Design of an adaptive weir

A case study of the replacement of weir Belfeld

R.S.J. (Ruben) Frijns

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by

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Preface

This thesis is the final result of the master study Hydraulic Engineering, specialization Hydraulic Structures, at the faculty of Civil Engineering and Geosciences of the Delft University of Technology. This study on the design of an adaptive weir has been proposed by the engineering firm ARCADIS. I am thankful to ARCADIS for formulating such a suitable and hot subject for my thesis and the possibility to execute most of the study on their offices in Rotterdam and Amersfoort.

More specific, this thesis focusses on the replacement of the weirs in the Meuse River. Seven weirs have been built to transport coals in the previous century. Although this is not the case anymore, the weirs and the water level control are indispensable. In the meantime, the weirs and their operation are ageing and replacement is demanded by the asset owner Rijkswaterstaat. This project contains a proposal to replace the weirs by adaptive weirs, which are based on an analysis of the total dammed section of the Dutch Meuse River. The future uncertainty is taken into consideration by the Dutch delta scenarios, which represent a wide spectrum of developments in the future. Eventually, an overview of useful measures in the specific weir section of weir Belfeld is given for the upcoming century to deal with these developments; partly by adapting the weir, partly by taking adaptation measures along the river section. Supporting analyses can be found in the appendices of this report.

Without support, this report would have not been established. First of all, I want to thank my entire thesis committee for their enthusiasm during the progress meetings. Jeremy Bricker, chair of my graduation committee, has been important from the beginning by initiating the contact between ARCADIS and me. I am also grateful to Mark Voorendt for his involvement during the project; I liked our pleasant relationship, also during other activities. Ronald van Nooijen is certainly worth mentioning as well, since his great input from the field of water management helped to solve and explain the related issues in a clear manner. Last, I really appreciate the support from ARCADIS, specifically from Henry Tuin and Hessel Voortman. Both assisted me in setting up my project plan and introduced me to the concept of adaptive designing. The progress during the nearly weekly meetings with them has been invaluable.

Last, a big thanks to all my family and friends. They supported me and gave me distraction during the challenging periods of this project. Without them, these periods would have been longer and harder as well. Special thanks go to Patrick Steskens, who reviewed the final report and gave some last useful feedback.

R.S.J. Frijns
Rotterdam, November 2019

Abstract

In contrast with other Dutch rivers parts, human measures in the upstream part of the River Meuse did not mainly focus on discharging surplus water, but on retaining water in dry periods. Almost 100 years ago seven weirs were constructed in the River Meuse to enable transport of coals. The structures reach, due to concrete degradation, the end of their technical lifetime and the manual operation does not meet the current ARBO-legislation; both make replacement of the weirs required. Rijkswaterstaat, asset owner of the waterways and weirs, invited the civil engineering sector to collectively develop weir replacement strategies in 2015. The future developments of the river and surroundings were an important subject during the meetings. With this in mind, during the co-creation meetings under the title 'Grip op de Maas', one of the proposed weir replacement strategies was called the Adaptive Meuse (De Bouwcampus, 2015). This perspective took the future uncertainty into account by proposing adaptive designing of the weirs. This study builds on this perspective by the objective of designing an adaptive weir in the River Meuse according to the approach of adaptive delta management.

This approach states that designs have to be flexible and able to switch between multiple strategies for future challenges concerning flood safety and freshwater storage. In this study, an overview of the measures required to deal with the development of specific purposes is provided by adaptation schemes. When and if a specific purpose applies, depends on which of the four Dutch delta scenarios, DRUK, STOOM, RUST and WARM, evolves. These scenarios are based on a unique combination of the rate of climate change and socioeconomic developments (Wolters, Van den Born, Dammers, & Reinhard, 2018). Adaptivity is obtained by regional adaptation measures over a particular stretch of the river and by weir adaptation measures. To address both the adaptivity of the river and the weirs, three design levels have been established. These levels are shown in Figure 1 and summed below:

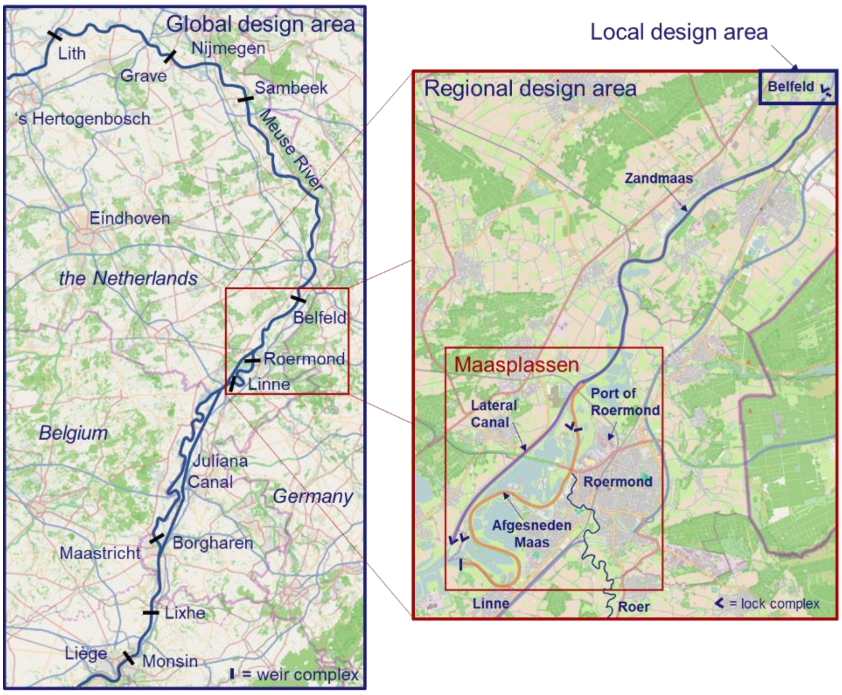

Figure 1: Differentiation of the global, regional and local design level (OpenStreetMap Nederland, n.d.).

- The <u>global design</u> level comprises the total dammed section of the Dutch River Meuse and two weir sections in Belgium. The series of weirs in the river still suffices the requirements; on this scale, no large adaptations have to be made now or in the future.

- The regional design level comprises the weir sections Roermond and Belfeld, since the adaptivity of these sections is the largest of all weir sections in the global design area.
- The local design level addresses the geometric design of weir Belfeld itself. The adaptivity of the designed weir enables the discard of regional adaptation measures with undesired implications.

Global design level: section Monsin – Lith

Since both dehydration and permanent flooding of the river valley have to be prevented and the water distribution over Belgium and the Netherlands is fixed in an agreement, the global adaptivity is limited. Weir removal or replacement of the current weir by a new weir at a different location is in most weir sections infeasible. Weir section Roermond forms an exception, since the commercial navigation uses the later dug parallel Lateral Canal, part of weir section Belfeld. Thus, the majority of weir section Roermond can be restricted to only recreational vessels. By modifications of weir Belfeld, it could possibly (partly) take over the functions of weir Roermond in future. In 2030 however, one-to-one weir replacement is selected to avert significant changes in groundwater table.

Regional design level: section Linne – Belfeld

For the regional design level, the future developments are split into the flexibility to groundwater changes, the use of freshwater for drinking water production, agriculture and industrial activities, the discharge of flood waves and the navigation on the River Meuse and to the port of Roermond. An adaptation scheme indicates what regional adaptation measures and weir adaptation measures are required to serve the purposes per time period in each of the four delta scenarios. On basis of this adaptation scheme, it is concluded that by designing an adaptive weir, measures along the entire weir section, for instance raising embankments or raising bridges, can be discarded in the future. The freedom of choice of the future waterway manager is preserved by an adaptive weir.

Local design level: weir Belfeld

In the last design level, an adaptive weir is proposed to replace weir Belfeld. The requirements to and the design of the adaptive weir are based on the regional adaptation scheme.

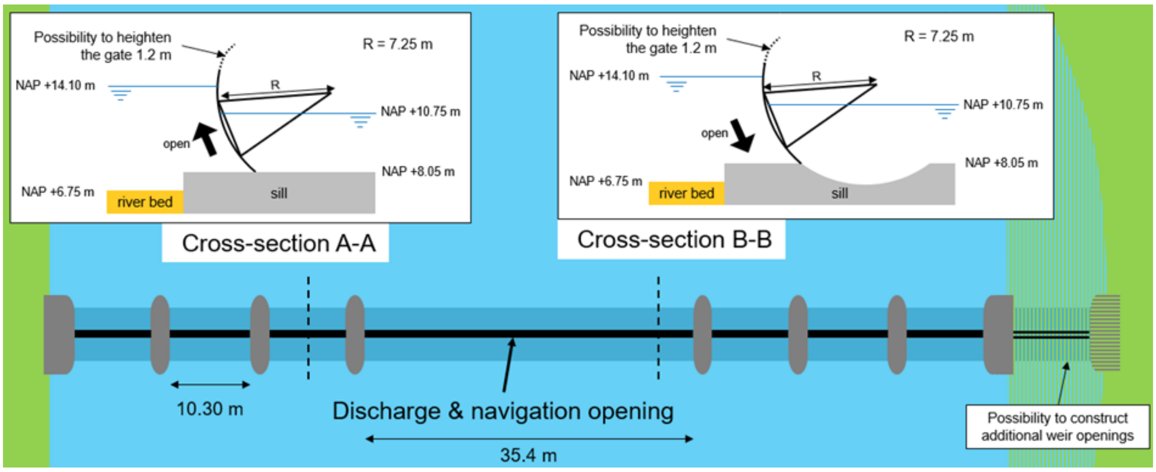

Figure 2: Overview of the proposed adaptive weir Belfeld.

The weir shown in Figure 2 can be adapted by:

- constructing additional weir openings at the eastern embankment, enabled by the location of the new weir, which is just a couple of hundreds meter upstream of the current weir.
- adjusting the management of the weir gates, enabled by the choice of radial gates. The location in the weir section at which the dammed water level is independent of the river discharge can be shifted throughout the weir section. This allows the air clearance and the water level dynamics to be managed for container transport and ecological development, respectively.

- heightening the dammed water level, also enabled by the choice of radial gates.
    - To withstand the larger water head, the initial investment increases by 30%. However, regional measures are saved in the future. Only the gates and height of the superstructure have to be adapted in the future to heighten the dammed water level.

In conclusion, on global level, a change of the locations and numbers of weirs in the River Meuse is presently not desired and required, since the functions are met with the current weir layout. To guarantee this in the entire upcoming century, adaptations are required in the weir section Belfeld in the River Meuse. Table 1 shows the resulting adaptation scheme after construction of the proposed adaptive weir. Regional and weir adaptation measures are presented that serve the mentioned scenario-dependent purposes. By the large adaptivity of proposed weir design, regional adaptation measures along the river with undesired implications can be discarded or minimized. Only if higher container vessels have to be accommodated on the Meuse River or the accessibility of the Prins Willem-Alexanderport has to be improved, regional measures are inevitable. The method used in this report can be used to set up adaptation schemes for all weir sections in the River Meuse. By involving Rijkswaterstaat and other stakeholders, the schemes can be turned into quantitative ones. Last, it is recommended to start structural calculations on the adaptive weir Belfeld.

Table 1: Adaptation scheme of weir section Belfeld after construction of the proposed design alternative.

Legend (A = regional adaptation measures; B = weir adaptation measures)
A ∩ B = intersection (A and B)
A ∪ B = union (A or B)
A ⊃ B = superset [(only A) or (minimized A + B)]

Purpose	*Scenario (year) in which the purpose applies*	*Regional adaptation measures*	*Binary operator*	*Weir Belfeld adaptation measures*	
Increasing the discharge capacity of the river valley	DRUK (2050)	'Room for the River' measures	⊃	Enlarging the flow opening	By 10%
	STOOM (2050, 2100) WARM (2100)				By 15%
Preventing more frequent flooding of the river valley	DRUK (2050)	Raising the main channel embankments ∪ dredging the main channel	∪	Enlarging the flow opening	By 10%
	STOOM (2050)				By 15%
				∪ shifting the set point location	
Accommodating higher container vessels	DRUK (2050) STOOM (2050)	Raising bridges on the Maasroute	⊃	Shifting the set point location	
Providing more freshwater storage	DRUK (2050, 2075) STOOM (2075, 2100) WARM (2075, 2100)	Dredging a new lake ∪ enlarging an existing lake	∪	Heightening to maximum	NAP +15.10 m
	DRUK (2100)				NAP +15.30 m
Increasing the dynamics in dedicated natural areas	DRUK (2050)	-	-	Shifting the set point location	
Accommodating larger vessels to the Prins Willem-Alexanderport	DRUK (2075)	Deepening the Prins Willem-Alexanderport	-	-	
Improving the accessibility of the Prins Willem-Alexanderport	DRUK (2100)	Deepening the Prins Willem-Alexanderport	∩	Removal of weir Roermond ∪ replacing weir Roermond upstream	
			⊃	Heightening to maximum NAP +15.30 m	
Providing more frequent flooding of the river valley	WARM (2075, 2100)	Lowering the river valley	∪	Heightening to maximum NAP +15.10 m	

List of symbols

Symbol	Description	Unit
A	Cross-sectional area	$[m^2]$
B	Width	[m]
C	Chézy-coefficient	$[m^{0.5}/s]$
D	Draught	[m]
$D_{aquifer}$	Saturated thickness of aquifer	[m]
G	Weight	[kN]
H	Energy head	[m]
L	Influence length	[m]
N	Infiltration	[m/day]
PV_t	Present value at time t	[€]
R	Discount rate	[%]
Q	Discharge	$[m^3/s]$
$c_{overflow}$	Discharge coefficient for overflow	[-]
$c_{freeunderflow}$	Discharge coefficient for free underflow	[-]
$c_{subunderflow}$	Discharge coefficient for submerged underflow	[-]
d	Water depth	[m]
d_e	Equilibrium water depth	[m]
g	Gravitational acceleration	$9.81\ [m/s^2]$
h	Height	[m]
i_b	Bed slope	[-]
k	Permeability	[m/day]
q	Specific discharge	$[m^2/s]$
u	Flow velocity	[m/s]
x	Location along the river	[m]
y	Cross-sectional location	[m]
z_b	River bed level	[NAP + m]
η	Water level	[NAP + m]
η_{GL}	Ground level	[NAP + m]
η_{GWT}	Groundwater table	[NAP + m]

Contents

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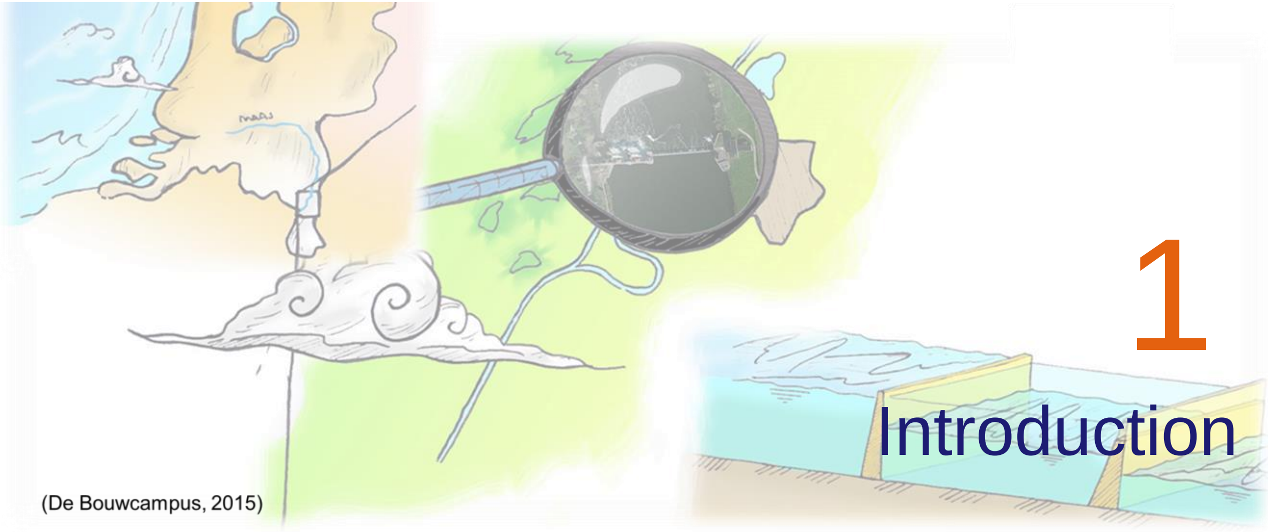

(De Bouwcampus, 2015)

1 Introduction

The Netherlands is inextricably linked with water; the location at sea, surrounding the mouth of large rivers, has been providing a strategic position in trade flows for many centuries. On the other hand, many river floods and storm surges have threatened the inhabitants. To diminish the flood risk, one has taken flood protection measures. The present course and nature of the Dutch coast and rivers have been steered by humans over the last millennia, whereof the human influence in the last 300 years is most evident nowadays.

The vast majority of the Dutch rivers traverse the delta, in which dikes, flood plains and polders are typical artificial features to manage and distribute water quantities in the low-lying area. The Dutch upstream section of the River Meuse, see Figure 1-1, however, is substantially different. The gradient is relatively large and the natural topography confines floods to the river valley. Instead of floods, the shortage of water has been decisive for the water management in this area. Weirs retain water to create a buffer for the summer during which the freshwater supply is small. In this way, one can utilize the river and its water intensively in summer as well. This still is a hot issue, as in the calendar year 2018 the greatest drought on record nearly occurred. Even in 2019, the groundwater table has not risen to the usual level and the freshwater use has been restricted by the regional water board (De Limburger, 2019). On top of that, the drinking water production sector notices a future shortage of water supply from the River Meuse (Van Heerde, 2019).

Figure 1-1: The location of the nine most downstream weirs in the River Meuse (OpenStreetMap Nederland, n.d.).

Since 1930, control of the water level has been achieved in the Netherlands by constructing seven weirs in the Dutch part of the River Meuse. Because the lifetime of the structures has nearly passed, Rijkswaterstaat, asset-owner of the waterways and weirs, invited the civil engineering sector in 2015 to develop weir replacement strategies. Under the title 'Grip op de Maas' (De Bouwcampus, 2015) perspectives have been generated and elaborated during four co-creation meetings. ARCADIS was one of the many companies which participated in those meetings and proposed a perspective focussing on the adaptivity of (the weirs in) the system of the River Meuse. Besides the river itself, the connected canals and creeks and the surrounding groundwater flow is of great importance in this replacement task, since weir replacement can have large effects on all of these elements. The other way around, future developments (of these elements) can change the boundary conditions and purposes the weirs have to serve.

1.1 Problem analysis

After presenting the concept versions of the perspectives, little progress has been made, while weir replacement comes closer. After weir construction in the previous century, only minor modifications have been implemented, while society, economy and the surrounding area did change surely. The focus lied on maintenance of the weirs to keep fulfilling their functions, yet decay of material and change of the boundary conditions demand a study to weir replacement and their role in the water system.

The first process, the decay of material, leads to a reduction of the structural safety and reliability. When the latter do not meet the prescribed requirements, the structure has reached the end of its technical lifetime. Due to the numerous Dutch infrastructural projects one century ago, this happens at many infrastructural structures in the current and future decades. Considering only the wet infrastructure, over 200 structures have to be addressed, ranging from water pumping stations and sluices to locks and weirs. Their replacement and/or renovation is one of the main tasks of Rijkswaterstaat and requires a billion-euro investment (Deltares, Marin, TNO, 2015).

The second process, the change of requirements and boundary conditions of the system, can induce the end of the functional lifetime. In the worst-case scenario, structures have to be replaced while they are still technically adequate. Maintaining the structure is no option, as it would lead to dissatisfied stakeholders for the rest of the structure's technical lifetime. The change of requirements and boundary conditions is a never-ending and above all uncertain process. The long technical lifetime of weirs, 100 years, makes changes of boundary conditions during its lifetime plausible.

The weirs in the River Meuse deal with both processes. Inspections, as part of the national replacement programme, show that the end of technical lifetime of the weirs will be in the interval 2025-2040 (Iv-Infra b.v., 2014). The end of functional lifetime is close as well, since many weirs are still operated manually, not meeting the ARBO-legislation. Therefore, approximately 1.5 billion euro is reserved for the replacement of the weirs in the River Meuse (Bartholomeus, 2019).

In summary, the actual problem is that:

- the weirs in the River Meuse approach the end of their lifetime. The structural safety and reliability will not satisfy from the period 2025-2040 and the manual operation is outdated and unsafe.
- unforeseen changes of boundary conditions, which can demand other requirements than the current ones, are expected during the long technical lifetime of weirs, 100 years.

1.2 Objective

To cope with the uncertainty, one can consider the worst-case scenario and design the structure based on this scenario. This, however, can result in large capital costs, which turn out inefficient if the worst-case scenario does not evolve. Because the national replacement programme requires a large investment, doing only efficient investments can make a significant difference in life cycle costs. One way of doing this is by adapting the structures in the future only if the changed boundary conditions impose other demands on the structure. The net present costs will then be lower, since investments are postponed to the future or even cancelled if a particular scenario does not evolve. To be able to adapt the structure later on, possible adaptations have to be considered during the design and construction of the new structure. This is the starting point in the approach of adaptive delta management, which proposes designing in an adaptive way to simplify the adaptations during the structure's lifetime. In the delta programme, the key issues of this approach are stated as below (Adaptief deltamanagement, n.d.):

- relating decisions to the challenges of flood safety and freshwater storage in the future;
- constructing flexible solutions;
- preparing for multiple strategies and switching between these if needed;
- combining investments in flood safety and freshwater storage with investments in the environment.

The perspective 'Adaptive Meuse' of the co-creation meetings proposes this approach for the replacement of the weirs in the River Meuse. This idea has only been elaborated very basically, which leads to the following objective of this study:

The objective of this study is to design an adaptive weir to replace a Dutch weir in the River Meuse by using the approach of adaptive delta management.

1.3 Design method

To achieve the objective, the Systems Engineering methodology is applied to end up with an adequate, structured analysis and design of the system. This methodology consists of an iterative process of a functional analysis, requirements analysis, design synthesis and design verification & validation (Department of Defense, 2001). The scale of analysis is downsized systemically during the design process to address the adaptivity on each scale. Moreover, by the overall process of downscaling, the functions, boundary conditions and requirements of the weir (sections) get clear from the entire water system. The three design levels are defined as below:

1. the <u>global design</u> level, which covers the section Monsin-Lith. It includes the entire Dutch dammed up section of the River Meuse and two weirs in Belgium, see Figure 1-1. The latter two are included, because they impose boundary conditions on the Dutch water management.
2. the <u>regional design</u> level, which is selected on basis of the proposed weir replacement strategies in the global design level. The regional design area includes the most adaptive weir section; in this section, most adaptation measures are feasible and useful to meet the changed requirements. The future uncertainty is specified in more detail in this design level.
3. the <u>local design</u> level, which addresses the design and feasibility of the adaptive weir itself. The results of the regional design level are important input; it defines the maximum desired adaptivity of the weir. A combination of weir adaptation measures and regional adaptation measures results in a total overview of the measures that have to be taken to meet the changed requirements.

The future uncertainty is taken into account by the four Dutch delta scenarios, according to the adaptive delta management approach. These four scenarios, shown in Figure 1-2, consist of combinations of two general (inter)national developments: the rate of climate change and socioeconomic developments. The scenarios focus on the developments until 2050, although further developments until the end of this century have been extrapolated. The plausible range of climate change and socioeconomic growth has been predicted by the Royal Netherlands Meteorological Institute (KNMI) and a combination of the Netherlands Bureau for Economic Policy Analysis (CPB) and the Netherlands Environmental Assessment Agency (PBL), respectively. According to its definition, the scenarios do not contain a specific probability. For more information on the delta scenarios is referred to Appendix A.

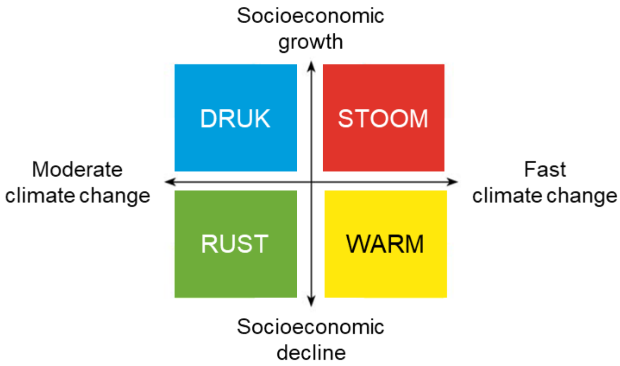

Figure 1-2: Schematic overview of the delta scenarios (Bruggeman, et al., 2016).

