

This chapter addresses the definition of functional performance indicators (step 3) and the conversion of indicator values to the functional performance assessment of the Meuse river. The functions navigation and flood safety are addressed separately, both answering their share of the following research question:

What indicators determine the current performance of the Meuse river regarding the functions navigation and flood safety?

Sections 4.1.4 and 4.2.4 present the relevant results of the hydraulic modeling (step 4) and functional performance assessments (step 5), addressing the following research questions:

How will water levels and discharges in the Meuse river change taking the altering discharge regime and large scale bed level changes into account?

What is the impact of the expected change of water levels and discharges on the functional performance indicators in both regulated and free flowing Meuse river stretches?

Section 4.3 presents a rough estimate of future costs for each function, caused by changing river conditions.

4.1 Navigation

4.1.1 Potential impact of defined trends

Bed degradation can have impact on the water depth at sills in the Meuse river in different ways. At first, it can decrease water levels in the upstream part of river basins as it has impact on the backwater curve in the basin. An prerequisite for this effect is that there is sufficient river discharge to form an actual backwater curve. At very low flows, this is not the case and bed erosion is not expected to have an impact in this way. Figure 4.2 shows the impact of a lower river bed on the backwater curve in the upstream part between two weirs.

Dredging activities in the main river stream form another risk for sufficient navigable depth. Dredging causes the water volume needed to sustain the CWL to increase. If, during periods of low river discharge, the lowering of the river bed cannot be compensated, this impacts the water levels in the basin, leading to potential increased limitations for ship drafts.

As explained earlier, weirs and locks in the Meuse river enable year round navigation. Bed erosion may undermine these constructions. In case one or more of these constructions does not function any more, the Meuse river navigation network is harmed. The erosion rates presented in Section 3.2 may not be directly harmful to the stability of constructions, but the presence of fine sands in the substrate forms a risk. At some place, fine sands are very close underneath a small layer of coarser particles. A small amount of erosion can expose these fine sands to the river main stream, potentially leading to big erosion pits. If this happens close to important river structures, navigation may be harmed (Prins, 1999; Asselman et al., 2018).

Another mechanism that can harm navigation at the Meuse river is the leakage under weirs. A lower bed level at one or both sides of a weir or lock can impact the leakage underneath such a structure. The bigger the leakage, the harder it is to sustain the CWL at a weir during periods of very low flow.

Next to bed degradation, altering discharge regimes can impact the river functioning as well. Bed degradation is essentially a problem when little river discharge is available. If low flows are more persistent in the future, the risk of the described mechanisms is pronounced.

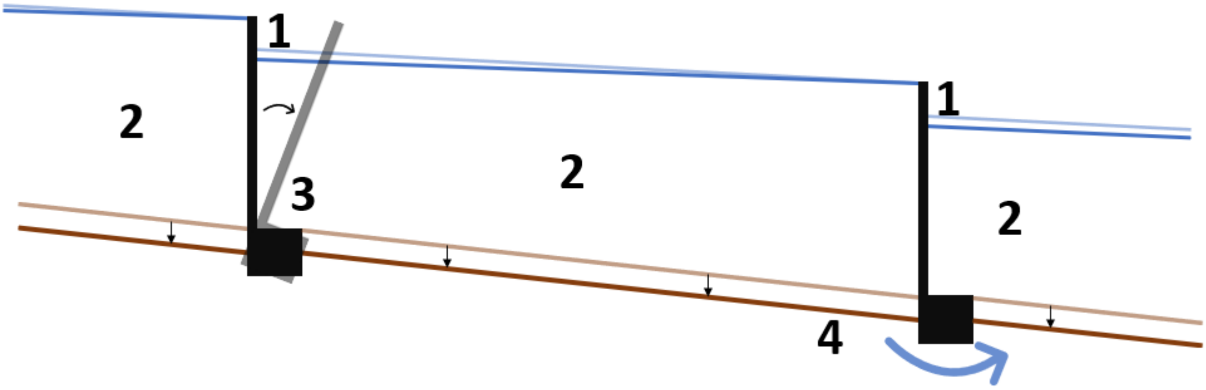

Fig. 4.2.: Potential impacts of bed degradation on the sustain of water levels needed for optimum navigation. Soft brown line is the original bed level, the harder one is the degraded bed level. 1: Draw down of backwater curve in upstream area of basin. The soft blue line is the water surface with the original bed, the harder blue line is the new water level. 2: Increase of basin volume. 3: Undermining of hydraulic structures. 4: Increased seepage under hydraulic structures.

At reaches where the water level is not controlled by weirs, bed degradation impacts the water level more directly. The expectation is that the water level in times of drought is directly related to changes in the bed level. In the most downstream reaches of the Meuse river, however, the water level is not controlled by a weir but by the downstream boundary water level at sea. The

expectation is that this is comparable to the CWL of weirs.
It has become clear that the impact of bed developments impacts different mechanisms. For river functioning regarding navigation, the geotechnical and geohydrological implications are not regarded. This is chosen because such an analysis would need an elaboration on the construction and subsoil of individual hydraulic structures. In doing so, the aim of regarding the Meuse river as a system would be out of sight. This leaves only the hydraulic effect on backwater curves to be included in this research. This means this study assumes that the CWL at weirs can always be maintained, as instability and leakage at these structures are not considered.
Under these conditions, a few hypotheses are defined. The hypotheses are tested in the hydraulic modeling phase and reflected upon.

- During very low flows, bed degradation does not impact the water level in controlled water level stretches.
- Bed degradation impacts the water level in controlled water level stretches in times backwater curves are formed.
- The downstream sill of lock Belfeld and sill Niftrik are the most important future bottlenecks for drafts of ships passing the Meuse river.

4.1.2 Functional performance indicators

For the Meuse river functioning as an optimal navigation facilitator, it is essential to enable ships to carry as much load as they are designed for and to facilitate a swift passage of the several locks located in the Meuse river system. Indicators that represent the functioning of the Meuse river with regard to navigation, have to cover the availability of these two essentials. The first indicator is the available water depth above the sills at Niftrik, lock Belfeld and lock Weurt. The first two are dependent on the characteristics of the Meuse river itself, the latter, however, is dependent on water levels at the Waal river side of lock Weurt. For the functioning, especially the ships designed for a draft of 3.5m are critical. Assuming a Large Rhine Vessel, the functioning of the Meuse river on this indicator is presented in Figure 4.3. In the figure, the relations between LF and the available depth is linear. This complies to the work of Van Dorsser (2015), who derived linear relations between draft and ship tonnage for several ships, including the large Rhine vessel. These linear relations are based on loading certificates of representative vessels.

The second indicator covers the passage of locks during periods of low river discharge. Especially at lock Maasbracht and lock Grave this might cause problems during periods of low flow. The indicator is defined as the available river flow available at the specific lock complex. For both locks, the maximum average waiting time is one hour. This is based on active Rijkswaterstaat policies that the locks operate at a frequency of at least once every 2 hours (Rijkswaterstaat, 2020b). The waiting time presented for Maasbracht is based on the research done at lock Maasbracht (Bolt, 2003). For the waiting time at lock Grave, no research is available. The margins between zero waiting time and maximum waiting time, however, are so small that a linear relation between the

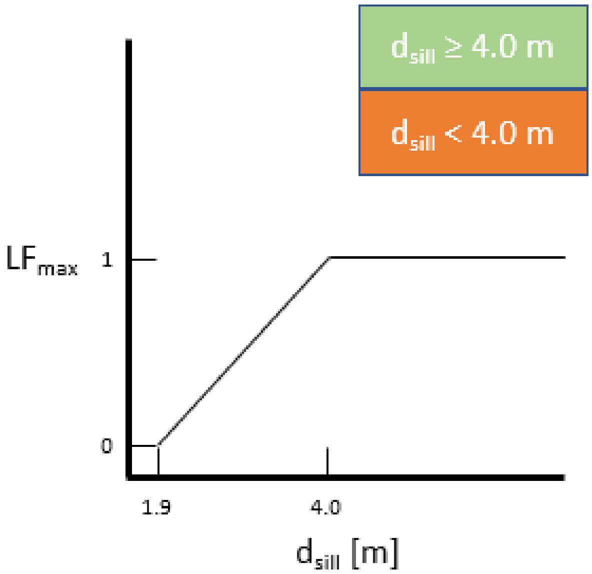

Fig. 4.3.: The functioning of the Meuse river with regard to available water depth at sills Niftrik, lock Weurt and lock Belfeld.

two is not assumed to be making a large difference compared to a relation that looks like the one found for lock Maasbracht. The functioning of this indicator is presented in Figure 4.4.

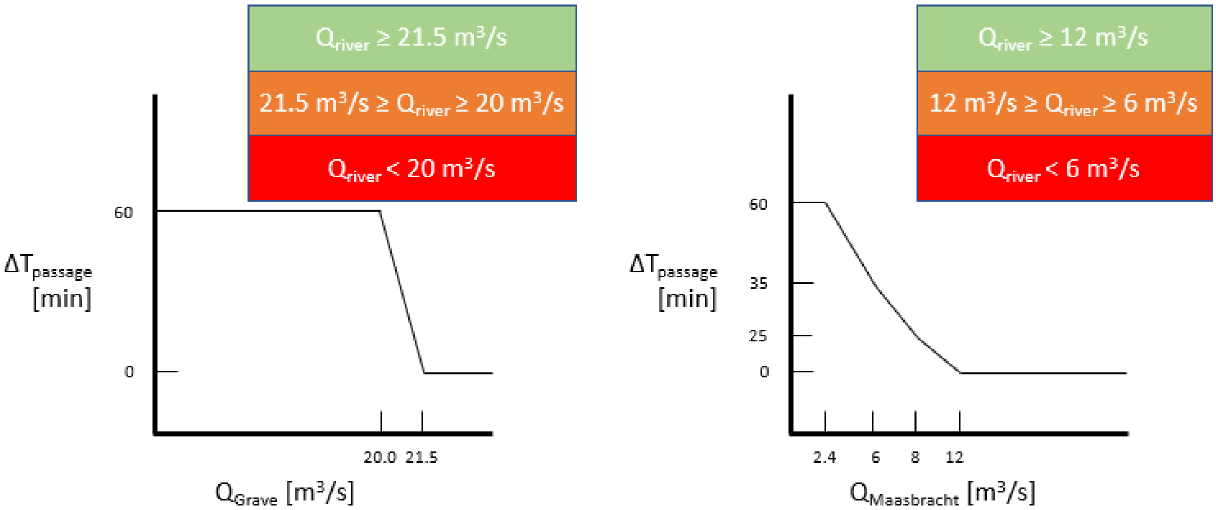

Fig. 4.4.: The functioning of the Meuse river with regard to available discharge at lock Grave (right) and lock Maasbracht (left). A lack of discharge is translated to an increase in lock passage time.

4.1.3 Functional performance assessment

Functional performance assessment - Draft

For the functional performance assessement, all information presented above is combined with the output of the hydraulic modeling phase. Section 3.4 explains that the output of the hydraulic model consists of daily discharges and water levels at numerous locations in the Meuse river. The daily water levels at vessel draft bottlenecks, combined with the sill levels results in information about the available depth on a daily basis. Applying the relation in Figure 4.3, this results in daily maximum LF. The LF is smaller than 1 in times the water depth is below the threshold of 4.0m. The lower figure in Figure 4.5 shows periods of time the draft is limited. Now the daily maximum LF on a certain shipping trip is known, the maximum efficiency of the transport of goods is known. To concretize the effect of a decreased LF, the decreased efficiency is translated to a number of extra ships needed per year. Equation (4.1) shows the relation to make this translation, with N_{min} the minimum amount of ships needed, T the transport demand in tonnes/day, LF the Load Factor [-] and T_{ship} the maximum tonnage of the observed ship (2700 tonne for a Large Rhine Vessel). An important assumption is that the daily demanded load T is taken constant. In that case, only the daily LF determines the number of ships needed to transport the load. This research presents the functional performance in the number of ships needed on a yearly basis. The yearly results are the sum of daily results in a particular year.

$$N_{min} = \frac{T}{LF \cdot T_{ship}} \tag{4.1}$$

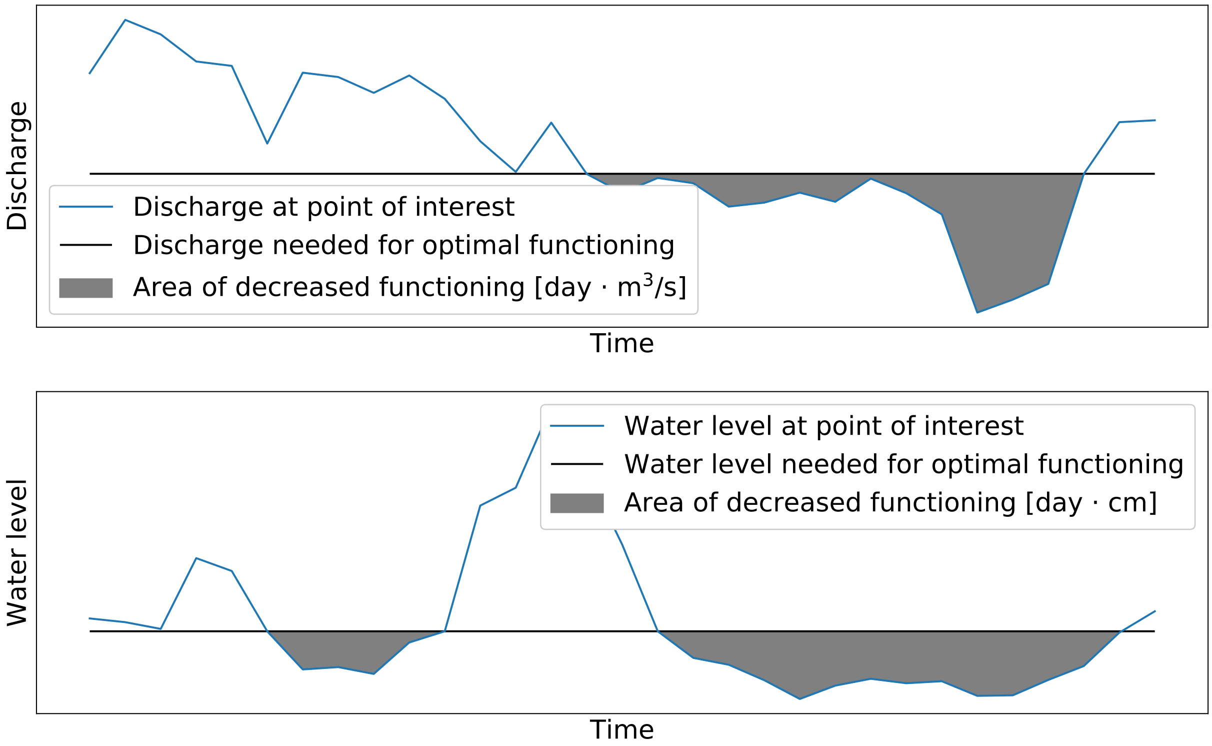

Fig. 4.5.: Periods of decreased functioning with regard to available discharge and available water depth.

Functional performance assessment - Waiting time

Using the daily discharge data at bottleneck locations from the hydraulic modeling part, the daily average waiting time for a ship is derived. Figure 4.5 shows periods of time in which the discharge limits the locking frequency. Figure 4.4 shows the relation between the discharge at two bottlenecks and the average waiting time for ships at the locations. This waiting time applies to each individual ship, so the total waiting time is obtained by multiplying the average waiting time by the number of ships passing the lock on that particular day. This number is based on Rijkswaterstaat (2019a) and taken constant. Again, the waiting hours are presented in yearly numbers, by adding up the daily waiting hours of a particular year.

Indication of financial implications

To translate both functional performance indicators into costs, a tool was found at Rijkswaterstaat (2017a). This tool consists of an Excel sheet in which basic shipping parameters (e.g. river system, ship type, load type) are entered. With some basic shipping information, the tool presents basic cost parameters such as shipping costs per tonne·km and waiting costs. For a fully loaded standard Rhine vessel (M8 category) navigating in the Netherlands and Belgium under average conditions, the costs are given at 1.41 euro cents per tonne·km.

The impact of limited draft at Belfeld and Niftrik was expressed in extra ships needed to transport the same goods flow. As the cost tool output consists of costs per ton·km, a base case needs to be defined in which the tonnage and shipping distance is defined. For navigation passing Belfeld, Rijkswaterstaat (2019a)shows that most ships passing Belfeld come from either the Amsterdam or Rotterdam harbour region and go to approximately Born, or vice versa. Both routes have a length of $\pm$ 200km. It is assumed that lock Belfeld is the only draft limiting factor on the navigation route. Ships passing Niftrik probably have a shorter route, between the Dordrecht area and the end of the West route at Cuijk. This route has a length of $\pm$ 110km. The most efficient amount of ships is equal to 3070 and 370 for Belfeld and Niftrik respectively. The tonnage the ships carry on average is calculated by Equation (4.2), in which L is the tonnage (tonnes), L_{max} the maximum tonnage (equal to 2700 tonnes), n_{min} the number of ships needed at minimum (3070 or 370 ships) and n_{extra} the number of extra ships needed.

$$T = T_{max} \cdot \frac{n_{min} - n_{extra}}{n_{min}} \tag{4.2}$$

The average T is entered in the cost tool, resulting in the average shipping price per tonne·km. The transported tonnes per year and the shipping distance are taken constant, so the price depends on the maximum LF only.

Waiting time at shiplocks costs are translated to monetary losses as well. The waiting costs depend per ship type and goods type. In this research a simplified representation of the fleet passing lock Maasbracht and lock Grave will be used. The fleet compositions are presented in Tables 4.1 and 4.2.

Tab. 4.1.: Fleet composition and waiting costs at Maasbracht.

Ship type	Share	Waiting costs (EUR/hour)
M2	33%	36
M6	32%	56
M8	35%	96
Averaged costs		63

Tab. 4.2.: Fleet composition and waiting costs at Grave.

Ship type	Share	Waiting costs (EUR/hour)
M2	24%	36
M3	49%	39
M8	27%	96
Averaged costs		54

Multiplying the averaged costs with the expected (mean) waiting times in 2050 gives us the expected waiting costs at both lock Maasbracht and lock Grave.

4.1.4 Results

Section 4.1 presents three hypotheses about the impact of bed degradation on navigation in the Meuse river. The hypotheses are addressed below.

During very low flows, bed degradation does not impact the water level in controlled water level stretches.

Bed degradation impacts the water level in controlled water level stretches in times backwater curves are formed.

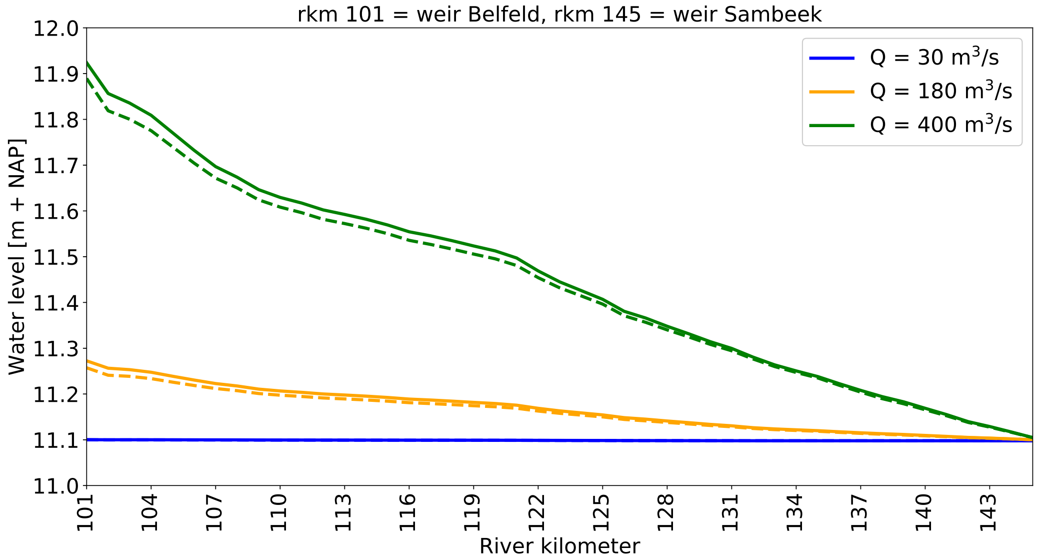

Fig. 4.6.: Water levels in the river basin upstream from weir Sambeek up to weir Belfeld, with (solid lines) and without (dashed lines) eroded river bed for different discharges.

Figure 4.6 confirms the first two hypotheses. It observes the Meuse river in between weirs Belfeld and Sambeek. At the downstream boundary (weir Sambeek) a CWL of 11.1 m + NAP is imposed. The figure shows that when the river discharge is about 30 m^3/s, the water level upstream in the basin equals the imposed CWL. When the discharge is about 180 m^3/s, a small backwater curve is formed already. The impact of bed degradation just downstream from weir Belfeld is in the order of a few centimeters. This impact stays about the same when the discharge is increased up to 400 m^3/s.

Downstream from lock Weurt, another effect is expected. Zuijderwijk et al. (2020) report that as long as the discharge in the Waal river is below bankfull, the water level responds one on one to the bed level decrease. Van Vuren et al. (2015) report the bankfull discharge of the Waal river at 3450 m^3/s. At this discharge, the draft at lock Weurt is not limited anymore (Rijkswaterstaat, 2020a). It is therefore justified to shift the water levels obtained from (Rijkswaterstaat, 2020a) down with 45cm in order to obtain the impact of bed degradation in the Waal river.

The downstream sill of lock Belfeld and sill Niftrik are the most important future bottlenecks for drafts of ships passing the Meuse river.

Because of the set-up of the hydraulic model, weirs can sustain their CWL at all times, regardless of bed degradation or river discharge. Under this condition, no other sill in the Meuse river itself can become as much of a bottleneck as the sill downstream of lock Belfeld and at Niftrik. At the Waal side of lock Weurt, however, the draft can be limited caused by low Waal river water levels. Figure 4.7 presents the two main navigation routes that cross the Meuse river.

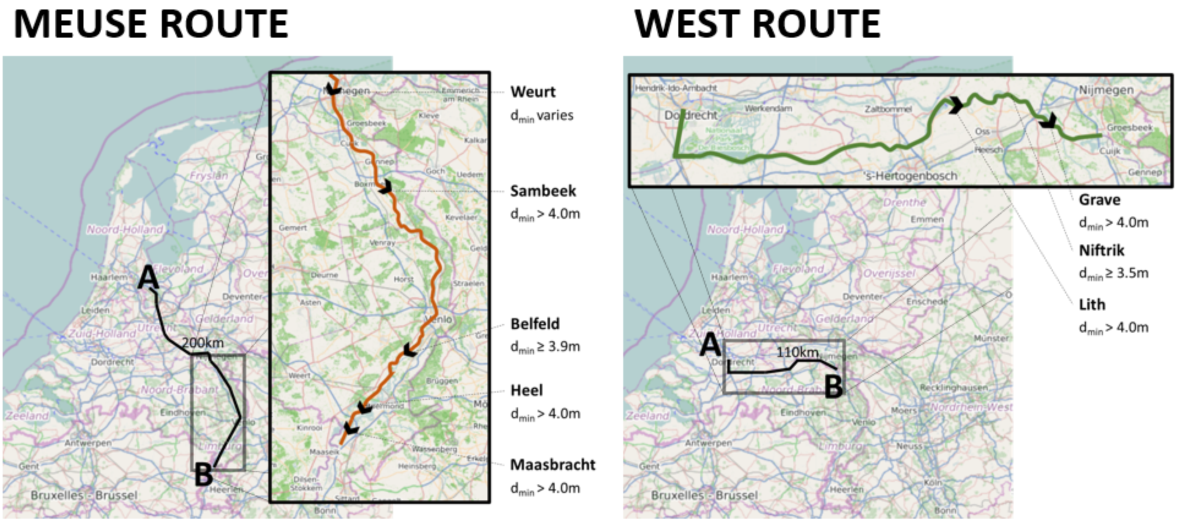

Fig. 4.7.: Representative shipping routes from A to B (or vice versa) crossing the West Route and the Meuse route and draft bottlenecks.