In a ‘normal’ design process, these scenarios are applied to generate designs which can cope with the developments in all scenarios, see Figure 1-3 on the left. This results in design alternatives which fulfil the requirements whatever scenario evolves. Only one scenario evolves, however, hence part of the investments turn out to be inefficient and unnecessary. In the adaptive delta management approach, the order is the other way around: design alternatives are generated and thereafter adaptations in each scenario are added, see Figure 1-3 on the right. This leads to flexible designs in which investments are only carried out to cope with the developments in that particular scenario.

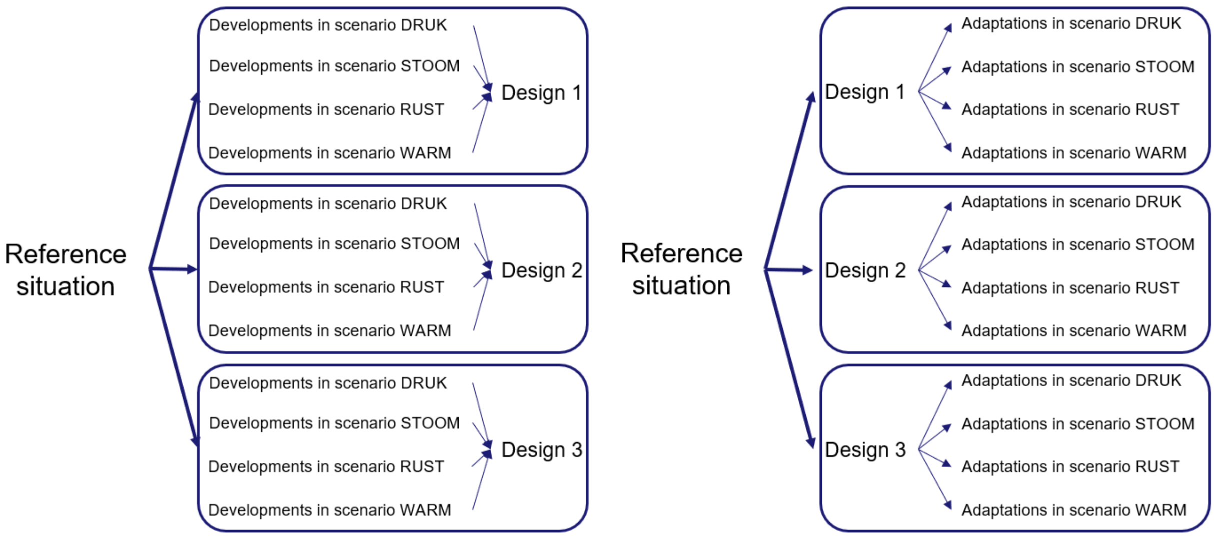

Figure 1-3: Generation of design alternatives in a ‘normal’ design process (left) and according to the approach of adaptive delta management (right).

1.4 Thesis outline

The outline of this thesis corresponds to the steps of the presented design method. First, Chapter 2 gives more context to the weirs in the River Meuse. This includes an analysis of the complete River Meuse and addresses the functioning and deficiencies of the current weirs in the project area. The information presented in this chapter provides the foundation of the waterway network and the role of the weirs in the waterway network.

Subsequently, in Chapter 3, 4 and 5 design alternatives are generated on, respectively, the global, regional and local scale. The outline of the beginning of these chapters is standardized: a description of the area is followed by a functional and requirements analysis. In the continuation of the chapters, the outline differs, as the objective of the chapters slightly diverges. In Chapter 3 weir replacement alternatives are proposed at each weir section to be able to address the adaptivity of the weir sections after evaluation. The most adaptive weir section is then selected as the regional design area. In Chapter 4, an adaptation scheme is set up for this area, which shows what measures are required to serve the purposes in each time period and each delta scenario. The measures consist of a combination of weir adaptation measures and regional adaptation measures. The feasibility of the weir adaptation measures is questionable, since the adaptive weir itself is only designed in Chapter 5. Keeping in mind the adaptation scheme, an adaptive weir is designed by verification on the requirements and evaluation on the criteria and its adaptivity. The chapter is concluded with the proposed design of the adaptive weir. The adaptivity of this weir design is used to end up with the final adaptation scheme, as part of the conclusions in Chapter 6. Recommendation for further research are mentioned in this chapter as well. Additional analyses are found in the appendices of this report.

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2 Framework of River Meuse's weirs

This chapter gives a more thorough introduction to the system of the River Meuse in Section 2.1 and 2.2, which addresses the hydrology and the development of the waterway network, respectively. Section 2.3 examines the global design area, focussing on the general operation of weirs and the weir structures themselves. Section 2.4 concludes this chapter concentrating on weir replacement.

2.1 The hydrology of the River Meuse

The River Meuse is the second largest river in the Netherlands after the River Rhine. The river springs in Northern France at the Plateau of Langres after which it flows through Belgium and the Netherlands to the North Sea, see Figure 2-1. The catchment area of the River Meuse does not include any high-elevated areas, glaciers are not present. Hence, the discharge of the River Meuse is solely dependent on the precipitation in the catchment area. The precipitation is drained via eight main tributaries, named in Figure 2-1, to the River Meuse. Appendix B.1 describes their characteristics.

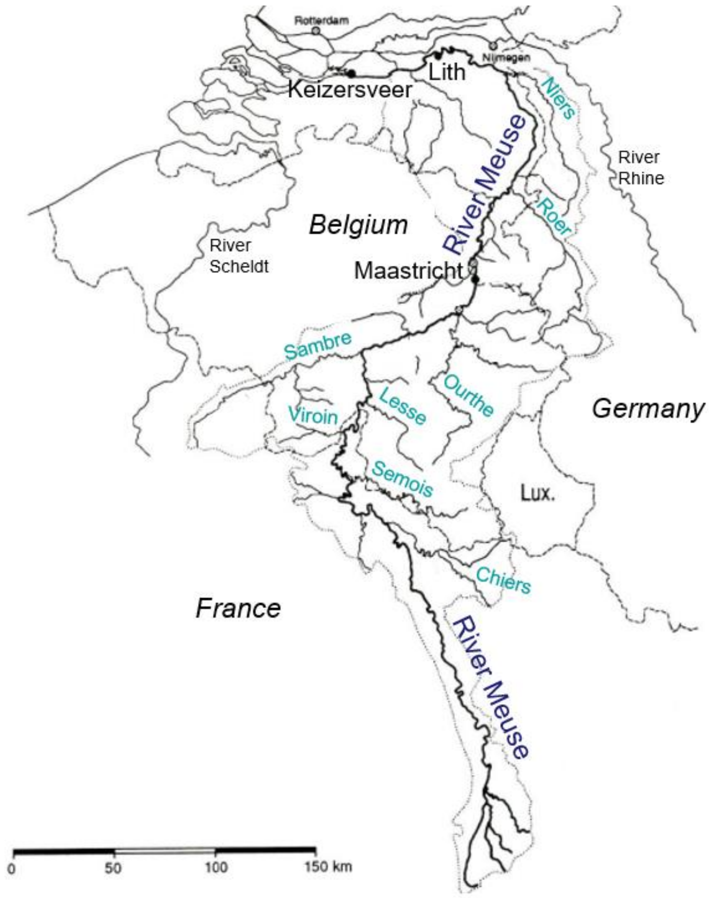

Figure 2-1: Overview of the catchment area and tributaries (in turquoise) of the River Meuse (Rijkswaterstaat, 1992).

The River Meuse is a calm flowing river just after its source unto the confluence with the Chiers. In Belgium, where the river flows through a hilly area, the Ardennes, the nature of the river changes. Figure 2-2 shows that many tributaries spring in this area of impermeable soils and steep slopes. These tributaries drain their water very fast to the River Meuse. Moreover, the yearly amount of rainfall in the Ardennes is larger than in other parts of the entire catchment area. Together, this causes the tributaries in the Ardennes to be a dominant factor in the (variation of the) discharge of the Dutch River Meuse.

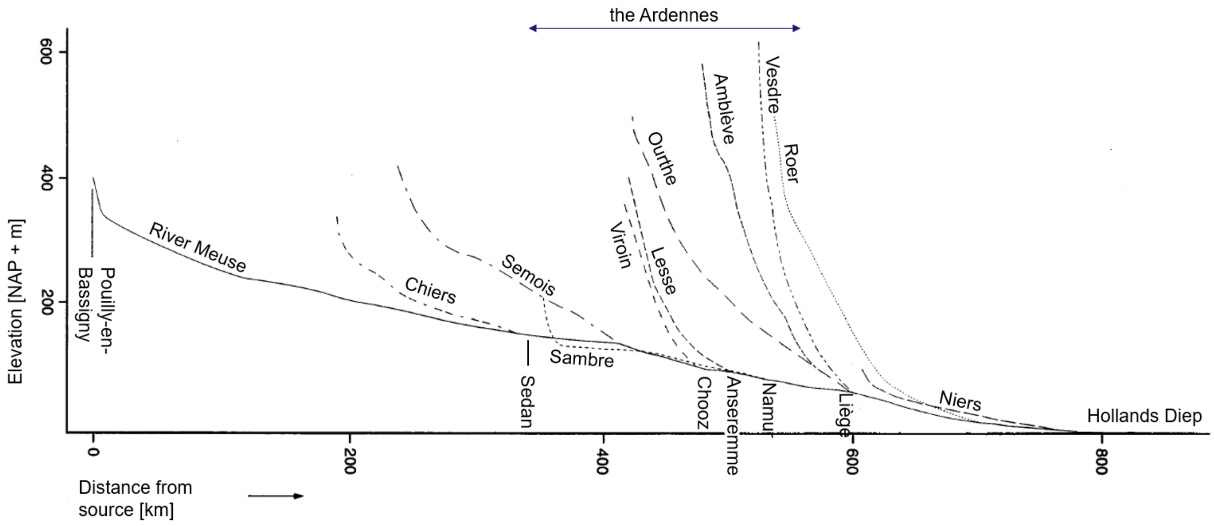

Figure 2-2: Gradient of the River Meuse and its tributaries (Rijkswaterstaat, 1994).

This influence is marked by the most upstream Dutch discharge measurements. Near Maastricht, the yearly average discharge is equal to 230 m^3/s, ranging from 132 m^3/s in summer and 320 m^3/s in winter (Van Schrojentstein Lantman, 2004). The discharge variation is large within and between years; the long-term minimum discharge is less than 30 m^3/s, the largest flood wave in 1926 had a maximum discharge of 3,000 m^3/s (Rijkswaterstaat, 1994). The propagation speed of the flood waves is very large as well; they travel from France to the Netherlands within a day, water draining from the Ardennes reaches the Netherlands even faster. More on yearly discharge variations and (the propagation of) flood waves can be found in Appendix B.2.

In a natural flowing river, discharge variation directly results in water level variation. High water levels cause floods; low water levels limit the freshwater supply to users and limit the water depth of the river and with that the navigation on the river. To mitigate floods, spillways have been constructed to discharge excess water and dikes to protect low-lying areas. In the last decade the programme 'Room for the rivers' has been added to even diminish the flood risk further. These measures together have led to a national system of flood protections in the Netherlands.

2.2 The development of the waterway network

However, the measures discussed above do not mitigate the limitations in periods of small discharge. To enable navigation in these periods, two measures are available in general: digging canals and damming the river by weirs. Already in the 19th century, one century after the start of navigation on small scale, the first canals have been dug, especially in Flanders and the Netherlands, because transport on water became increasingly important here. The resulting waterway network is shown in Figure 2-3; all canals that are connected to the River Meuse are named, the River Meuse itself is shaded blue. The gradient of canals is negligible; the height difference between origin and destination is overcome stepwise by locks instead of by the natural gradient of the river.

To enable navigation on the River Meuse itself, damming the river was required. During dry periods, the water level of a free flowing River Meuse would be that low that vessels could not navigate on the river. Weirs have been applied to store fresh water and create sufficient water depth for navigation during these periods. As in canals, vessels use locks; this time to overcome the head over the weirs. The right side of Figure 2-3 shows the locks and weirs in or adjacent to the River Meuse.

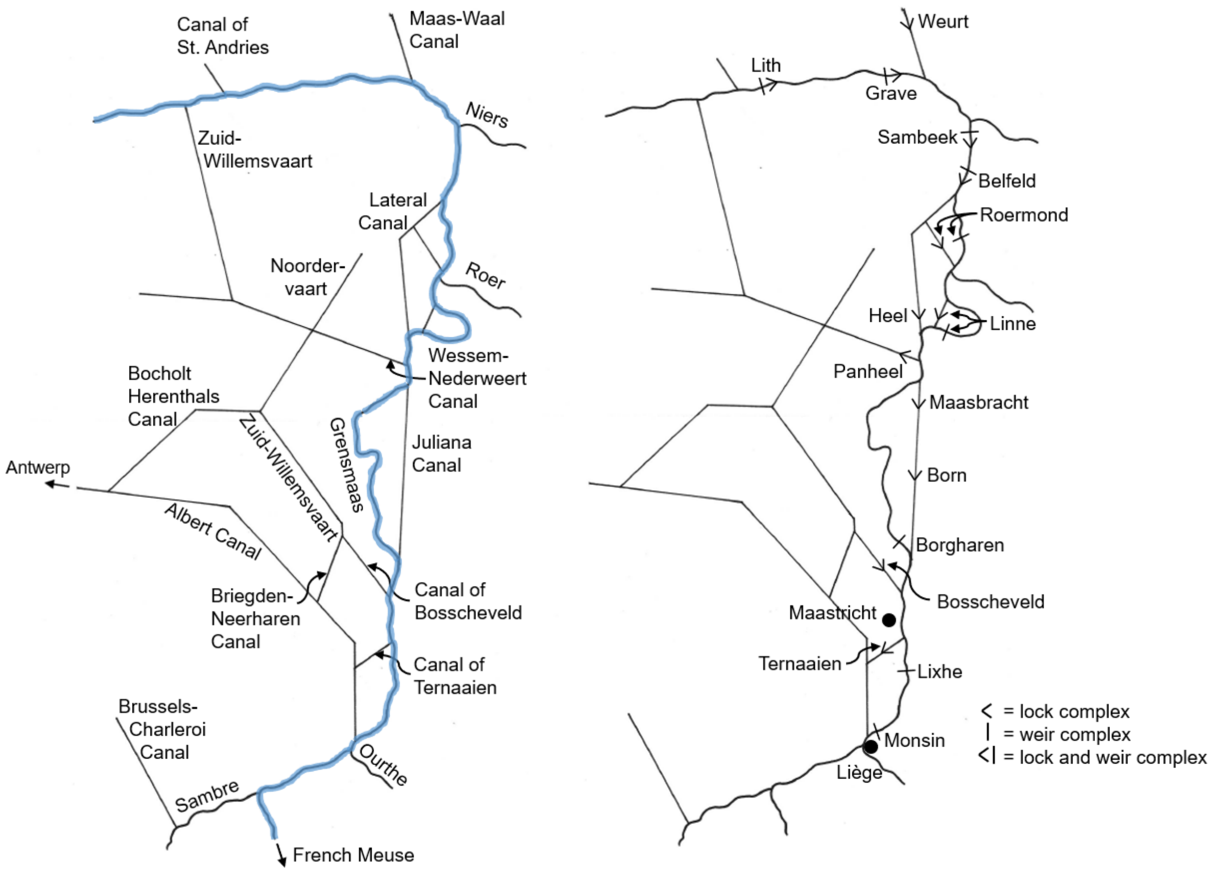

Figure 2-3: Waterway network connected to (left) and lock and weir complexes in or adjacent to (right) the River Meuse.

The waterway network of today, a combination of canals and a canalized River Meuse, is the product of the human interventions. A decisive factor of influence has been the competition between the ports of Rotterdam and Antwerp. For decades, the contradictory interests of Belgium and the Netherlands led to arguing about water distribution, proposing canalization plans and disapproving the measures executed by the other country. World War I worsened the relationship and the Dutch import of mine products stopped, whereupon the Netherlands started to mine its own coal products near Maastricht. An inland transport network for the mine products was provided in 1927 after canalization of the River Meuse on Dutch territory by construction of weirs Linne, Roermond, Belfeld, Sambeek and Grave and the completion of the Maas-Waal Canal.

Navigation on the Grensmaas (in English: Border Meuse), jointly owned by Belgium and the Netherlands, was still impossible by then, since no agreement had been reached on its canalization. In the end, both countries choose their own path: the Dutch constructed the Juliana Canal in 1935, including inland ports, to improve domestic transport of coal, the Belgians, on their turn, dug the Albert Canal to connect the industry of Liège with the port of Antwerp.

Floods in the same period induced further improvement of the River Meuse. This included bend cut-offs downstream of weir Grave, which led to smaller water depths in summer and the need for weir Lith. In 1972, the Lateral Canal was finished, the last major intervention in the system of the River Meuse. Appendix B.3 describes the historical development of the waterway network in more detail.

2.3 Functioning of the current weirs

Presently, nine weirs help in the water management in the global design area, whereof seven are located in the Netherlands. In this section, the water level control is addressed, after which the controlling components in this system, the weirs themselves, are examined.

2.3.1 Water level control

The control of water level is achieved by operation of the weir gates. It is, however, important to note that there are two river modes distinguished:

- a free flowing river during which the weirs are open;
- a dammed river during which the weirs are operational.

In a free flowing river, the water depth is relatively large. The weir gates are fully opened and the weir does not affect the water level. The bed friction and the gravitational force component in streamwise direction are in equilibrium. The corresponding water depth, commonly named the equilibrium water depth, is sufficient for navigation as long as the discharge is larger than a threshold. If not, weirs have to dam up the water level. The threshold value is dependent on the characteristics of the river section, such as the Chézy value, the river's width and gradient and on the draught of the governing vessel. Due to the large gradient, a free flowing river only occurs five days per year on average in the River Meuse.

The rest of the year, the water level is controlled by operation of the weirs by a negative feedback control system, as shown in Figure 2-4. The disturbance (a change in river discharge) enters the system (of the River Meuse) and causes a change in the controlled variable (the water level elevation). This result in a deviation between the measurement of the controlled variable and the set point, which is defined as the target value of the controlled variable. By operation of the controller (the weir) it is aimed to achieve a steady state situation, in which the measurement and set point are equal.

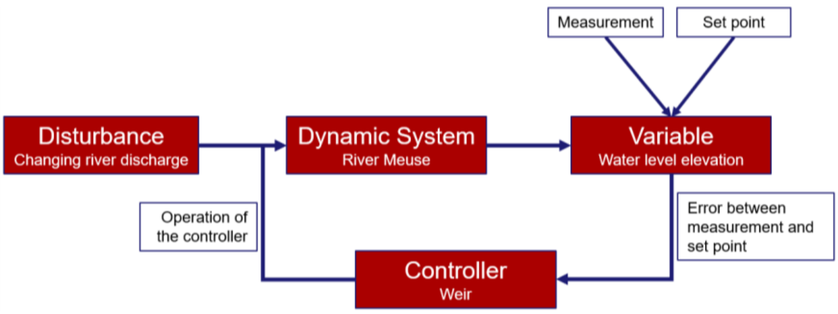

Figure 2-4: Control system of the weirs in the River Meuse.

The set point of each weir section is the main input of the control system in the River Meuse. Besides, the set point itself can be changed by modifying the maximum weir height, the location of the set point can be shifted throughout the weir section. Here, two locations are highlighted to clarify the differences. The set point is currently located just upstream of the weir itself, as shown in the left graph of Figure 2-5. In the right graph of Figure 2-5, the set point is located at the most upstream navigable location in the weir section (Bezuyen, Molenaar, & van der Toorn, Structures in hydraulic engineering 2: Weirs, 2010). As the latter location is educated at university, this is called the theoretical location of the set point. The two mentioned graphs show the water levels for various discharges in the weir sections of Belfeld and Roermond. The weirs are, respectively, located at km 0 and km 17; the upstream parts of the weir sections are not navigable, since vessels use parallel canals and locks at these parts. The resulting backwater curves has been obtained with the hydraulic model described in Appendix C.1; the model calculates the water levels in the River Meuse numerically for a steady state situation.

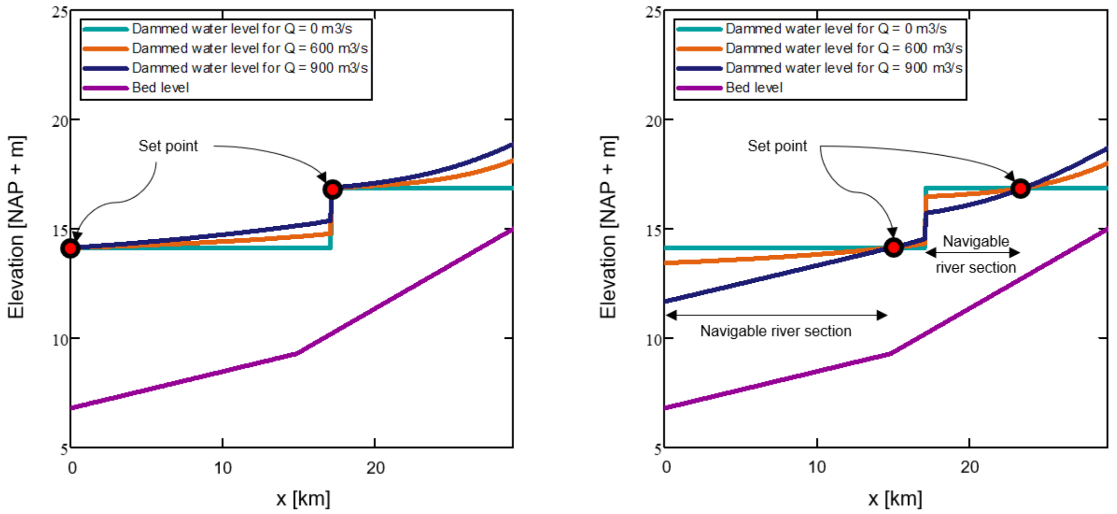

Figure 2-5: Dammed water levels for various discharges with the current location (left) and theoretical location (right) of the set point.

As defined, the water levels at the set points do not change for various discharges. During zero discharge, the water level in the entire weir section is equal to the set point of that weir section. Upstream of the set point, the water level increases if the discharge increases; downstream of the set point, the water level decreases if the discharge increases. The water depth remains, however, sufficiently large for navigation throughout the entire navigable section.

The difference between the current and theoretical location of the set point is clearly visible in Figure 2-6. In both graphs, the water level just downstream and just upstream of weir Roermond are plotted for discharges from 0 m³/s to 2,000 m³/s.

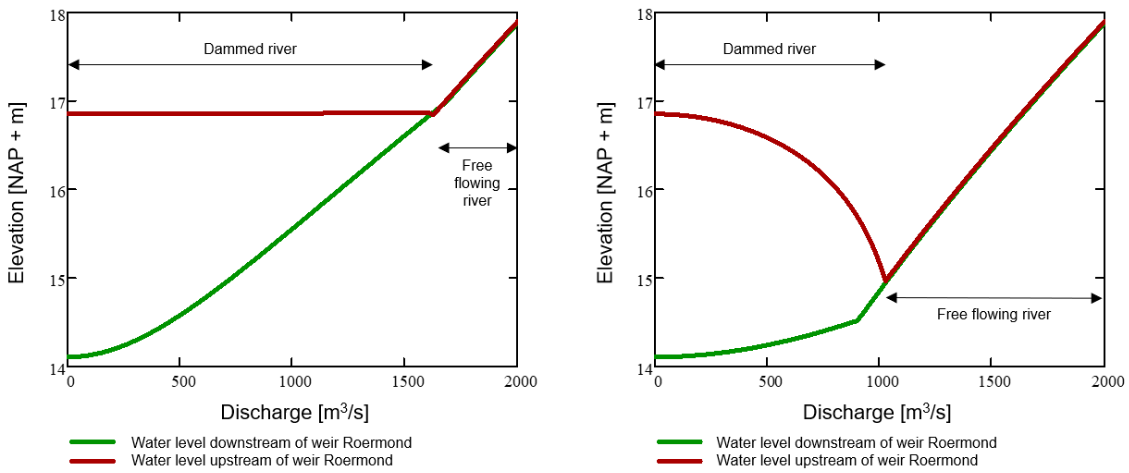

Figure 2-6: Water levels at weir Roermond with the current location (left) and theoretical location (right) of the set point.

The differences are listed below:

- current location of the set point;
  - The water level just upstream of weir Roermond does not change in the dammed river mode, since the set point of weir Roermond is located here.
  - The water level just downstream of weir Roermond increases gradually in the dammed river mode, since the set point of weir Belfeld is located more downstream.
  - The threshold discharge of weir Roermond is approximately 1,600 m³/s. The water level downstream has then risen to the set point of weir Roermond.

- theoretical location of the set point.
    - The water level just upstream of weir Roermond decreases gradually in the dammed river mode, since the set point of weir Roermond is located more upstream.
    - The water level just downstream of weir Roermond increases only a little in the dammed river mode, since the set point of weir Belfeld is located just downstream.
    - The threshold discharge for weir Belfeld is approximately 900 m^3/s, for weir Roermond approximately 1,050 m^3/s. The difference is caused by the difference in slope.

A longitudinal overview of the weir sections in the River Meuse is mostly shown in the zero-discharge situation. Thus, the indicated horizontal water levels in Figure 2-7 are equal to the set points of the corresponding weirs. The location of the seven Dutch weirs is indicated by the Maaskilometre, which is zero at the location where the River Meuse enters the Netherlands and increases in streamwise direction.

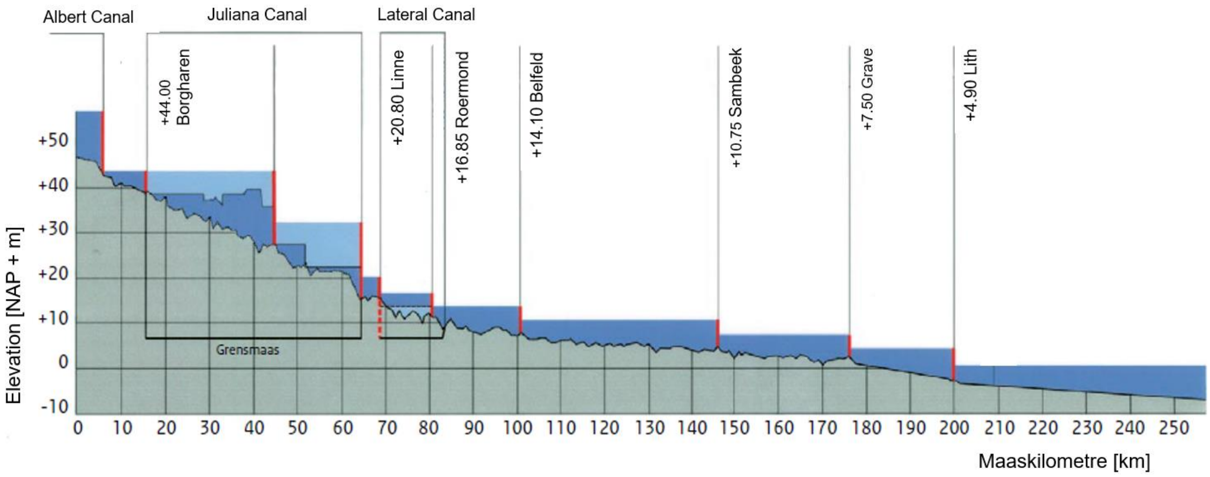

Figure 2-7: Set points and location of weirs in the River Meuse (Ministerie van Infrastructuur en Milieu, Ministerie van Economische Zaken, Landbouw en Innovatie, 2012).

2.3.2 Operation of the weirs in the River Meuse

Many types of weirs have been constructed over the world to obtain the desired dammed water level in rivers. Because of the simultaneous construction of the weirs in the River Meuse, the weir structures are very similar. Weirs Borgharen and Lith are equipped with wheel-gates which are lifted if the discharge exceeds the threshold. More accurate water level control is achieved by small flaps on top of the gates. The weir of Grave is combined with a traffic bridge; the weir elements are rotated onto the bridge deck in case of a flood wave. The rest of the Dutch weirs (Linne, Roermond, Belfeld and Sambeek) all consist of two parts by which it deals with the large discharge variability of the River Meuse; a Stoney part and a Poirée part, which can be seen in Figure 2-8 and Figure 2-9.

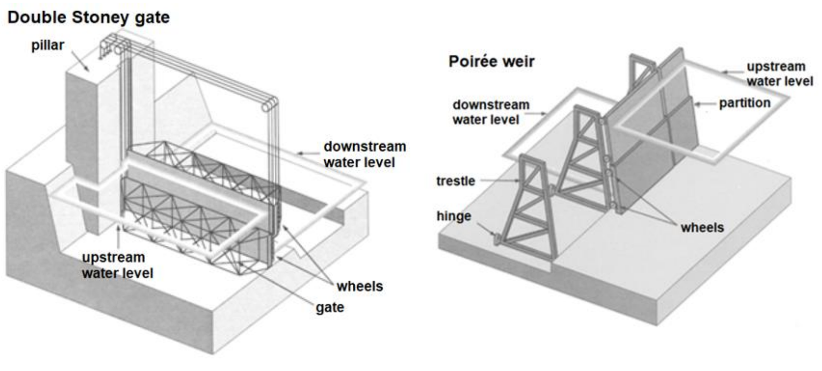

Figure 2-8: Structure of the Stoney weirs (left) and a Poirée weirs (right) applied in the River Meuse (Schot, Lintsen, Rip, & De la Bruhèze, 1998).

Figure 2-9: Indication of the Stoney and Poirée part of weir Belfeld.

The Stoney weir contains double gates, one after another, which close off the opening between concrete pillars. The Stoney parts, applied for fine regulation of the water levels, of the weirs in the River Meuse comprise two or three openings. The fast and mechanical operation of the gates is used to keep the overflow height over the Poirée weir constant for various discharges. Hence, the set point is currently located just upstream of the weir.

For water level control in a larger discharge range, the Poirée weir is required. Erecting and placing of partitions takes more time than operation of the Stoney weir and is only adequate for rough regulation. All partitions of the Poirée weir can be pulled out and stowed at the river bank within a few hours. Then, the trestles are laid down on the sill and a free flowing river is created (Schot, Lintsen, Rip, & De la Bruhèze, 1998). Vessels cannot use the locks in this situation, because the water levels rise above the top of the lock walls and large flow velocities make vessel manoeuvring impossible. Therefore, as shown in Figure 2-10, vessels navigate over the foundation of the Poirée weir. In this way, navigation is still possible during a flood wave, even without the delay affiliated with the lockage process. A more detailed description of all weirs within the project area is added as Appendix C.3.

Figure 2-10: Photographs of weir Belfeld in a dammed river mode (left) and a free flowing river mode (right).

2.4 Need for replacement of the current weirs

The water level control system still functions by operation of the current weirs. Though, there are multiple reasons to replace the weirs completely. And also in neighbouring countries, weirs approach the end of their lifetime and renovation activities have been executed.

2.4.1 Deficiencies of the present Dutch weirs

Within the national programme 'Risico Inventarisatie Natte Kunstwerken (RINK)' (in English: Risk Assessment of Wet Infrastructure) each weir structure has been inspected. This quantitative assessment has been used in the 'Vervangingsopgave Natte Kunstwerken (VONK)' (in English: Replacement Task of Wet

Infrastructure) to determine the end of technical and functional lifetime of all structures. The outcome is a time window of 2025-2040, in which it is very likely that the Dutch weirs in the River Meuse reach the end of their lifetime (Iv-Infra b.v., 2014). Figure 2-11 shows the hydraulic structures in the Dutch dammed section of the River Meuse which have to be replaced in the upcoming decades. The end of lifetime, the deficiencies and risks are mentioned for each weir.

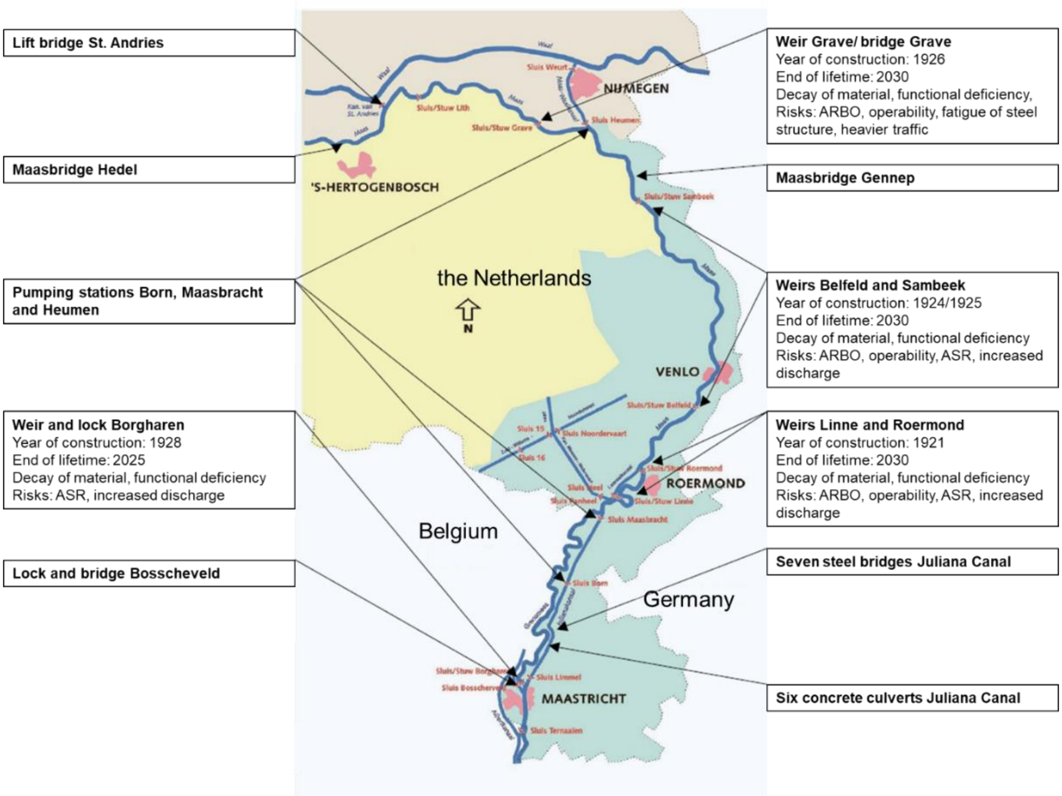

Figure 2-11: Overview of the structures in need of replacement in the Dutch dammed section of the River Meuse (Ministerie van Infrastructuur en Milieu, Ministerie van Economische Zaken, Landbouw en Innovatie, 2012).

The inspections in 2009 showed that many weirs are at risk of alkali-silica reactions, denoted as ASR in Figure 2-11, going on in the concrete. These reactions form an expansive gel inside the structure, which pushes the concrete apart. However, more recent inspections of the weirs in the River Meuse, as part of the RINK-programme, have not confirmed alkali-silica reactions. Hence, the presence and degree of alkali-silica reactions is unclear. Additional inspections should provide clarity, after which the end of technical lifetime can be estimated more exactly (Iv-Infra b.v., 2014).

Besides the alkali-silica reactions, the labour conditions during erecting and lowering of the Poirée weirs of Linne, Roermond, Belfeld and Sambeek are not sufficiently safe according to ARBO-legislation. A crane moves over a rail on top of the Poirée weir and stows the partitions one-by-one and row-by-row at the river bank (Verduijn, 2014). The workmen assist the crane without any attachment; falling into the fast flowing river would lead to a life threatening situation (Iv-Infra b.v., 2014). On top of that, the functionality of the Poirée weir is deficient, as the desired accuracy of water level control is not achieved by adding and removing partitions (Antea Group, 2014).

2.4.2 Replacement of weirs

Since the state of the Stoney weir is unknown regarding the degradation of the concrete and the operation of the Poirée weirs is outdated, renovation and life-extending measures are doubtful strategies. These can keep the weirs operational until 2030, for the period thereafter even a large-scale renovation is not considered to be sufficient (Antea Group, 2014). This conclusion has also been drawn in the French part of the River Meuse. The French weirs are even older than the Dutch ones. A complete replacement of these weirs is currently going on, incorporating more modern technology to improve the functionality of the weir (Chapital, 2015). The implementation of modern technology is a recurring part in weir replacement tasks in neighbouring countries anyway, see Appendix D. The proposed renovation and replacement activities mainly focus on the structures themselves; only in Belgium, the waterway network of canals is significantly modified as a whole. Though in that project, the replacement of hydraulic structures deals particularly with lock replacement.

The replacement projects mentioned in Appendix D range from construction of a complete new weir to replacement of only weir gates or addition of a fish trap and a hydropower station. This wide range is caused by the different replacement periods of the weir components. In general, moveable components and/or components in an innovative sector have to be replaced first. In accordance, Table 2-1 shows the typical replacement periods of weir components.

Table 2-1: Typical replacement periods for several components of a hydraulic structure (Voortman & Veendorp, 2011).

Type of component	*Typical replacement period*
Foundation	100 to 200 years
Substructure	100 to 200 years
Gates and mechanical components	10 to 50 years
Electrical components	20 to 30 years
Electronic components	10 to 20 years
Software	5 to 10 years

The examination of the reference projects aligns with this table: the weirs constructed in the 19th century are completely replaced by a new weir, at more recently constructed weirs only the gates and the associated components to enable weir operation are replaced. The gates of the Nußdorf weir in Austria have been replaced even twice, whilst the foundation is still the original one.

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3 Global design: section Monsin-Lith

This chapter presents the global design of the dammed River Meuse from weir Monsin to weir Lith. The chapter starts in Section 3.1 with an area analysis, after which functions are allocated to the weir sections in Section 3.2. Section 3.3 introduces the global requirements corresponding to these functions. For each weir (section), multiple modifications are proposed in Section 3.4. Each weir modification is verified and evaluated in Section 3.5 to the current requirements. The weir section with most feasible modifications possesses the largest adaptivity and is selected in Section 3.6 as case study area for the regional design, which is subject of Chapter 4.

3.1 Area analysis

The nature of the River Meuse and its environment change over the course of the river. In this section, the Dutch river part is divided into six sections. These sections can be seen in Figure 3-1 and are addressed below in streamwise direction.

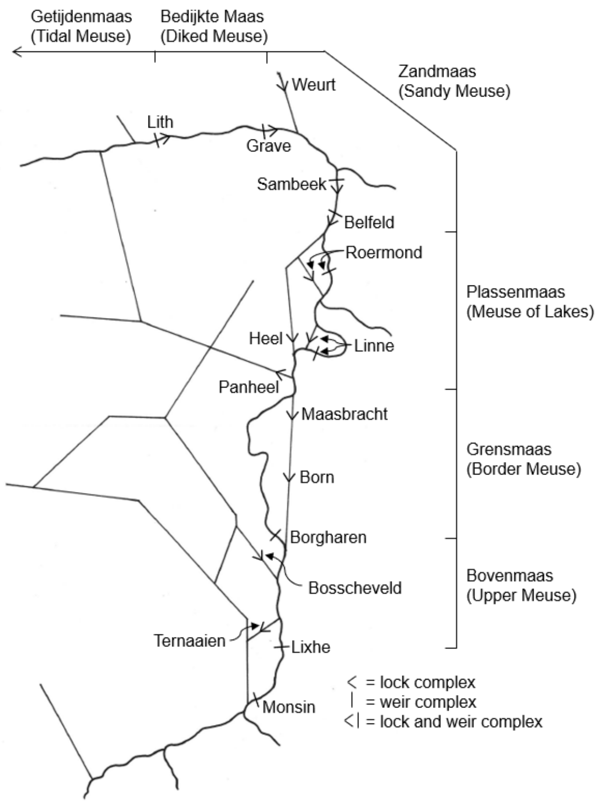

Figure 3-1: The sections of the Dutch River Meuse.

Bovenmaas

The Bovenmaas (in English: Upper Meuse) is the Dutch most upstream section of the River Meuse unto weir Borgharen. At several locations gravel has been extracted in the past, creating lakes, now used for recreational activities (Kater, Makaske, & Maas, 2012). The inflowing upstream discharge is irregular due to the hydropower station next to weir Lixhe. It consists of three turbines with each a design discharge of 85 m^3/s, resulting in equally sized stepwise variation of the outflow.

Grensmaas

The Grensmaas (in English: Border Meuse) is the meandering gravel river section from weir Borgharen to roughly Maasbracht. Human interventions, among which gravel extraction, fixed the gravel riverbed of the main channel. Flood waves are discharged via this main channel, on the contrary, in summer the water depth is very limited. Therefore, vessels pass this section via the parallel Juliana Canal. Currently, measures are taken to improve both the ecological value and flood safety of this section (Smart Rivers, 2019).

Plassenmaas

The Plassenmaas (in English: Meuse of Lakes) is located north of Maasbracht. A local geological fault near Roermond created a wide low-lying area, now indicated as the valley of the River Meuse (Kater, Makaske, & Maas, 2012). For many centuries, gravel was deposited by the river in this subsided area; in the previous century much gravel has been extracted. Remnants of these extractions are the unique characteristic lakes, called the Maasplassen (in English: Meuse Lakes) (Smart Rivers, 2019).

Zandmaas

North of the Plassenmaas, unto weir Grave, the river is called the Zandmaas (in English: Sandy Meuse), named after the sandy subsoil. The area distinguishes itself by the terraces formed by geological uplift. The River Meuse has incised into these terraces and does not show any large bends. Sideways of the river, shallow seepage channels, fed by groundwater flow, are found (Smart Rivers, 2019).

Bedijkte Maas

The most downstream dammed section is called the Bedijkte Maas (in English: Diked Meuse). As is in the name, the River Meuse is bordered by flood plains and dikes. The normalisation of this section in the 20s of the previous century can be seen by the abandoned oxbow lakes. The backwater curve of weir Lith did increase the groundwater table in the area substantially (Smart Rivers, 2019).

Getijdenmaas

Downstream of weir Lith the tide influences the water level, which is why this section is called Getijdenmaas (in English: Tidal Meuse). The construction of The Haringvliet sluices reduced the tidal range considerably to a maximum of 0.30 m (Smart Rivers, 2019).

3.2 Functional analysis

First in this section, three main functions of the River Meuse's system are introduced and elaborated. Thereafter, these functions, supplemented by other ones, are allocated to the weir sections.

3.2.1 Discharge of water and sediment

The vast majority of water and sediment is discharged by the River Meuse itself. The gradient of the river is determinative from this viewpoint; the larger the gradient, the faster the discharge of water and the larger the sediment particles that are transported. The negligible gradient of the connected canals leads to their negligible contribution to the discharge capacity of the global waterway network. On top of that, the nature of the river is more dynamic by the transport and deposition of sediment. Figure 3-2 shows that the natural river gradient in the upstream subsections is relatively large; apparently from Section 3.1 it is sufficiently large to transport sand, since mainly gravel is deposited in these subsections. From the Plassenmaas, the river gradient decreases and mainly sand has been deposited, after which the Zandmaas is even named. More downstream in weir sections Grave and Lith, the river gradient increases a little, because numerous bend cut-offs have been executed to improve the discharge of flood waves in this area. Construction of the weirs reduced flow velocities and sediment transport greatly in the vast majority of the year. From morphological point of view, the free flowing river mode is of much more interest (Sieben, 2008).

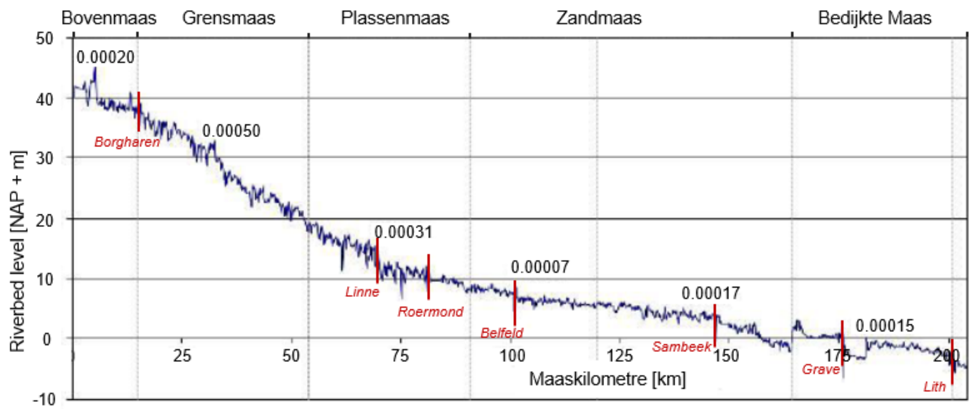

Figure 3-2: Gradient of the Dutch River Meuse (Kater, Makaske, & Maas, 2012).

3.2.2 Navigation

Navigation on the River Meuse has been the main reason to construct the weirs in the River Meuse. The River Meuse is nowadays part of a European navigation network due to its reliable water depth in dry periods. Vessels in Europe are classified by their dimensions and differentiated into motor vessels, barges and convoys. On top of that, Rijkswaterstaat introduced subclasses to the international classification. Appendix E.1 presents the total classification system of vessels ranging from CEMT Class I to Class VII.

The classification of the navigation network is coupled to the vessel's classification. The class of a waterway is equal to the maximum allowable vessel's class on that waterway. Figure 3-3 shows on the left the classification of the River Meuse and the linked waterway network and on the right the intensity of each waterway (Rijkswaterstaat, 2009). A couple of notes on the realization of Figure 3-3 have been listed in Appendix E.1.

The main navigation route from the Belgian industries and waterways to the Port of Rotterdam and German industry along the River Rhine is called the Maasroute. This intensively used route consists of the River Meuse, the Juliana Canal, the Lateral Canal and the Maas-Waal Canal, which are all classified as CEMT Class Va. Although, a couple of size restrictions do hold: the draught of vessels is restricted to 3.0 m and the maximum allowable vessel's length and beam varies per section as shown in Table 3-1.

Table 3-1: The maximum allowable vessel's length and beam on the Class Va waterways of the Maasroute.

Upstream boundary of section	*Downstream boundary of section*	*Maximum allowable vessel's length [m]*	*Maximum allowable vessel's beam [m]*
Lock of Ternaaien	Start of Juliana Canal	137.5	14.0
Start of Juliana Canal	Port of Stein	110.0	12.0
Port of Stein	Lock of Born	137.5	14.0
Lock of Born	Start of Maas-Waal Canal	137.5	15.5

The narrow profile of the Juliana Canal creates the most stringent bottleneck on the Maasroute. The sharp Bend of Elsloo, just south of Stein, limits the maximum allowable vessel's length to 110.0 m on the southern canal section. Currently, the canal is upgraded with wider sections where vessels can pass each other. Widening of the Bend of Elsloo to accommodate Class Vb vessels is just feasible (De Vries & van de Wiel, 2014).

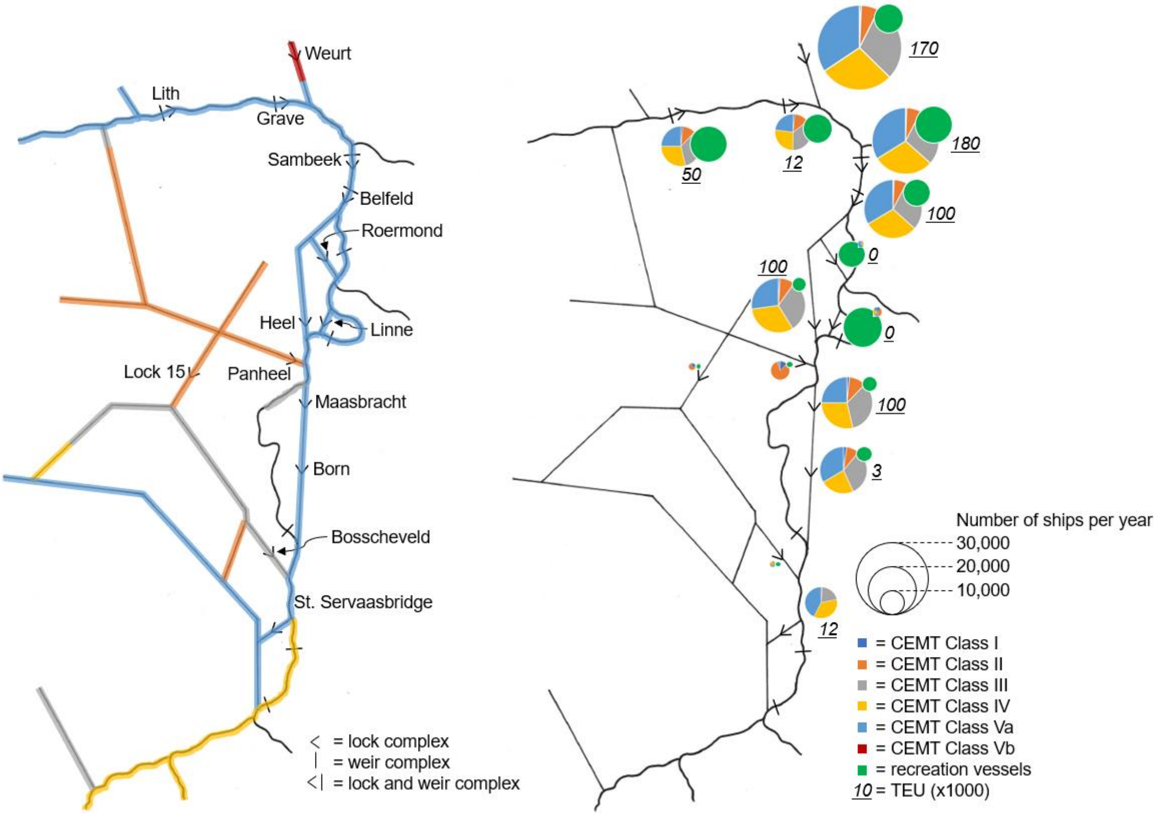

Figure 3-3: Classification (left) and intensity (right) of the waterways in the global design area.