For a ship navigating from A to B, the minimum depth on the route determines the maximum LF. For ships navigating on the Meuse route, it is assumed that either the water level at the downstream end sill (Waal river side) of lock Weurt or the water level at the downstream end sill of lock Belfeld is determining the maximum LF of the ship. For the West route, the LF of ships is assumed to be determined by the water level at sill Niftrik. Section 4.1.3 explains that the functional performance is expressed in the number of extra ships needed to compensate for draft limitations on the shipping route. Figure 4.8 presents the number of extra ships needed in each scenario caused by draft limitations at both lock Weurt and lock Belfeld. In this figure, only the expert judgment bed degradation scenarios are presented. Appendix E shows that the impact of the doubled bed degradation is of a similar order of magnitude.

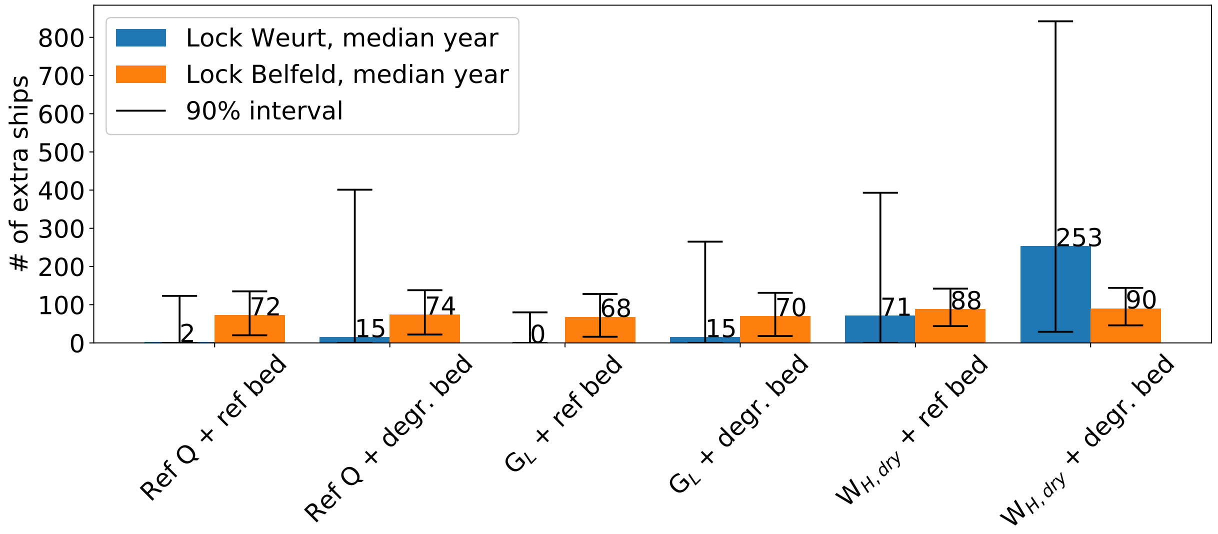

Fig. 4.8.: Number of extra ships needed to compensate for draft limitations at lock Weurt and at lock Belfeld for different discharge regime and bed level scenarios.

Figure 4.8 shows that in the median years, lock Belfeld is expected to form a bigger harm to efficient shipping than lock Weurt. However, in the driest discharge regime with a degraded river bed (on the Waal river), the harm at lock Weurt becomes several times bigger than the harm at lock Belfeld. In the 5% driest years, the impact of low discharge on the Waal river impacts the functional performance a lot more than low discharges on the Meuse river. The harm caused by draft limitations at lock Belfeld is on average probably bigger than the harm caused by draft limitations at lock Weurt, but it is relatively constant when comparing different scenarios. The harm caused by draft limitations at lock Weurt is on average smaller, but way more volatile throughout different scenarios.

Figure 4.9 presents the number of extra ships needed in each scenario at sill Niftrik. In this figure, only the expert judgment bed degradation scenarios are presented. Appendix E shows that the impact of the doubled bed degradation is of a similar order of magnitude. Regardless the scenario, the results show that solving draft limitations at lock Belfeld or lock Weurt separately will not have the desired effect: if one sill is lowered, the other one will still harm the navigation efficiency. In that way, the hypothesis that the sill at Lock Belfeld is unilaterally determining the draft limitations at the Meuse route is falsified. The draft limitations at lock Weurt are expected to be of the same order of magnitude on average.

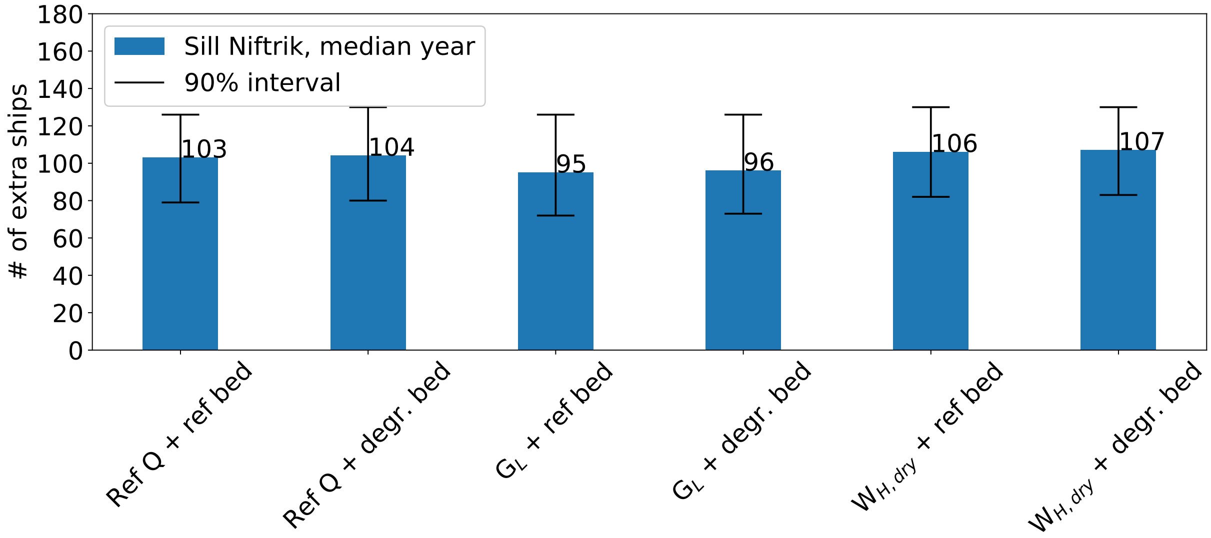

Fig. 4.9.: Number of extra ships needed to compensate for draft limitations at sill Niftrik for different discharge regime and bed level scenarios.

Figure 4.9 shows that the harm to shipping efficiency caused by draft limiations at Niftrik is relatively constant throughout the different scenarios. When comparing the absolute number, the harm done by the sill at Niftrik is comparable to the harm done by Belfeld. At the West route, however, the demanded goods flow is way smaller than at the Meuse route. So, the relative impact of sill Niftrik is bigger than the relative impact at Belfeld. The hypothesis states that sill Niftrik determines the maximum draft of vessels sailing on the West route is confirmed by these results.

Bottlenecks for a quick transport from A to B are the locks at Maasbracht and Grave. The waiting times depend on the available discharges only, so scenarios with imposed bed degradation are not addressed. Figure 4.10 presents the total annual waiting hours at both lock Maasbracht and lock Grave.

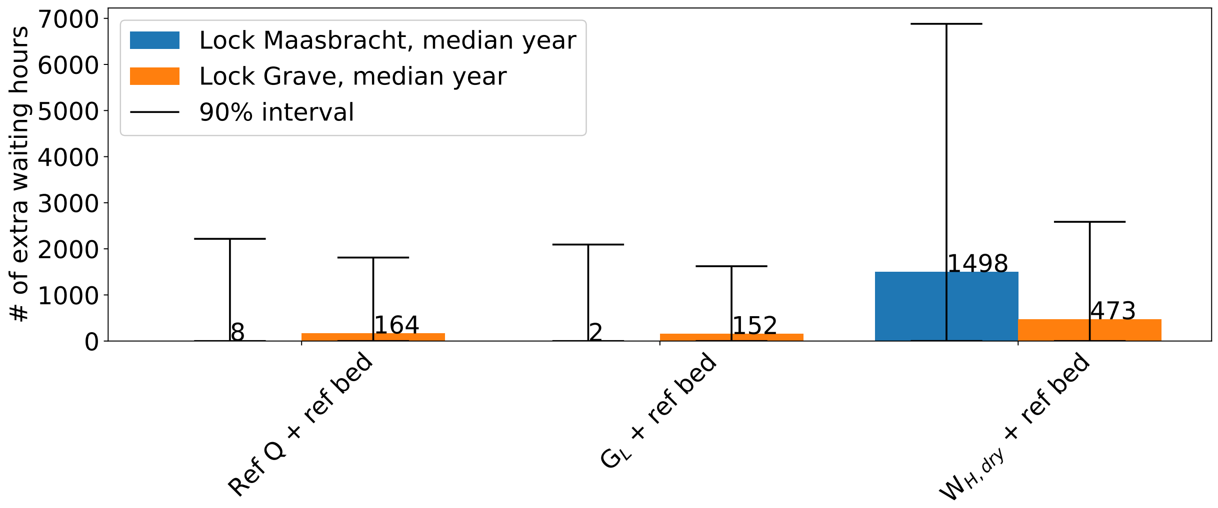

Fig. 4.10.: Number of extra waiting hours due to limited locking frequency at lock Maasbracht and Grave for different discharge regime scenarios.

Figure 4.10 shows that a changing discharge regime can have a large impact on waiting hours at both Maasbracht and Grave. The five percent of driest years in any scenario cause much more harm than the median years.

4.2 Flood safety

4.2.1 Potential impact of defined trends

This research aims at assessing the impact of river trends on river functioning. Before defining indicators that represent the current and future functioning of the Meuse river regarding flood safety, the impact of bed developments and altering discharge regimes is qualitatively assessed.
The primary effect of a decreased riverbed level is the decrease of peak water levels during extreme discharge events. For flood safety, this is a positive effect, as the hydraulic load on flood protection structures decreases. The expected water level decrease is not as big as the imposed bed level decrease, due to water flowing over the floodplains as well. There is no erosion imposed on the floodplains.
A flood wave routing through a river will flatten out over distance and time. The speed with which a discharge wave travels through the river depends among others on the water depth. If this water depth increases, the wave is expected to travel at a higher celerity. The lower the wave celerity, the more it dampens out over distance (Blom, 2017). When bed erosion is imposed, the flood wave is expected to arrive at the downstream end earlier. On top of that, the flood levels are expected to increase at reaches where no bed erosion is imposed. Higher flood magnitudes,

caused by an altering discharge regime, cause flood wave celerities to increase as well.
As explained in Section 4.1, only a small amount bed erosion can lead to large erosion pits. These pits can not only undermine weirs and ship locks, but form a risk for the undermining of flood safety structures as well.
Both bed erosion and larger flood wave peaks are expected to lead to different peak water levels. Along the Meuse river, at several places retention areas are constructed. These retention areas have inlet weirs are designed in such way that they flatten the peak of the flood wave as efficient as possible. A change in peak water levels can impact the retention area effectiveness.
It has become clear that that the impact of bed developments and altering discharge regimes can impact flood safety functioning in different ways. This research observes only the hydraulic effects, disregarding the potential effect on structure stability and retention are effectiveness.
Under these conditions, two hypotheses are defined. The hypotheses are tested in the hydraulic modeling phase and reflected upon.

- At reaches with imposed bed erosion, peak water levels will decrease.
- Both bed erosion and higher flood wave magnitudes will cause the flood wave celerity to increase.

4.2.2 Functional performance indicators

When using this simplified approach, a change in representative water levels, is assumed to directly result in an extra levee height demand. This results in a similar failure probability contribution of the failure mechanisms overtopping and overflow. Likewise, a change of representative water levels is assumed to directly result in an extra levee berm width demand as well. This results in a similar failure probability contribution of the failure mechanisms piping and macro stability. In the assessment of functional performance with regard to flood safety, only relative values are observed. Therefore, the functioning of the current Meuse river system is by definition equal to zero. Only when bed levels or peak discharges are varied, the indicator has a non-zero value.

In Figure 4.11, a direct translation between the indicator score and levee crest height demand is given. For this second indicator, this translation can be made accordingly. A geotechnical solution for the increased failure probability would be to expand the levee (berm) width. The simplest, most generalizing way is to use the most conservative version of the Bligh rule as explained in Foerster et al. (2012). This method comes down to the following rule of thumb: for every meter water level increase at discharge event with a return period of 100 year, the levee berm should become 18 meters wider. This factor 18 is called the creep factor. After discussion with a flood protection expert, it turns out that a creep factor of 18 is not considered a conservative estimate for levees along the Meuse river. Instead, experience learns that a creep factor of 35 is closer to reality with regard to the Meuse river in the Netherlands (Personal communication, W. Janssen, flood protection expert at Arcadis B.V., April 30^{th} 2020). This number is based on levee strengthening projects, in which the method of Sellmeijer (Foerster et al., 2012) was applied. In

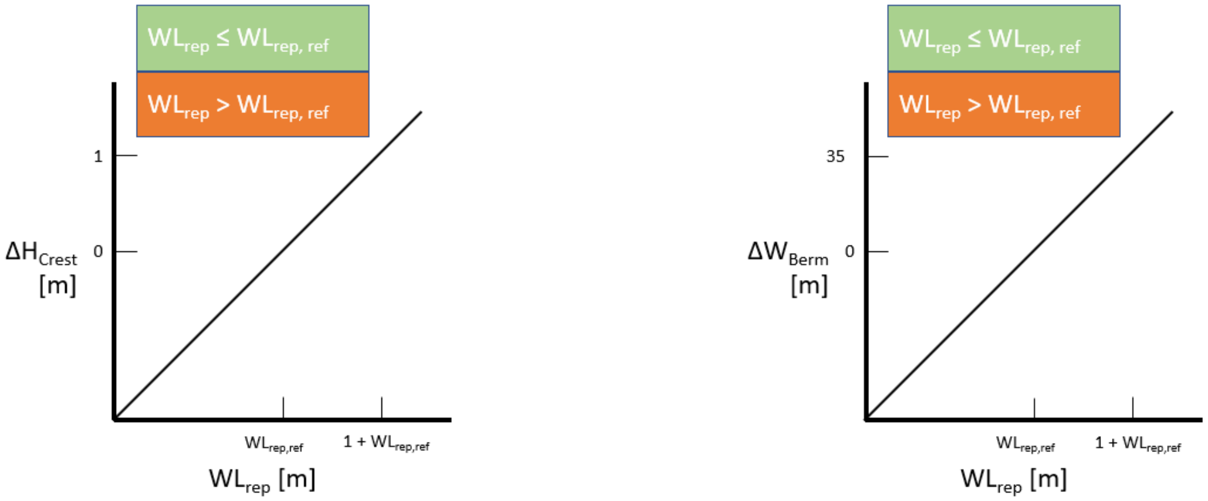

Fig. 4.11.: Functional performance indicator for flood safety and the translation to levee crest height and berm width demands. In this research it is assumed that a change in representative water levels is translated directly to a change in demanded levee dimensions.

this method more geotechnical factors are included, leading to more reliable results. The results of the Sellmeijer method were reversely engineered to creep factors. In this light, a creep factor of 35 is considered a conservative choice. The implication of the varying indicator value is shown in Figure 4.11.

4.2.3 Functional performance assessment

Figure 4.11 shows the translation from a change in water level to a levee crest height demand and a change in levee berm width demand at an arbitrary levee. To apply this on actual Meuse river levees, levee locations and levee lengths are used (Rijkswaterstaat, 2020c; Slootjes and Wagenaar, 2016). The river kilometers along which a levee stretch is located are matched to levee. From the hydraulic model results, water levels in different scenarios are obtained, allowing for comparison between the scenarios. In this way the relative functional performance is assessed, leading to average representative water level differences along levees. Consequently, river stretches that are not accompanied by levees are not included in this analysis.

Indication of financial implications

In Eijgenraam (2005), the costs of levee heightening for several levee rings along the Meuse river are presented. Since not all levee rings are incorporated in the report, an assumption on a price for all levee rings has to be made. Of the levee rings reported by Eijgenraam (2005), the levee ring Maaskant is located geographically the most central compared to the whole Meuse river stretch in the Netherlands. The price of levee heightening at Maaskant is EUR 27000 /cm/km. This price is taken as an unity price for levee heightenings along the whole Meuse river. In Eijgenraam (2005), fixed costs for levee heightening projects are presented as well. However, as along the complete

Meuse river flood safety challenges are already present, fixed costs will not be taken into account in this research (Barneveld et al., 2019).

The total costs of levee heightening challenges is calculated by multiplying the average crest level by the total levee length of 400km and the unit price of EUR 27000.

4.2.4 Results

The maximum water levels during flood waves with a return period of 100 and 3000 years are presented relative to the water level in the scenario with the reference discharge regime and reference bed level. This happens using longitudinal plots, presenting the river kilometer (or chainage) on the x-axis and the relative water level on the y-axis. In the figures, the decrease in estimated bed erosion rate in downstream direction is recognized. This leads to the biggest drop in water levels on the Common Meuse and Plassenmaas, while at the Tidal Meuse no water level drop is observed. The figures present the results of the hydraulic model in relative water levels, while the averaged results of the translation to levee dimensioning challenges are presented in tables. The results per levee ring are presented in Appendix G. In Section 4.2.1 two hypotheses were defined. The hypotheses are addressed one by one. The first one is:

At reaches with imposed bed erosion, peak water levels will decrease.

Figure 4.12, presents the water levels resulting from discharges with a return period of 100 years for the scenarios with the reference bed level and degraded river beds.

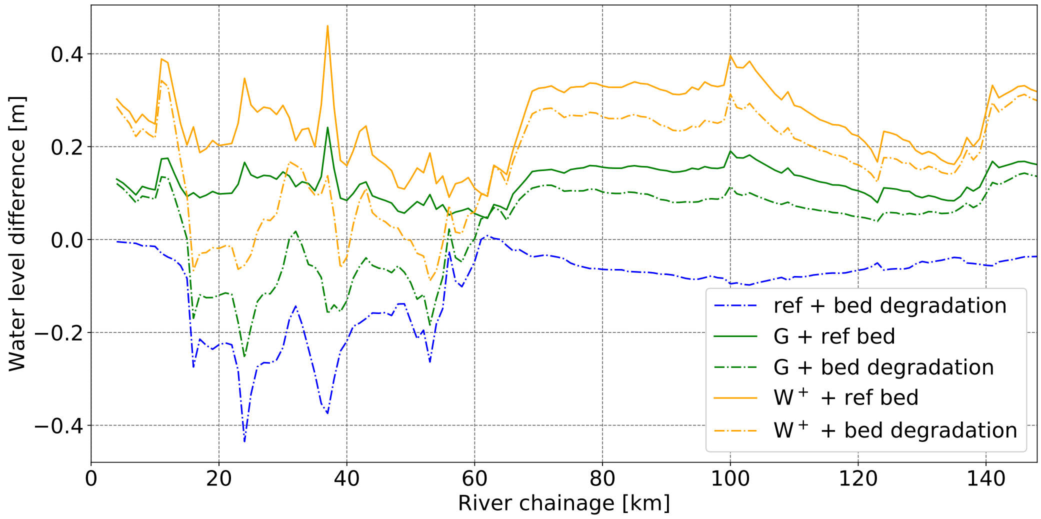

Fig. 4.12.: Maximum water level differences for all scenarios with the original or degraded river bed during a 100 year flood wave, relative to the reference scenario.

It becomes clear that in the degraded bed scenarios, the first kilometers of Upper Meuse do not show large variations in water level. This is explained by the zero bed degradation that is imposed in this stretch. In the Common Meuse stretch, the water level differences grow to maximum of about two third of the imposed bed level degradation near kilometer 25. In between kilometer 54 and 65, the effects of bed level degradation get close to zero. The reason for this is the presence of a side channel called the Oude Maas (in English: Old Meuse). The inlet for this side channel has a fixed weir crest. The discharge that flows over the crest is directly related to the water level on the Common Meuse. When bed degradation causes the water level to decrease at equal discharge, the Oude Maas inlet drains less water from the Common Meuse. This causes the effect of bed degradation to decrease in the stretch between river kilometer 54 and 65. After this point, the effect of a lower riverbed increases until to kilometer 100. At kilometer 100, the imposed bed level degradation decreases compared to the Plassenmaas.
From river kilometer 15 to 60 (the Common Meuse) the estimated bed degradation is such that it might completely counteract the effects of an altering discharge regime. From kilometer 60 on, the changing discharge regimes cause the water levels to rise stronger than the bed degradation causes the water levels fall. The net effect of the expert judgment bed degradation in combination with higher discharges will be an increase in water level. Figure 4.13 presents the implications for water levels along the Meuse caused by a double bed degradation rate.

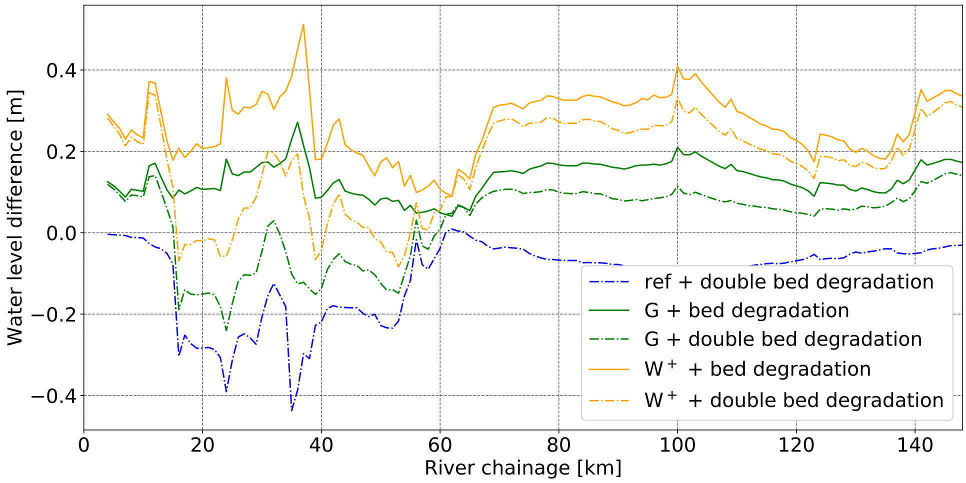

Fig. 4.13.: Maximum water level differences for all scenarios with a degraded or double degraded river bed during a 100 year flood wave, compared to the reference scenario with a degraded river bed.

When comparing Figure 4.12 and Figure 4.13, it becomes clear that doubling the degradation rates approximately doubles the impact on the maximum water levels.

Table 4.3 presents the averaged effects of the scenarios on the water levels at levees in the first 147 kilometers of the Dutch Meuse. Table 4.3 shows that a changing discharge regime probably has a bigger impact on representative water levels at levees than bed degradation. Only in case of the doubled degradation rates, the G discharge regime shows negative change in averaged representative water levels. In the reference and G discharge regime, the double degraded riverbed has a larger relative impact on the berm width demands than the degraded riverbed. In the W^+ scenario, however, the relative impact of the double bed degradation rates is equal.

Tab. 4.3.: Averaged effects on maximum water levels at levees during a 100 year discharge wave in the first 147 kilometers of the Dutch Meuse in different scenarios. The numbers are in centimeters.

Scenario	Ref	G regime	W^+ regime
Reference riverbed	0	13	27
Bed degradation	-10	4	18
Double bed degradation	-20	-6	9

Figure 4.14 presents the impact of bed level developments on a 3000 year reference discharge.

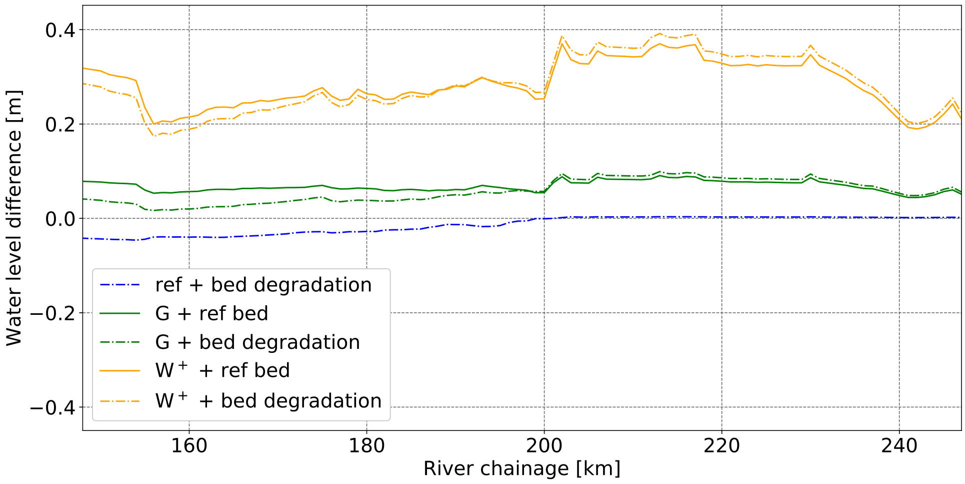

Fig. 4.14.: Maximum water level differences for all scenarios with the original or degraded river bed during a 3000 year flood wave, compared to the reference scenario.

Until river kilometer 201, 10cm of bed degradation is imposed in the hydraulic model. Figure 4.14 shows that until that location, bed degradation lowers the water levels with about half the erosion rate.

From river kilometer 201 on, the bed degradation upstream causes the water levels in the G and W^+ regimes to rise above the water levels with the reference bed level. This effect is explained as follows. The bed degradation causes the water depths to increase. A discharge wave routing through the river naturally flattens along its course. The shallower the river, the faster this flattening happens. The expectation is that the bed degradation causes a slower flattening, leading

to higher peak discharges at the downstream end.
Figure 4.15 presents the implications for water levels along the Meuse caused by a double bed degradation rate.

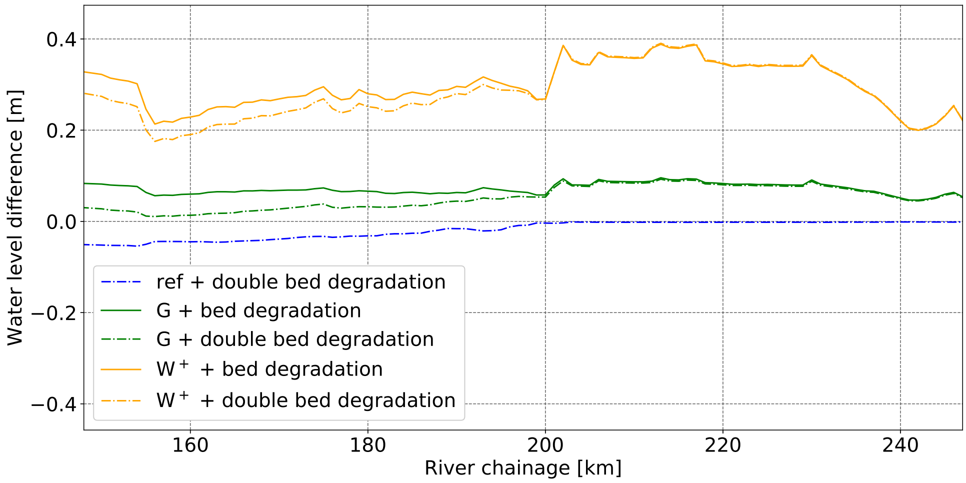

Fig. 4.15.: Maximum water level difference for all scenarios with a degraded or double degraded river bed during a 3000 year flood wave, compared to the reference scenario with a degraded river bed.

Doubling the degradation rates has a comparable effect on the water level differences as the expert judgment degradation rates, since the differences between Figure 4.14 and Figure 4.15 are rather small. In the Tidal Meuse, however, doubling the degradation rates does not lead to even higher water levels in that river stretch. Table 4.4 presents the averaged effect of the combinations of different bed levels and discharge regimes.

Tab. 4.4.: Averaged effects on maximum water levels at levees during a 3000 year discharge wave from river kilometer 147 to 248 in different scenarios. The numbers are in centimeters.

Scenario	Ref	G scenario	W$^+$ scenario
Reference riverbed	0	7	29
Bed degradation	-1	6	29
Double bed degradation	-3	4	27

Table 4.4 shows that the bigger the peak discharge, the smaller the impact of bed degradation is. The bigger peak discharges, cause higher water levels. As the bed degradation rates are equal for different discharge regimes, the relative bed degradation is smaller for the higher discharges, leading to a smaller effect of the bed degradation on the water levels. In the most extreme altered discharge regime, the expert judgment bed degradation leads to lower water levels in the first fifty kilometers, but this is completely counteracted by the higher water levels in the last fifty

kilometers. This points out that bed degradation does not necessarily have a net positive effect on levee height demands.

Figure 4.16 shows the combined results at levees along the whole Dutch Meuse river. In this table, for all Meuse river levees the water level differences at representative discharge waves are averaged.

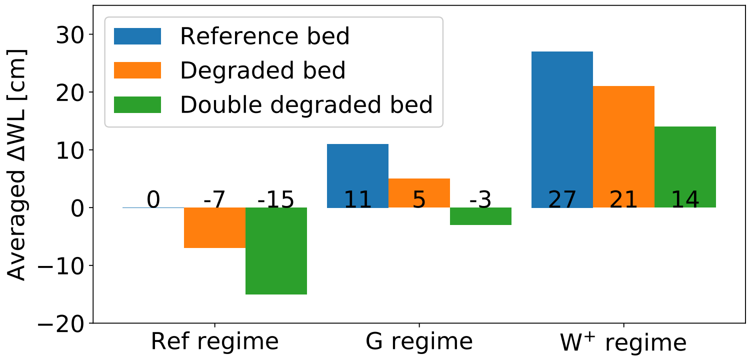

Fig. 4.16.: Averaged effects on maximum water levels at levees during a representative discharge wave along the whole Dutch Meuse in different scenarios.

The second defined hypothesis is:

Both bed erosion and higher flood wave magnitudes will cause the flood wave celerity to increase.

Figure 4.17 shows three different flood waves passing by river kilometer 200 (near Lith).

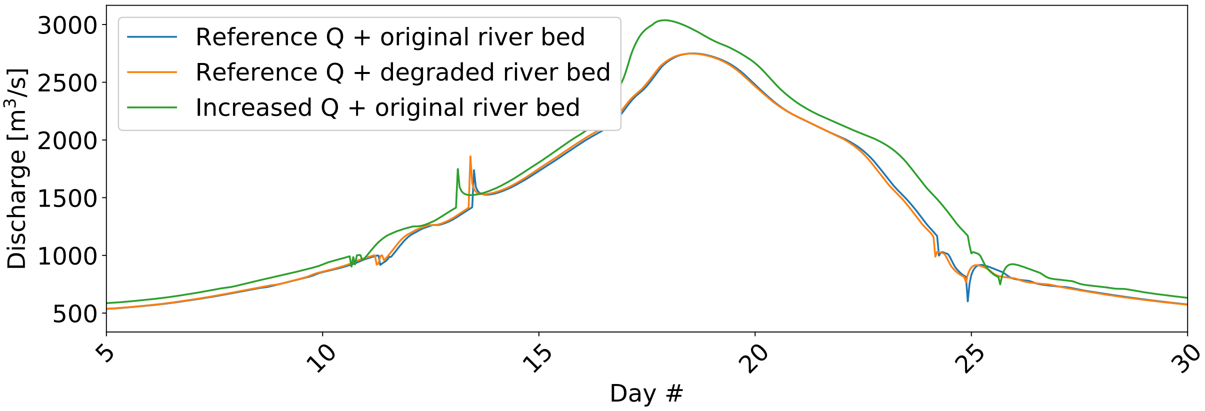

Fig. 4.17.: Hydrographs of different kind of flood waves at river kilometer 200.

The figure confirms the defined hypothesis. The earlier arrival of the peak discharge with the increased Q (W$^+$ discharge regime) is clearly visible, while the flood wave celerity increase in case of the degraded river bed is way smaller.

4.3 Financial comparison of impacts

This section aims at comparing the impact of bed level developments and an altering discharge regime on the functioning regarding the two addressed functions. It helps in answering the last research question:

Reflecting on these results, what recommendations can be given for water managers responsible for the Meuse river?

A more elaborated answer on this question is provided in Section 5.3, but this financial analysis aims at supporting the reasoning in that section.
To do so, the explained cost indication methods are used. It is stressed that the presented numbers are only a global indication of the real costs. The defined base cases for navigation are based on rough assumptions and estimates. On top of that, only the draft limitations at lock Belfeld are translated to costs. Belfeld was chosen because the mean draft limitations are bigger than at lock Weurt. Still, in reality there will be situations in which there is sufficient water depth at lock Belfeld, while at lock Weurt the draft is limited. This method neglects these situations. For the waiting times at locks, only lock Maasbracht and Grave are addressed, while in practice other locks can limit their locking frequency as well. Regarding the levee strengthening demands, only levee heightening is taken into account. Levee widening is a at high costs as well.

Net present value
With the net present value formula, the present value of future cash flows is calculated. In Equation (4.3), the net present value formula is presented with NPV the net present value [EUR], t the period [years], CF the cash flow [EUR] and r the discount rate [-]. A discount rate of 3%, seems appropriate for this analysis (Hiemstra, 2019). When a linear development of a decreased functioning in navigation is presumed, the net present value of the decreased functioning can be calculated. The investments in levee heightenings are assumed to be done 5 years before the horizon year 2050, which is 25 years from now. In Table 4.5, the net present value of economical harm caused by draft limitations, extra waiting times and a change in crest level demands.

$$NPV = \sum_{t=1}^{n} \frac{CF}{(1+r)^t} \tag{4.3}$$

For navigation, costs of decreased efficiency of transport come back each year. For this function, all costs in between 2020 and 2050 are added up to give the total costs until 2050. For simplicity, it is assumed that the future changes in functional performance will occur perfectly linear in time. For flood safety, increasing a levee's crest is done only one time. In this research it is assumed that this is done in 2045, 5 years prior to the time horizon. Table 4.5 presents the net present value of economical harm caused by draft limitations, extra waiting times and a change in crest level demands.

Tab. 4.5.: Net present value of extra costs until 2050 due to a changing functional performance over time. The costs are presented in 10^6·EUR. Negative costs indicate an improved river functioning.

Draft limitations	Ref	G_L	$W_{H,dry}$
Reference riverbed	0	-6	13
Bed degradation	0	0	13
Double bed degradation	0	0	13
Extra waiting time			
Reference riverbed	0	0	0
Levee crest heightening			
Reference riverbed	0	35	86
Bed degradation	-22	16	67
Double bed degradation	-47	-10	45

Table 4.5 shows that the costs of draft limitations by bed degradation are easily outweighed by the cost reduction in levee heightening demands. This is true even if the investments in levees is done relatively late. The chosen discount rate is based on a rough estimate and may very well vary in reality. If the discount rate increases, future costs become less important while present costs become more relevant. This would decrease the large gap between . If the discount rate is smaller

Discussion

5

In this study, the effects of large-scale bed level developments and a changing discharge regime on until the functional performance of the Meuse river until 2050 is determined. The river functions included in this study are navigation and flood safety.

In this chapter, first, the applicability of the research methodology on other river systems is addressed. After that, the sensitivity of the methodology results to assumptions is discussed. Next, Section 5.3 presents a reflection on the results from a water manager's perspective.

5.1 Applicability of methodology

Hiemstra (2019) performed comparable research work in which he assessed the future functional performance of a Waal river stretch. In his research, the functions navigation, flood safety and nature are included. A big difference between the Waal river and the Meuse river is the fact that the Meuse encompasses mostly stretches in which the water level is controlled by weirs, while the Rhine river system is mostly a free flowing river. This causes the effect of low flows on water levels to be way more severe. Another major difference is the economical interest of the navigation sector in the Waal river compared to the Meuse river. The goods flow through Hiemstra's case-study area is about 5 times bigger than the goods flow over the Meuse route. On top of that, since the Waal river water is not controlled by weirs, the impact of low flows on the navigation is way bigger on the Waal river. These differences put the study results in another perspective. What stands out in the study by Hiemstra is that the interest of navigation is so big (in monetary units) that losses prevented in that sector probably weigh up to heightening levees or taking other flood defense measures. In the Meuse river, the navigational draft limitaitons have a clear lower boundary formed by the weirs. This makes the balance between interests in the river more precarious.

Another difference with the study by Hiemstra (2019) is the scale at which the analysis is applied. Hiemstra applied his methodology on a river stretch with a length of about 30km, while in this study points of interest in almost 250km of river length are incorporated. At the same time, Hiemstra presented different management strategies and an insight in the costs that come with different management strategies, while such an analysis turned out to be unfeasible during this study.

The research steps taken in this research are generally applicable to river systems comparable to the Meuse river. The approach in this study assumes the river (stretch) in question serves several functions, which do not have a clear mutual socio-economical or legal hierarchy of importance. In such river systems, it should be possible to select one or multiple future developments that have impact on the hydraulic characteristics and to quantify the impact of those developments on several river functions. As the approach deals with hydraulic parameters, it is a prerequisite that

the functional performance of the functions in question rely on hydraulic parameters as well.
If a study area complies to these demands, it is expected that by following these research steps a solid estimate of the future river performance on the selected functions can be made. As for this study, the research would then support the decision making process river managers deal with in order to facilitate a spread of functions.
When other functions are included, this potentially causes the functional performance assessment to change. In this research, for instance, no seasonal demands of river functions are included. When including the facilitation of ecology and/or leisure activities, this might demand the analysis to focus on a seasonal scale.

5.2 Sensitivity to assumptions

In the analysis of water levels, it is assumed that the weirs in the Meuse river can maintain the Controlled Water Levels (CWL) at all times. This is chosen because water level measurements have not pointed out situations in which the CWL could not be maintained (Rijkswaterstaat, 2020e). This assumption is of big importance for the results of the analysis. Section 4.1.1 presents different mechanisms that can falsify this assumption. If the CWL cannot be maintained at (weir-)lock complexes, this can have big complications for navigation. In that case, the clear lower boundary of damage to navigational functioning is not there anymore, leading to a multitude of draft limitations than pointed out in this research.
Moreover, there is another concern regarding the maintenance of the CWL. At weir-lock complex Grave, however, a constant leakage of 20 m^3/s is assumed for the analysis on waiting time for ships. The hydraulic model results show that discharges sometimes underceede this threshold. This would point at the river basin between weir Grave and weir Sambeek to drain slowly. When the outflow is bigger than the inflow, the water level should undeniably drop. If the water level drops, this will have (among others) implications for the navigability on the Meuse river, especially for ships passing lock Sambeek. It might well be that the assumption of the CWL maintenance causes another potential problem for navigation to be ignored.

The future bed level trends are based on an expert judgement following from a discussion attended by a spread of river engineering experts. Of course, choosing other bed level trends would result in different study results. The sensitivity of the main conclusions, however, is expected to be small. Also for the doubled bed degradation scenarios, the effects of bed degradation on river functioning are smaller compared to the effects of changing discharge regimes. This means that the results of the study rely more on the accuracy of the altering discharge regimes than on the accuracy of the bed level trends. Knowing the exact bed level developments is especially essential for the functioning on flood safety, as this is the only way the bed developments can have a positive impact on river functioning.

This brings us at the sensitivity of the study results for the assumption of future discharge regimes. In this study the regimes were considered as a given, but further research into the global and regional effects of global warming may alter the discharge regime scenarios. When the scenarios alter, the results of this study may alter significantly as well. The results in this study show a spread from a slightly wetter discharge regime to a seriously drier discharge regime. This means the spread in expected future river functioning is still quite big, pointing at a relatively high sensitivity of the research outcomes to the future discharge regime.

When assessing the impact of draft limitations at sills in the river or at locks, the impact was expressed in the number of extra ships needed to transport a given amount of goods. This implicitly assumes that the load factor (LF) would be equal 1 if it would not be limited at the observed sills. This is a rather optimistic representation of reality. In practice, it may well be that a ship's draft is limited by another sill on its journey. From Rijkswaterstaat (2019a) it becomes clear that most ships passing Belfeld come from the Rotterdam Harbour area or the Amsterdam harbour area. Most fairways in this areas allow for a draft of 3.5m, but local conditions at for instance harbours may limit the draft as well. It is considered unfeasible to quantify the effects of secondary draft limitations, but it is beyond question that the impact of draft limitations at both Niftrik and lock Belfeld overestimate the real impact.

When discussing with flood protection experts and when consulting literature on this topic, it becomes clear that the approach of the flood safety assessment in this research is rather imperfect. When considering flood safety on a more local scale, local river conditions play a very large role for the determination of levee dimensions. In this research only two representative discharges are used for each considered discharge regime scenario. With this approach, wave conditions for instance are ignored. The assumption under this approach is, however, that all conditions stay equal except for the still water level caused by the representative discharge wave. This means that levee dimensions cannot be based on the absolute water levels following from this analysis. When analyzing the relative impact, however, the results of this study give insight in the order of magnitude of levee dimensioning challenges for the future.

The Sobek 3 model that is used for this study is supplied by Deltares. Before the model is suited for the type of analysis of this research, some adjustments were made. One of the adjustments was the removal of all retention areas. The reason for this was that the effectivity of retention areas is highly unpredictable when the river conditions change. In this way, leaving the retention areas unchanged means there is a risk of modeling the effects of changed retention area effectivity instead of modeling the effects of bed level developments and altering discharge regimes. As a check whether this choice is justified, the flood wave analysis was done with and without the retention areas. The difference is presented in Figure 5.1.

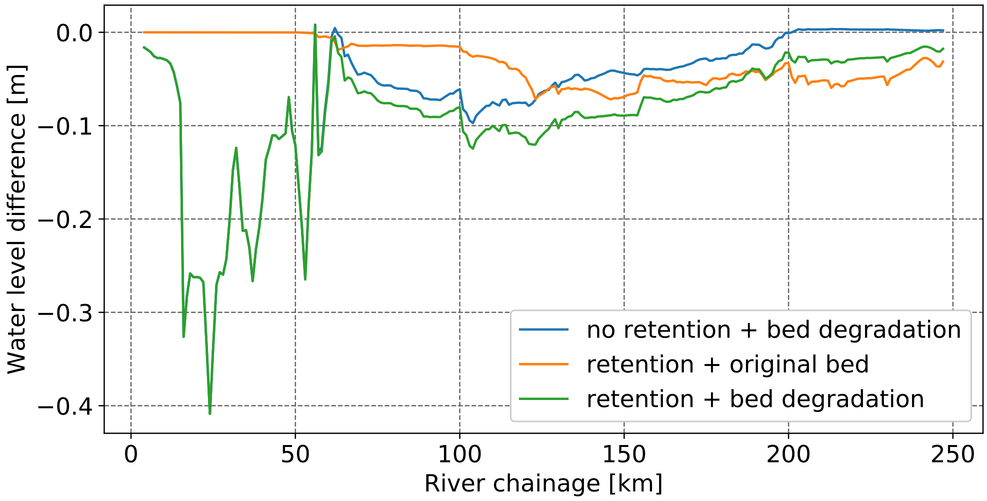

Fig. 5.1.: Maximum water level differences for a 3950 m^3/s (T = 3000 year) discharge wave for model runs with and without active retention areas for the original and degraded bed levels. The water levels are plotted relative to the water levels resulting from a model run with original bed levels and no active retention areas.

Especially in the last kilometers of the modeled river stretch, the impact of retention areas on the study findings becomes clear. When retention areas are present, water levels increase in the last fifty kilometers of the modeled river stretc. This points out that for modeling the impact of bed degradation and altering discharge regimes only, it is wise to remove the retention areas. It points out as well, that the retention areas impact water levels in the Meuse river significantly. Therefore it is recommended to gain more insight in the working of the retention areas in combination with the large scale river developments addressed in this study. Doing such a study with a 1D hydraulic model as was used in this study is not expected to give sufficiently reliable results.

5.3 Reflection for Water Management

In this chapter, the research set-up and results are approached from the point of view of a water manager. First, the two functions this thesis deals with are illustrated and the indicators representing each function's performance are explained. Then the main findings for each function are presented, together with a reflection on the findings for the specific functional performance. At last, the Meuse river's functional performance will be reflected from a more integrated point of view.
This chapter addresses the following research question:

How can the functional performance assessment support water management decision making?

In Figure 5.2, the positioning of this chapter in the research process is summarized.

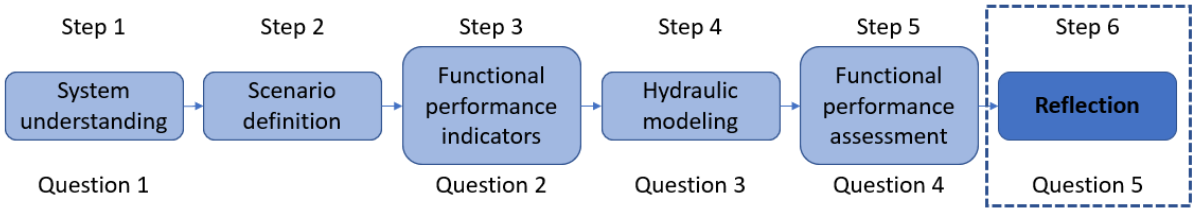

Fig. 5.2.: Summary of research steps. The current chapter deals with step 6.

The goal of this study is to assess the impact of bed level developments and a changing discharge regime on the functional performance of the Meuse river for the year 2050. In this study two functions of the Meuse river are assessed: navigation and flood safety. The functional performance assessment is done by defining hydraulic indicators representing the river's functioning. These indicators are quantified using an hydraulic model. In the hydraulic model, the current discharge regime and current bed levels are used as a reference. Subsequently, two future discharge regimes and two bed degradation scenarios are implemented in the hydraulic model. The discharge regimes represent the bandwidth of discharge regime developments caused by global warming. This means the study results represent a discharge regime emerging from relatively mild global warming scenarios (the G_L or G discharge regime) and a discharge regime emerging from relatively severe global warming scenarios (the $W_{H,dry}$ or W^+ discharge regime). For the bed degradation, an estimate of expected degradation rates until 2050 is imposed on the hydraulic model. In order to be able to compare the effect of different bed degradation rates, a scenario with doubled degradation rates is included as well.

5.3.1 Functioning of the Meuse river

The functional performancen of the Meuse river is assessed by making use of indicators. The two functions navigation and flood safety are addressed separately, resulting in a summarizing paragraph at the end of this section.

Navigation

Navigation on the Meuse river is separated in two main shipping routes: the Meuse Route from the Waal at Nijmegen to Maastricht and the West route from the river mouth up to Cuijk. From an economical point of view, the Meuse route is more important than the West route, since it facilitates about 3 times as much navigational transport (±18 mln tonnes vs ±6 mln tonnes in 2018). Compared to the Waal river, however, navigational transport on the Meuse river is rather small, as the Waal river facilitates about 7.5 times as much navigational transport than the Meuse route (± 135 mln tonnes in 2018). For an optimal functional performance, ships on the Meuse river need to carry as much goods as possible from A to B with the least possible delays on their way.