The other parts of the Maasroute are upgraded by Rijkswaterstaat from a Class Va to a Class Vb waterway as well. This requires multiple modifications, stretched out over the entire Maasroute. The activities include deepening the navigation channel, widening river bends and enlarging locks (Rijkswaterstaat, n.d.). The upgrade is finished before the weirs have to be replaced.

3.2.3 Freshwater supply to adjacent areas

Despite the construction of the weirs, periods of low discharge still put pressure on the waterway network. The limited supply of fresh water has to be distributed over multiple interests, while the freshwater demand may even increase. In the Netherlands, a sequence has been set for water distribution, starting with the interest with the highest priority for receiving water (Kenniscentrum InfoMil, n.d.):

1. stability of flood defences and irreversible damage including settlements and ecological damage;
2. user functions like drinking water production and generation of energy;
3. small-scaled, high-valued usage like capital intensive agriculture and process water;
4. remaining interests like navigation, other agriculture, industry, recreation and fishery.

This domestic sequence, however, does not hold for the Belgian weir sections in the global design area. To mitigate the consequences of limited freshwater supply in Belgium and the Netherlands, both countries have signed a bilateral agreement. Flanders receives fresh water via the Albert Canal, diverting from the Meuse River at Monsin, and via the inlet structure at Bosscheveld near Maastricht. The starting point of the agreement is an equal freshwater distribution for Dutch and Flemish use. The minimum discharge of the Grensmaas of 10 m^3/s, however, is prioritized, because of ecological concerns. Also, the discharge variations in the Grensmaas have to be limited. The priority of the Grensmaas is infeasible and cancelled as the discharge of the River Meuse falls below 30 m^3/s. The exact regulations of the agreement are included in Appendix G.

Lockage and seepage through weirs even diminishes the freshwater availability in the upstream area, as water thereby flows to the downstream weir section. Part of this discharge is needed from the viewpoint of water quality, but the remainder is a loss of fresh water. In both countries, measures have been taken to reduce this loss in canal and weir sections. In Flanders, pumping stations have been constructed next to multiple lock complexes. Though, this is deficient for providing sufficient water depth for navigation on the Albert Canal. As an additional measure, currently more fresh water is diverted to Flanders than stated in the agreement; Flanders compensates the Netherlands by contributing to the additional pump costs made at for example lock Maasbracht (Vansina, et al., 2017). The daily average discharge of the locks of Maasbracht is 16 m^3/s, a significant amount with respect to the long-term minimum discharge of the River Meuse, see Section 2.1. The pumping station pumps back a maximum of 12 m^3/s to the Juliana Canal upstream (Hensen, 2005). Besides pumps, at lock Panheel, water is stored in reservoirs to use it in the next lock cycle. Via this lock and the Wessem-Nederweert Canal fresh water is supplied to the Province of Noord-Brabant (Rijkswaterstaat, 2015). Additionally, the number of lock cycles is limited to reduce water loss at locks; a time window is set or lockage is only permitted when the lock chamber is completely filled.

3.2.4 Function allocation

Figure 3-4 shows the River Meuse from weir Monsin to weir Lith schematically, including the Juliana Canal and the Lateral Canal. The internal and external boundaries are formed by weirs, locks, bifurcations and confluences; the complete list of these boundaries is found in Appendix F.

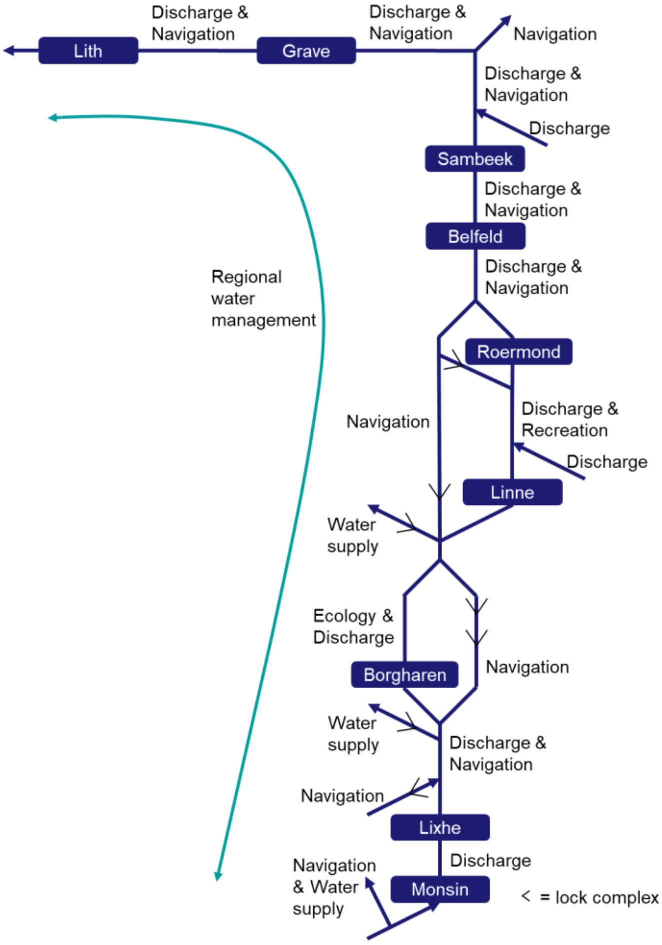

Figure 3-4: Schematisation of the global design area and the function of each section.

The schematisation results in a waterway network of parallel and serial components. The main functions, discussed in the previous paragraphs, have been complemented by the other functions and subsequently allocated to the components of the waterway network. Summation of the functions leads to the functions of the overall water system:

- managing the regional water management;
- discharging water and sediment;
- enabling commercial navigation;
- distributing fresh water;
- maintaining ecology;
- providing recreation.

The regional water management has not been allocated to specific components, since the waterway network as a whole contributes to this. In the last century, the land use is based on the current groundwater table, which is indirectly maintained by the backwater curves. In addition, it is worth noting that the Juliana Canal and Lateral Canal have taken over the navigation function from the parallel River Meuse's sections. The absence of commercial navigation in these two river sections, the Grensmaas and Plassenmaas, has led to the establishment of the high-valued ecosystem and recreational activities, respectively.

The weir functions have been derived from the functions of the overall system. One important difference is made, however: the discharge of water and sediment is not a function of a weir, as a weir should only not hamper this function. Table 3-2 shows the functions of the weirs, which are determinative on the global design level. The importance of regional water management and navigation stands out.

Table 3-2: Determinative functions of the weirs on the global design level.

Function	Mon-sin	Lixhe	Borg-haren	Linne	Roer-mond	Belfeld	Sam-beek	Grave	Lith
Regional water management	V	V	V	V	V	V	V	V	V
Navigation	V		V	V		V	V	V	V
Water distribution	V		V	V					
Ecosystem			V						
Electricity generation		V							
Recreation					V				

3.3 Requirements analysis

The requirements have been composed with reference to the functions described in the previous section of this chapter and Appendix G. It is assumed that the waterway network remains unmodified until the weir replacement project starts, except the CEMT Class upgrade of the Maasroute. Legislation and the bilateral agreement remain unchanged as well. This results in the following requirements to the global design area:

- Flooding of surrounding areas has to be prevented.
  - The water level in the zero-discharge situation has to be lower than the current embankments of the main channel and linked water bodies such as lakes.
  - The water levels in dammed mode should never exceed the crest of dikes and the ground level of higher-elevated areas bordering the river valley.
- Dehydration of areas has to be prevented.
  - Dammed water levels in a sandy area may not be lowered.
  - The water supply from the Meuse River to the Province of Noord-Brabant has to be at least equal to the current water supply.

- The waterway network has to facilitate reliable, fast and safe navigation.
    - The guaranteed water depth of the navigation route between Liège and the River Rhine has to be sufficient to facilitate a vessel with a draught of maximum 3.5 m.
    - The travel time of the navigation route between Liège and the River Rhine may not be extended by a detour.
- The water distribution over the Grensmaas, Flanders and the Netherlands has to comply with the bilateral agreement.
    - The discharge variation of the Grensmaas has to comply with the agreement to not affect the ecosystem.
    - The dammed water level in the Grensmaas may not differ from the current dammed water level.
- The fresh water available for the recreational, agricultural and industrial sector has to be at least equal to the current freshwater availability.
- The modification of the system has to be completed before 2030.
    - During implementation of the modifications, all other requirements have to be met.

3.4 Proposed weir replacement strategies

Potential modifications of the global waterway network have been developed for this study. The modifications focus on the replacement of the current weirs on global level. Three weir replacement strategies have been proposed:

1. removal of a weir and replacing the first downstream weir by a new, higher weir;
2. replacing a current weir by a new weir at a different location; either for several kilometres or to a preceding or subsequent section of Figure 3-4.
    a. downstream
    b. upstream
3. replacing a current weir at the same location by a new weir with a different height.
    a. lowering
    b. heightening

For each of the seven weirs in the Dutch River Meuse all alternatives have been investigated. The two weirs in Belgium are part of the global design area, but replacement of these weirs is a concern for the Belgian waterway manager. One-to-one replacement of these two weirs without a change of weir functions has been assumed.

3.5 Verification & evaluation of weir replacement strategies

Firstly, each of the proposed modifications is verified and secondly, if it does meet the requirements, evaluated qualitatively. The evaluation focusses mainly on commercial navigation and the future water distribution by application of the following four criteria:

- the travel time between Belgium and the River Rhine and between destinations within the global design area;
- the accessibility of destinations within the global design area;
- the possibility to store fresh water for prolonged periods of small discharge;
- the possibility to increase the water supply to adjacent areas.

Additional measures can be taken in the global design area if the proposed weir replacement strategy only just not meets the requirements. The costs of these additional measures are considered qualitatively as well. The extensiveness of the measures is restricted by the realization time and/or the associated costs. Additional measures to be taken along an entire weir section before 2030 are considered to be undesired and infeasible.

Table 3-3 shows the result of the verification and evaluation. An explanation of the verification and evaluation of each proposed modification is presented in Appendix H. The requirements that restrict the weir replacement strategies the most are:

- in the two most upstream weir sections, the compliance with the bilateral agreement and the facilitation of navigation on the Maasroute. Weir Borgharen is indispensable for regulation of the water level (variation) in the Grensmaas and the water depth in the Bovenmaas and the southern part of the Juliana Canal. Modification of weir Linne is infeasible, since it affects the dammed water level in the Grensmaas as well.
- the prevention of dehydration on the one hand and the prevention of permanent floods of embankments on the other hand. Replacement of a weir at an upstream location in a sandy area does lead to the dehydration over the shift of replacement; removal of a weir and facilitating navigation on the Maasroute by heightening the downstream weir leads to permanent floods of embankments, see Figure 3-5.

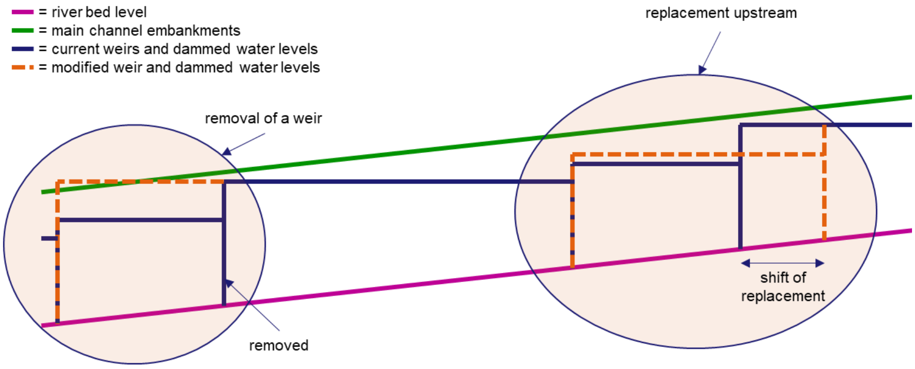

Figure 3-5: Limitations on the removal and upstream replacement of a weir.

- the navigation on the Maasroute. Replacement by a lower weir does not meet the related requirements without dredging the main channel in the entire weir section.

Table 3-3: Overview of verification & evaluation of proposed modifications. Modifications that meet the requirements are indicated with □; modifications that on top of that score positive on one of the criteria with ■.

Modification	Borgharen	Linne	Roermond	Belfeld	Sambeek	Grave	Lith
1. Removal			■				
2a. Replacement downstream		□	□	□	□	□	□
2b. Replacement upstream	□		■				
3a. Lowering			□				
3b. Heightening	□		■	■	■	■	■

After verification, it is clear that replacement by a new, higher weir or at a location downstream meets the requirements in most weir sections. Evaluation, however, shows that replacement of the weir at a location downstream is not beneficial; in most weir sections a new lock complex has to be constructed next to the new weir to facilitate navigation. This induces additional costs, though it does not contribute positively to one of the criteria. Replacement by a new, higher weir does; it contributes to the storage of fresh water.

The weir section Roermond forms an exception in many respects. Removal of weir Roermond or replacement by a new weir upstream are feasible modifications provided that navigation via lock Linne and the Maasplassen area is restricted to only recreational vessels, as shown in Figure 3-6. The required water depth for recreational vessels is relatively small, which enables a new higher weir at Belfeld to provide this water depth without causing floods of the main channel embankments. Commercial navigation is not hampered by the restriction, since the Lateral Canal can be used, as the vast majority already does nowadays, see Figure 3-3. The accessibility of the port of Roermond is increased in both proposed modifications, since navigation between the Maasroute and this port is accomplished without lockage. The latter is not achieved if weir Roermond is replaced by a new, higher weir at the same location, but this modification can play an important role in future freshwater storage. Reservoirs in Germany guarantee a minimum discharge of the Roer of 10 m^3/s, which can be stored in the large water surface area of the Maasplassen or can be pumped to weir section Linne and even to the Wessem-Nederweert Canal and the Province of Noord-Brabant.

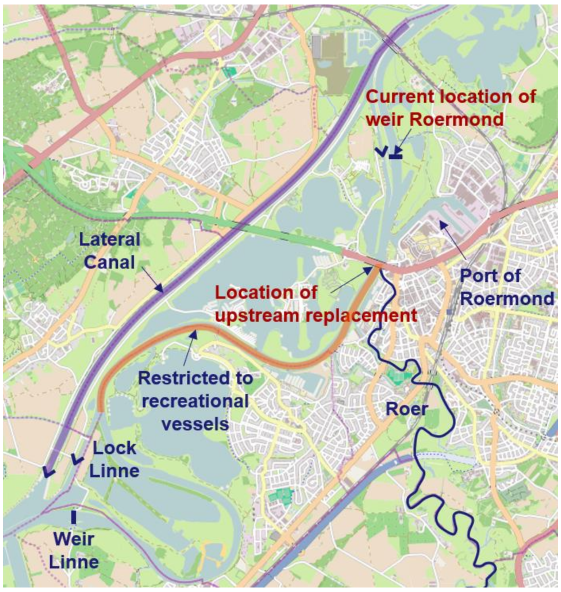

Figure 3-6: Possibly feasible modifications in the weir section Roermond.

3.6 Selection of regional design area

The analysis of the dammed River Meuse from weir Monsin to weir Lith made clear that possible modifications in the waterway network are limited. This is caused by current regulations and the current environment, which are partly based on former requirements and functions and/or aligned with the current dammed water levels. Since weir section Roermond is not part of the Maasroute anymore and thus commercial navigation in this weir section can be restricted to the port of Roermond exclusively, this forms an exception. Weir removal, weir replacement by a new weir at an upstream location and weir replacement by a higher weir at the same location are feasible modifications of weir (section) Roermond, whether or not in combination with modifications of weir (section) Belfeld. These feasible modifications indicate a large adaptivity of these weir sections, which can be possibly used in the future to adapt the weirs and the river area to new developments and water-related challenges. Concludingly, the weir sections of Roermond and Belfeld are selected as regional design area.

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(Tettero, 2015)
(Bruggeman, et al., 2016)

4 Regional design: section Linne-Belfeld

Based on the previous chapter, section Linne-Belfeld has been selected as regional design area. After an area analysis in Section 4.1, the functions, derived during the global analysis, are extended by functions on regional scale in Section 4.2. Thereafter, the requirements and the changes in boundary conditions and requirements are subject of Section 4.3. These are applied in Section 4.4 to generate regional design alternatives, consisting of a weir replacement strategy and additional measures in the regional design area. The verification and evaluation of the regional design alternatives in Section 4.5 is employed to define the maximum desired adaptivity of the weir and to set up an adaptation scheme, which shows the adaptation measures required to serve specific purposes. This all is summarized in Section 4.6.

4.1 Area analysis

The regional project area is confined by the weir and lock complex Belfeld in the north and by weir Linne and the locks of Heel and Linne in the south. Since the Maaskilometre shows a number of deficiencies in this section, a new coordinate system is introduced with kilometre 0 at weir Belfeld. The location of the most essential lakes, structures, such as weirs, locks, bridges and ports, and tributaries is shown in Figure 4-1. The exact location of all of them is found in Appendix I. In addition, Figure 4-2 shows a longitudinal cross-section of the waterway network. The waterway network within this area is split into three main branches:

- the Lateral Canal: the 8 kilometre long canal from lock Heel to Buggenum, part of the Maasroute.
- the Afgesneden Maas (in English: Cut-off Meuse): the meandering river part from weir Linne to Buggenum. Most of the Maasplassen are connected to the Afgesneden Maas. The Afgesneden Maas and the Maasplassen area can be roughly split into a northern and a southern part:
    - The northern part forms the centre of leisure near the city of Roermond. Smaller lakes are completely taken by marinas; the larger lakes are used by marinas and for water sport activities, boating, beach recreation and events. Commercial navigation makes use of this river part as well by navigating to the Prins Willem-Alexanderport.
    - In the southern part, high-valued ecosystems have developed. Navigation and recreation on water is prohibited in the Loop of Linne and the linked lakes. Flora and fauna developed due to seepage and the dynamic character of the water levels, which is directly linked to the current location of the set point of weir Roermond, see Figure 2-5.
- the Zandmaas: the river part north of the confluence at Buggenum. The Maasroute runs via the Zandmaas, yet it also contributes to recreation and ecology. Marinas are situated in small lakes along the river and biodiversity is large in former river bends, draining creeks and tributaries.

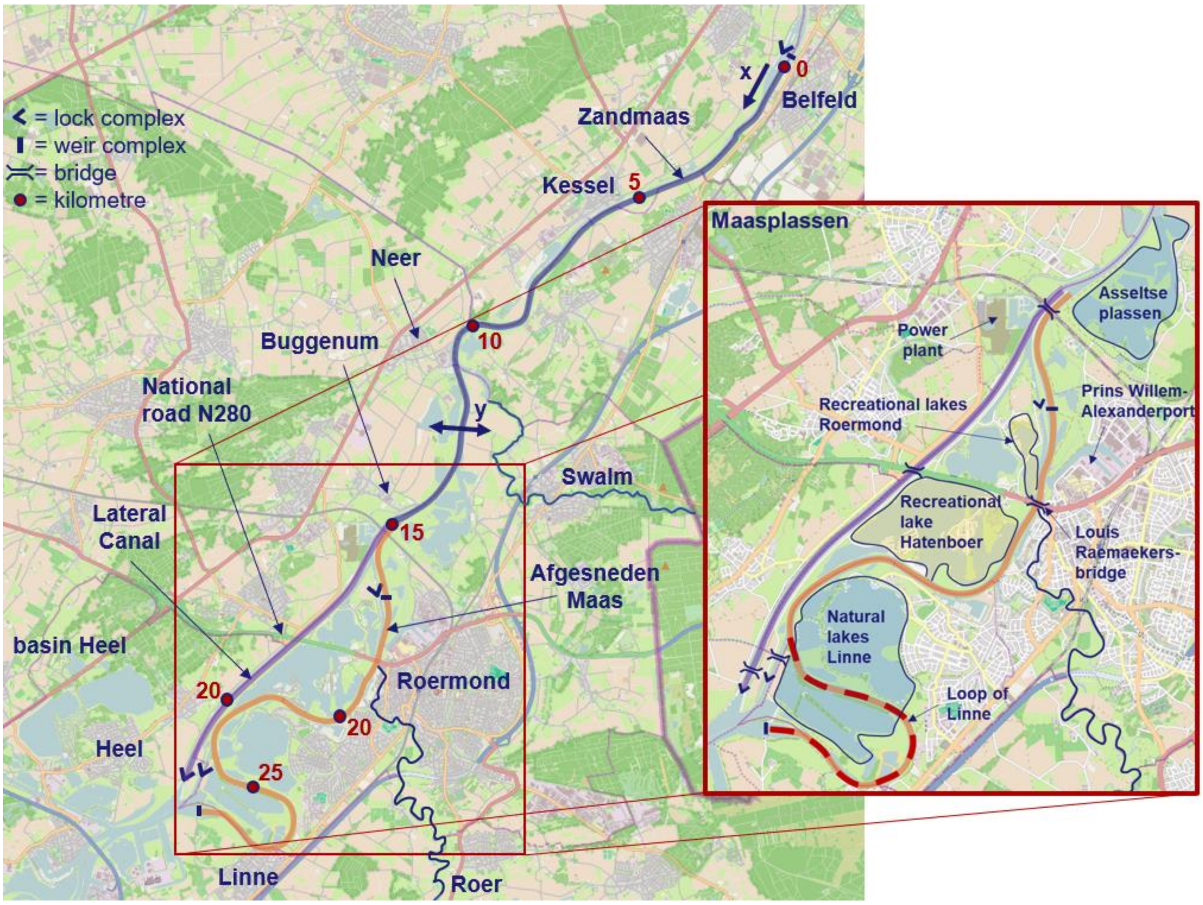


Figure 4-1: Top view of the regional project area (OpenStreetMap Nederland, n.d.).