Both the West route as well as the Maas route are officially assigned a maximum draft of 3.5m as they have CEMT classes of Va an Vb respectively. Hard sills in the Meuse river's shipping routes tend to limit the draft of ships navigating on the Meuse river. The sills limiting the draft most are located at Niftrik (a crossing bundle of pipelines or *Leidingenstraat Niftrik*) and the entrance at shiplock Belfeld. A draft limitation at these locations, generally means that ships cannot fill their barges optimally, leading to a smaller transport efficiency. As ships sailing from the Waal river to the Meuse river passes lock Weurt as well, the draft limitations at the Waal side of lock Weurt are assessed as well. These limitations turned out to be much smaller than the draft limitations at Belfeld.

For the assessment of the Meuse river functioning with regard to navigable depth, the water level at Niftrik and at the downstream side of lock Belfeld are used as indicators. The draft limitations at these locations are expressed in the number of ships needed each year to compensate for the load factor deficits. The critical depth needed for optimal functioning is 4.0m, assuming a keel clearance of 0.5m. Based on this study, both bed degradation and an altering discharge regime are expected to negatively impact the draft limitations of lock Belfeld and the sill at Niftrik. At Belfeld, the load factor constraints stay limited to a few percent (maximum of 3%) of the maximum theoretical load factor (which is 1). At Niftrik however, the maximum load factor constraint is in the order of 30%, which significantly limits the transport efficiency for ships passing Niftrik.

When navigating on the Meuse river, ships usually have to pass several locks. When the ship can enter a lock immediately at arrival, it takes time (about 20 minutes) to pass a ship lock. In periods of low river flow, however, the lock would discharge too much water from the upstream to downstream side for the natural river flow to compensate for this. In thse periods of time, the locking frequency is decreased, allowing ships to enter the lock chamber only in groups. These measures increase the delays at ship locks. In the current discharge regime, especially lock Maasbracht forms a bottleneck for smooth navigation. The lock spans a relatively big water level difference resulting in relatively large locking loss discharges (12 m^3/s under normal circumstances). Also, lock Grave is vulnerable to this mechanism. Although the locking losses are very small (1.5 m^3/s under normal circumstances), the leakage losses at weir Grave are considerable ($\pm$ 20 m^3/s).

The discharges at lock Maasbracht and lock Grave are defined as indicators for the extra waiting time at these locks. The result of this assessment is expressed in extra waiting hours because of ships being delayed by the limited locking frequency.

Lower future river discharges due to an altering discharge regime will have impact on the waiting times at both lock Maasbracht and lock Grave. In the milder (wet) future discharge regime, the impact will be very small, but positive. In more severe discharge regime, waiting times will increase with hundreds of hours per year.

Flood safety

Along large parts of its course, the Dutch Meuse is separated from its surroundings by levees. These levees protect the hinterland from flooding. The levees comply to safety rules, in order to guarantee a certain maximum annual probability of failure. In the more upstream reaches of the Dutch Meuse, these failure probabilities are in the order of once every 100 or 300 years, while in the more downstream reaches failure probabilities have to be in the order of every 3000 years. In other words, the spread in safety standards of levees along the Meuse river is wide. To assess this variety of safety standards, in this research the guidelines of the so-called Rivierkundig

Beoordelingskader (RBK, in English: River Engineering Assessment Framework) is used. These guidelines are designed such that the impact on the flood safety can be assessed quickly on a relatively big scale, instead of assessments on individual levee traject scale. In the RBK it is stated that interventions in the riverbed are assessed with regard to their impact on flood safety by making use of two representative discharge waves: one with a return period of 100 years and one with a return period of 3000 years. The first discharge wave represents the levee failure probability caused by piping or macro stability issues. The latter discharge wave represents the levee failure probability caused by overtopping or overflow. In this research, the water levels along the Meuse that result from these two representative discharges are defined as indicators for the river's performance on flood safety. It is assumed that an increase in water levels resulting from a 100 year discharge, is translated to a levee berm width demand, while in increase in water levels resulting from a water 3000 year discharge, is translated to a levee crest height demand. The functional performance assessment happens only relative to the water levels in the reference scenario.

Bed degradation causes representative water levels to decrease, leading to lower levee berm width and crest height demands. Higher representative discharge magnitudes, however, overcompensate for this possible positive, since they lead to bigger representative water level increases. So when combining the two effects, a increase of levee strengthening challenges is expected.

5.3.2 An integrated perspective

It has become clear that both bed level developments and discharge regime changes until 2050 have impact on both navigation and flood safety. It is interesting to see where large-scale river developments have a similar impact on river functioning and where they have a counteracting impact on river functioning.

Bed degradation amplifies the draft limitations at sills in the river, but decreases the future levee strengthening challenges. Compared to the impact of a changing discharge regime, the impact of bed degradation on navigational functioning is rather small, while the positive impact on the flood safety is comparable to the impact of a more extreme discharge regime. It is therefore advised to keep on monitoring the bed level developments throughout the whole Meuse river, without an immediate need to intervene in the river morphology. During the last decade, the riverbed developed rather slow, but as the conditions in the Meuse river are very volatile, monitoring and reporting the developments is essential to stay in control of future river functioning. In this research, the decrease in flood water levels due to bed degradation is reported as a positive impact on levee dimensions. This profit is only true profit when the positive effects of bed degradation are actually acknowledged by policymakers. This means updating the theoretical bed levels in the Meuse river with the measured bed levels is necessary.

Bringing the riverbed back to a historic bed level profile, is not expected to sufficiently counteract the effects of the more persistent and more extreme low flows of the future. At the same time, however, increasing bed levels is expected to have a significant impact on flood water levels across the whole river stretch. When monitoring bed levels, it should be kept in mind that bed degradation in the upstream stretches, might lead to an increase of flood water levels at the more downstream stretches.

The overall decrease of water levels and discharges during periods of low flow has a general negative impact on river functioning. Navigation suffers from this tendency. The biggest issue for waiting times at locks is the water scarcity. Locks demand a certain level of river flow for optimal functioning. Increasing the base flow or water buffer capacity in the Meuse river system would have a positive impact on both functions. If the basins in between the weirs in the river are assigned a buffering function by maintaining a higher controlled water at the beginning of a dry period, this will increase the resilience of the draft limiting sills in the Meuse river, but it might also allow for more frequent locking during low river flows. Personal communication with water management specialist P. Weerts (Rijkswaterstaat, June 23 2020) points out that maintaining a higher CWL is hard, as leakage losses increase. This points out the importance of mapping the severity of these losses and mitigating the leakage discharges. For waiting time issues at lock Grave, it is recommended to mitigate the leakage discharges as soon as possible in order to prevent delays. This seems to be a more practical solution than general buffer increasing measures.

Conlusions & recommendations

6

6.1 Conclusions

1. What mechanisms determine the response of the Meuse riverbed to human interventions in the river system?

The Meuse river is a sediment supply-limited river and human interventions in the last century have caused the sediment carrying capacity to increase. These two mechanisms cause the river bed to erode over time. At the same time, the river substrate characteristics are such that a static armor can form, counteracting this degrading trend. The interplay between these degrading and stabilizing mechanisms determine the response to human interventions in the river system.

2. What indicators determine the current performance of the Meuse river regarding the functions navigation and flood safety?

Four functional performance indicators represent the river functioning regarding the two observed functions. For navigation these are the water levels at draft limiting sills at the downstream end of locks Belfeld and Weurt, and the sill at Niftrik. The discharge available for locking at ship locks Maasbracht and Grave is a second indicator for navigation.

Regarding flood safety, the maximum water levels at levees during representative discharge waves indicate the functioning. For levees upstream from river kilometer 147 (lock Sambeek), the representative discharge wave has a peak magnitude with a return period of 100 years. Downstream from this point, the representative discharge wave has a peak magnitude of 3000 years.

3. How will water levels and discharges in the Meuse river change taking the altering discharge regime and large scale bed level changes into account?

In areas where the water level is generally controlled by weirs, the water level in the upstream parts of impounded stretches depends on the backwater curve that is formed. At the downstream parts of river basins, the water level is still governed by the Controlled Water Level. Bed degradation or an altering discharge regime do not have impact on that. In the upstream parts of impounded reaches, bed degradation decreases the water level if backwater curve is formed, while altering discharge regimes determine how often the backwater curve is formed.

At the Common Meuse and during extreme discharge events, when the weirs are opened, the impact of bed degradation is more pronounced. Locally, this leads to water level drops of about two third of the imposed degradation. On average, an increase of extreme discharges overrules this trend.

4. What is the impact of the expected change of water levels and discharges on the functional performance indicators in both regulated and free flowing Meuse river stretches?

In impounded river stretches, the impact of changed water levels and discharges is relatively small. If the CWL is maintained, the damage bed degradation and persistent low flows cause to navigation is limited: In the order of a few percent. Persistent low flows do seriously impact the shipping time for ships passing locks, increasing waiting times potentially with a factor 2 or 3. In a more favorable discharge regime the river functioning slightly improves from a navigation perspective.

When the weirs are opened during extreme flows, representative water levels increase in the order of 10 to 30cm due to higher representative discharge by 2050. The expected rates of bed degradation do not fully counteract this tendency.

5. Reflecting on these results, what recommendations can be given for water managers responsible for the Meuse river?

Based on the relations addressed in this research, the negative impact of bed degradation on navigation efficiency is very small, while it can decrease water levels during representative flood events considerably. To prevent drawing premature conclusions, it is recommended to investigate other potential negative impacts of bed degradation regarding the stability of hydraulic structures and the capabilities of weirs to sustain the CWL. At the same time, the decrease of the bed level has to be recognized by policy makers in order to let it have a real impact on the dimension demands of flood protection structures. To do so, bed developments should be monitored thoroughly and the implications should be examined on a levee stretch scale.

Waiting times at lock Grave depend heavily on the leakage losses at weir Grave. It is recommended to find ways to mitigate these losses. This would decrease the harm to navigation efficiency.

The hydraulic conditions in the Meuse river currently enable it to facilitate navigation and a high level of flood safety. However, the hydraulic river conditions in 2050 will be different from the current conditions. Periods of low discharges and consequently lower water levels will become more persistent and extremely high discharges will have a bigger magnitude, leading to higher flood water levels. Bed level developments can decrease water levels in the low flow periods even more, while they can partly counteract the increased flood water levels.

For navigation, this means that bottlenecks for the draft of ships will become more critical under the future river conditions. Still, if weirs can maintain the CWL, the harm to navigation efficiency is limited to a few percent. Besides, longer periods of low river flow will cause the locking frequency to be decreased more often, leading to an increase in overall waiting times for ships at locks with a factor 2 or 3.

The representative discharges for flood safety will increase for future discharge regimes, consequently leading to an increase in representative water levels with 10 to 30cm. The expected bed degradation will decrease the representative water levels with 5 to 10cm. Combining the two, it is expected that the required levee dimensions will increase. This means levee crest levels will have to be increased up to 20cm, while levee berms are to be widened in the order of several meters.

The functioning of the Meuse river is expected to be put under pressure by the year 2050, urging water managers to monitor the developments closely and to look for possible effective measures mitigating the negative impact of these developments, while recognizing the positive impacts.

6.2 Recommendations

Study the risk of fine sands located directly under the riverbed

At various locations in the Meuse river, layers of fine sandy material are located just beneath the more coarse particles of which the current riverbed consists (Prins, 1999; Asselman et al., 2018). When the riverbed degrades further in the coming decades, there is a serious risk these fine sands are exposed. As fine sands erode easily, this might lead to rapidly advancing erosion, which could potentially lead to undermining of riverbanks or hydraulic constructions like weirs or quay walls. This type of developments could deteriorate infrastructure in the Meuse river, potentially leading to way more damage to river functioning than the type of developments addressed in this research. It is recommended to perform research to this type of riverbed behaviour and the impact on the functioning of the Meuse river. As a starting point, the most vulnerable spots should be identified.

Investigate the mechanisms that might undermine the sutaining of CWL at weirs

It might well be that in the future the CWL at weirs cannot be maintained as good as assumed in this study. Section 4.1.1 briefly addresses mechanisms that might cause weirs to be unable to sustain the CWL. Bed degradation causes the volume of impounded stretches to increase, this means more water is needed to sustain the CWL.

Leakage at weirs might become such a problem during persistent low flows that water levels drop significantly below CWL, leading to a variety of problems surrounding navigation, groundwater tables and other interests. On top of that, bed degradation surrounding weirs might lead to an increase in leakage losses. It is recommended to do research to this issue, starting with the notion that in practice, water levels have not dropped below CWL at for instance lock Grave, while discharges in the Meuse river have most probably underceeded the given leakage discharges. It is important to quantify the leakage losses at weirs and to find ways to mitigate the leakage losses if issues arise.

Consider more river functions

In this research, the number of river functions is constrained to two: navigation and flood safety. A river like the Meuse, however, facilitates more functions than these two only. Especially the function of ecology is an important one that is not represented in this research. Both bed level developments and altering discharge regimes are expected to have impact on the functioning of the river as an ecology facilitator. Ecology as such is a broad definition of a function, but this could be specified in the facilitation of specific habitats that exist at specific locations or stretches along the river. The expectation is that these habitats flourish under certain hydraulic conditions and these conditions may be altered by bed level and discharge regime developments. Hiemstra (2019) translated the facilitation of ecology to specific hydraulic parameters, allowing for assessment of this function

Make use of future function demands

A good option for further research is to take trends in function demands into account as well. In this research, only the facilitation of functions is assessed by observing how hydraulic conditions alter. On the demand side, there may be huge differences as well. For instance, the number of ships passing sills on the Meuse is taken as a constant in this research, while this strongly depends on the decisions of policy makers and economical developments. The same could hold for the freshwater demand or the dropping of toxic chemicals in the Meuse river catchment. Only in this way, a more accurate estimate of the functional performance of the Meuse river in 2050 can be assessed.

Consider the whole transport route when improving navigation facilitation

This research points out that on the Meuse route, for example, both the sill at lock Weurt and at lock Belfeld can limit the draft of vessels going from A to B. The limitations can occur at the simultaneously at both places, but can also occur separately. Mitigating draft limitations at one place, might not lead to the desired improvements as the problem is only replaced instead of resolved.

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A

River functioning regarding drinking water supply

This appendix addresses the functional performance of the Meuse river wit regard to drinking water supply. When elaborating on this subject, no relation between bed degradation trends and the performance on this function was found. That is why the function is addressed here. The same structure as in the main report is followed, starting with the definition of the functional performance indicator.

A.1 Functional performance indicator

There is a spread freshwater users along the Dutch Meuse river that depend on water from the Meuse river system. There are several industrial and agricultural water users involved, but in this analysis the focus is on the Dutch drinking water companies. These companies take in surface water directly from the Meuse river, to deliver it to the end user after several water treatment steps. In order to analyse the freshwater supply system, first an overview of the different water users and the supply network is given below.

The freshwater supply system

In order to understand the Dutch freshwater supply from the Meuse river, it is necessary to involve a part of the Belgian Meuse river as well. This analysis starts about 20 km upstream from rkm 0 at Monsin (near the city of Liège). At this location, the Belgian Albertkanaal starts. A weir in the Meuse river can divert water to the Albertkanaal. This water is used to compensate the water losses of the chain of locks in the Albertkanaal. Furthermore, this water is used for drinking water supply in the west of Belgium (Antwerp region). The Albertkanaal first runs parallel to the Dutch-Belgian border past the city of Maastricht and then continues to the west of Belgium. For a visualization of the canals that use Meuse river water, see Figure A.1. This figure and the description of used Meuse river water below is based on conversations with Rijkswaterstaat water management experts P. Zebregs (December 13th 2019) and P. van Aubel (January 9th 2020).

Just downstream from Maastricht, Meuse water can be diverted in three ways. It can be diverted into the Zuid-Willemsvaart (a canal), the Common Meuse and the Julianakanaal (a canal running parrallel to the Common Meuse). Water that flows into the Zuid-Willemsvaart 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 m^3/s. Supplying water at a smaller rate means there is a risk of irreversible harm to the ecosystem in De Groote Peel NP.

After the bifurcation of the Zuid-Willemsvaart, Meuse river water flows into the Common Meuse or the Julianakanaal. Both merge close to Linne. The Common Meuse is an important ecological asset

Fig. A.1.: The Meuse river and canals that depend on Meuse water in the South West Netherlands region.

for both the Netherlands and Belgium and needs running water in order to sustain its ecological value. From the Julianakanaal at Urmond, water is drained for the Chemelot industrial complex. At this complex about 1.5 m^3/s is drained, filtered and used in the industrial processes. About

Tab. A.1.: Meuse water distribution as defined in the Meuse Discharge Treaty.

Discharge Q [m^3/s] at Monsin	Belgium's share	Dutch share	Common Meuse share
$Q > 60$	> 25	> 25	> 10
$30 < Q \leq 60$	$(Q\text{-}10) \cdot 1/2$	$(Q\text{-}10) \cdot 1/2$	10
$Q \leq 30$	$Q \cdot 1/3$	$Q \cdot 1/3$	$Q \cdot 1/3$

10% is used as cleaning water and flows back into the Meuse river system via the Ur river, which ends up in the Common Meuse near Urmond (De Maaswerken, 2012).
Drinking water is drawn off at three different locations along the Meuse river (from upstream to downstream) at Heel (Lateraalkanaal), Brakel (Afgedamde Maas) and Biesbosch National Park (Amer). According to Schasfoort et al. (2019), drinking water companies (WML, Dunea, Evides) tap 20, 75 and 127 Mm^3 of water per year respectively. For an optimal drinking water supply, water is drained at a perfectly constant rate of 0.7, 2.4 and 4.1 m^3/s respectively.
Next to water extractions, there are minor rivers contributing to the Meuse river as well. The most important ones are the Roer, the Niers and Dieze rivers. The contributions of these rivers to the Meuse river are highly volatile on a daily basis, but Section 3.4 explains that the weekly mean contributions of these small rivers show strong correlations with weekly mean Meuse river discharges. Consequently, the contributions of the Roer, Niers and Dieze are based on those relations. For an overview of Meuse water extractions and tributaries, see Figure A.2.

International and Dutch policies on water division

In 1995, Flanders and the Netherlands signed the Meuse Discharge Treaty. This treaty regulates the distribution of Meuse river discharge at Monsin/Liège (Rijksoverheid, 1995). The treaty applies on Meuse discharges below 60 m^3/s at Monsin. Table A.1 presents the shares for discharges smaller 60 m^3/s.

In times of drought, the hierarchy in which the limited water in the Netherlands is used is defined in Dutch law (Waterwet, 2009). In this law, it is described which water users/user groups are prioritized over others. The water hierarchy is summarized Table A.2 (Kort and Hoppenbrouwers, 2019).

Tab. A.2.: The Dutch water use hierarchy (Kort and Hoppenbrouwers, 2019).

Cat. 1	Cat. 2	Cat. 3	Cat. 4
Safety and preventing irreversible damage • stability of levees • prevention of subsidence • prevention of irreversible damage to nature	**Utilities** • securing drinking water supply • securing energy supply	**Small-scale premium use** • temporary irrigation of premium crops • handling industrial process water • water quality of urban areas	**Other users** • navigation • agriculture • nature • industry • drinking water • industry

First, it is noted that the mentioned Meuse discharge treaty overrules the Dutch national law. The amounts of water that must be discharged to Belgium and the Common Meuse according to the treaty cannot be adjusted because of this hierarchy described in Dutch national law.
It is important to stretch that the water demanded by de Groote Peel NP is in the first category of the water hierarchy. Meuse river water is not used for the stability of levees or the prevention of subsidence.
If the supply security of drinking water companies is at risk, their position in category 2 is claimed. Otherwise, the companies are sorted to category 4.

Based on the discharge at Monsin numbers, it is determined how much water is left for Dutch water users. For an optimal functional performance, users along the complete Dutch Meuse can profit from the water without hindering each other. This means that apart from the legal obligation to supply De Groote Peel NP with sufficient water first, sufficient water is available for locking, navigation, industry and drinking water purposes as well.

Drinking water supply

For the drinking water sector, water quantity is important, but water quality as well. Water can only be extracted if it is polluted to a limited extent. In the Deltares effect modules of Schasfoort et al. (2019), for every drinking water extraction location one chemical indicator is determined. The concentration of this one chemical represents the water quality at the particular water inlet. In this research, the same approach is followed. The choice for the chemical indicator, however, is essential for the correctness of the analysis. After consulting G. Zwolsman (personal communication, February 18th 2020), freshwater quality expert at Dunea drinking water company, it was decided to assess the most critical toxic chemicals, instead of using glyphosate and carbamazepine like Schasfoort et al. (2019). From the measurements, the chemical aminomethylphosphonic acid (or AMPA) is exceeding the normative threshold most frequently, so choosing this chemical as critical indicator chemical makes sense. The presence of AMPA in the Meuse river system has different sources. First of all, AMPA is the degradation product of the chemically unstable chemical glyphosate. Although the glyphosate concentrations in the Meuse river system decline over the years, this trend is not true for the AMPA concentrations. In the last years of sampling (2017 and 2018) the concentrations at Keizersveer and especially Heel have increased. Apart from glyphosate, the chemical industry forms another source of AMPA. Industry along the Julianakanaal and elsewhere in the Meuse catchment flush chemical installations with Meuse river water. This causes AMPA from the industry to flow into the Meuse river system (Volz, 2010). Rijksoverheid (2015) shows that intake stops originate from accidental toxic excretions more often than from chemicals that are transported at a more or less constant load. These accidental pollution events, however, are considered impossible to incorporate in the research framework of this study, that is why the accidents are not taken into account.

The water quality is denoted as a weight of harmful chemicals per volume of Meuse river water (the concentration in μg/l). This means that when the load (in μg/s) is constant, lower river

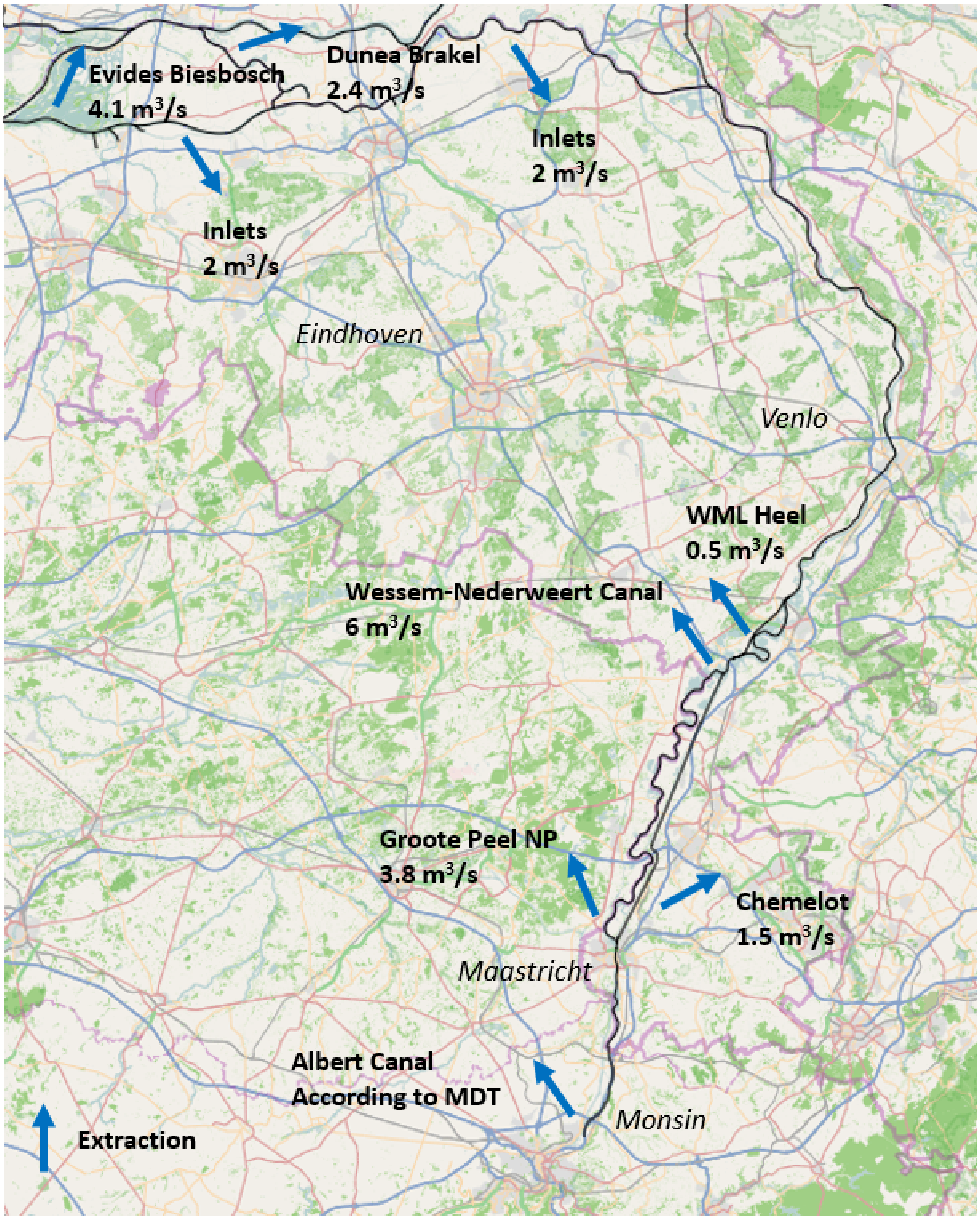

Fig. A.2.: The Meuse river (highlighted) and its main freshwater extractions (OpenStreetMap Nederland, n.d.).

discharges result in higher concentrations. In this way, the concentration of harmful chemicals is directly related to the discharge. In a theoretical situation, the load is perfectly constant and the concentration C follows the relation of Equation (A.1), with C (μg/l) the concentration, l (μg/s) the load and Q (m^3/s) the discharge.

$$C = \frac{l}{Q} \tag{A.1}$$

Using the AMPA measurements at Heel and Keizersveer and the discharges at those locations at the sampling day, Figure A.3 is constructed. The expected relation between the discharge Q and the AMPA concentration C is clearly visible in the figures.

Using the linear least squared error method, the Q-C relations for AMPA at both Heel and Keizersveer can be derived. The strength of the relation is characterized by the R^2 between the derived relation and the measured concentrations. From a theoretical point of view, the Q-C relation for AMPA would abide Equation (A.1). However, this study uses a more practical method with the aim to derive the strongest relation possible. After several tries, the strongest relation for both locations is found using Equation (A.2), in which C is the concentration (μg/l), Q the discharge (l/s) and a (μg/s) and b (dimensionless) a consant.

$$C = a * 1000 * Q^b \tag{A.2}$$

Although the physical foundation is lacking here, the fits through the measured concentrations are way stronger for both Keizersveer and Heel (see Figure A.4). Gertjan Zwolsman advised to use only the last three years of measurements when deriving the Q-C relations. This is because the load of toxic chemicals can differ over several years. Using measurements from a smaller timeframe is expected to give more uniform results.

For deriving the Q-C relation for AMPA at Heel, the measured discharge at Eijsden is used, as this is the discharge measurement location that is closest by the drinking water intake Heel. Moreover, the discharges bigger than 400 m^3/s are neglected for the location Heel. Deciding to do so led to more reliable results for discharges between 100 and 200 m^3/s. Figure A.4 shows the derived relations and measurements for the complete discharge range.

Figure A.4 shows that the derivations following Equation (A.1) lead to weaker relations. On top of that it shows that they are less reliable in the range surrounding the normative threshold of 1 μ/l. For the drinking water intake at Brakel in the Afgedamde Maas, no Q-C relation was derived because the geographical position of this intake in the Meuse river system. The residence time in the Afgedamde Maas, before the water is taken in by the drinking water company, is 5-6 weeks (G. Zwolsman, personal communication, February 18th 2020). This causes a direct relation between the discharge in the Meuse main stream and the water quality near Brakel to be nonexistent. It

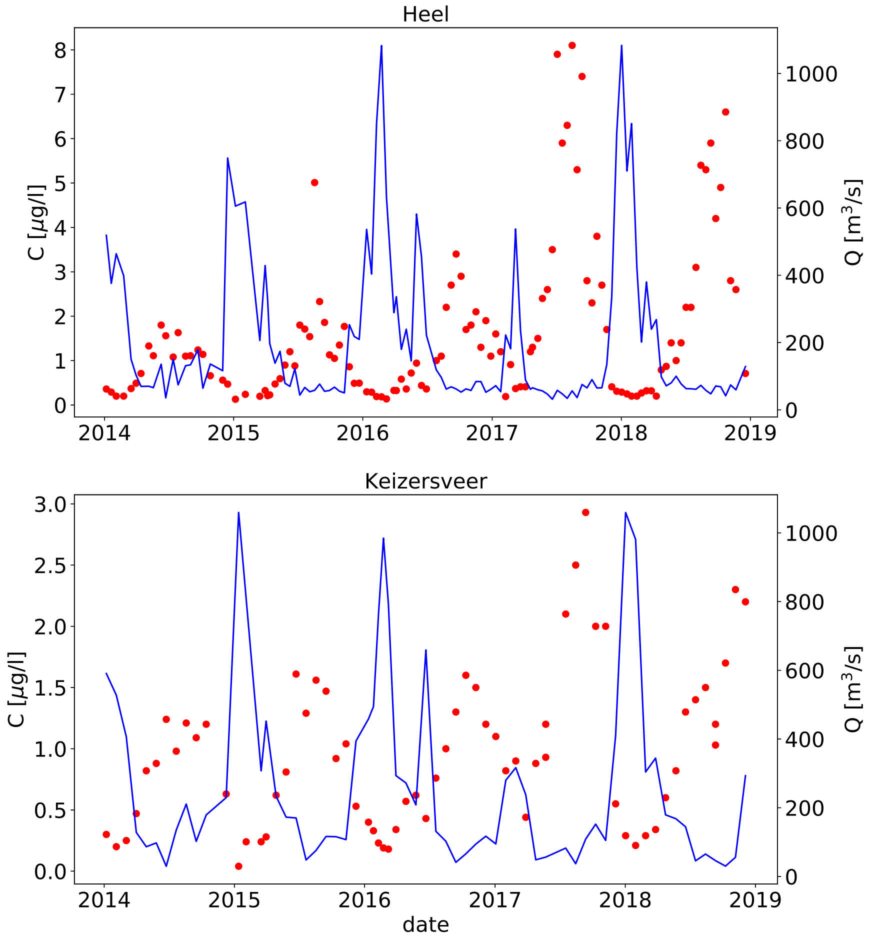

Fig. A.3.: AMPA concentration measurements (red dots) versus discharge (blue line) at Heel and Keizersveer between 2014 and 2018. The Keizersveer dataset is retrieved from (Rijkswaterstaat, 2020e), the heel data is retrieved via personal contacts at Dunea (G. Zwolsman, February 18th 2020).

turns out, however, that the AMPA concentration at Brakel follows the one at Keizersveer pretty close, be it with a delay of 5-6 weeks. In order to be able to qualify the Meuse drinking water supply functioning at all attached drinking water inlet locations, this research assumes that the water quality at Keizersveer is representative for Brakel as well as for Gat van de Kerksloot.

Indicators of drinking water supply functioning

For the function drinking water supply the AMPA concentration near drinking water inlet Heel and at Keizersveer are declared indicators. Figure A.5 summarizes the woring of these indicators. In the figure, the relation between the AMPA concentration and the inlet discharge is sketched binary. In practice, drinking water companies can request dispensation at the applicable drinking water

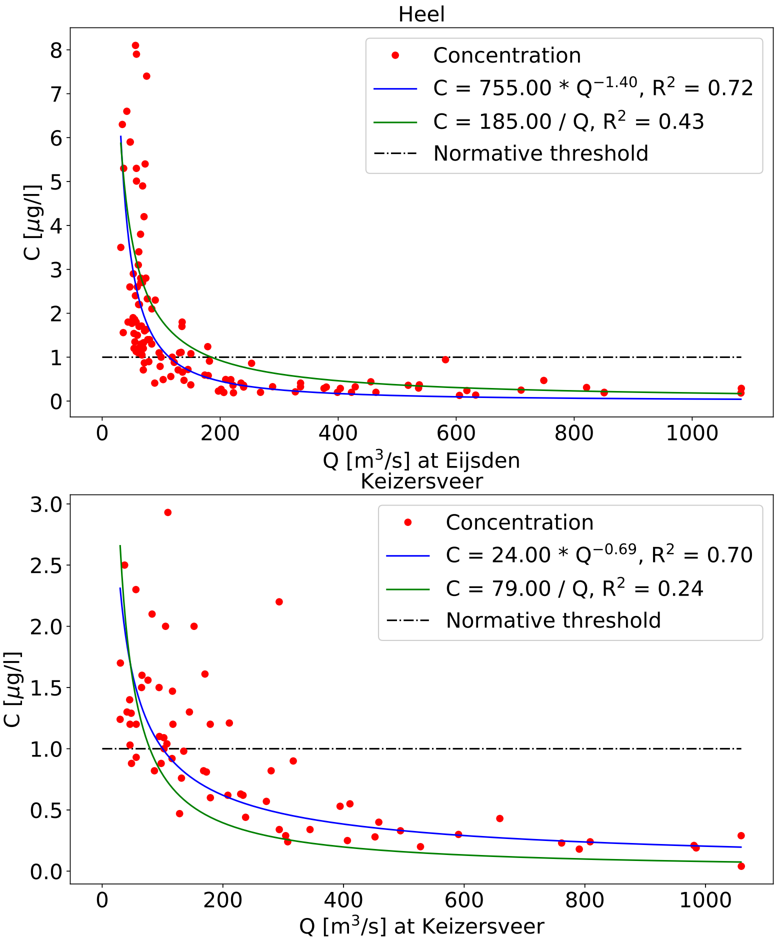

Fig. A.4.: Derived Q-C relations for AMPA at Heel and Keizersveer for measurements in 2016, 2017 and 2018.

authorities in order to take in water longer than strictly allowed. These dispensations, however are always temporary. Therefore they are neglected in this research. This remark stresses that the results of this research with regard to water quality should be analysed in a relative way, instead of claiming that the absolute downtime periods are accurate

It is concluded that for the functioning of the Meuse river with regard to drinking water supply, the impact of bed level developments do not play a role. As this research focuses on the impact of both bed level developments and a changing discharge regime, this notion is remarkable. It was chosen to include the function of drinking water supply in this research as it was expected that bed level developments would have had impact on either the water quality or the intake structures (or both). When consulting literature dealing with drinking water supply challenges for the future,

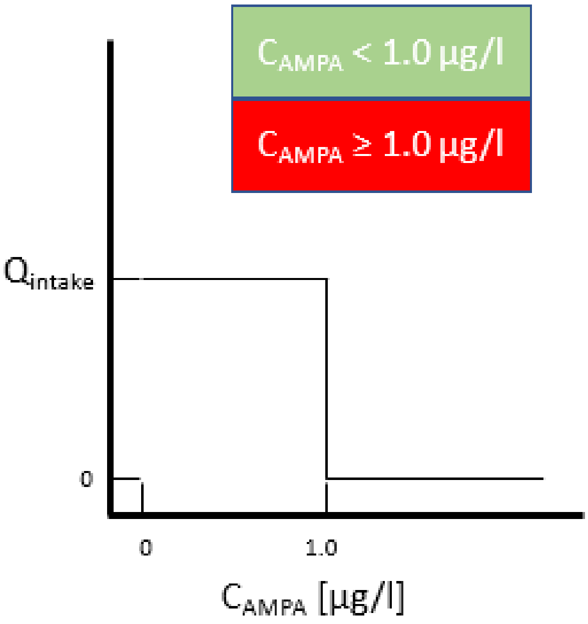

Fig. A.5.: Functioning of the Meuse for the function drinking water supply. When the AMPA concentration equals or exceeds 1.0 μg/l at the representative river location, the river fails to function for drinking water supply.

however, these expectations were not confirmed (among others Burgdoffer, 1991; Breukel et al., 1992; Volz, 2010; Van der Aa et al., 2014; Schasfoort et al., 2019). For drinking water quality, the focus in literature was on anthropogenic toxics originating from industry or wastewater treatment plants, rather than toxics that originate from stagnant water or other sources. With regard to the drinking water inlets, it was on beforehand unknown where these inlets were located. When it turned out that the water level variations at these inlets have a sharp lower limit because of weirs and the stowing effects of the sea, the relation with bed level degradation faded away.

drinking water supply

For the drinking water supply that the Meuse river facilitates, the water quality at the intake locations is essential. The AMPA concentration at these locations is determining whether the water inlets can take in water. In Figure A.6 an exceedence plot of the AMPA concentration at Heel is presented.

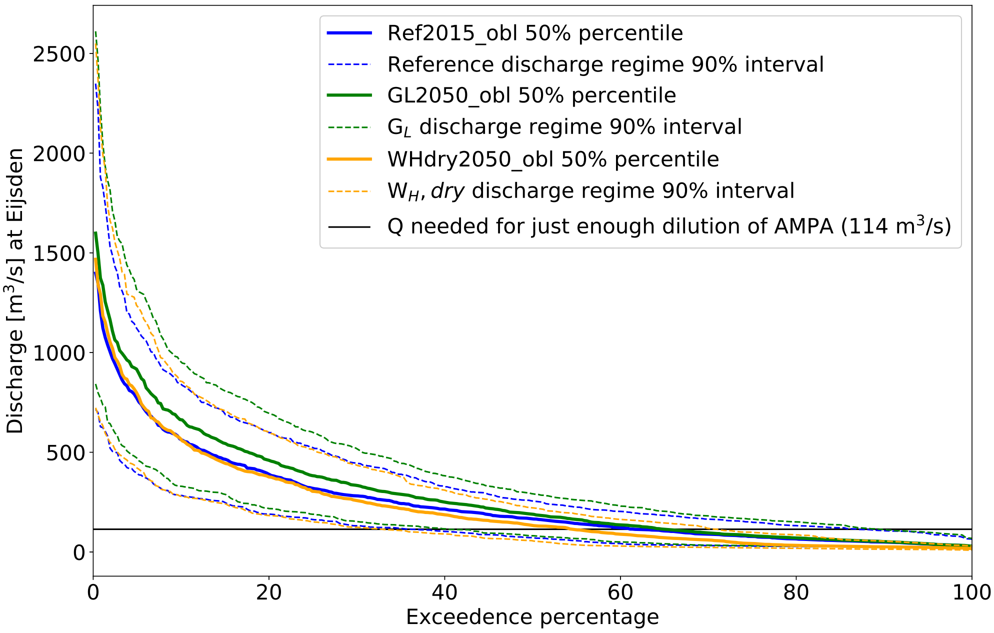

Fig. A.6.: Discharge exceedence at Eijsden, representative for water inlet Heel, for the reference discharge regime and two discharge regime scenarios. When the AMPA load is taken constant, at least 114 m^3/s of discharge is needed at Eijsden to dilute the AMPA load such that the AMPA concentration is below 1.0 $\mu g/l$.

The plot shows that the drinking water inlet at Heel is restricted to take in water for about 40% of the time, or about 140 days in the median year in case of the reference regime. This seems to be an overestimation of the current downtime of the drinking water inlet, as Rijksoverheid (2015) reports inlet stops in the order of 140 days as an exception rather than as a regularity. The downtime percentage in the $W_{H,dry}$ scenario increases with 5 percentage points to about 45%, while the situation improves a bit in the G_L scenario. An interesting notion is that the 5^{th} percentile lines of the three discharge scenarios show a smaller variation than the 50^{th} percentile lines. This means that the overall percentage of downtime increases, but that the impact of the extremely dry years does not increase that much. This notion is confirmed by the duration of the longest downtime for each scenario. This criterion determines the biggest buffer that is needed in order to secure delivery security at all time. The number of consecutive days of downtime follows the trend observed in the 5^{th} percentile lines of the exceedence plot. The maximum consecutive periods of exceedence are 244, 243 and 259 days in the reference, G_L and $W_{H,dry}$ scenario respectively.

In Figure A.7 an exceedence plot of the AMPA concentration at Keizersveer is presented. The water quality at Keizersveer is assumed to represent the downtime of drinking water inlet Brakel and the drinking water inlet at the Biesbosch NP.

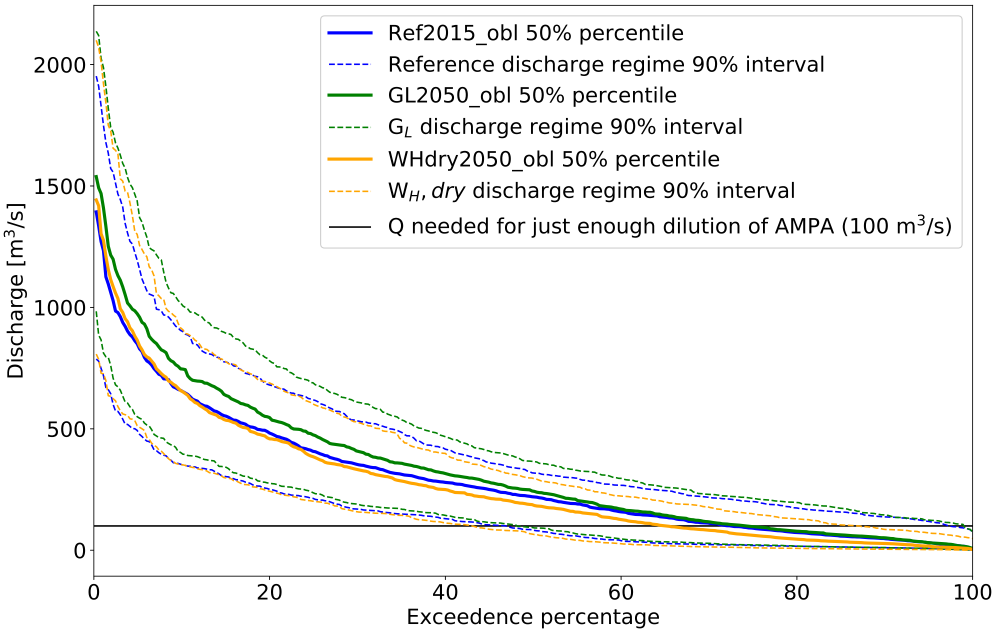

Fig. A.7.: Discharge exceedence at Keizersveer, representative for water inlet Brakel and Biesbosch NP for the reference discharge regime and two discharge regime scenarios. When the AMPA load is taken constant, at least 100 m^3/s of discharge is needed at Keizersveer to dilute the AMPA load such that the AMPA concentration is below 1.0 μg/l.

At inlet Keizersveer the situation improves a bit in the G$_L$ scenario as well. In the reference scenario, the median downtime is about 25%, reflecting the real situation better than the downtime at Heel in the reference scenario. With the G$_L$ discharge regime, the downtime stays about 25%, while 10 percentage points are added when the W$_{H,dry}$ discharge regime is modeled. As for inlet Heel, also at Keizersveer the lines of the 5th percentile in the different discharge regimes are closer together than the median lines. This points out that the situation might change on average, but the extremely bad years may be comparable in the future. The maximum consecutive timespan of exceedence of 1 μg/l AMPA concentration is 237, 236 and 241 days for the reference, G$_L$ and W$_{H,dry}$ discharge regime respectively. This means that in the future, drinking water buffers do not seem to be enhanced at a big scale.

A.2 Reflection for Water Management

From a water manager's perspective, the future functioning regarding drinking water supply are emerging. On the one hand, there is a serious risk the average downtime of drinking water inlets increase significantly. This urges drinking water companies to increase on site or natural buffers or to search for other sources of drinking water. If water buffers in the Meuse river catchment are

enhanced, the discharge would be large enough to dilute toxics sufficiently for longer periods of time. The advise is however, to find ways to decrease the toxic load. As AMPA is considered the most critical toxic, it would make sense to first decrease the AMPA load. To a considerable extent, AMPA in the Meuse river originates within the Dutch borders. This notion might make regulating the AMPA load more feasible.
Just as the advise in Section 5.3, also for the drinking water supply it is essential that weirs can maintain the CWL in impounded river stretches. If this is not the case, fresh water inlets surrounding the whole Meuse river get into problems.

A.3 Discussion

The calculated downtime duration of drinking water intakes is based on the assumption that the toxic chemical load is constant over time. Only if this is the case, the toxic concentration is related to discharge as directly as pretended in this research. In practice, intake stops are often caused by accidents causing a quick increase in concentration of a particular toxic chemical. During periods of low river discharge, the river is more vulnerable to these accidents, but this is not translated to actual downtime in this research. Following this reasoning, this research underestimates the total downtime of drinking water inlets, but the extent to which it is underestimated is hard to say.

A.4 Conclusion

The river functioning regarding drinking water supply is represented by the toxic AMPA concentration at drinking water inlets. For future drinking water supply, sufficient discharge for the dilution of toxic chemicals at drinking water inlets will be potentially unavailable at longer periods of time. This causes periods of drinking water downtime to increase.

B

Human interventions in the Meuse river

As stressed before, human interventions are omnipresent in the Dutch Meuse river. To explain the morphological effects these measures had and perhaps still have, fundamental river engineering principles are used. These river engineering principles are explained in Janssen et al. (1979) and De Vriend et al. (2011). The sediment transport relation used in these reports is the one from Engelund and Hansen (1967). For this research it is not necessary to zoom in to specific discharge-sediment transport relationships, but using a generalized conceptual relation like Equation (B.1) suffices.

$$S = B \cdot m \cdot u^n \tag{B.1}$$

In Equation (B.1), B is the river width in meter, m is a constant heavily depending on grain size in $\frac{s^4}{m^3}$, u is the flow speed in m/s, the exponent n (dimensionless, n>1) is a constant that depends between different discharge-sediment transport relations and S is the sediment carrying capacity in m^3/s. The relation expresses that a higher flow speed results in a potential sediment load that is disproportionately bigger.

Literature is concerted in the fact that the Meuse riverbed is out of equilibrium (Vermeer, 1990; Waterloopkundig Laboratorium, 1994; Murillo-Muñoz, 1998; Van Dongen and Meijer, 2008; Sieben, 2008; Rijkswaterstaat, 2018), but what the equilibrium will look like and how the river will work towards this state is unknown until now. For this study explaining the mechanisms with help of Equation (B.1) is sufficient.

Changes in river width

The first major interventions in the Meuse river system occurred in the second half of the 19^{th} century when the Meuse river was normalized on a large scale (Breukel et al., 1992). Before normalisation, the Meuse was a typical natural river consisting of multiple dynamic braided river channels and islands. Restoring the river flow to one channel only is called normalisation. This single channel typically has a smaller total width, a larger water depth and higher flow speeds compared to the more natural braided river system. The mechanism behind the degrading morphological response of the river is explained using the general sediment transport formula Equation (B.1). The smaller river width causes the flows speed to increase. Figure B.1 explains that a continuously higher sediment carrying capacity results in a milder river slope over time. This does not only influence the normalized stretch, but also the the riverbed upstream from the intervention. It is observed that the equilibrium river slope upstream from the constriction/normalisation has not changed, but because of the smaller slope in the normalised stretch, the whole upstream river becomes incised.