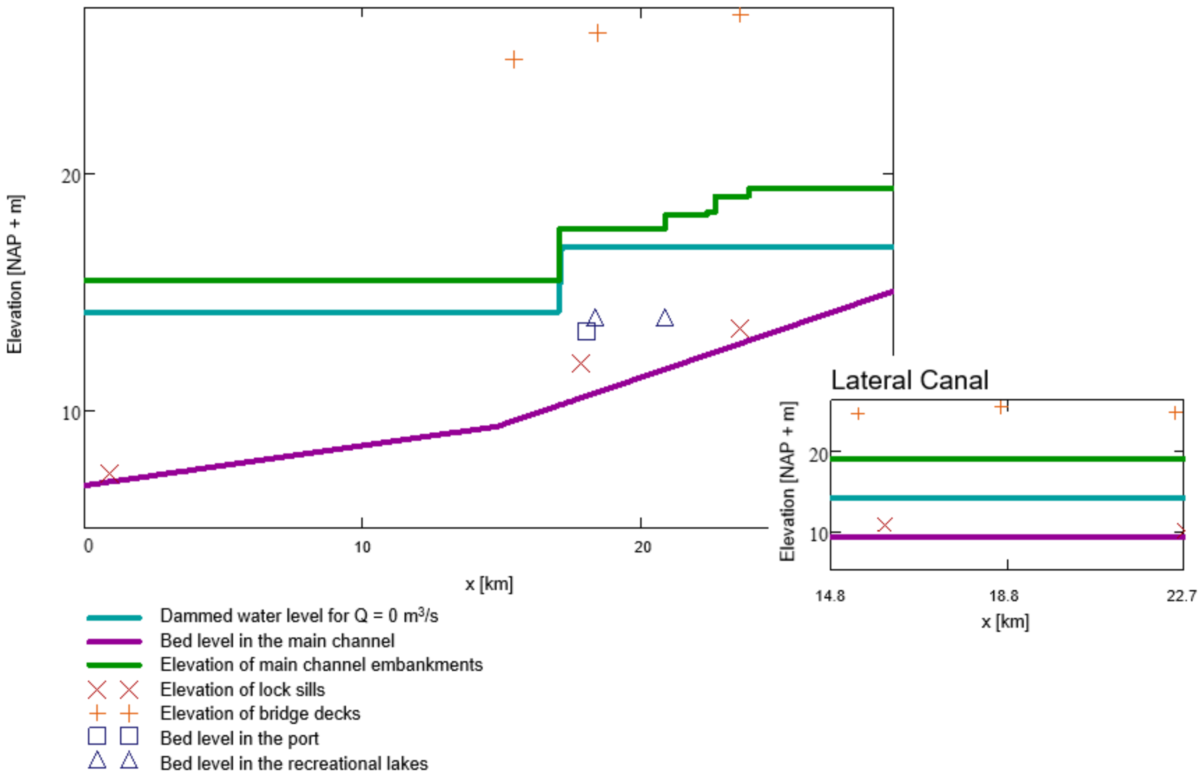


Figure 4-2: Longitudinal cross-section of the project area.

4.2 Functional analysis

The functions of weir sections Roermond and Belfeld have already been addressed in Section 3.2. On regional scale, these functions still hold and are supplemented by regional interests. All functions are dealt with below, as well as their autonomous developments until the end of lifetime of the new weirs. Scenario-dependent developments are subject of Section 4.3.

4.2.1 Regional water management

The River Meuse is the main supplier of fresh water to the region. Water is extracted from the River Meuse for the production of drinking water, the cultivation of crops and the cooling and processing of industrial activities. Furthermore, the dammed water levels naturally maintain the groundwater table in the surroundings. A modification of the dammed water level, modifies the amount of freshwater storage and the groundwater table, which can involve settlements of buildings. The risk on the latter is addressed in the next paragraph; thereafter the regional human freshwater use is described.

Geohydrology

The interaction between a river and groundwater flow in an area is very complex. At first, variable river water levels, net infiltration of precipitation and artificial withdrawal lead to a non-steady situation. Second, the space-dependency (in 3D) is large due to the stratification of soil layers and differences within soil layers. On top of that, the risk on settlement is very dependent on the individual foundations of structures. Therefore, the greatly simplified method explained in Appendix J.1 only serves as a first indication of the groundwater table (change) in a cross-section of the River Meuse.

Retrieved groundwater data show that the groundwater table is elevated higher than the dammed water levels. The River Meuse acts as a drain of the, in the model, constant infiltration in the influence area. By assuming zero inflow at the outer boundary of this area and a constant dammed water level in the river, the differential equation has been solved. Figure 4-3 shows a cross-sectional view of the resulting groundwater table at Belfeld for a dammed water level at NAP +14.10 m and NAP +15.10 m. The Meuse River is located at y=0 m, the outer boundary of the influence area at y=1,900 m.

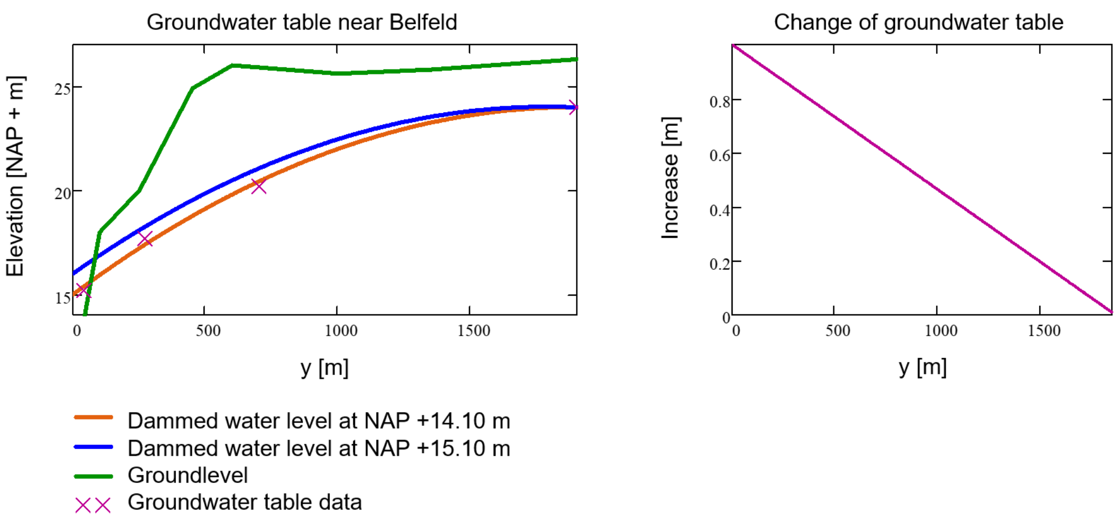


Figure 4-3: Groundwater table change in a cross-section of the River Meuse near Belfeld (Waterschap Limburg, 2019) (ESRI Nederland, 2019).

With the help of the flow chart in Figure 4-4, the results in Figure 4-3 can be interpreted. The risk on damage in residential area is dependent on the change of the groundwater table and the depth of the groundwater table with respect to the ground surface. Elevation data, collected in Appendix J.1, show that the ground level of villages near the River Meuse is at least more than 3.5 m above the local groundwater table.

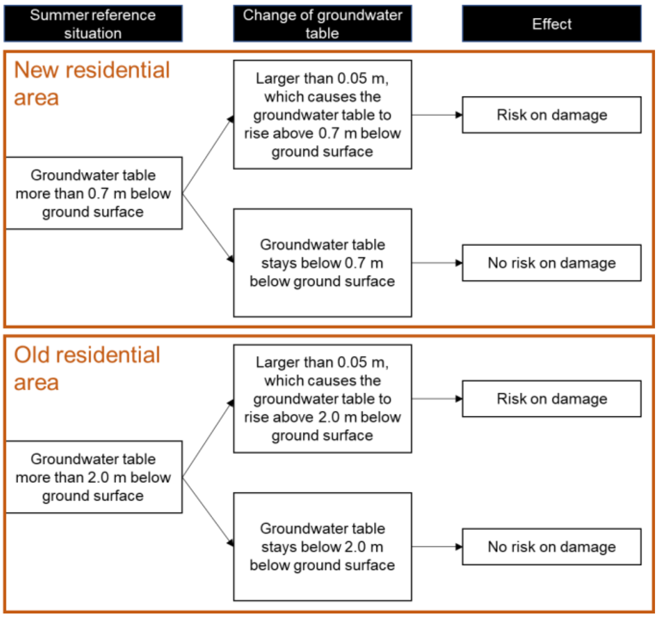


Figure 4-4: Effects of a groundwater table change on residential areas (Rijkswaterstaat, 2006).

Thus, on basis of Figure 4-4, no damage is expected. Cautiousness is required, however, since:

- The calculation of the groundwater table includes large uncertainty, caused by the uncertainty in the data, the model and the assumptions made. The inflow at and location of the outer boundary of the influence area will change by a modification of the dammed water level, a passage of a flood wave and intense precipitation or severe drought.
- Recently, additional measures had to be taken in the Wilhelmina Canal at Tilburg (Van der Maat, 2015). By removal of a navigation lock, the water level in the canal would be lowered with 2.5 m. Though, complementary geohydrological calculations expected unacceptable settlements. After this research, it has been decided to enlarge the lock instead of removing it. Nonetheless, the situation at Tilburg is not completely comparable with the section Linne-Belfeld, because:
  - the groundwater table is much closer to the ground level at Tilburg. According to Figure 4-4, this leads to a larger risk.
  - the soil stratification at Tilburg includes peat layers. These cause large settlements if elevated suddenly above the groundwater table. The settlement of the sand layers in section Linne-Belfeld will be less.

  Despite these differences, Rijkswaterstaat is suspicious to considerable groundwater table changes.

Agriculture

Agriculture possesses the majority of the regional surface area. On top of that, it is one of the major water users in the area, as this sector applies water to cultivate crops. Due to the sandy, very permeable subsoil, the groundwater table drops below the reach of the crops' roots. Especially in summer, when the buffer of the winter is consumed, rainfall is insufficient to compensate for evaporation. To reduce drought damage to the crops, large irrigation systems have been installed in the area; via these systems water of good quality is supplied from a deep aquifer. Surface water from creeks and drainage channels is used as well, provided that the quality is sufficient (Klijn, Van Velzen, Ter Maat, & Hunink, 2012).

Drinking water production

The water company WML provides drinking water in the Province of Limburg. Just like the agricultural sector, a confined deep aquifer functions as a source. The confinement, safeguarded by the prohibition of drilling activities, guarantees the water quality (Van der Aa, Tangena, Wuijts, & De Nijs, 2015). Beside the deep aquifer, 25% of the drinking water is retrieved by surface water embankment filtration (Klijn, Van

Velzen, Ter Maat, & Hunink, 2012). The intake facility with a capacity of 1 m³/s is located in the Lateral Canal. After intake, water passes numerous artificial filters and is stored in the basin near Heel, see Figure 4-1. Despite these filters, the intake stops dozens of times in summer, during which the small river discharge leads to insufficient quality of the surface water. The size of the basin is sufficient to supply drinking water for 2-3 weeks without intake at the Lateral Canal; after that time, the confined aquifer is applied as source exclusively, by which the drinking water production is guaranteed for half a year (Klijn, Van Velzen, Ter Maat, & Hunink, 2012).

Industry

The only significant industrial water users in the section Linne-Belfeld are the chemical company Solvay near Linne and Kuypers Kessel, a transshipment company of dry bulk. Their water use is restricted to 0.5 m³/s (Raadgever, 2004); it is, however, not supposed that this limit is reached continuously. Major industrial water users, such as Chemelot and the power plant at Maasbracht, use water from the Meuse River, but lie upstream of Linne. Cooling water for the power plant at Buggenum, which is much smaller than the one at Maasbracht, is not needed nowadays, as it is out of order because of the low energy price (NUzakelijk, 2013).

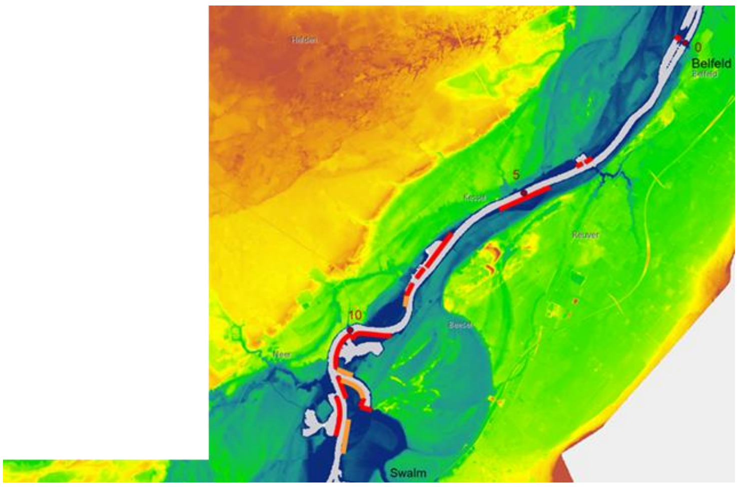
4.2.2 Discharge of flood waves

The discharge of surplus water has been one of the major challenges in river areas for many decades. The flood defences in the regional design area are incomparable with the vast majority of Dutch flood defences. Continuous summer dikes and flood plains are absent; dikes only border the Lateral Canal and smaller-sized flood defences prevent flooding of villages or other valuable areas in the river valley. River floods are confined by the river valley borders. The valley of the River Meuse is clearly visible in Figure 4-5, in which the low-lying areas are indicated in blue and high-elevated areas in red. Ancient river bends and draining creeks and tributaries can be identified as well. The river channel itself is confined by the main channel embankments, of which the crest elevation does not gradually decrease in downstream direction. The lowest embankments are indicated in red and orange in Table 4-1 and Figure 4-5. In Figure 4-2, the indicated elevation of the main channel embankments is the minimum elevation upstream of that location.

Table 4-1: Elevation of the lowest main channel embankments in the regional design area (ESRI Nederland, 2019).

	Weir section Belfeld	*Weir section Roermond*
Red	NAP +15.5 m	NAP +17.6 m
Orange	NAP +16.0 m	NAP +18.3 m

As stated before, weirs do not have a function in discharging water, but they may not hinder the discharge of flood waves. In addition, dependent on the location of the weir's set point, dammed water levels raise above the main channel embankments if the discharge increases; in this way, weirs have a direct effect on the flood frequency of low-lying parts of the river valley.



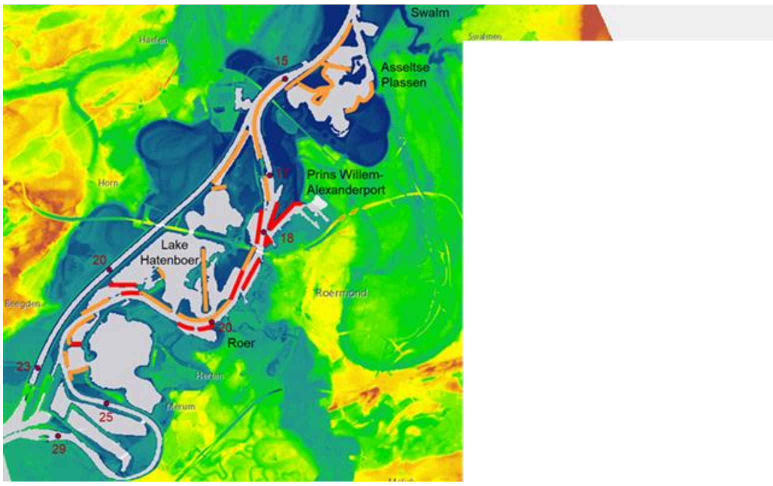


Figure 4-5: Elevation of the regional area and the lowest main channel embankment sections in red and orange (ESRI Nederland, 2019).

4.2.3 Navigation

Commercial navigation uses the Zandmaas and the Lateral Canal intensively, as they are part of the Maasroute. Approximately 75% of the vessels passing the locks at Belfeld and Heel has a domestic destination and/or origin; the rest is mostly oriented at locations in Belgium. Counts at the locks of Panheel and Bosscheveld, see Figure 3-3, show that most vessels in the latter category are Class III vessels or smaller (Rijkswaterstaat, 2009). The governing vessels, Class Va and in the future Class Vb, are thus orientated at the inland ports of Born and Stein at the Juliana Canal. These ports are main regional hubs for respectively container and bulk transport, see Appendix E.2. Within the section Linne-Belfeld, the Prins Willem-Alexanderport is located, which provides access to the waterway for the adjacent manufacturing industry. Especially raw materials are transhipped in this port (Parkmanagement Midden-Limburg, 2019).

(Development of) container transport

As the port of Born is one of the main inland container terminals in the Netherlands, the Maasroute is one of the main inland container transport routes. Therefore, it has to accommodate vessels with four layers of containers stacked on top of each other. The associated required air clearance is 9.10 m, including 30 cm safety margin (Brolsma, Corridoranalyse containers, 2015). Because this air clearance is relative to the water level with 1% exceedance probability (Vreeker & Heijster, 2016), the Maasroute does currently not meet this requirement. Yet, during the zero-discharge situation, all bridge clearances of the Maasroute do exceed 9.10 m, see Appendix E.2.

However, in the field of container transport, the rise of high cube containers in the last decades is indisputable. Initially in Europe, these high cubes were only applied for the import of Asian goods with low specific weight. Transport of these goods has become that dominant that the share of high cubes has passed the 50%; even more than 90% of the new fabricated containers is high cube nowadays. Bearing in mind that containers have a lifetime of 15 years, high cubes become the standard in the upcoming decades (Brolsma, Rapportage containerhoogtemetingen, 2013). Since the conventional 20 and 40 ft containers have a height of 8 ft and 6 inch and high cubes have a height of 9 ft and 6 inch, the height of container vessels will change, regardless of the future scenario.

Updated calculations and the consideration of high cubes led to the height of empty, average loaded and completely loaded container vessels, including the safety margin, as indicated in Figure 4-6 (Brolsma, Rapportage containerhoogtemetingen, 2013). Requirements on the air clearance will probably be based on these calculations in the future. After weir replacement in 2030, the Maasroute has to accommodate container vessels with four layers of high cubes which are average loaded, which means that 65% of the vessel is loaded with containers of which 65% of the containers is loaded.

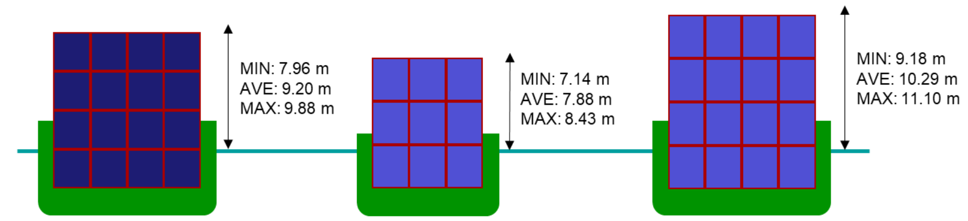


Figure 4-6: Height of container vessels with(out) high cubes (Brolsma, Rapportage containerhoogtemetingen, 2013).

4.2.4 Ecology

The Meuse River is closely connected to the ecosystems in the surroundings. Ecosystems thrive by freshwater supply (of good quality) and a dynamic environment. The first aspect is dominated by the groundwater seepage in the river valley; the River Meuse can be polluted and flood waves can contain much suspended silt particles, which block sunlight and hamper water flora and fauna. In the second aspect, the role of the River Meuse is much stronger. Since the dynamics of groundwater seepage is small, the dynamics have to be provided by the dynamics of the river water levels, which is strongly linked to the location of the weir's set point, see Figure 2-5. Not surprisingly, the high-valued nature sites Loop of Linne and Asseltse Plassen, categorized as gold green areas in Figure 4-7, have developed far away from the current location of the set points. In these areas protection of the ecological value has priority; in the silver green and bronze green areas, the ecological development has to be fitted to multiple, wide-ranging functions, such as recreation, agriculture and flood protection (Provinciale Staten van Limburg, 2014).

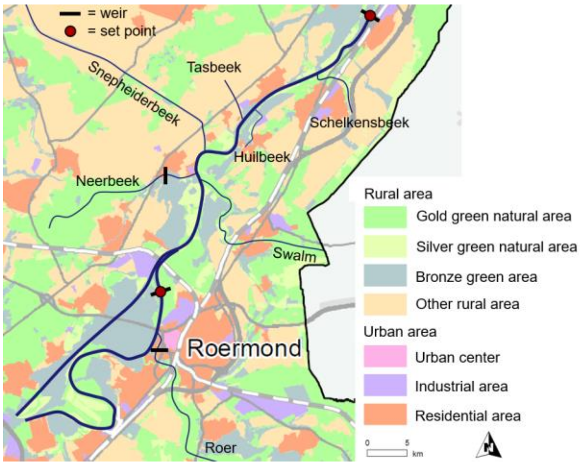


Figure 4-7: Zoning and creeks of the regional design area (Provinciale Staten van Limburg, 2014).

All creeks and tributaries in the regional project area are shown as well in Figure 4-7. Appendix J.2 addresses the ecological importance of and the influence of the dammed water levels in the River Meuse on each creek and tributary. It is concluded from this appendix that only the ecosystems of the Schelkensbeek and Swalm are high-valued and directly influenced by the dammed water levels in the River Meuse.

4.2.5 Recreation

Recreation in the regional area focusses on the area of the Maasplassen, since it is the only large recreational water-related area in the region. It provides recreation facilities for motor and sailing vessels around the Afgesneden Maas and a couple of lakes and marinas south of lock Linne and north of lock Roermond. The weirs provide sufficient draught in the lakes, the Afgesneden Maas and the lock of Linne. If commercial navigation is prohibited here, the draught of recreational vessels is governing. As a recreational waterway, the Maasplassen area is classified as a Class BZM waterway with, based on the counts of recreational vessels at locks, a normal intensity. Appendix E.2 gives more information on the classification of recreational waterways and its corresponding requirements. As bridges cross the Afgesneden Maas at Roermond and Linne, the height of sailing vessels leaving or entering the Maasplassen area is restricted.

Autonomous development of recreation

Looking into the future, significant changes to the recreational waterway class are not expected. Vessels of Class BZM already require the largest draught for waterways functioning as a separate recreational area. Establishment of a connection to other recreational areas is unlikely, since these do not lie in the surrounding area. Also, the intensity of recreational navigation will not change significantly; over 50% increase or over 75% decrease has to take place to change the intensity class. Because of this, the recreational function and its coupled requirements on guaranteed water depth and air clearance stay the same during the lifetime of the weirs.

4.3 Requirements analysis

As the boundary conditions change during the lifetime of the weirs, the demands to the regional design area can be changed during the lifetime of the weir as well. Therefore, first, the requirements in the period 2030-2050 are listed, and, second, the scenario-dependent evolution of the boundary conditions and requirements is discussed.

4.3.1 Requirements to the regional design in the period 2030-2050

Based on the current functions of the waterway network, a list of requirements has been generated for the regional design in the period 2030-2050. The guaranteed minimum water depths are based on Richtlijn Vaarwegen, as shown in Figure 4-8 and Figure 4-9.

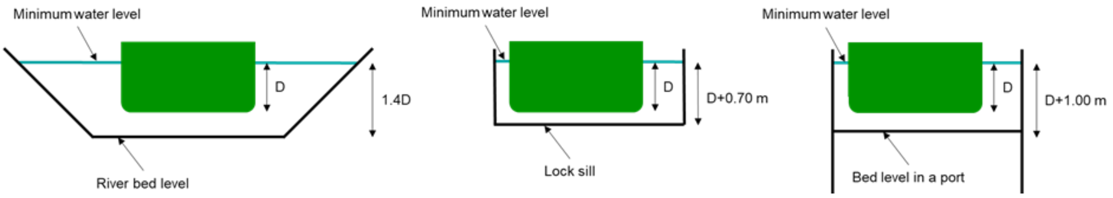


Figure 4-8: The water depth requirements in a commercial navigation waterway in a cross-section of a river (left), a lock (middle) and an inland port (right) (Rijkswaterstaat, 2017).

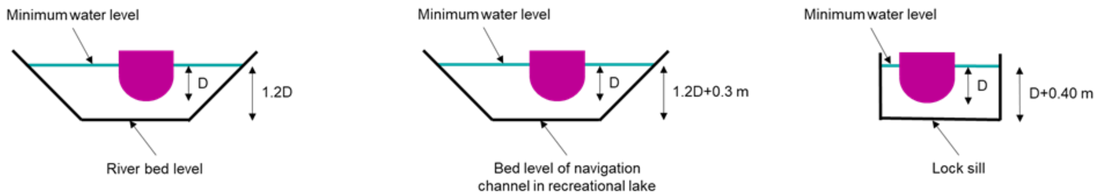


Figure 4-9: The water depth requirements in a normal-intensity recreational navigation waterway in a cross-section of a river (left), a navigation channel in a recreation lake (middle) and a lock (right) (Rijkswaterstaat, 2017).

- To prevent unacceptable risks of groundwater-related damage in residential areas, dammed water levels may be modified maximum 1.0 m.
- The discharge capacity of flood waves may not be lowered with respect to the current discharge capacity.
  - The flood frequency of the main channel embankments may not increase.
  - The flood frequency of the borders of the higher-elevated areas may not increase.
- The Maasroute has to meet the requirements of Class Vb waterway with a limited draught of 3.5 m according to the Richtlijn Vaarwegen.
  - The guaranteed minimum water depth in the Zandmaas and the Lateral Canal have to be 4.9 m.
  - The guaranteed minimum water depth above the upstream lock sill of Belfeld and the downstream lock sill of Heel have to be 4.2 m.