During the last decades, river widening has occurred as well (Van Dongen and Meijer, 2008;

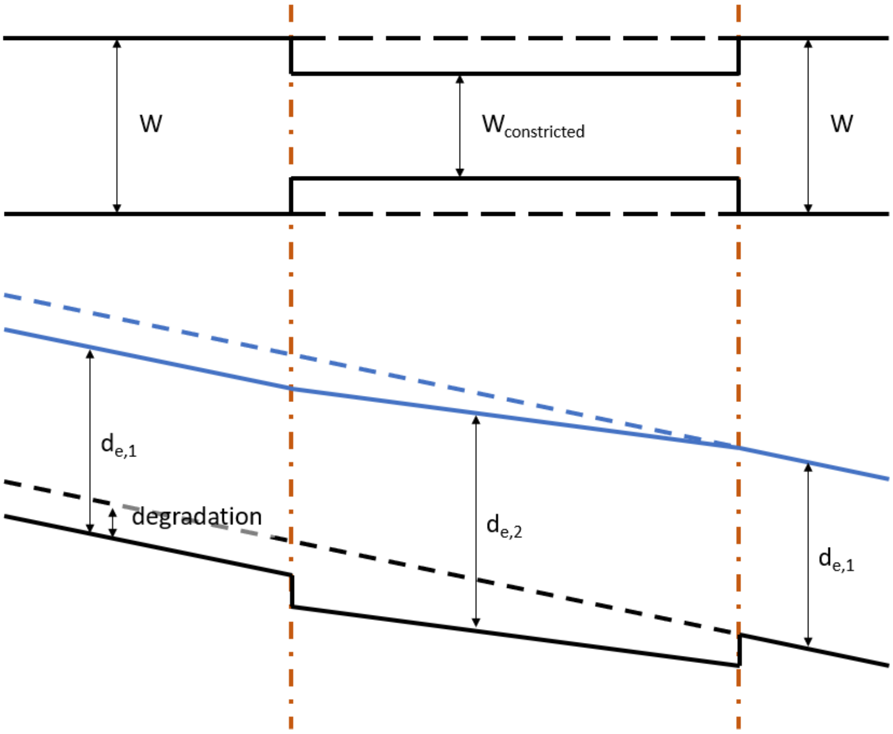

Fig. B.1.: Long-term equilibrium over riverbed. Adjusted from (Mosselman, 2012).

Breukel et al., 1992). Where river narrowing causes incision of the river bed, river widening has an opposite effect. It leads to a smaller specific discharge and consequently to a steeper equilibrium river slope. The river widening projects occurred at a way smaller scale than the normalisation works. Consequently, the widening projects are not expected to counteract the incision caused by normalisation works.

Cutting off river bends

In order to discharge flood waves downstream faster, many Meuse river bends were cut off in the 20^{th} century (Breukel et al., 1992). Downstream from Grave, about 10 river bends were cut off and also two bends near Gennep. These cut offs affect the equilibrium state of a river as well. At the reach that cuts off the bend, the river slope is steeper than the equilibrium slope, leading to increasing flow speeds. The consequence is a higher sediment carrying capacity in the cut off stretch, resulting in bed erosion. This erosion will migrate upstream and lead to riverbed incision upstream from the river bend cut off. Figure B.2 pictures the short-term and long-term river response.

Regulation of the river flow by weirs and dams

In the Dutch Meuse, seven weirs are constructed near Borgharen, Linne, Roermond, Belfeld, Sambeek, Grave and Lith (see Figure 2.2). These weirs were constructed in the first half of the 20^{th} century (Breukel et al., 1992). They were constructed to control the water level upstream from the weir. In this way, the water levels during low flows would increase in order to allow

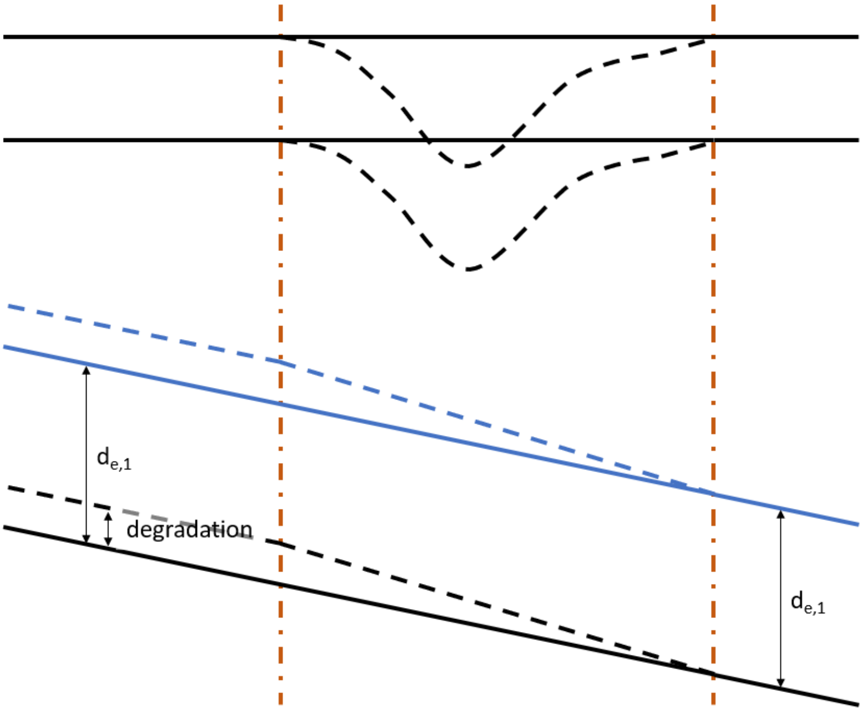

Fig. B.2.: short-term river response and long-term equilibrium of a river after a river bend cut-off. Adjusted from (Janssen et al., 1979).

navigation throughout the full year.

Upstream from the Dutch Meuse stretches in Belgium and France, dam, weir and reservoir construction have caused the bed load transport at the border between Belgium and the Netherlands to become close to zero (Micha and Borlee, 1989).

Like the dams upstream, the weirs in the Dutch stretches of the Meuse river act as a sediment trap as well. When the sediment is trapped upstream from a weir, erosion would be expected at the downstream part. When following the river downstream until the next weir, sedimentation would be expected again. In this way, the equilibrium slope of the river stretch between to dams is expected to decrease, with the hinge point of the river bed in between the two weirs. Figure B.3 visualizes this effect.

In the Meuse river, however, this effect is not expected to occur. Vermeer (1990) has done a study to the Meuse river for a morphological model in the Dutch part of the river. In this study it was decided to ignore the weirs in the Dutch river for the long-term, larger-scale morphological processes. The reasoning was based on specific characteristics of the Meuse river. First, the weirs in the Meuse are not fixed weirs. During high flows (larger than approximately 1250 m^3/s at Borgharen) the gates in the weirs can be opened to allow the river to transform into a more or less free flowing river. This opening of the weirs usually happens for several days a year. Apart from Vermeer (1990), several other studies conclude that sediment transport in the Meuse river mainly occurs during these high flow events (Murillo-Muñoz, 1998; Burgdoffer, 1991). In other words, in times of little morphological activity in the river, the weirs trap the available sediment. On a

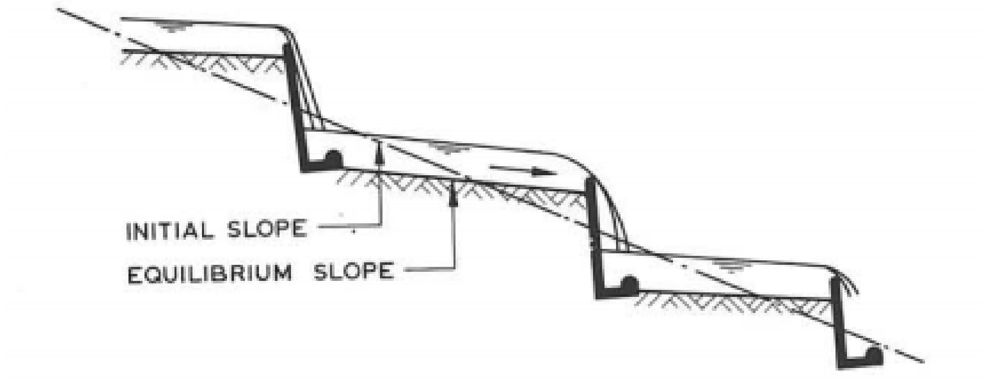

Fig. B.3.: Expected river slope equilibrium in river stretches between weirs (Janssen et al., 1979).

yearly basis, however, this trapped sediment is set to motion during high flows and transported downstream through the opened weirs. In this way, the weirs in the Netherlands do not have an enduring impact on the long-term morphological behaviour of the Meuse river. Later on this reasoning was confirmed by Waterloopkundig Laboratorium (1994) and Sieben (2008).

Although the weirs in the Dutch Meuse are not expected to effect the morphology as explained in Figure B.3, they still act as a sediment trap just as the dams and reservoirs in Belgium and France do. The effect of trapping sediment is explained in Figure B.4.

Excavation of the riverbed

Since the 1940's, several riverbed excavations have occurred in the Dutch Meuse (Breukel et al., 1992; Rijkswaterstaat, 2018; Schropp, 1999). The main aim for these projects was to improve the navigable depth and/or the flood safety. In a deepened river stretch, the flow speed reduces as the cross-sectional area inreases. Consequently, according to Equation (B.1), the sediment load capacity of the river stretch decreases, causing sediment to settle in the excavated stretch. In this way, the excavation functions as a sediment trap. If the excavation is not maintained, the sediment trap has a temporal influence on the downstream river morphology. In case the excavation is maintained and the excavated sediments are put back in the river downstream, the effects are only local. In the Meuse, however, maintenance dredged sediments are sometimes withdrawn from the river system. In that case, the effect of an excavated stretch has a similar effect on the downstream morphology as a dam in the river. The sediment load downstream of the sediment trap is artifically reduced, leading to a certain sediment load capacity (following Equation (B.1)) that is not fed from upstream. This 'hungry' flow causes the river reach below the sediment trap to incise in the landscape.

Excavations in the floodplains have occurred frequently in the Meuse, especially in between Linne and Roermond. This river stretch is characterized by many lakes that are situated in the river's floodplains. The excavations were done for the purpose of mining. The gaps that mining activities leave behind act as sediment trap during high flows, when the floodplains are inundated. Like excavations in the summer bed, excavations in the floodplains lead to an overall decreased

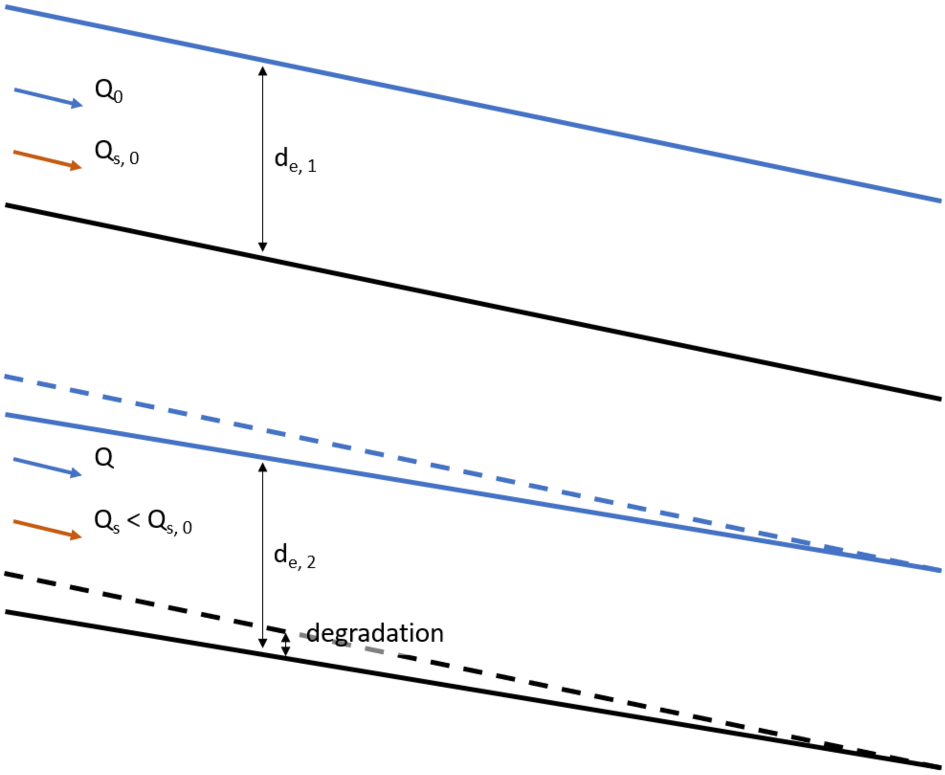

Fig. B.4.: Long term morphologic equilibrium after sediment input reduction.

sediment load in the Meuse river, leading to an overall smaller equilibrium slope.

Nature friendly riverbanks

In the last 20 years, large stretches of the Meuse riverbanks were made more nature friendly Chrzanowski (2018). In the times of normalization and canalization, the banks were often protected by coarse gravel or rip-rap, preventing the banks from eroding and keeping the river narrow. In 2000, the EU adopted the Water Framework Directive. This directive demands a more natural state of all European rivers. Bringing the riverbanks to a more natural shape is part of the solution to that. The riverbanks are not managed actively, but mainly monitored

The riverbanks allow for erosion again and bring in new sediments. From contact with Rijkswaterstaat experts, it becomes clear that unpublished, preliminary sediment surveys indicate that these sediments do not tend to clog the navigable parts of the river, but stay close to the banks.

C

Points of Interest

The points of interest are based on the river functioning analysis presented in Chapter 4 and summarized in Figure C.1. A more detailed look into the points of interest is presented in this appendix.

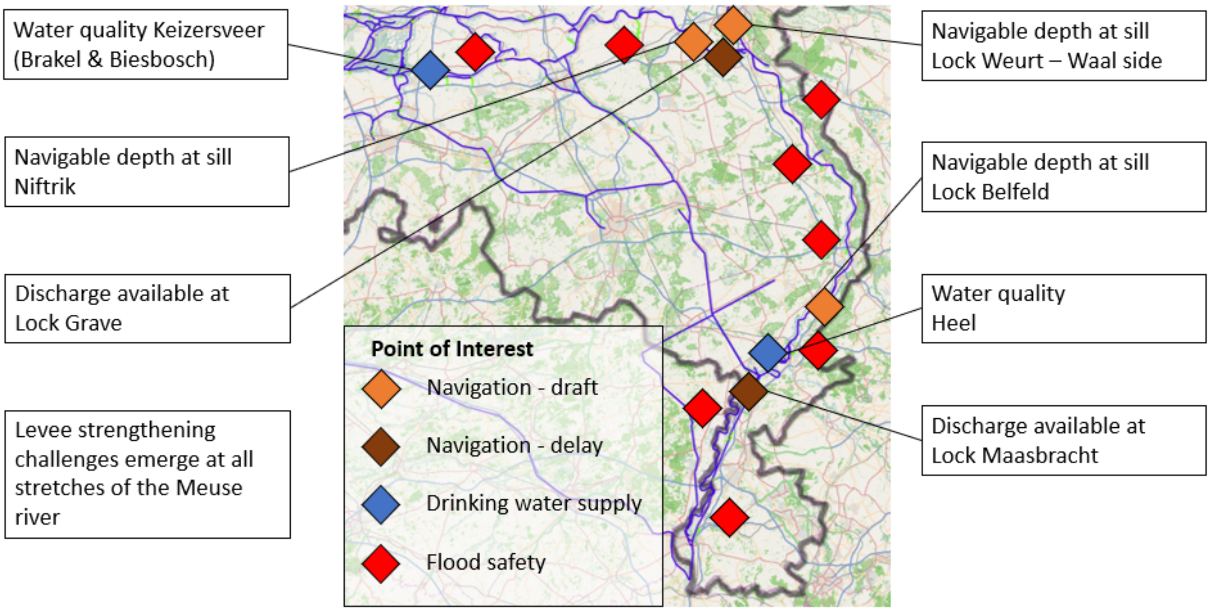

Fig. C.1.: Points of interest for functioning of Dutch stretches of the Meuse river.

C.1 Lock Maasbracht

An overview of the location and positioning of the lock-weir complex of Maasbracht is given below.

Fig. C.2.: picture obtained from: https://www.seconed.nl/portfolio-item/sluis-maasbracht-maasbracht/.

Lock Maasbracht consists of three lock chambers. Two have dimensions of LxW = 142x16 and a downstream sill level of CWL -4.0m (NAP + 16.8m). The biggest one has dimensions of LxW = 225x16 and a downstream sill of CWL -4.0m (NAP + 16.8m). At lock complex Maasbracht, the water level difference between the CWL upstream and downstream is 11.8m.

C.2 Inlet Heel

An overview of the location and positioning of drinking water inlet Heel is given below.

Fig. C.3.: picture obtained from: https://www.wml.nl/over-wml/organisatie/missie-en-visie.

C.3 Lock Belfeld

An overview of the location and positioning of the lock-weir complex of Belfeld is given below.

Fig. C.4.: picture obtained from: https://www.heijmans.nl/nl/projecten/sluizen-sambeek-en-belfeld/.

Lock Belfeld consists of three lock chambers. Two have dimensions of LxW = 142x16 and a downstream sill level of CWL -3.65m (NAP + 7.45m). The biggest one has dimensions of LxW = 241x16 and a downstream sill of CWL -2.85m (NAP + 7.25m). At weir-lock complex Belfeld, the water level difference between the CWL upstream and downstream is 3m.

C.4 Lock Weurt

An overview of the location and positioning of the lock complex of Weurt is given below.

Fig. C.5.: picture obtained from: https://www.omroepgelderland.nl/nieuws/2436463/Rijkswaterstaat-pakt-Sluis-Weurt-aan.

Lock Weurt consists of two lock chambers. Both have dimensions of LxW = 260x15.7. One has a downstream sill level of NAP + 4.5m. The other one has a downstream sill level of NAP + 1.5m.

C.5 Lock Grave

An overview of the location and positioning of the lock-weir complex of Grave is given below.

Fig. C.6.: picture obtained from: https://www.youtube.com/watch?v=Uz-i2SuL4T0.

Lock Grave consists of one lock chamber. It has dimensions of LxW = 142x16 and a downstream sill level of CWL -4.0m (NAP + 1.0m). At weir-lock complex Belfeld, the water level difference between the CWL upstream and downstream is 3m.

C.6 Sill Niftrik

An overview of the location of sill Niftrik is given below. As the actual sill is located under water, it is invisible in the pictures

Fig. C.7.

The sill at Niftrik has a level of 1.5m + NAP.

C.7 Inlet Brakel

An overview of the location and positioning of drinking water inlet Brakel is given below.

Fig. C.8.: picture obtained from: https://www.dunea.nl/drinkwater/onze-bronnen/afgedamde-maas.

C.8 Inlet Gat van de Kerksloot

An overview of the location and positioning of drinking water inlet Brakel is given below.

Fig. C.9.: picture obtained from: https://evides.onlineblad.nl/2018/02/evidespag4.html.

D

Tributary analysis

For the determination of the discharge tributaries add to the Meuse river main stream, weekly averaged discharge measurements at Eijsden, Venlo, Megen and Keizersveer are compared (Rijkswaterstaat, 2020e). Venlo is the closest discharge measurement location downstream from the Roer river mouth, Megen is the closest discharge measurement location downstream from the Niers river mouth and Keizersveer is the closes discharge measurement location downstream from the Dieze river mouth. Although more tributaries of a smaller magnitude are present in the Dutch Meuse catchment, these are not explicitly included. In reality, however, the smaller tributaries are implicitly included as they are represented by the discharges of the Roer, Niers and Dieze rivers. In fact, the Roer tributary now represents all tributaries from Eijsden to the Roer mouth, while the Niers tributary now represents all tributaries from the Roer mouth to the Niers mouth and the Dieze tributary now represents all tributaries from the Niers mouth to the Dieze mouth.
The locations of the Roer, Niers and Dieze mouth are pictured in Figure D.1.

Fig. D.1.: Mouth locations of the Roer, Niers and Dieze rivers.

Weekly averaged discharges at Eijsden and at Venlo, Megen and Keizersveer are presented in Figures D.2 to D.4. In the figures, the orange line is the line at which the discharge at Eijsden equals the discharge at the measurement point downstream. It becomes clear that the discharge increases in downstream direction of the Meuse river. Based on weekly averaged discharges at Eijsden (obtained from the discharge series of Kramer and Mens (2016)), the tributary discharges are calculated and included in the Sobek 3 model. For the tribuatary discharges of the Roer river, the difference between the discharge at Eijsden and the discharge at Venlo is used. For the tributary discharges of the Niers river, the difference between the calculated discharge at Venlo and the discharge at Megen is used. For the tributary discharge of the Dieze river, the difference between the calculated discharge at Megen and Keizersveer is used. Following the relations of the fitted lines in blue, the discharge downstream at some point reaches under the discharge upstream. In the model, no negative tributary is included, but the tributary discharge is set to zero then.

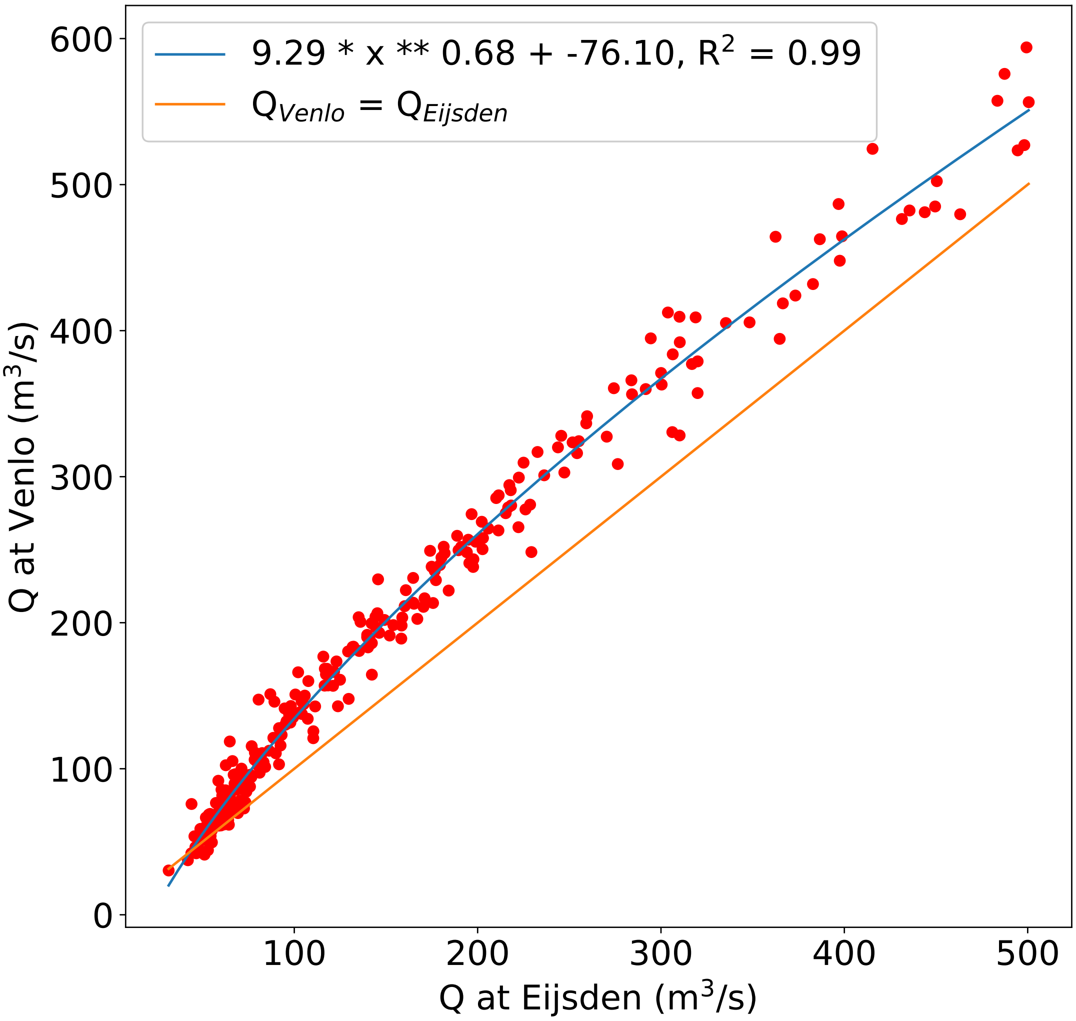

Fig. D.2.: Weekly averaged discharges at Eijsden and Venlo, representing the Roer river tributary.