- The Maasroute has to accommodate average loaded container vessels with four layers of containers during the zero-discharge situation.
    - The minimum air clearance on the Maasroute has to be 10.29 m in the zero-discharge situation.
- The Prins Willem-Alexanderport has to be accessible for a governing vessel, which has a draught of 2.6 m according to the Richtlijn Vaarwegen.
    - The guaranteed minimum water depth above both lock sills of Roermond has to be 3.3 m.
    - The guaranteed minimum water depth in the Prins Willem-Alexanderport has to be 3.6 m.
- The freshwater storage in summer may not be smaller than the current freshwater storage in summer.
- The ecological value in Natura 2000 sites has to be maintained or, otherwise, the loss has to be compensated according to the European legislation.
- Recreational waterways have to meet the requirements of a normal intensity Class BZM waterway, although with a reduced air clearance.
    - The guaranteed minimum water depth of the Afgesneden Maas has to be 2.3 m.
    - The guaranteed minimum water depth of the navigation channels in the recreational lakes has to be 2.6 m.
    - The guaranteed minimum water depth above the downstream lock sill of Linne has to be 2.3 m.
    - The minimum air clearance of the Afgesneden Maas has to be 4.0 m in the zero-discharge situation.

4.3.2 Change of boundary conditions and requirements

A combination of socioeconomic developments and rate of climate change leads to a unique changing environment in each of the four scenarios. As a result, the boundary conditions and the design area itself change as well. Figure 4-10 shows which specified socioeconomic developments and climate change indicators have been used to translate the (inter)national developments to the developments on regional scale. The latter is eventually divided per subfunction and the development rate is addressed on basis of literature and the technological innovation rate in each scenario. The recreation function does not appear in Figure 4-10, since no scenario developments are taken into account for this function, see Section 4.2.5. Appendix A.1 addresses the translation in more detail.

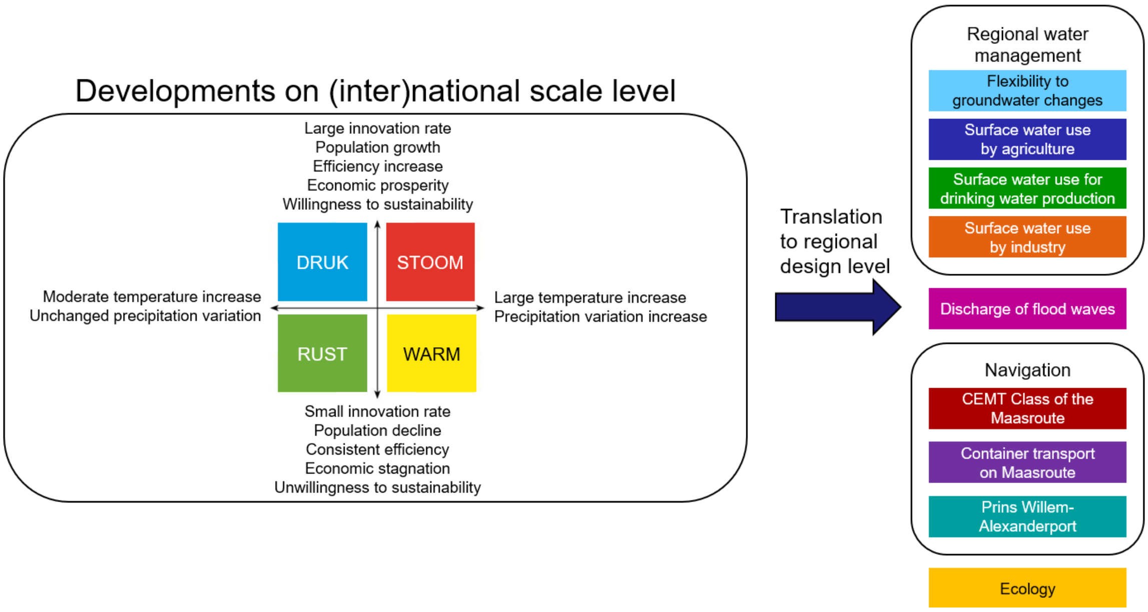


Figure 4-10: Translation of the (inter)national scenario developments to the regional scenario developments.

The developments on regional scale impose new boundary conditions or demands to the design of section Linne-Belfeld. Eventually, these developments can force Rijkswaterstaat to set less stringent or more stringent requirements to the weir and waterway design. Appendix A.2 shows an overview of the changed boundary conditions and requirements per scenario. Table 4-2 summarizes the least stringent and most stringent boundary conditions and requirements per subfunction. The requirements related to surface water use and ecology are only qualitative, since too little information is found to base a quantitative analysis on. The scenario in which the most stringent requirements evolve, differs per subfunction; thus, not all most stringent requirements occur simultaneously. Overall, however, the regional developments in scenario STOOM put the most stringent collection of boundary conditions and requirements to the regional design. On the other hand, in scenario RUST the total collection of requirements to the regional design is less stringent in comparison with the other scenarios.

Table 4-2: The least and most stringent boundary conditions and requirements with the corresponding scenario.

<table>
<tr><th>Function</th><th>Subfunction</th><th>Least stringent boundary conditions and requirements</th><th>Most stringent boundary conditions and requirements</th></tr>
<tr><td rowspan="4">1. Regional water management</td><td>Flexibility to groundwater changes</td><td>± 3.0 m (DRUK and RUST)</td><td>± 0.5 m (STOOM)</td></tr>
<tr><td>Surface water use by agriculture</td><td>Decrease (RUST)</td><td>Increase (STOOM and WARM)</td></tr>
<tr><td>Surface water use for drinking water production</td><td>Ceased in summer (STOOM and WARM)</td><td>Increase (DRUK)</td></tr>
<tr><td>Surface water use by industry</td><td>Decrease (DRUK and RUST)</td><td>Increase (STOOM)</td></tr>
<tr><td colspan="2">2. Discharge of flood waves</td><td>Unchanged (RUST)</td><td>+30% (STOOM)</td></tr>
<tr><td rowspan="3">3. Navigation</td><td>CEMT-class of the Maasroute</td><td>Class Va (STOOM and WARM)</td><td>Class Vb (all scenarios)</td></tr>
<tr><td>Container transport on Maasroute</td><td>Empty three-layered (RUST and WARM)</td><td>Empty four-layered (DRUK and STOOM)</td></tr>
<tr><td>Prins Willem-Alexanderport</td><td>Closure (WARM)</td><td>Governing draught of 3.0 m (DRUK)</td></tr>
<tr><td colspan="2">4. Ecology</td><td>Less attention paid to ecological value (STOOM)</td><td>Development of large interconnected nature sites in the river valley (DRUK)</td></tr>
<tr><td colspan="2">5. Recreation</td><td colspan="2">Class BZM (all scenarios)</td></tr>
</table>

4.4 Synthesis of regional design alternatives

To meet the requirements, regional design alternatives haven been generated, consisting of three components: a replacement strategy for the weirs Roermond and Belfeld, exact weir heights and set point locations, supplemented with regional measures. The considered regional measures are intended:

- to increase the discharge capacity and prevent more frequent flooding of the river valley by 'Room for the River' measures as shown in Figure 4-11;
- to accommodate navigation in the regional design area by measures as shown in Figure 4-12;
- to increase the freshwater storage in the regional design area by dredging a new lake or enlarging an existing lake;
- to maintain the ecosystem of the nature sites by compensating the loss of ecological value.

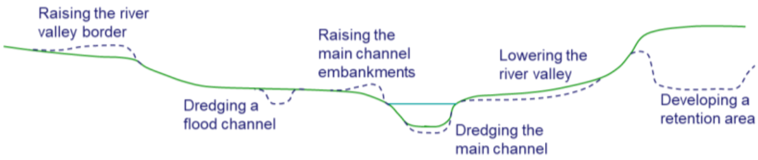


Figure 4-11: Regional measures to increase the discharge capacity.

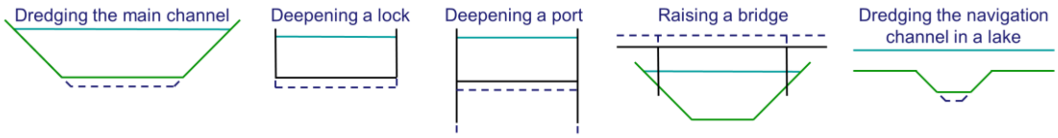


Figure 4-12: Regional measures to accommodate vessels of larger draught and/or higher container vessels.

4.5 Verification & evaluation of regional design alternatives

Many alternatives can be developed by combining these measures. Although all design choices are interconnected, the verification and evaluation can be done in a logical sequence, after which the preferred design alternative is obtained. This section leads to this alternative systematically.

4.5.1 Number and location of weirs

Firstly, the weir replacement strategy, see Section 3.4, is examined. The global design alternatives differ in the number and location of the weirs. Since the foundation and substructure are non-adaptive elements, the choice made in 2030 is decisive for the entire weir lifetime. Replacement or removal of a weir before the end of its technical lifetime has been reached is undesired.

The requirements list for the first period of the weir's lifetime, see Section 4.3.1, is applied for verification of the weir replacement strategies. In contrast with the conclusion of the previous chapter, the global design alternative including the removal of weir Roermond turns out infeasible. It does not meet the first requirement, whichever weir height is designed and whichever regional measures are taken. Replacement of weir Roermond by a new weir at the same location or at a location upstream, indicated in Figure 4-13, are feasible for multiple combination of heights and locations of the set points. In both alternatives, the new weir Roermond is located downstream of the confluence of the River Meuse and the Roer; the guaranteed minimum discharge of the Roer of 10 m³/s can be employed for freshwater storage in the Maasplassen.

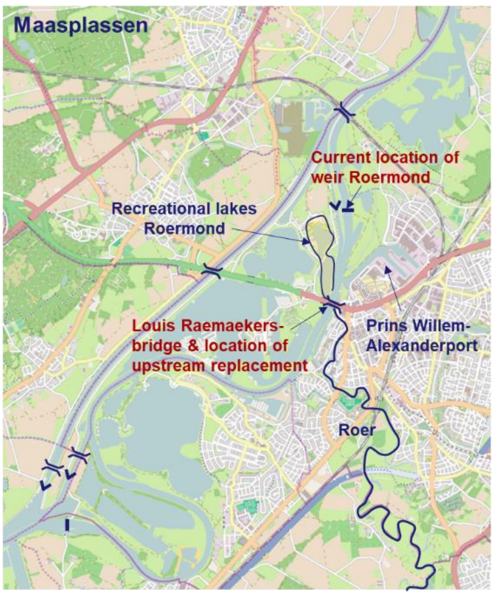


Figure 4-13: Global design alternatives of the replacement of weir Roermond (OpenStreetMap Nederland, n.d.).

A number of global design alternatives are feasible, since they are combined with regional measures. Appendix K gives an overview of the regional measures that have to be taken for multiple alternatives to pass the verification. The required magnitude of deepening and dredging is calculated with help of the hydraulic model of Appendix C.1. The magnitude is that large in a number of alternatives that the feasibility and practicability is questionable; additional measures may be induced to make it technically feasible, but this is beyond the scope of this project.

Replacement of the current weir Roermond by a new weir at the Louis Raemaekersbridge transfers the Prins Willem-Alexanderport and the recreational lakes of Roermond from weir section Roermond to weir section Belfeld. Deepening of both is indispensable then, since their depth is based on the dammed water levels of weir Roermond and the new weir Belfeld can be maximum 1.0 m higher than the current weir Belfeld. On top of that, a new lock for recreational vessels has to be constructed next to the new weir. Summarizing, on the one hand, this global design alternative results in more costs in comparison with the global design alternative in which weir Roermond is replaced by a new weir at the same location. On the other hand, the Prins Willem-Alexanderport is then accessible from the Maasroute without lockage. Whether this benefit outweighs the additional costs has to be decided after more research. In the remainder of this project, replacement of weir Roermond in 2030 by a new weir at the same location is assumed.

4.5.2 Heights and set point locations in 2030

As the number and locations of the new weirs have been set, the more adaptive components of the weirs can be designed: the height and the location of the set point. Again, reference is made to Appendix K to compare the design alternatives. From this appendix, it is clear that the least regional measures have to be taken if the height and location of the set point of the new weirs Roermond and Belfeld are taken both equal to the current weirs. Constructing a lower weir involves deepening the locks and ports and dredging the main channel, the navigation channels in the recreational lakes and a new lake for freshwater storage. Constructing a higher weir involves raising embankments and/or raising bridges. Shifting the set point location affects the current nature sites negatively, which induces additional measures to compensate the ecological loss. All these additional measures involve extra costs, though no additional benefits.

Looking more into detail, the regional design can be optimized on the container transport on the Maasroute by a discharge-dependent location of the set point. By shifting the location of the set point from the current location, weir Belfeld itself, to the theoretical location, Buggenum, if the river discharge exceeds 525 m^3/s, average loaded container vessels stacked with four layers of high cubes can then still pass the rail bridge at Buggenum, see Figure 4-14. Provided that in other weir sections these container vessels can also pass all bridges, container vessels can navigate on average one month per year extra. By the shift of the set point location, the water level variation in the tributary Swalm and the Asseltse Plassen is reduced, but this reduction only occurs if the discharge exceeds 525 m^3/s, which is mostly in autumn and winter, see Table B-1. For the ecosystem, the water level variation in spring and summer is more important: in these seasons the variation is only restricted 10 days per year on average. This drawback is considered to be smaller than the benefits for container transport.

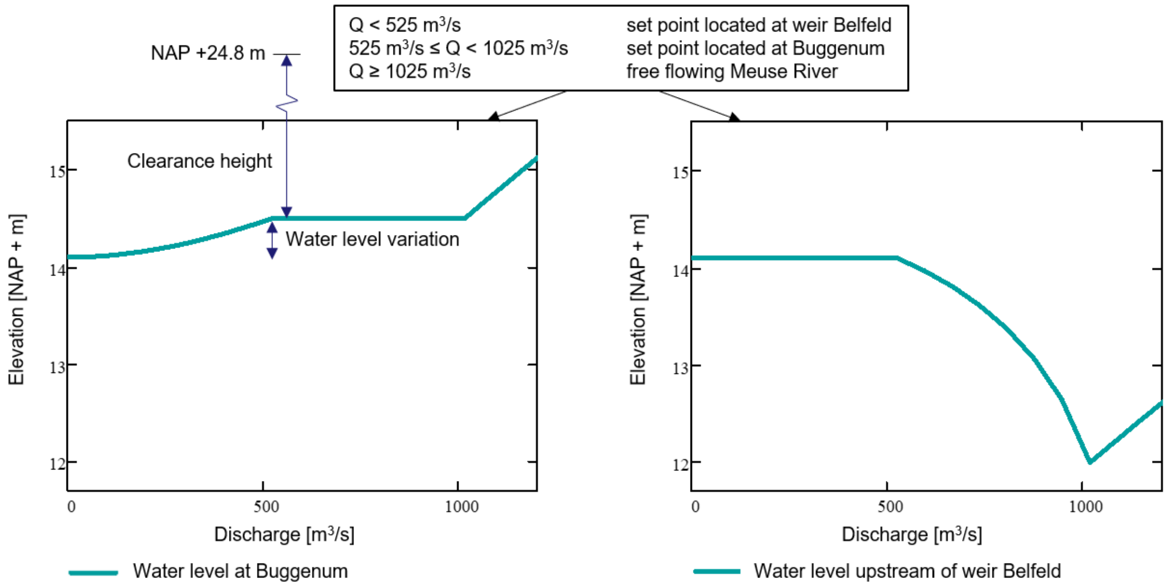


Figure 4-14: The water level at Buggenum (left) and upstream of weir Belfeld (right) for various discharges with a shift of the set point location.

Summarizing, the selected regional design for 2030 includes:

- a new weir Roermond at the same location as the current weir with a dammed water level at NAP +16.85 m in the zero-discharge situation and the set point located at the weir itself;
- and a new weir Belfeld at the same location as the current weir with a dammed water level at NAP +14.10 m in the zero-discharge situation and the set point located at the weir itself for discharges smaller than 525 m^3/s and located at Buggenum for discharges larger than 525 m^3/s.

This regional design meets the requirements until 2050. On top of that, adaptations are required if the boundary conditions change thereafter.

4.5.3 Adaptation scheme

The required adaptations are dependent on which scenario evolves. The adaptation measures can be split into two categories:

- adaptations made in the regional design area. The regional measures presented in Section 4.4 are possible adaptations as well to cope with the evolved boundary conditions and requirements.
- adaptations made to the weirs itself.

The evaluation of these adaptations is done in future when an adaptation is required and/or demanded. It depends on (the relative importance of) the criteria applied by then which adaptation is selected. Therefore, it is impossible to evaluate these adaptations nowadays, although, the current design can influence the choice of adaptation measures in the future. Designing an adaptive weir adds adaptation options for the future waterway managers. The following weir adaptations can contribute in meeting the evolved requirements:

- heightening weir Belfeld and/or Roermond;
  - providing more storage of surface water;
  - providing more water depth in the Prins Willem-Alexanderport.
- lowering weir Belfeld or shifting the set point location of weir Belfeld to Buggenum;
  - providing more air clearance for container transport.
- shifting the set point location of weir Belfeld and/or Roermond;
  - providing more water level dynamics in dedicated natural areas.

- enlarging the flow opening of weir Belfeld and/or Roermond;
  - providing more discharge capacity.
- replacing weir Roermond by a new weir at the Louis Raemaekersbridge;
  - providing improved accessibility of the Prins Willem-Alexanderport.
- removing weir Roermond;
  - providing improved accessibility of the Prins Willem-Alexanderport;
  - providing more water level variation in the Loop of Linne.

An overview of the required adaptation measures during the weir's lifetime are shown in Table 4-3. The second column indicates in which scenario and year each purpose applies, which is based on the evolution of boundary conditions and requirements, see Appendix A.2. The adaptation measures that have to be taken to serve these purposes are split into regional and weir adaptation measures. Note that this adaptation scheme assumes the construction of unlimited adaptive weirs at Roermond and Belfeld. The feasibility of this unlimited adaptivity is addressed in the next chapter.

Table 4-3: Adaptation scheme of the weir sections Roermond and Belfeld.

Legend (A = regional adaptation measures; B = weir adaptation measures)
A ∩ B = intersection (A and B)
A ∪ B = union (A or B)
A ⊃ B = superset [(only A) or (minimized A + B)]

<table>
<tr><th>Purpose</th><th>Scenario (year) in which the purpose applies</th><th>Regional adaptation measures</th><th>Binary operator</th><th colspan="2">Weir Belfeld and weir Roermond adaptation measures</th></tr>
<tr><td rowspan="2">Increasing the discharge capacity of the river valley</td><td>DRUK (2050)</td><td rowspan="2">'Room for the River' measures</td><td rowspan="2">⊃</td><td rowspan="2">Enlarging the flow opening</td><td>By 10%</td></tr>
<tr><td>STOOM (2050, 2100)
WARM (2100)</td><td>By 15%</td></tr>
<tr><td rowspan="3">Preventing more frequent flooding of the river valley</td><td>DRUK (2050)</td><td rowspan="3">Raising the main channel embankments
∪
dredging the main channel</td><td rowspan="3">∪</td><td rowspan="2">Enlarging the flow opening</td><td>By 10%</td></tr>
<tr><td>STOOM (2050)</td><td>By 15%</td></tr>
<tr><td></td><td colspan="2">∪
shifting the set point locations</td></tr>
<tr><td>Accommodating higher container vessels</td><td>DRUK (2050)
STOOM (2050)</td><td>Raising bridges on the Maasroute</td><td>⊃</td><td colspan="2">Lowering weir Belfeld
∪
shifting the set point location of weir Belfeld</td></tr>
<tr><td rowspan="2">Providing more freshwater storage</td><td>DRUK (2050, 2075)
STOOM (2075, 2100)
WARM (2075, 2100)</td><td rowspan="2">Dredging a new lake
∪
enlarging an existing lake</td><td rowspan="2">∪</td><td rowspan="2">Heightening with maximum</td><td>1.0 m</td></tr>
<tr><td>DRUK (2100)</td><td>3.0 m</td></tr>
<tr><td>Increasing the dynamics in dedicated natural areas</td><td>DRUK (2050)</td><td>-</td><td>-</td><td colspan="2">Shifting the set point locations</td></tr>
<tr><td>Accommodating larger vessels to the Prins Willem-Alexanderport</td><td>DRUK (2075)</td><td>Deepening the Prins Willem-Alexanderport</td><td>⊃</td><td colspan="2">Heightening weir Roermond with maximum 1.0 m</td></tr>
<tr><td rowspan="2">Improving the accessibility of the Prins Willem-Alexanderport</td><td rowspan="2">DRUK (2100)</td><td rowspan="2">Deepening the Prins Willem-Alexanderport</td><td>∩</td><td colspan="2">Removal of weir Roermond
∪
replacing weir Roermond upstream</td></tr>
<tr><td>⊃</td><td colspan="2">Heightening weir Belfeld with maximum 3.0 m</td></tr>
<tr><td>Providing more frequent flooding of the river valley</td><td>WARM (2075, 2100)</td><td>Lowering the river valley</td><td>∪</td><td colspan="2">Heightening with maximum 1.0 m</td></tr>
</table>

The weir adaptation measures can be taken in combination with or instead of the regional adaptation measures; this is indicated by the binary operators in the table. In a number of cases, adaptation of a weir involves less undesired implications: for example, heightening weir Roermond with 0.20 m provides as much extra freshwater storage as a 1 km^2 new lake of 1.50 m depth. In other cases, adaptation of a weir supports an adaptation measure in the regional design area: for example, enlarging the flow opening of a weir makes dredging of the main channel a more effective measure to discharge a larger part of a flood wave via the main channel. Other 'Room for the River' measures with undesired implications can then be possibly discarded.

Last, it has to be mentioned that the weir adaptation measures in the table may contradict with another simultaneously appearing purpose. In this situation, additional adaptation measures are required to meet the requirements regarding the other functions of the weir section. For each weir adaptation, the contradicting purpose and the additional adaptation measures, which can be a regional adaptation measure or a weir adaptation measure, are presented in Table 4-4. The need of the additional regional measures, however, is highly uncertain, because it is unknown how the regional design area changes during the lifetime of the weirs. For example, to increase the discharge capacity of the main channel, the embankments of the main channel can be raised or the main channel can be dredged. If the first is executed and, later on, more surface water storage is required, heightening a weir does not have to involve further raise of the embankments. Nonetheless, if the second was executed, further raise of the embankments is involved and the waterway manager may opt for dredging a new lake instead of heightening a weir.

Table 4-4: Contradicting purposes and additional adaptation measures per weir adaptation.

Legend (A= first adaptation measures ; B= second adaptation measures)
A ∩ B = intersection (A and B)
A ∪ B = union (A or B)
A ⊃ B = superset [(only A) or (minimized A + B)]

Weir adaptation measure	*Contradicting purpose*	*Additional adaptation measures*
Heightening the weir	Preventing more frequent flooding of the river valley	Raising the main channel embankments ∪ shifting the set point location (discharge-dependent, as in Figure 4-14)
	Accommodating higher container vessels	Raising bridges on the Maasroute ⊃ shifting the set point location of weir Belfeld (discharge-dependent)
Lowering the weir	Accommodating commercial navigation	Dredging the main channel ∩ deepening the locks
Removal or replacing weir Roermond upstream	Accommodating vessels to the Prins Willem-Alexanderport	Dredging the Prins Willem-Alexanderport
	Recreational boating in the Maasplassen area	Dredging the navigation channels in the recreational lakes
Shifting the location of the set point	Maintaining the ecosystem of the current nature sites	Taking compensation measures ∪ shifting the set point location discharge-dependent

Since weir Belfeld dams the water level in part of the Maasroute, the adaptations are more complex in this weir section. Moreover, if the accessibility of the Prins Willem-Alexanderport has to be improved, weir Roermond has to be removed or replaced by a new weir upstream and weir Belfeld has to be heightened. Therefore, the adaptivity of weir Belfeld serves more purposes. From the adaptation scheme, it is concluded that the largest desired adaptivity of weir Belfeld, providing the most freedom of choice in the future, includes:

- enlarging the discharge capacity by 30%;
- shifting the location of the set point (depending on the discharge);
- lowering the dammed water level to NAP +13.70 m and heightening the dammed water level to NAP +17.10 m.

4.6 Weir replacement and adaptivity in section Linne-Belfeld

After analysis of the section Linne-Belfeld in more detail, removal of weir Roermond turns out to be infeasible in 2030. The other two replacement strategies, replacement of the weir by a new higher weir or a new weir at an upstream location, have to be combined with a couple of regional measures. Replacement of both weir Roermond and Belfeld in 2030 by new, equally high weirs at the same location as the current weirs has been selected after comparing the amount of required regional measures and advantages. Nevertheless, there is a difference with the current weirs: the location of the set point of weir Belfeld is shifted from weir Belfeld to Buggenum when the river discharge exceeds 525 m^3/s to accommodate average loaded container vessels, stacked with four layers of high cubes, during large discharges.

The scenario-dependent developments in the subsequent century require adaptations to this design alternative. The adaptation scheme, shown in Table 4-3, presents an overview of the future developments for each time period and scenario and links to them the adaptation measures that are required in case of specific developments. The adaptation measures are split into weir adaptations and regional adaptations in the river area. From this adaptation scheme, it is concluded that an adaptive weir provides more freedom of choice for the future waterway managers. By adapting the weir, regional measures with undesired implications for local governments and inhabitants can be discarded. The largest freedom of choice is preserved if the weir is adaptive to the most stringent combination of evolved boundary conditions and requirements, see Table 4-2. Finding out whether this adaptivity is feasible, is part of the next chapter. If it is not, the freedom of choice has to be restricted: a combination of smaller adaptations to the weir and adaptations in the regional design area will then be required to serve the purposes in the future.

5 Local design: weir Belfeld

This chapter investigates the feasibility of the weir adaptivity proposed in the previous chapter. First of all, the local project area is described in Section 5.1. Subsequently, Section 5.2 includes the functions and requirements on local scale, which are partially derived from the functions and requirements on regional scale. These functions and requirements and the changing boundary conditions are applied to generate and verify design alternatives in Section 5.3: first the exact location of the new weir is selected, second the applicability of gate types is studied and last the design alternatives are elaborated. Evaluation of these is, with special attention to the adaptivity of the alternatives, executed in Section 5.4. This all is used to conclude this chapter with a conceptual design of the adaptive weir at Belfeld in Section 5.5.

5.1 Area analysis

The lock and weir complex Belfeld consists of one weir and three locks, see Figure 5-1. Vessels approach the locks via a separate canal, in which mooring places are located, at which vessels can wait for lockage. The later constructed east lock chamber is longer than the other two and therefore suitable for Class Vb vessels. The weir of Belfeld is located east of the lock complex in the River Meuse with the Stoney part closest to the locks. The Poirée parts are stored at the eastern bank during a flood wave. Fish can pass the weir via the fish passage, which is located between the weir and the lock complex.

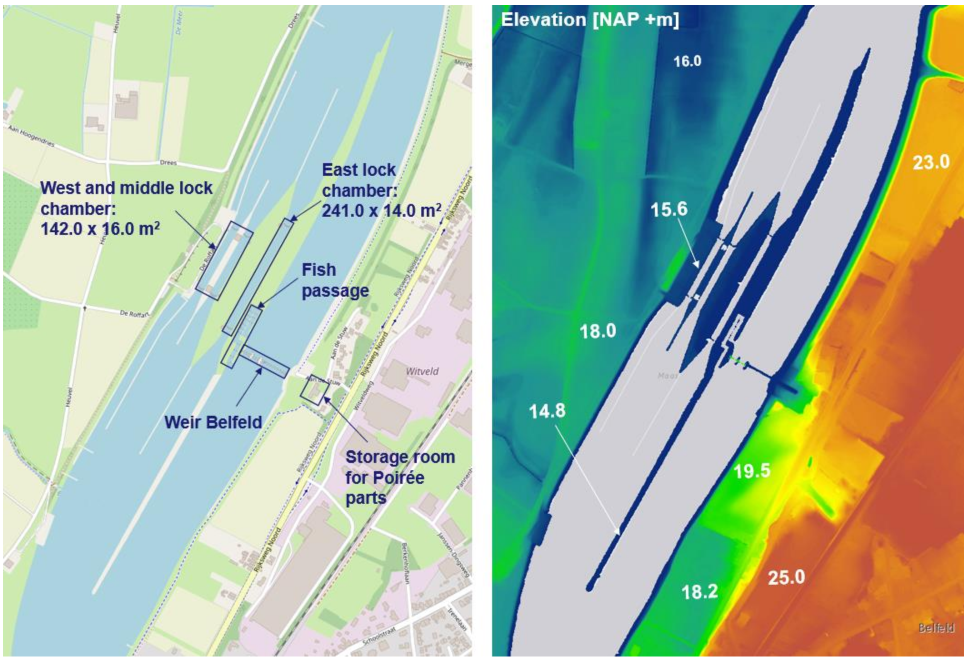


Figure 5-1: Overview of the lock and weir complex Belfeld (OpenStreetMap Nederland, n.d.) (ESRI Nederland, 2019).

The overview on the right of Figure 5-1, a detailed view of Figure 4-5, shows the ground level. Downstream of weir Belfeld, the dammed water level is determined by weir Sambeek. It is assumed that this dammed water level, NAP +10.75 m in the zero-discharge situation, remains unchanged. The lock walls and approach structure rise above the dammed water level of weir Belfeld, NAP +14.10 m in the zero-discharge situation, to maintain the water head over the weir. If a large flood waves passes, first the western river embankment floods; the terraces in the east, upon which the village of Belfeld is situated, are seldom flooded because of their high elevation, above NAP +23.0 m.

Based on the previous chapter, the riverbed level at Belfeld is assumed at NAP +6.75 m and the top of the upstream lock sills at NAP +7.25 m. Both just enable navigation of vessels with governing draught on the Maasroute. The sill of the current weir protrudes from the riverbed to NAP +8.05 m (Rijkswaterstaat, 1989). The height difference is the result of riverbed subsidence, caused by the sand extraction in the Maasplassen and dredging of the Zandmaas for navigation purpose. Further autonomous riverbed subsidence is, however, not expected in the Zandmaas (Ministerie van Verkeer en Waterstaat, 2007).

5.2 Functional and requirement analysis

As in the previous chapters, the design starts with the functions of and requirements to the design. The global and regional design show the functions of weir Belfeld clearly. On local scale, additional functions and requirements come into play. For example, fish has to be able to pass the weir and electricity can be generated by a hydropower station. Space has to be reserved for fulfilling these two functions; this study does not go into more detail about them. This section focusses on the fulfilment of the requirements related to the regional design area: the water level control and the passage of flood waves. Furthermore, the feasibility of constructing a navigation opening in the weir is addressed.

5.2.1 Water level control

To constantly control the water level in weir section Belfeld, weir gates are needed of which the position can be adjusted to the river discharge. At the current weir, operation of the Stoney gates is sufficient to provide the desired water level for discharges smaller than 200 m^3/s, a discharge which is only exceeded 37% of the year on average, see Table B-1. The rest of the year, especially in summer, the Poirée part is closed and untouched. Regardless of the type of gates in the new weir, water level control during small discharges by an assigned part of the weir is favourable: movement of all gates simultaneously uses more power and gives rise to wear of the hoist mechanism, such as cables and/or wheels. If the discharge is smaller than the threshold value, the full discharge passes the assigned weir part, provided that the flow velocity through the discharge opening is acceptable.

The threshold value is dependent on the dimensions, width and sill's elevation, of the discharge opening and the water levels upstream and downstream of the weir. If the difference between the upstream and downstream water level is large, free flow occurs; otherwise it is called submerged flow. During free flow, the discharge through the weir is not hampered by the downstream water level, whereas it is during submerged flow. The underlying hydraulics and transition between the two flow situations are addressed in Appendix C.2, from which Figure 5-2 has been obtained as well. The figure shows that for the same discharge range, the crest of an overflow gate has to be adjusted more than the bottom of an underflow gate. Therefore, the overflow gate is more suited for accurate water level control.

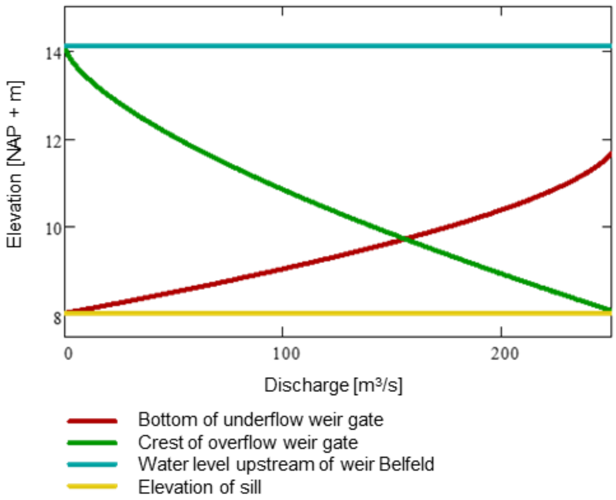


Figure 5-2: Water level control by an overflow and underflow weir.

5.2.2 Passage of flood waves

As mentioned before, a weir has no function in flood safety. It has, however, to be prevented that the weir forms a bottleneck in the discharge of flood waves, resulting in undesired floods upstream.

If the current weir is opened completely, the width of the flow opening equals 97 m. Although the governing flood wave nowadays is larger than just after construction of the weir, it is assumed that this width is sufficient for discharging the currently governing flood wave with a peak discharge of 3800 m³/s (Bruggeman, et al., 2011). It is assumed that regional 'Room for the River' measures, as shown in Figure 4-11, have been taken in the last century to diminish the possible bottleneck effect of the current weir Belfeld.

The discharge capacity of the weir in open state is calculated on basis of the total flow area above the sill. Literature shows that during the governing peak discharge the water level at Belfeld is approximately equal to NAP +20.0 m (Rijkswaterstaat Zuid-Nederland, 2013), resulting in a total flow area above the sill of the current weir of 1160 m². In future, at maximum an increase of 30% is required. This increase can be realized by deepening the weir's sill and/or widening the weir. Figure 5-3 gives an indication of the required combination of these two dimensions to discharge the governing flood wave.

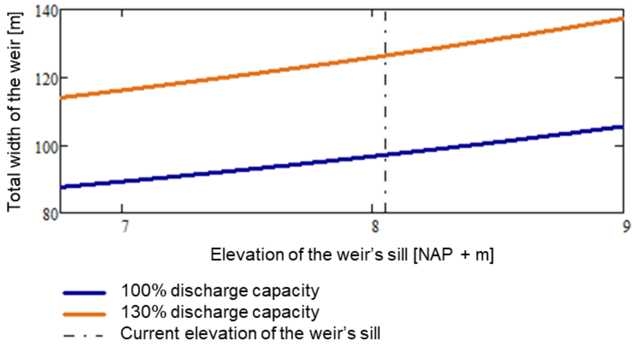


Figure 5-3: Required width and depth of the weir to discharge the governing flood wave.

5.2.3 Navigability

The weirs in the River Meuse enable the navigation on the river. On the other hand, the weir itself is an obstacle in the transport route and passing the adjacent locks leads to additional travel time. A few days per year, these locks are even unusable, since the lock walls overflow (Rijkswaterstaat Zuid-Nederland, 2013) and the strong flow in this case makes manoeuvring impossible. Navigation on the Maasroute, however, does not come to a hold, because, by removal of the Poirée part, the vessels can navigate over the foundation of the weir.

The dimensions of the navigable opening in the weir are related to the dimensions of the governing vessel. The governing draught and height of the vessels navigating on the Maasroute has been addressed in the regional design. The evolution of the governing vessel's beam, however, was not an issue on that scale level; for the width of the navigation opening it can be. In two scenarios, the development of the transport of pallet-wide containers leads to an increase of the container vessels' beam from 11.4 m to 12.0 m. However, this does not result in more stringent requirements, since Table 3-1 shows that the maximum allowable vessel's beam on the Zandmaas is currently already equal to 15.5 m.

To enable navigation through the weir without hindrance for the navigation sector, the navigation opening has to be equal to the river width. Because the span of the gate has to be very large in this case, the costs are very high. By using VTS systems near the weir, safe and efficient navigation through two one-lane openings or one two-lane opening can be established. Two one-lane openings are preferred, because a two-lane opening, more expensive due to its large span, does not hold any nautical advantages (Blokland, 1955). The corresponding requirements of a one-lane opening are:

- The width and water depth have to meet the guidelines of the Richtlijn Vaarwegen when the weir is about to open, see Figure 5-4. The crosswind results in the surcharge of 9 m.

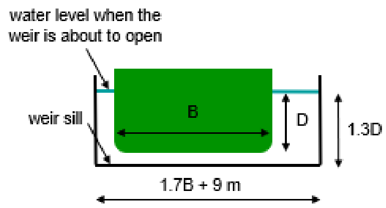


Figure 5-4: The dimensional requirements of a navigation opening in a weir (Rijkswaterstaat, 2017).

- The weir may not be located within 380 m, which is two times the length of the governing vessel, from the bifurcation of the river and the lock canal (Rijkswaterstaat, 2017).
- The air clearance has to be equal to that of bridges, see Figure 4-6, when the weir is about to open.

Lastly, it is worth mentioning that the frequency of opening of weir Belfeld for navigation is dependent on the height of the weir and the location of the set point, see Figure 5-5. Heightening the weir decreases the frequency of opening and thus the added value of a navigation opening through the weir. On top of that, heightening the weir could involve reinforcement of the locks themselves, which is an opportunity to make them suitable for lockage during high water levels. In contrast, shifting the set point location to the theoretical location increases the frequency of opening significantly. Moreover, the head over the locks is smaller in this situation, which speeds up the lockage process.

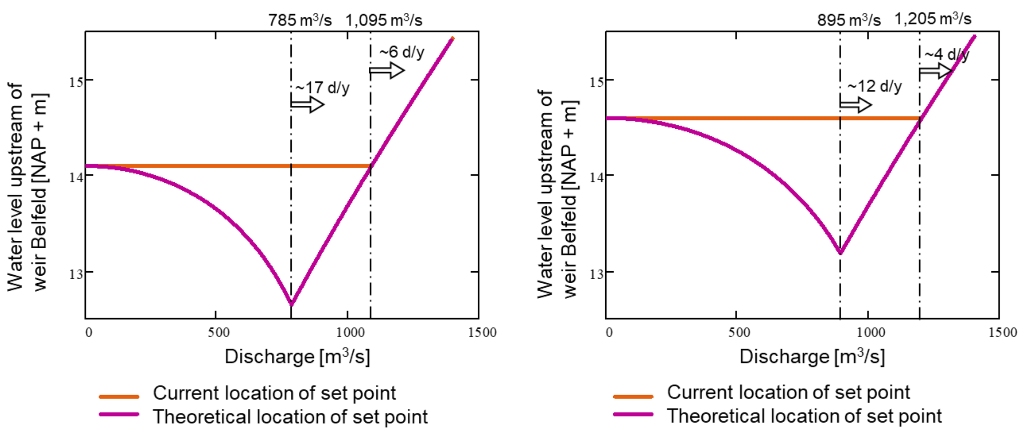


Figure 5-5: Frequency of the weir in open state for a dammed water level of NAP +14.10 m (left) and a dammed water level of NAP +14.60 m (right).

5.2.4 List of requirements

Based on the functions above, a list of requirements is set up, including special attention to the weir adaptivity and feasibility of a navigation opening:

- Construction of the new weir has to be finished before the current weir reaches the end of its lifetime.
- During construction of the new weir, the discharge function of the river and navigation through the locks may not be hampered.
- The total flow opening of the new weir has to be sufficient to discharge the currently governing flood wave as good as the current weir.
- The new weir has to be able to provide the currently desired water level in weir section Belfeld, which is equal to NAP +14.10 m in the zero-discharge situation.
- Fish has to be able to pass the weir by a fish trap.
- The local flow conditions at the weir must not affect the navigation on the Zandmaas and the lock canal.
- The water level control has to be provided on average at least half of the year by gates able to control this accurately.
- If feasible,
    - shifting the location of the set point of weir Belfeld has to be made possible;
    - enlarging the weir's capacity to discharge flood waves with maximum 30% has to be made possible;
    - adapting the dammed water levels ranging from NAP +13.70 m to NAP +17.10 m has to be made possible;
    - navigation of the governing vessel through/over the weir in open state has to be made possible in compliance with the requirements in Richtlijn Vaarwegen;
    - addition of a hydropower station has to be made possible.

5.3 Design synthesis & verification of local alternatives

The design alternatives have, again, been generated by first focussing on the non-adaptive design aspects. One of these aspects is the location of the weir. The required amount of earth-moving activities and the feasibility to enlarge the discharge capacity of the weirs and to add secondary functions in a couple of decades are decisive for the site selection. The second non-adaptive design aspect deals with the concrete superstructure. The dimensions of the weir openings determine the water level control throughout the year and whether vessels can pass through/over the weir in open state. At last, the adaptivity of the weir, more specific the adaptivity of the weir gates, is considered.

5.3.1 Selection of the new weir's location

The location of the new weir is considered on three locations *A*, *B* and *C*, as shown in Figure 5-6. Since no (old) river bends are present in the vicinity of the current weir, see Figure 4-5, constructing the weir outside the area shown in Figure 5-6 is not advantageous. This namely requires a complete new lock complex as well.

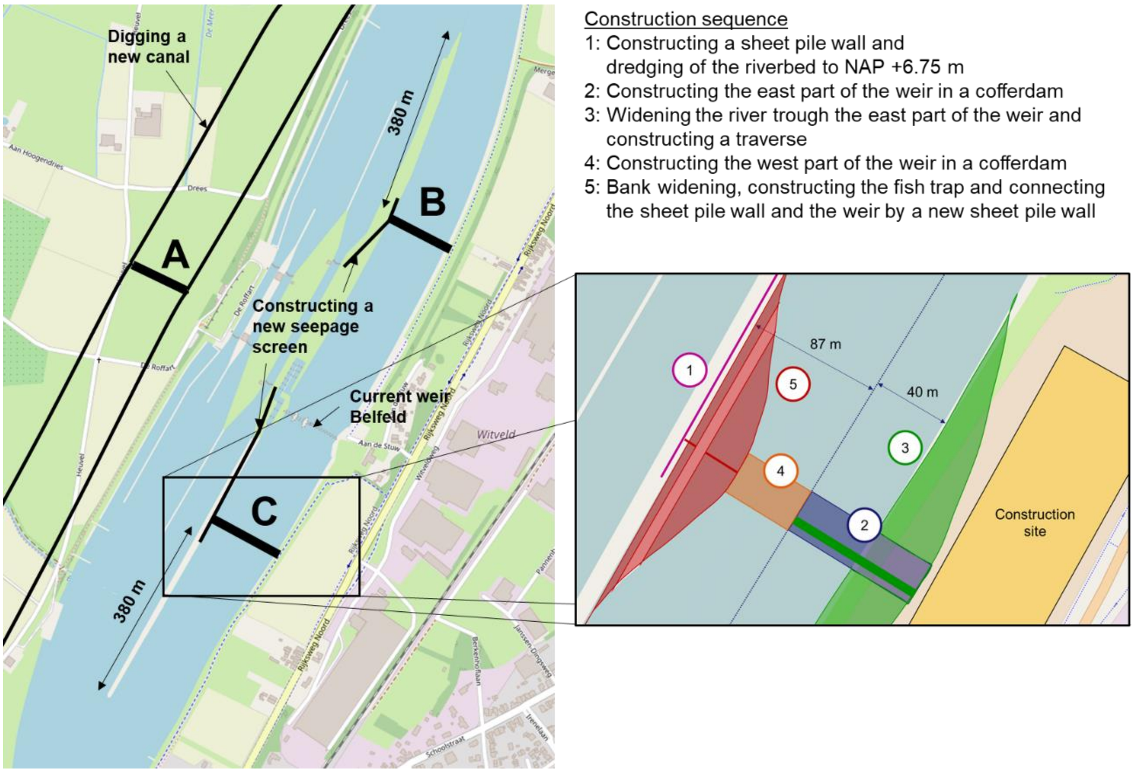


Figure 5-6: Considered locations of new weir Belfeld (left) and construction sequence of the new weir at location C (right) (OpenStreetMap Nederland, n.d.).

To not disturb the calm flow conditions in the waiting area in the canal lock, a new weir at location *A* involves a kilometres long new canal. Construction is relatively easy, since the weir is constructed outside the current river: navigation and river discharge is not hampered by the construction process. On top of that, future widening and, for example, addition of a hydropower station, is easily implemented into the surroundings, since there is much space in this low-lying part of the river valley. On the other hand, the new canal represents a large expense.

Constructing a new weir at location *B* and *C* is more complicated, yet it does not include a kilometre-long canal. Both sites are located sufficiently far from the bifurcations of the river and the lock canal. Looking more into the feasibility of enlarging the weir's discharge capacity, it turns out that widening the weir is cheaper and easier than deepening the weir's sill. If the new weir's sill is elevated at the same elevation as the current weir's sill, the total flow opening has to be widened by 30 m maximum according to Figure 5-3. At both locations this can be implemented, but since location *B* is bordered by a higher-elevated terrace on which buildings are located, location *C* is preferred over location *B*.

A second point of attention is the construction of a weir at location *C*. The construction process proposed at the right of Figure 5-6 provides sufficient discharge capacity of the river during all construction phases. Because of the limited depth of the River Meuse, 4.9 m, a cofferdam is inevitable to construct the pillars in situ. The cofferdam, however, partly obstructs the flow in the river, which is why the construction of the weir itself is split into multiple stages. First, the east part is finished, after which a traverse over this part is needed to reach the cofferdam for the west part of the weir. The prefabricated weir gates can be transported via the River Meuse and be installed from the vessel via the upstream side. Note that the downstream side is unreachable by ship after the start of construction stage 4, thus the downstream bed protection has to be finished before. After complete construction of the weir itself, the discharge opening at the west is not needed anymore. This area is then utilized for the construction of the fish trap and possibly in the future, the hydropower station, to not obstruct later widening of the weir to the east.

With the proposed construction plan in mind, location *C* is selected as site for the new weir Belfeld.

5.3.2 Geometric design of superstructure

A weir mostly consists of multiple weir gates next to each other. Because of the small span between the concrete pillars, the costs of the gates are low. On top of that, specific weir gates can then be assigned to control the water level accurately and/or to provide the passage of vessels during a flood wave. Consequently, the adjacent weir gates do not have to meet these functions, which can result in lower total weir costs. Based on the literature research, performed in Appendix L, a couple of gate types turn out inapplicable for the new weir at Belfeld. Gates moving horizontally or rotating around a vertical axis are not even part of Appendix L, since this way of opening is only possible if one single weir opening spans the entire river width. On top of that, widening of the weir in future is impossible with these type of gates. The following gate types are not considered further as well further:

- roller gates and visor gates. These are economically not competitive since, respectively, no large floating ice masses have to be discharged and no navigation opening of comparable width as in the Nederrijn and Lek is required, 35.4 m versus 48 m.
- drum gates and bear-trap gates. Their maximum applicable height, both less than 4.0 m, is not sufficient to dam the water level at Belfeld. This height is only feasible if the sill of the weir is raised significantly, but this results in a very wide, costly weir.
- sector gates are not adaptive, since operation is performed by regulation of the water pressure in the recess chamber. A higher dammed water level requires complete replacement of the gate and the recess chamber.

Figure 5-7 shows the remaining applicable gate types for the new weir at Belfeld. Their geometric limits are presented in this figure as well. For perspective, the gate height of the current weir Belfeld, 6.05 m, is indicated by the red line.