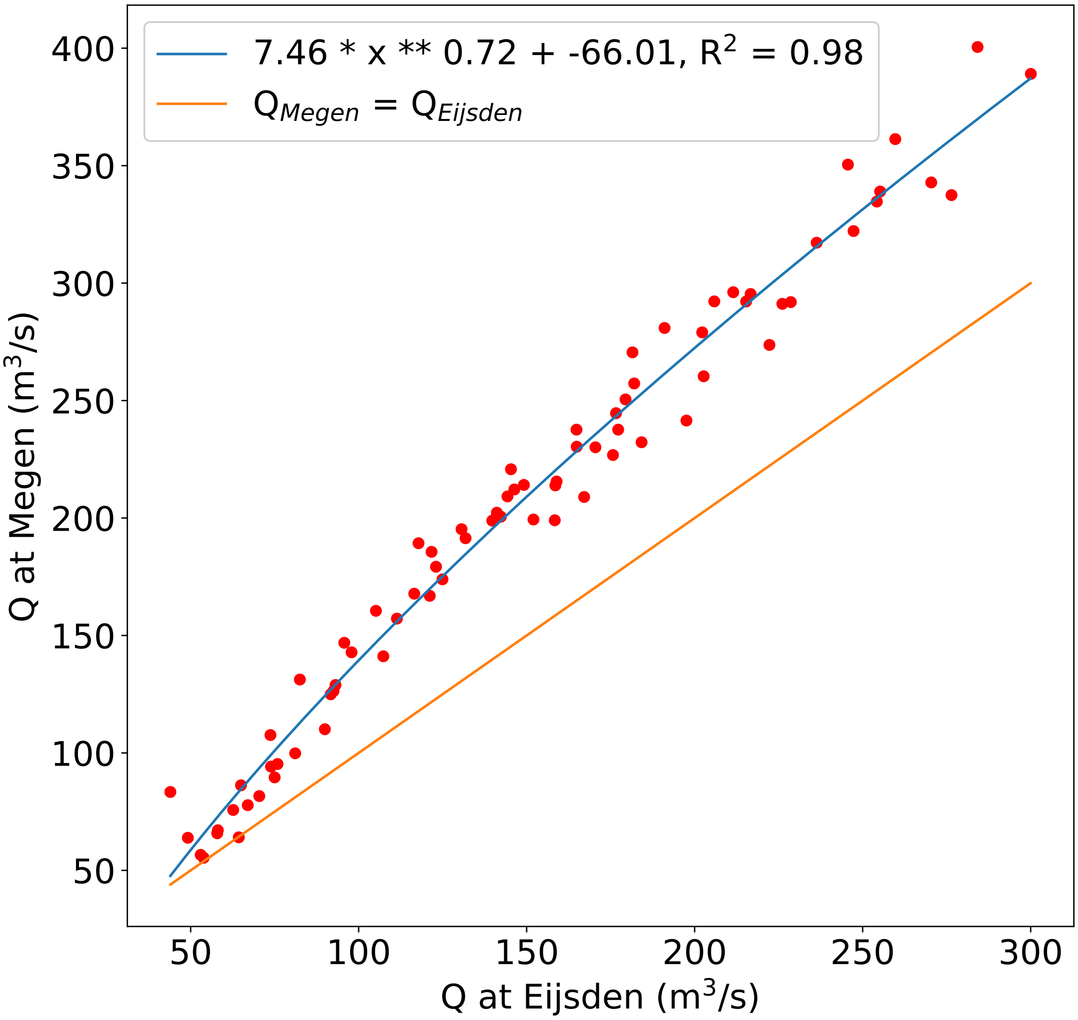

Fig. D.3.: Weekly averaged discharges at Eijsden and Megen, representing the Niers river tributary.

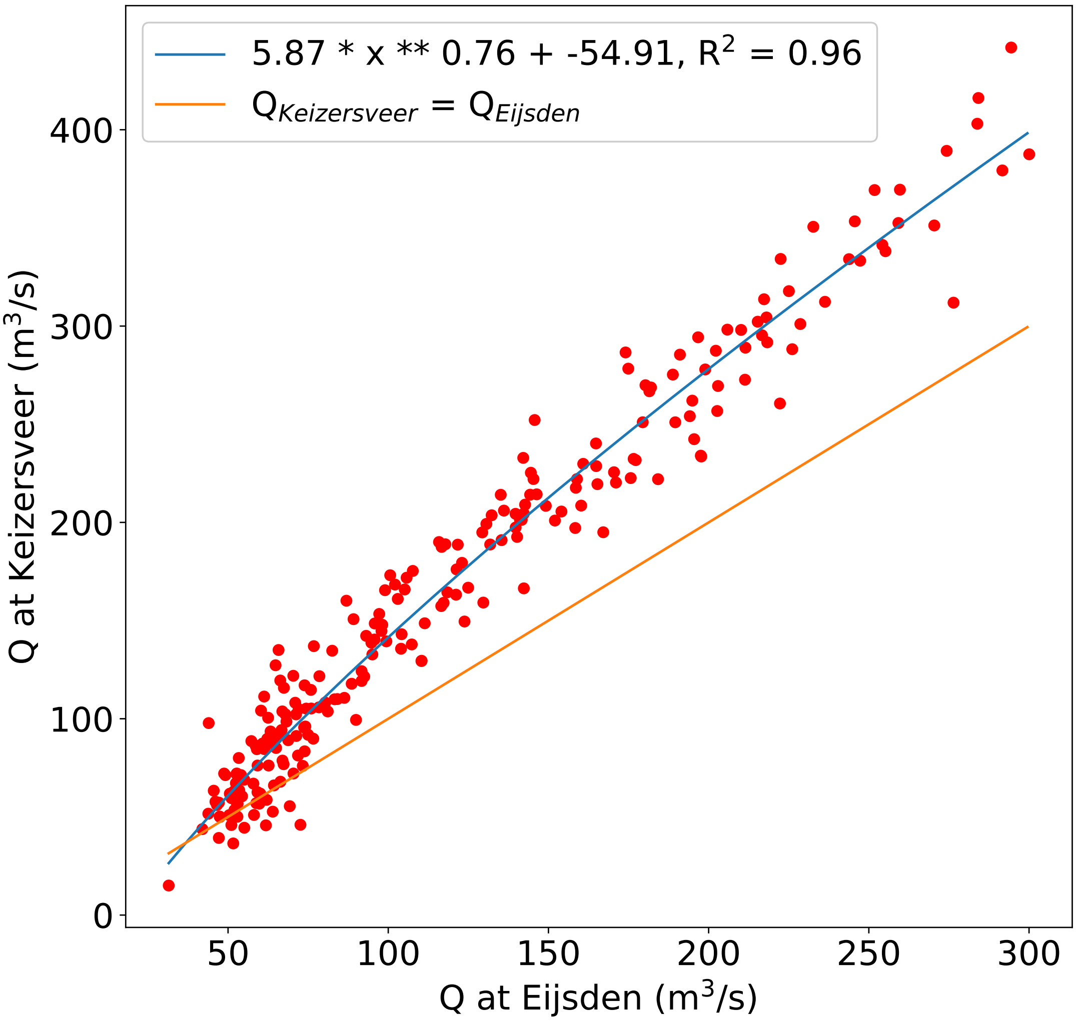

Fig. D.4.: Weekly averaged discharges at Eijsden and Keizersveer, representing the Dieze river tributary.

Additional results for navigation

E

Lock Belfeld

Figures E.1 and E.2 show that the impact of bed level developments is marginal compared to the impact of changing discharge regimes. In Appendix E the additional plots for the other scenarios are presented.

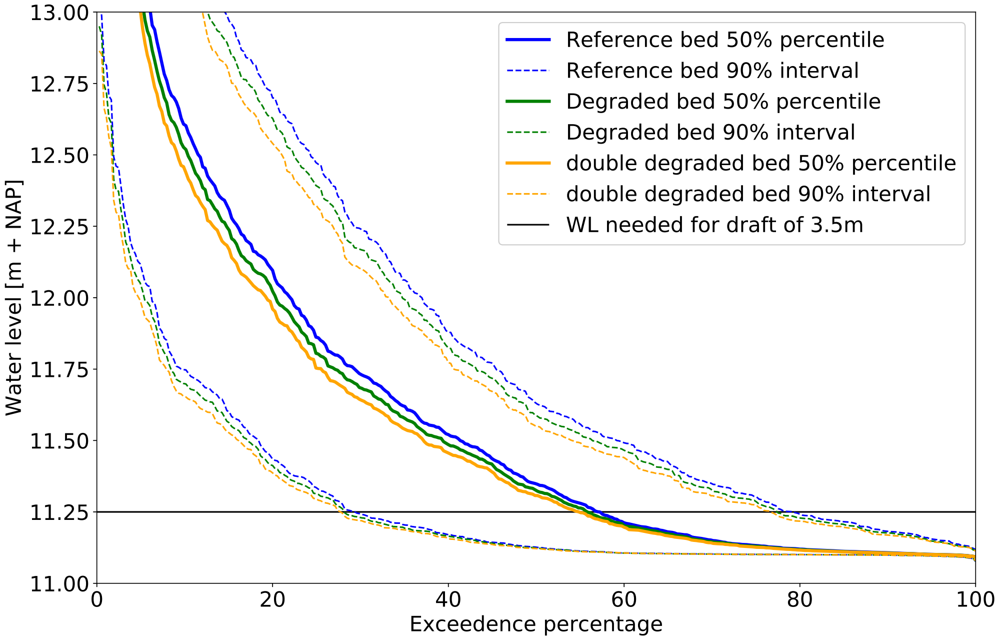

Fig. E.1.: Water level exceedence downstream from lock Belfeld for the reference riverbed and two degraded riverbed scenarios, all in combination with the reference discharge regime.

Figure E.1 shows that bed degradation impacts the water levels when the exceedence is below ± 80%. Between an 80 and 100% exceedence, the discharges (that are linked to the water levels) are so low, the CWL at the downstream weir governs the water level upstream in the weir basin rather than discharge induced backwater curves. The 50^{th} percentile line in Figure E.1 just exceeds the black horizontal line (threshold for optimal functioning) at about an exceedence of 75%. At that point, differences between water levels in the reference bed level scenarios start to differentiate from the water levels in the degraded bed scenarios. This exceedence of 75% matches to a discharge of about 180m^3/s. Figure 4.6 shows that the impact of a lower bed level is indeed observed at a discharge of about 180 m^3/s.

Figure E.2 presents the impact of changing discharge regimes on the water level exceedence just downstream from lock Belfeld.

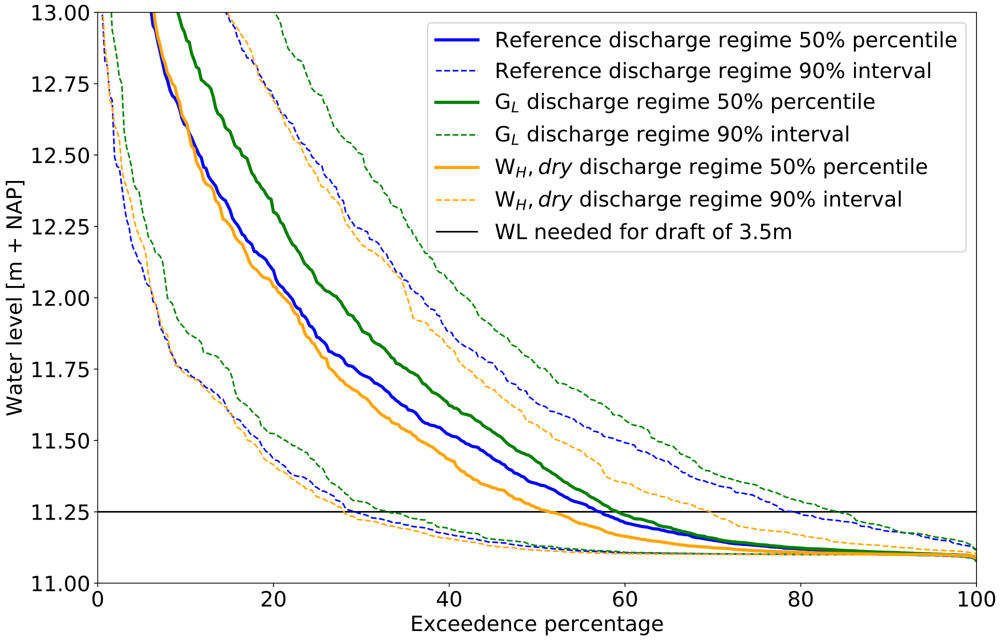

Fig. E.2.: Water level exceedence downstream from lock Belfeld for the reference discharge regime and two discharge regime scenarios, all in combination with the reference riverbed.

In the wetter discharge scenario G$_L$, the exceedence of the critical water level improves a little bit compared to the reference discharge regime. In the drier W$_{H,dry}$ scenario, however, the exceedence declines seriously. What becomes clear from the figure as well, is that even in the driest years of the driest scenario, the lower boundary of the water level is at 11.10m + NAP. The weir at Sambeek clearly maintains its CWL, which limits the draft constraints downstream from lock Belfeld. The fact that the CWL is sustained at all times, is caused by the model settings, which do not necessarily reflect reality.

The results show that the impact of bed degradation is way smaller than the impact of a changing discharge regime. This is confirmed in the numbers of the median year as well as by the numbers matching the 5th and 95th percentile. What stands out when comparing the outcomes of the different percentiles, is that the dry years in the changing discharge regimes become even drier, but that the relatively good years worsen as well. The wet future discharge regime G$_L$ improves the situation for the very dry years (5th percentile), but for the median and 5% best years, it still harms the functioning of lock Belfeld compared to the reference. The W$_{H,dry}$ regimes causes more relative harm in the 5th percentile diagram than in the 95th percentile diagram. This points out that the already volatile conditions in the Meuse river become even more volatile, harming the functioning of the Meuse river with regard to navigation.

Niftrik

As Chapter 4 stressed already, the sill at Niftrik forms a major restriction for ships navigating on the West route. In theory, the allowed draft at this part of the Meuse is 3.5m, just as in the other stretches. In practice, however, a draft of 3.5m is not realistic most of the time. In the reference scenario the water level allows for a draft of 3.5m only about 23% of the time. For practical reasons, the standard allowed draft at this river stretch is 3.2m. As the official CEMT Va class demands a draft of 3.5m, this will be the benchmark for the functional performance analysis of the sill at Niftrik

Figures E.3 and E.4 present the results of the impact of bed level developments and changing discharge regime respectively. Appendix E shows the additional plots for the other scenarios.

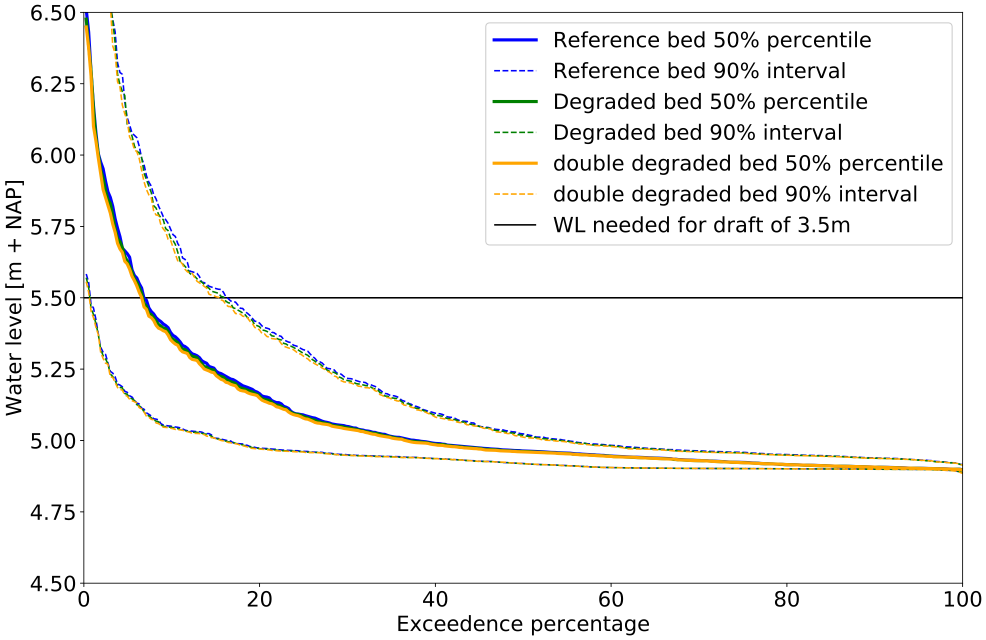

Fig. E.3.: Water level exceedence downstream from lock Niftrik for the reference riverbed and two degraded riverbed scenarios, all in combination with the reference discharge regime.

The relative impact of bed level developments and a changing discharge regime are of a different order of magnitude. The imposed bed degradation causes the exceedence of the optimal water level boundary to increase for less than a percentage point. A changing discharge regime, however, has a bigger relative impact on the available navigable depth at Niftrik. It becomes clear that the current functioning of the Meuse river at Niftrik has no optimal years. Even in the best 5% of the years of the discharge regime, a draft of 3.5m is possible in about 20% of the time only. This number increases for the G_L discharge regime and stays about equal in the $W_{H,dry}$ discharge regime. In the changed discharge regimes, a draft of 3.5m is possible only in a few percent of the days.

It is remarkable that in the 5% worst years, the draft limitations at Niftrik do not differ a lot for the different discharge regimes. The discharge needed at Niftrik to allow for a draft of 3.5m is

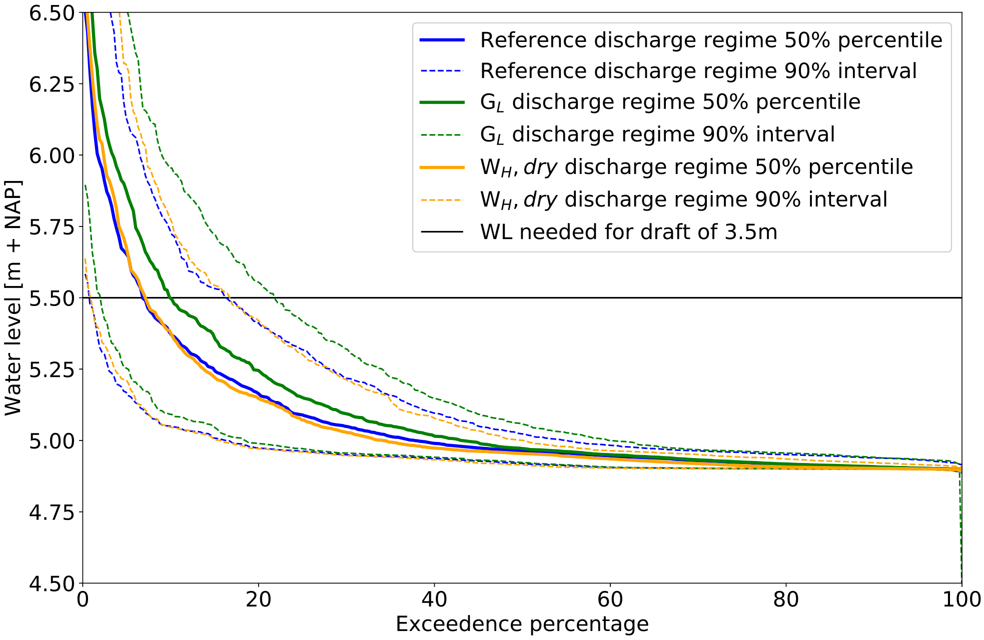

Fig. E.4.: Water level exceedence downstream from lock Niftrik for the reference discharge regime and two discharge regime scenarios, all in combination with the reference riverbed.

exceeded only 10 or 15% of the time. This points out a large discharge is needed for this. In the G$_L$ scenario, this discharge happens a lot more often than in the reference and W$_{H,dry}$ scenario.

Weurt

The location of lock Weurt is at the beginning of the Meuse-Waal Canal and the downstream side of lock Weurt is in direct connection to the Waal river. This means the navigable depth determining the maximum draft for ships passing lock Weurt is at the Waal side of the lock. In principle, the Waal river is not part of this research, but as navigational transport lines are not limited to one river system or another, it is important to have a look at this bottleneck as well. A lot of ships passing by bottlenecks Sambeek and Belfeld will pass lock Weurt as well. So when draft limitations at one lock are solved, there is a risk that an other lock will be limiting the draft next. That is why it is important to know to what extent lock Weurt is limiting the navigable depth of ships navigating from the Waal the Meuse river.
As noted already, the Waal river is not part of the research scope and is consequently not included in the hydraulic model that was deployd for this study. At online water availability tool WABES (Rijkswaterstaat, 2020a) the water levels at Nijmegen for different Rhine discharge regime scenarios are available. For this study, the mildest discharge scenario and the most extreme discharge scenario are observed.

When comparing Figures E.2 and E.5, it becomes clear that the draft limitations at lock Weurt are smaller than the limitations at lock Belfeld. It is remarkable that the low flows in the W$_{H,dry}$

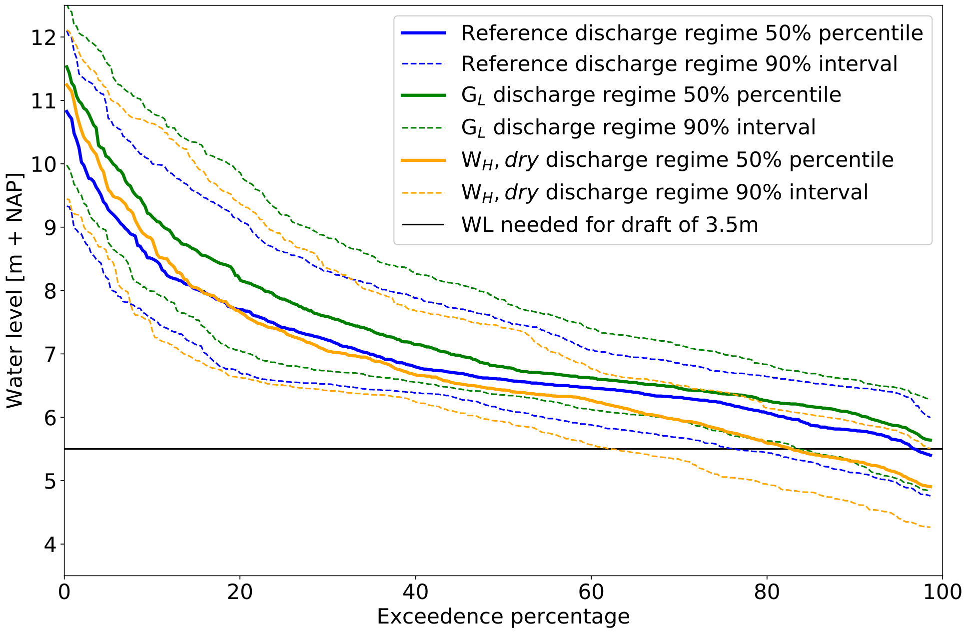

Fig. E.5.: Water level exceedence at the Waal side of lock Weurt for the reference, G$_L$ and W$_{H,dry}$ discharge regime. No bed level developments at the Waal river are included.

discharge regime have a larger impact on water levels in the Waal than on the Meuse river. The reason for this is that the Waal river is a free-flowing river while water levels on large stretches of the Meuse are controlled by weirs.

The riverbed of the Waal river degrades over time (Blom, 2016). If this degradation continues the coming decades, the draft limitations at lock Weurt can increase. The lock at Weurt connects the upper Waal to the Meuse-Waal Canal. Until 2050, a degradation rate of 1.5cm/y is expected in the upper Waal (Hiemstra, 2019). This means that bed levels at the Waal side decrease with 45cm between 2020 (ref) and 2050, in case no measures are taken against this bed degradation. Zuijderwijk et al. (2020) report that as long as the discharge in the Waal river is below bankfull, the water level responds one on one to the bed level decrease. Van Vuren et al. (2015) report the bankfull discharge of the Waal river at 3450 m^3/s. At this discharge, the draft at lock Weurt is not limited anymore (Rijkswaterstaat, 2020a). It is therefore justified to shift the water levels in Figure E.5 down with 45cm in order to obtain the impact of bed degradation in the Waal river.

From Figure 4.8 it becomes clear that the draft limitations at lock Weurt currently have a smaller impact on navigational functioning than the draft limitations at lock Belfeld or sill Niftrik. When bed degradation in the Waal river is considered, however, the conditions rapidly worsen. What stands out that the free flowing Waal river is much more vulnerable for drier years (5th percentile) and for the driest discharge scenario W$_{H,dry}$ than the impounded stretches of the Meuse river. The question if lock Belfeld is determining the maximum draft of ships shipping on the Meuse route has a rather ambiguous answer. If no measures are taken against bed degradation in the Waal river, lock Weurt potentially becomes the determining link in the Meuse route.

E.0.1 Locking restriction

An operating ship lock transfers water from upstream to dwonstreawm. When this transferred discharge is bigger than the water supply upstream of the lock, the locking frequency is decreased in order to restore the water balance (and sustain the CWL).

Lock Maasbracht in the Julianakanaal, needs at least 12 m^3/s of dischargeto allow for a normal locking frequency and minimal delay for ships passing the lock. Near Urmond, about 1.5 m^3/s is drained from the Julianakanaal for industrial purposes, so for an optimal locking process, a total discharge of 13.5 m^3/s is needed.

At weir-lock complex Grave, water is transferred from upstream to downstream through the ship lock as well. On top of this discharge, water leaks through the weir construction. When the Meuse river discharge at the weir-lock complex is bigger than the locking and leaking discharge combined, the excess water is spilled over the weir crest towards the downstream side of the weir-lock complex. The average locking discharge at lock Grave is about 1.5 m^3/s, while the average leakage losses are estimated at 20 m^3/s. Combining the two, at least 21.5 m^3/s of Meuse river discharge is needed to allow a minimum delay for ships at lock Grave.

The scenarios incorporating bed level developments in the Meuse river do not have any influence on the discharge availability at lock Maasbracht and lock-weir complex Grave, so this study does not address the impact of these scenarios on the locking processes. Figures E.6 and E.7 present the impact of different discharge regimes on availability of locks Maasbracht and Grave.

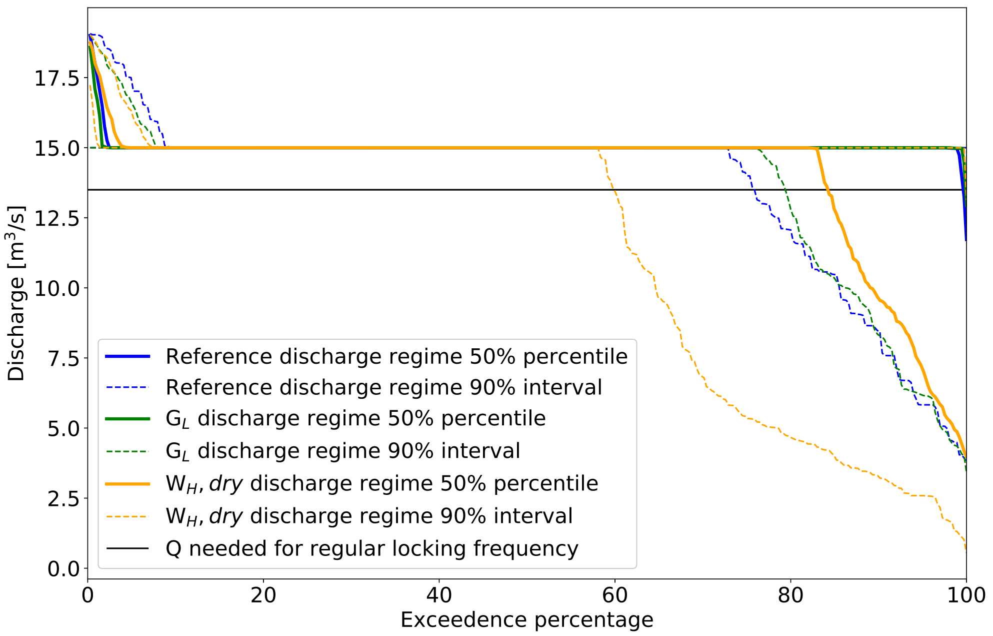

Fig. E.6.: Discharge exceedence at lock Maasbracht for the reference discharge regime and two discharge regime scenarios.

Figure E.6 shows that the discharge deficit hindering an optimum locking frequency increases in the $W_{H,dry}$ discharge regime, while the situation stays roughly equal in the G_L discharge regime. In the Reference and G_L scenario, the waiting hours are of the same order of magnitude. The slight improvement in the G_L scenario consists mainly of shorter waiting times for ships that would have waited only for 15 minutes. In the $W_{H,dry}$ scenario, however, both the amount of ships that have to wait longer than half an hour and the amount of ships that have to wait up to half an hour increases strongly compared to the reference scenario. The 5^{th} percentile results show that waiting hours in the worst years grow rapidly compared to the median year.

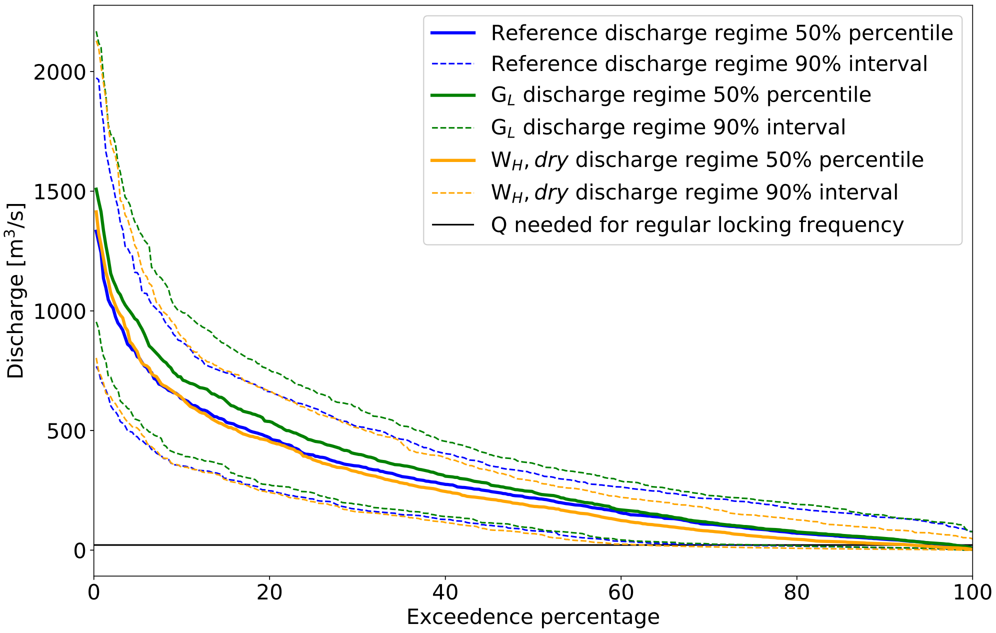

Fig. E.7.: Discharge exceedence at lock Grave for the reference discharge regime and two discharge regime scenarios.

In Figure E.7 it is observed that in the reference discharge regime, already problems arise at lock Grave, as the critical discharge of 21.5 m^3/s is not always exceeded. In the wet G_L discharge regime, the situation improves slightly as the lowest discharges increase a little bit. In the driest discharge scenario for the year 2050, however, discharges underceede the critical discharge more frequently. This notion causes lock-weir complex Grave to be potentially a bigger future bottleneck for the facilitation of navigation on the Meuse river.

F

Longitudinal side views chain of locks

In Figure F.1 the chain of locks of the Meuse route is presented. From the Controlled Water Levels and sills it becomes clear that at lock Belfeld the difference between the controlled water level and the lock sill is smallest. This presented in Figure 4.3 as well.

In Figure F.2 the chain of locks of the West route is presented. From the Controlled Water Levels and sills it becomes clear that at sill Niftrik the difference between the controlled water level and the sill is smallest. This presented in Figure 4.3 as well.

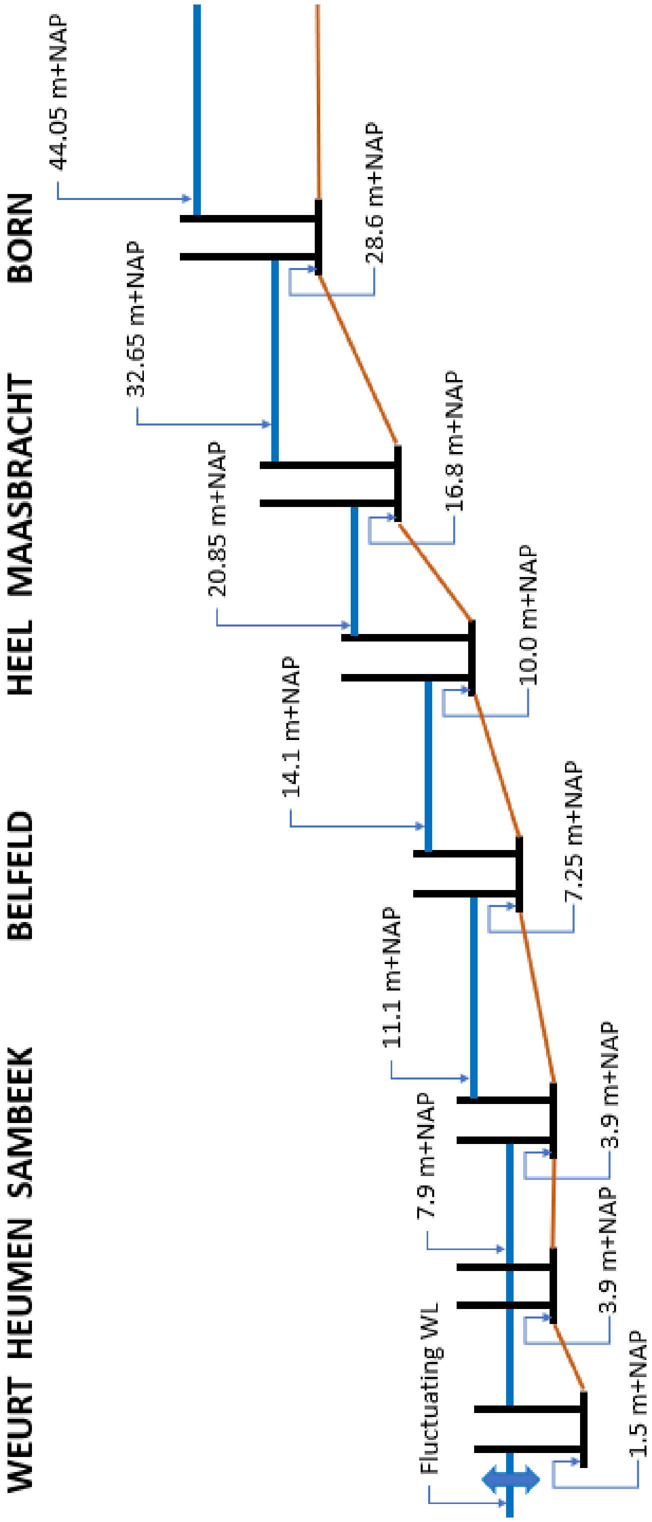

Fig. F.1.: Longitudinal side view of the chain of locks in the Meuse route.

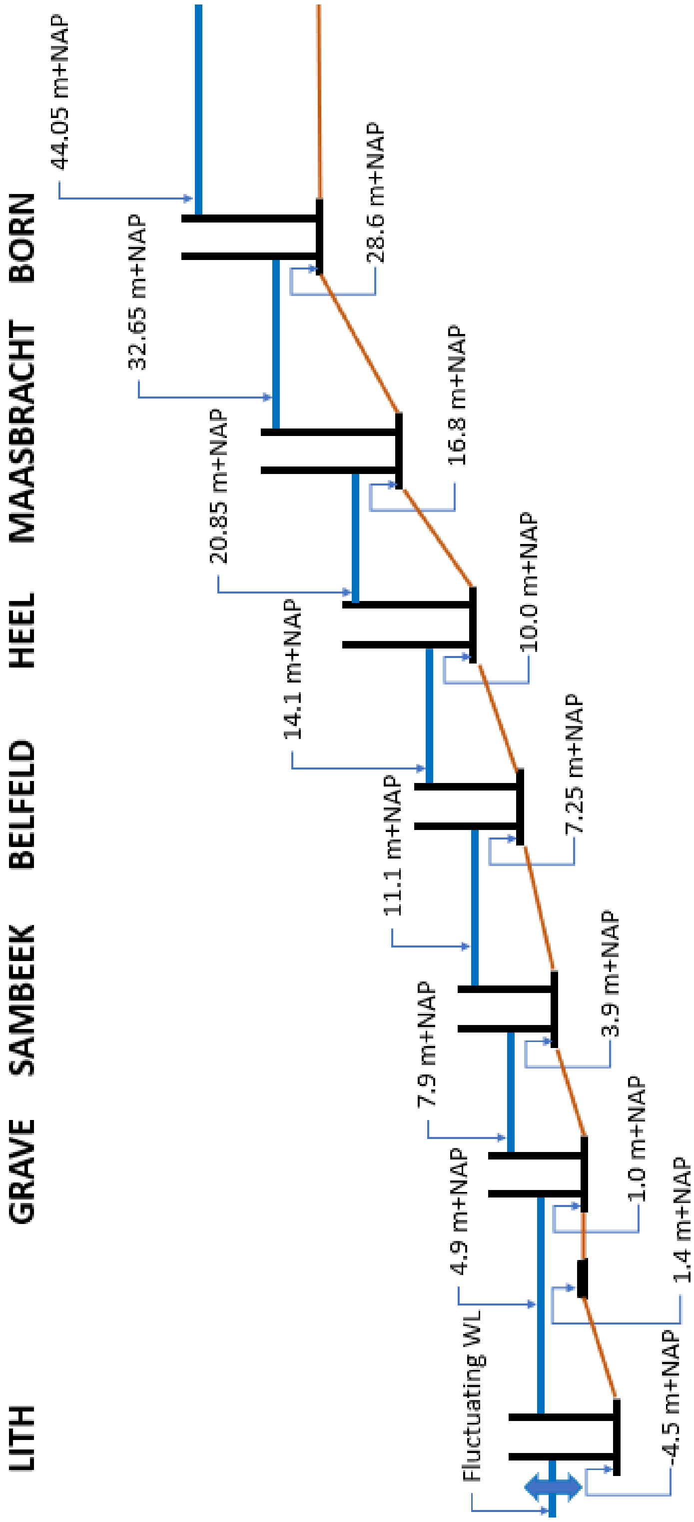

Fig. F.2.: Longitudinal side view of the chain of locks in the Meuse route.

G

Levee strengthening challenges per levee ring

In the tables below, the results of the translation of changes in representative discharges to levee dimension demands are presented per levee ring. For practical reasons, the codes of the levee rings are mentioned. The levee name that belongs to each code is presented first (Table G.2). The scenarios are numbered following Table G.1

Table G.3 and Table G.4 present the consequences of changing representative discharges for all levee rings.

Tab. G.1.: Overview of future developments considered in this research.

Discharge regime	Bed level	Scenario #
Reference	Reference	1
	expert judgment 2050	2
	doubled 2050	3
G_L, G	Reference	4
	expert judgment 2050	5
	doubled 2050	6
$W_{H,dry}$, W^+	Reference	7
	expert judgment 2050	8
	doubled 2050	9

Tab. G.2.: Levee ring names and codes.

Name	Code	Name	Code
Land van Altena 1	24-1	Aan de Maas	88-1
Nederhemert	37-1	Voulwames	89-1
Bommelerwaard - Maas	38-2	Itteren	91-1
Heerenwaardense afsluitdijk en schutsluis St. Andries	224	Borgharen	92-1
Heerewaarden - Maas	40-2	Maastricht	90-1
Land van Maas en Waal - Maas	41-3	Eijsden	95-1
Land van Maas en Waal - Maas	41-4	Donge 1	35-1
Ottersum - Mook	54-1	Land v Heusden / de Maaskant	36-5
Gennep	55-1	Land v Heusden / de Maaskant	36-4
Afferden	56-1	Land v Heusden / de Maaskant	36-3
Nieuw-Bergen	57-1	Land v Heusden / de Maaskant	36-2
Bergen	59-1	Keent	36a-1
Well	60-1	Land v Heusden / de Maaskant	36-1
Arcen	65-1	Groeningen	58-1
Venlo - Velden Noord	68-2	Wanssum	61-1
Venlo - Velden Noord	68-1	Blitterswijck	63-1
Belfeld	71-1	Broekhuizenvorst	64-1
Beesel	73-1	Lottum	66-1
Roermond	76-2	Grubbenvorst	67-1
Roermond	76-1	Blerick Noord	69-1
Roermond	76a-1	Baarlo	70-1
Roermond	77-1	Kessel	72-1
Maasbracht	80-1	Neer	74-1
Stevensweert	81-1	Buggenum	75-1
Aasterberg	82-1	Beegden	78a-1
Grevenbicht Visserssweert	83-1	Heel	78-1
Urmond	85-1	Thorn-Wessem	79-1
Maasband	86-1	Bosscherveld	93-1
Meers	87-1	Maastricht - West	94-1

Tab. G.3.: Consequences of changing representative water levels for levee heightening (1/2). For levee widening demands, these number have to be multiplied by a creep factor of 35.

Scenario #		2	3	4	5	6	7	8	9
Code	L [km]	dh · L [m^2]	dh · L [m^2]	dh · L [m^2]	dh · L [m^2]	dh · L [m^2]	dh · L [m^2]	dh · L [m^2]	dh · L [m^2]
24-1	18	4.1	1.3	108.7	118.7	114.8	454.1	481.1	483.7
37-1	5	1.5	0.5	38.9	42.5	41.2	164.2	174	175
38-2	20	6.1	2.3	163.7	179	173.4	685	724.9	728.7
224	1.5	0.5	0.2	12.8	14	13.5	52.5	55.3	55.6
40-2	6.5	1.9	0.8	51.4	56.3	54.5	218.9	231.1	232.2
41-3	27	-32.1	-73	173	149.6	103.7	764.4	775.1	740.6
41-4	20	-62	-133	128.6	72.9	-2.4	514.4	485.3	425.5
54-1	12.5	-49.3	-104.7	72.7	27.5	-30	276.9	245.8	198.5
55-1	8	-34.9	-75.9	57.1	25.6	-17.1	229.1	202.3	164.6
35-1	14	2.9	0.9	76	83	80.2	318	336.9	338.7
36-5	17	4.9	1.7	129.4	141.4	136.9	545	577.6	580.7
36-4	20	5.8	1.7	165.6	180.7	174.7	695.1	734.3	737.7
36-3	26.5	-37.3	-82.6	163.6	134.3	83.8	725.7	730.3	690.8
36-2	21	-65.1	-139.6	135.1	76.6	-2.5	540.1	509.6	446.8
36a-1	4.5	-12.7	-27.2	28.2	16.8	1.2	113.9	108.5	96.4
36-1	17.5	-72.4	-156	114.4	48.4	-38.4	448.9	398.1	323.7
56-1	3	-11.9	-22	49.7	41.5	31.1	97.9	91.6	82.8
57-1	2	-10.3	-19.4	31.1	23.2	13.7	61.3	54.8	46.8
59-1	6	-32.1	-63	71.6	48.6	20.5	138.6	119.9	97.8
60-1	5.5	-23.6	-47.2	53	37.7	17.6	103.3	90.9	76.3
65-1	5	-30.8	-62.9	48.5	23	-7.4	102.2	74.5	48.5
68-2	5	-38	-77.6	63.4	31.9	-5.9	132.2	98.4	66.7
68-1	10	-88.2	-180.2	157.4	84	-4.7	330	249.6	175.2
71-1	1	-8.9	-18.6	17.3	10.3	1.5	36.4	28.5	21.3
73-1	1	-8.5	-17.6	15.1	8.1	-0.4	32.2	24	16.9
76-2	1.5	-9.8	-20	23.1	14.9	4.7	49.2	39.1	30.6
76-1	2.5	-15.9	-32.6	39.2	26.2	9.6	83.2	66.9	53.2
76a-1	1.5	-9.4	-19.2	23.9	16.3	6.5	50.6	41.1	33.1

Tab. G.4.: Consequences of changing representative water levels for levee heightening (2/2). For levee widening demands, these number have to be multiplied by a creep factor of 35.

Scenario #		2	3	4	5	6	7	8	9
Code	L [km]	dh · L [m^2]	dh · L [m^2]	dh · L [m^2]	dh · L [m^2]	dh · L [m^2]	dh · L [m^2]	dh · L [m^2]	dh · L [m^2]
77-1	8.5	-41.6	-84.2	128.5	91.8	44.9	278.4	230	189.8
80-1	1.5	-3.9	-8	18.2	13.9	9.6	38.6	33.1	29
81-1	14	-51	-93	84	22.6	-22.6	168.4	111.4	49.6
82-1	1	-2.6	-4.3	5.3	2.3	0.5	9.1	7.3	4.8
83-1	16	-285	-596.1	135.2	-142.4	-442.6	258.3	15.2	-285.2
85-1	0.5	-15	-30.5	7.6	-7	-21.9	14.3	2.6	-13.2
86-1	1.5	-35.3	-62.5	18.1	-8.1	-42.2	35.9	17	-14.4
87-1	5.5	-126.4	-255.6	69.3	-19.5	-148.1	136	70.7	-30.4
88-1	2.5	-75.9	-147.2	34	-40.3	-112.7	70.5	-1.9	-74
89-1	0.5	-14.1	-29.5	6	-8.9	-23.2	12.5	-3.2	-17
91-1	3.5	-81	-180.2	35.3	-42.9	-134.1	72.8	-6.4	-87.8
92-1	3.5	-85.6	-182.7	33.4	-50.5	-143.2	75.2	-16.9	-102.8
90-1	6.5	-40.9	-82	81.5	37.1	-2.3	184.4	130.5	91.9
95-1	1	-0.5	-1	12.6	11.5	10.8	29.5	27.7	26.7
58-1	1.5	-6.7	-12.5	24.2	19.2	13.2	47.5	43.6	38.5
61-1	7	-30	-60.1	67.5	48	22.4	131.4	115.7	97.1
63-1	5.5	-31.5	-63.1	55.5	31	0.7	113.6	89.5	65.1
64-1	2	-11.7	-23.7	18.9	9.3	-2.1	39.6	29.5	19.8
66-1	1.5	-10.3	-21	16.2	7.6	-2.6	34.1	24.8	16.1
67-1	0.5	-3.7	-7.6	6.2	3.1	-0.6	12.9	9.6	6.5
69-1	4.5	-37.6	-76.7	65.9	34.6	-3.1	137.4	103.6	72.1
70-1	5	-46.1	-94.4	84.1	45.7	-0.8	177	134.5	95.4
72-1	0.25	-2.1	-4.4	3.8	2	-0.1	8.1	6	4.2
74-1	2	-14.9	-30.6	29.7	16.9	1.4	64	48.7	35.4
75-1	1.5	-10.5	-21.5	23.7	15	4.2	50.7	40	31
78a-1	0.5	-3.5	-7.1	7.9	5.1	1.5	17	13.5	10.5
78-1	7.5	-19.4	-39.9	90.9	69.7	48.2	192.9	165.6	144.9
79-1	8	-11.7	-21	69.4	51.2	40.4	143.9	127.8	107.9
93-1	2.5	-47.7	-100.4	23.6	-23.9	-74	52.8	-0.2	-46.7
94-1	1	-3.4	-6.4	17.4	13.4	10.5	38.5	33.6	30.7