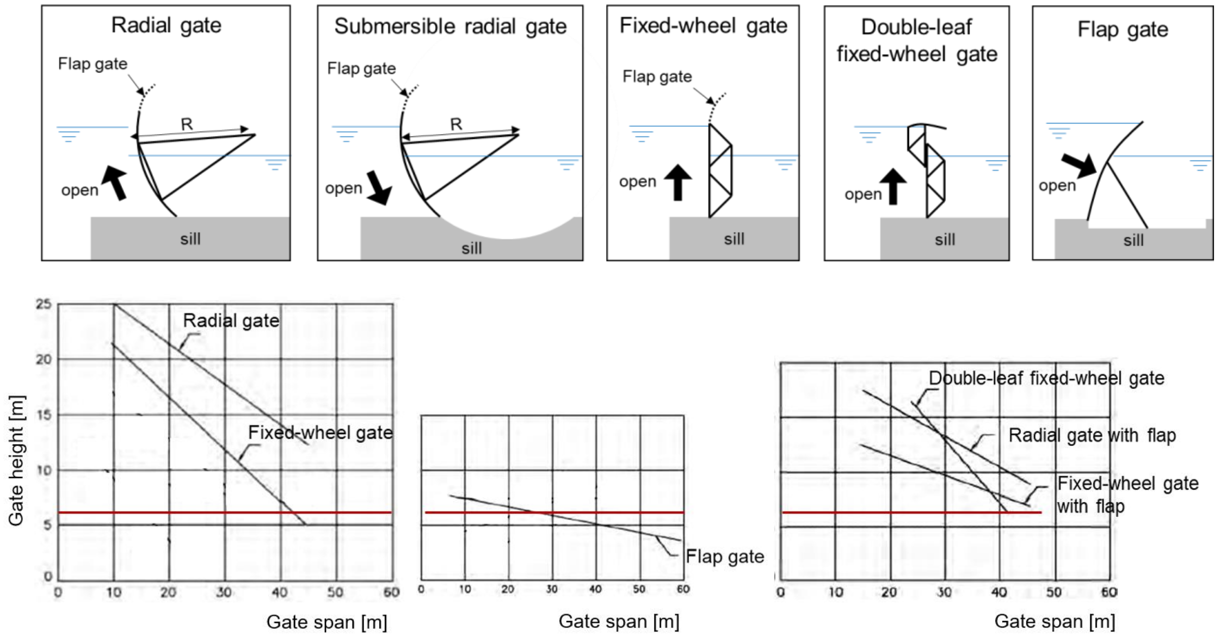


Figure 5-7: Geometric limits divided into underflow gates (left), overflow gates (middle) and over- and underflow gates (right) (Erbisti, 2014).

The applicability of the remaining gate types for accurate water level control and the passage of vessels is shown in the first two columns of Table 5-1. Some gate types are not suitable, indicated by a red X, some are suitable, indicated by a green V, and other are suitable but limit the freedom of choice in the future, indicated in yellow.

Table 5-1: Applicability of gate types for accurate water level control and for passage of vessels and the adaptivity of gate types.

Gate type	Used for accurate water level control	Used for the passage of vessels	Adaptivity of gates to modified desired dammed water levels
Radial gate	X	X	Adaptive by reinforcing the truss and arms to the bearing points + • adding, replacing or heightening the flap gate on top; • heightening the curved skin plate. Adaptivity limited by economical limits: $1.0h_{gate} \leq R_{gate} \leq 1.2h_{gate}$
Radial gate with flap	No adaptivity in a shift of the set point location	X	
Submersible radial gate (with flap)	V	V	
Fixed-wheel gate	X	V	Adaptive by reinforcing the fixed-wheel gate + • adding, replacing or heightening the flap gate on top; • heightening the fixed-wheel gate.
Fixed-wheel gate with flap	No adaptivity in a shift of the set point location	V	
Double-leaf fixed-wheel gate	No adaptivity to a shift of the set point location	V	Adaptive by reinforcing the lower fixed-wheel gate + reinforcing and heightening the upper fixed-wheel gate
Flap gate	V	Limited draught directly after opening of the weir if the location of the set point is shifted	Adaptive by reinforcing and heightening the flap gate. Adaptivity limited by geometric limits, see Figure 5-7.

The limitations of adaptivity are explained below:

- If accurate water level control is achieved by an over- and underflow gate, shown on the right of Figure 5-7, a shift of the set point location to the theoretical location is impossible, since the water level upstream of the weir has to decrease if the discharge increases. This decrease is larger, see Figure 5-5, than a feasible height of the flaps or the upper gate of double-leaf fixed-wheel gates.
- Using a flap gate in the navigation opening if the set point location is located at the theoretical location limits the draught of the navigation opening when the weir is about to open. This is the result of the high-elevated sill, which is required, since the maximum height of a 35.4 m wide flap gate is 5.5 m.

The last column of Table 5-1 addresses the adaptivity of each gate type. On top of that, the adaptivity of the concrete sub- and superstructure, which is worse than the gate adaptivity, determines the adaptivity of the total weir. Investments in 2030 are required to prepare the weir's structure for changing demands and requirements. In general, the concrete sub- and superstructure have to be strengthened to withstand a larger head over the weir. In addition, a couple of specific investments are distinguished per gate type:

- radial gates: reinforcement of the bearing points;
- fixed-wheel gates: reinforcement and raise of lift towers to
    - lift the heightened gates completely above the water level during the governing flood wave;
    - not limit possibly future transport of empty four-layered container vessels.
- flap gates: enlargement of the recess chamber.

If these investments are done, the concrete sub- and superstructure does not limit the adaptivity of the weir. The gates, however, are not unlimited adaptive as well. Geometrically, only flap gates, see Figure 5-7, can be limiting, especially if these are used in the navigable opening with a large span. The geometric limits of fixed-wheel and radial gates come only into play if the dammed water level is increased by meters. From economical viewpoint, radial gates can be limiting. To achieve an economical design, the radius of radial gates has to be within 1.0 to 1.2 times the total height of the gate (Erbisti, 2014). As Figure 5-8 shows, a larger radius requires a wider sill and higher lifting in case of a flood wave and a smaller radius requires more usage of steel, especially for the skin plate.

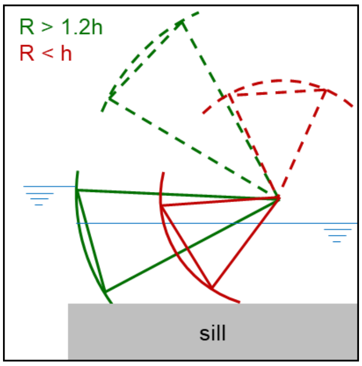
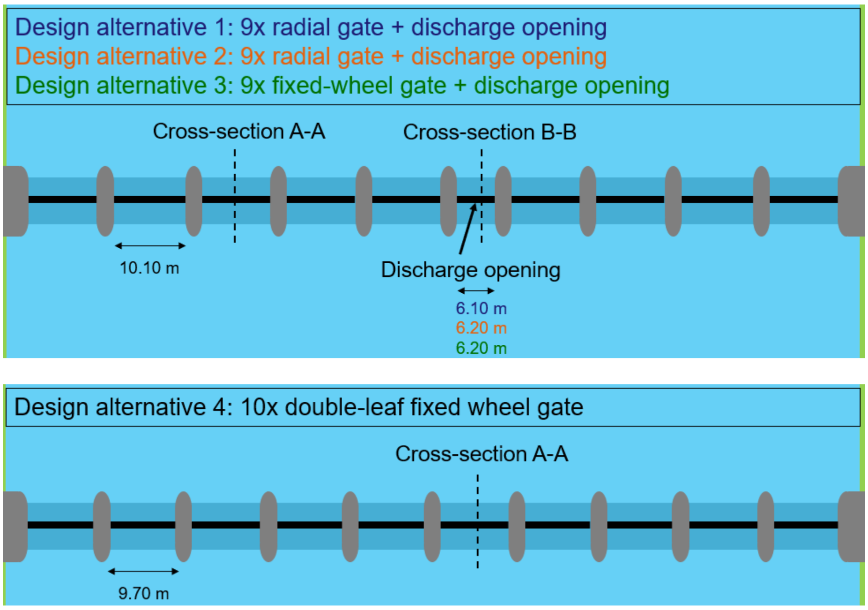


Figure 5-8: Uneconomical designs of radial gates.

5.3.3 Generation of design alternatives

With the help of Table 5-1 and Figure 5-7 a sensitivity analysis with several gate types of varying dimensions and varying elevations of the weir's sill has been executed. Table 5-1 clearly shows that none of the gate type is applicable for accurate water level control and the passage of vessels without limiting the adaptivity. The width of the discharge and navigation opening is related to the set requirements, the width of the other weir openings is selected close to 10 m from an economical viewpoint: smaller spans lead to more concrete pillars, larger spans lead to more expensive gates. The sill's elevation of the new weir is taken equal to the one of the current weir, NAP +8.05 m. A higher elevated sill is not desired, since this involves a wider weir, by which the space for widening in the future is reduced. Construction of a the sill at a lower level is more expensive than constructing an additional weir opening in the future to achieve the same discharge capacity.

Figure 5-9 and Figure 5-10 give the top and cross-sectional overviews of the ten local design alternatives that have been generated. They all meet the requirements and they are distinctive by their own colour. Numbers and elements in black are part of each of the alternatives mentioned in that subfigure.



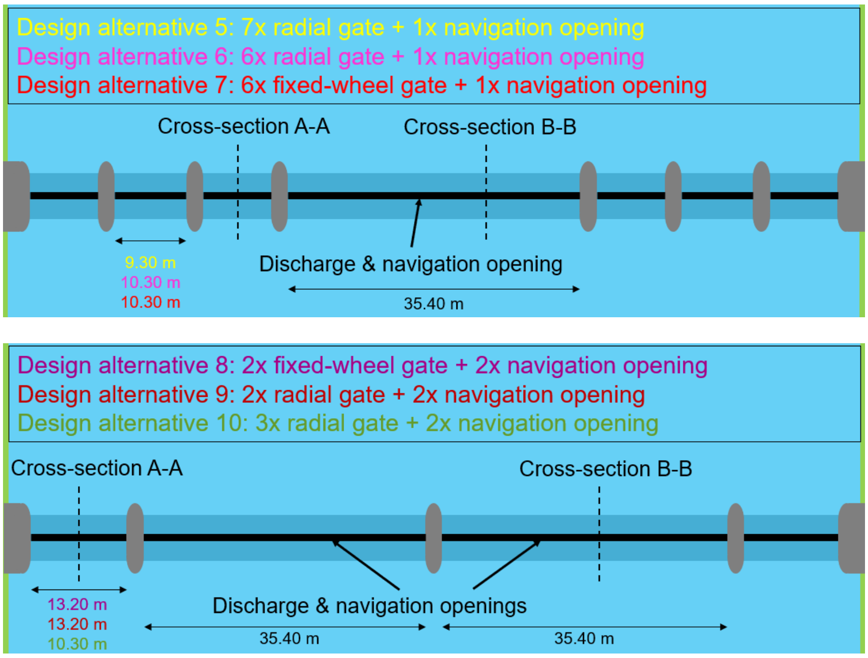
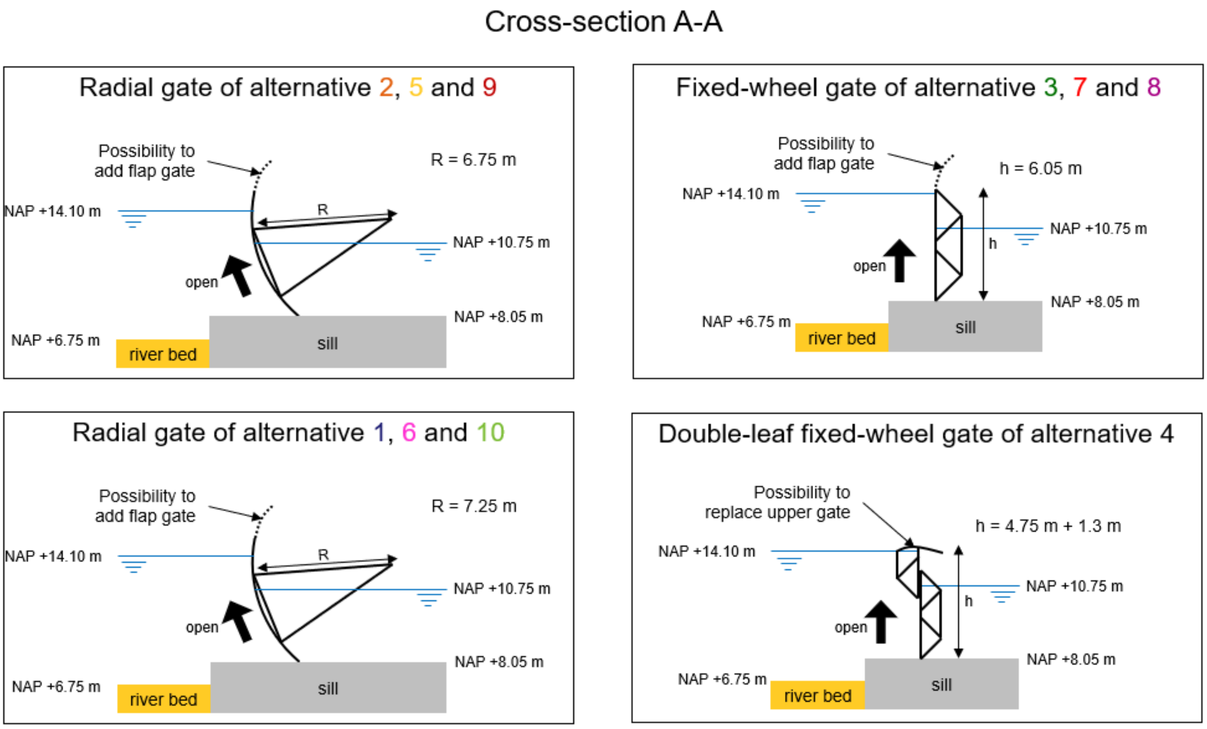


Figure 5-9: Top view of the local design alternatives.



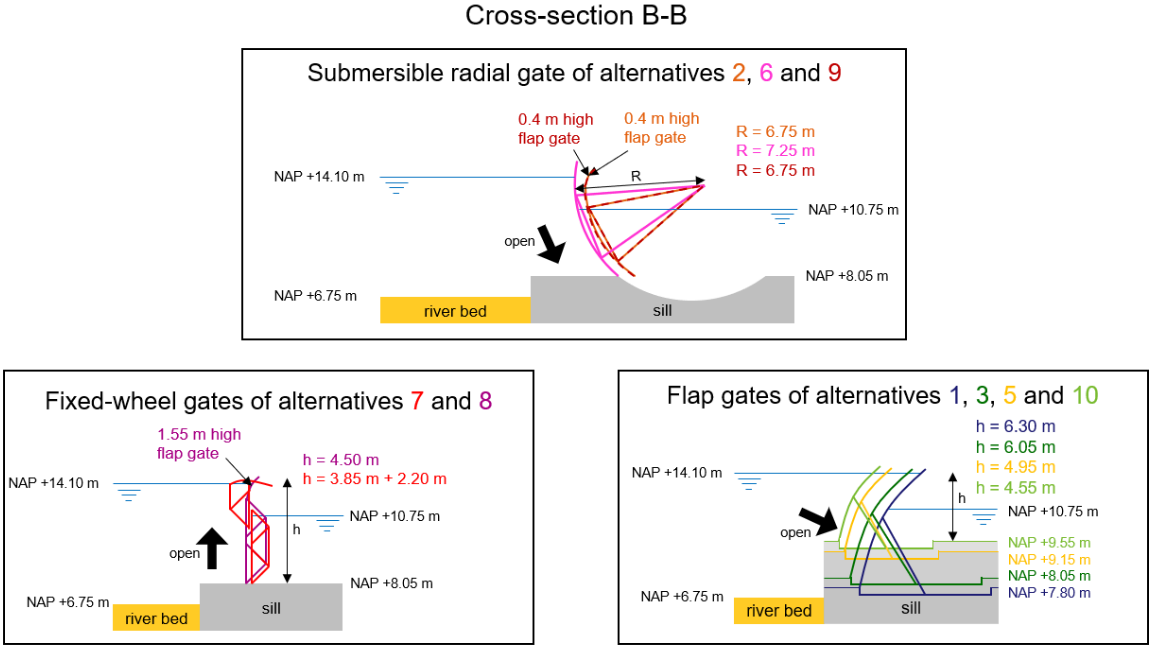


Figure 5-10: Cross-sections of the local design alternatives, in which cross-section A-A is taken at the discharge and/or navigation opening and cross-section B-B is taken at one of the other openings.

5.4 Evaluation of local design alternatives

Evaluation of the ten local design alternatives has been executed in two phases. During the first phase a multi-criteria analysis is executed and in the second phase the adaptivity of the alternatives is addressed. The applied criteria in the first phase are maintainability, operationality, reliability, social impact and navigability (PIANC, 2006). The assessment of these criteria is based on more specific sub-criteria, see Appendix M.1. The score on each criterion ranges from 1 (worst) to 5 (best), which leads to the average scores of each alternative as shown in Table 5-2.

Table 5-2: Unweighted score of the local design alternatives.

Design alternative	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Unweighted score	3.0	4.0	2.0	3.4	2.8	4.2	3.2	2.8	4.0	3.0

Life cycle costs

The life cycle costs of the new weir consist of the initial investment for establishment of the weir, (yearly returning) operation costs, gate replacement costs and adaptation costs. Appendix M.2 presents a complete calculation of these costs. To compare all ten alternatives fairly in the multi-criteria analysis, adaptation costs are excluded, since these are highly depending on the adaptation path that is followed in the upcoming century.

The average total initial investment for weir construction is dependent on the total width of the weir B, the height of the weir h and the head over the weir ΔH. The height and head are approximately constant for all design alternatives, since the sill is predominantly elevated at NAP +8.05 m and the weirs have to dam the water level at NAP +14.10 m. Despite the alternatives differ in number of piers, the total width of all design alternatives is considered to be equal to 130 m for all alternatives. This is justifiable, because the lesser the number of piers, the wider the piers have to be to accommodate the mechanical installations of the wider and heavier gates. Variation in costs between the design alternatives is caused by the difference in applied gate types and the need of lift towers in a number of alternatives.

Summarizing, the average initial investments to establish the weir equal €118.5 mln; the average operational expenditures amount €2.2 mln/year. Subsequently, all expenditures are converted to their present value, according to equation (5.1), to end up with the life cycle costs.

$$PV_{2030} = \sum_{t=0}^{t=100} \frac{(CAPEX + OPEX)_t}{(1+R)^t} \tag{5.1}$$

The present value in year 2030 (PV_{2030}) of the life cycle costs is calculated by applying a discount rate R of 5% to discount the capital expenditures, CAPEX, and operational expenditures, OPEX, in year t, since expenditures in the future are less valuable than expenditures nowadays. It is assumed that the establishment of the weir takes four years and CAPEX, are equally distributed over these years. Replacement of the weir gates is assumed to takes place in the year 2075 by identical weir gates. The resulting unweighted assessment of the local design alternatives is shown in Figure 5-11.

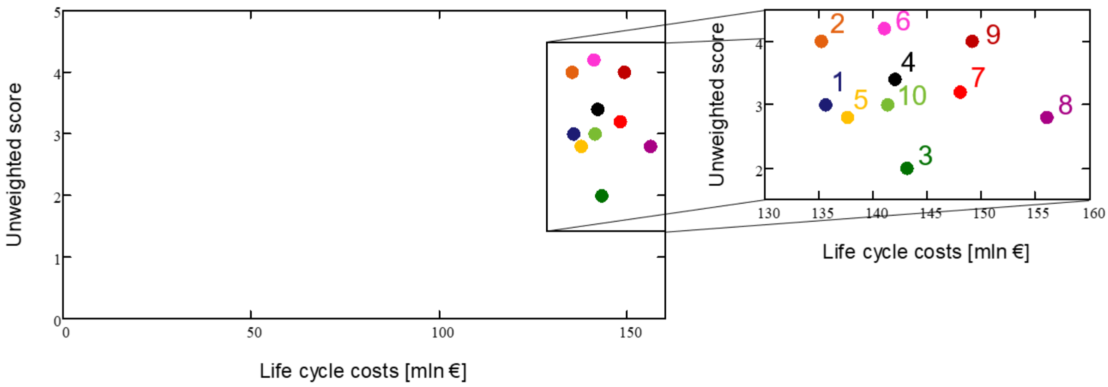


Figure 5-11: Unweighted assessment of the local design alternatives.

Because the weighted score does not differ substantially from the unweighted score, this assessment can be found in Appendix M.3. The weighted score is determined by the weight factors given to the criteria. The sensitivity of the weighted score to the weight factor of navigability is shown in Figure 5-12, since the scores of the alternatives differ clearly on this criterion. If navigability is relatively unimportant, local design alternative 2, which lacks a navigation opening, scores the best. For very large importance, design alternative 9, including two one-lane navigation openings, turns out the best. Nonetheless, such a large weight factor is not expected, hence design alternatives 2 and 6 are the only options which have to be considered in the following evaluation phase. All other design alternatives have higher costs and a lower score than one of these two alternatives.

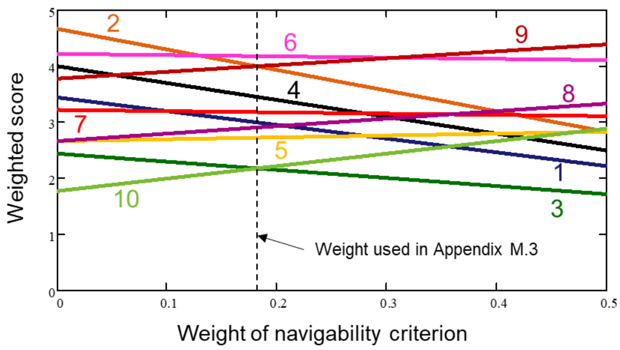


Figure 5-12: Sensitivity of the weighted score to the weight factor of the navigability criterion.

Adaptivity

The adaptivity of the design alternatives is addressed with two sub-criteria:

- the ability to shift the location of the set point;
- the ability to adapt the dammed water level.

With the help of Table 5-1, Figure 5-13 is generated, which shows the adaptivity of all local design alternatives: the gate adaptation costs are plotted against the dammed water level after the adaptation. The maximum adaptivity of a design alternative is indicated by the coloured dots in the right graph. Design alternatives that are not able to shift the location of the set point to the theoretical location are plotted by the dotted lines. The indicated dammed water levels NAP +17.10 m and NAP +15.10 m are the maximum desired dammed water levels in, respectively, the scenarios DRUK and STOOM and the scenario WARM.

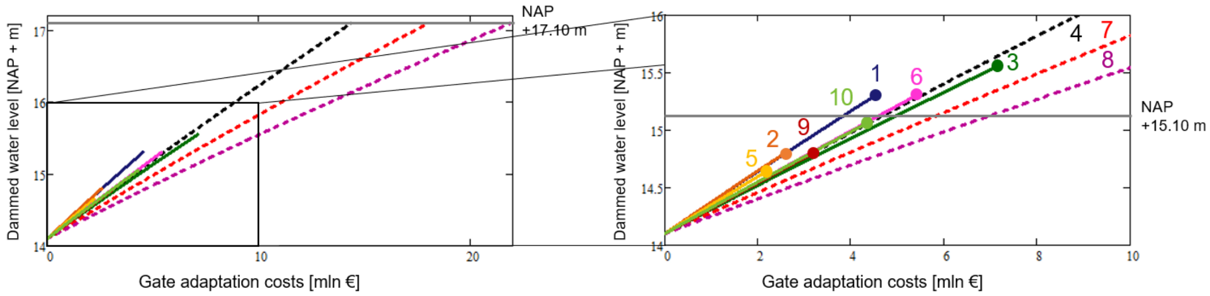


Figure 5-13: Adaptivity of the local design alternatives regarding the dammed water level and the location of the set point.

These graphs include a number of remarkable aspects:

- The largest adaptivity regarding the dammed water levels is obtained by a weir consisting only of fixed-wheel gates, provided that the strength and height of the, in 2030 constructed, lift towers does not limit the adaptivity. The initial investment in the lift towers is an eminent example of non-adaptivity, since only after the lifetime of the weirs, it turns out if this investment has been efficient. Moreover, these weirs are not able to control the water levels accurately after a shift of the location of the set point to the theoretical location. Thus, the large adaptivity regarding the dammed water level goes at the expense of the adaptivity regarding the location of the set point.
- The variation of the gate adaptation costs between the alternatives is small. On top of that, the absolute value of the gate adaptation costs is low compared to the life cycle costs of the weir.
- The adaptivity of the alternatives 2, 5 and 9 seems worse than that of 1, 6 and 10 regarding the dammed water levels, because the first three alternatives consist of radial gates of smaller radii, see Figure 5-10. However, thanks to these smaller radii, an economical gate design is still achieved if a decrease of the dammed water level to NAP +13.70 m is desired. This is not achievable if design alternative 1, 6 or 10 is selected.

Focussing on design alternatives 2 and 6, Table 5-3 compares their weir adaptivity with the adaptation scheme set up in the regional design analysis, see Table 4-3. If the weir adaptivity is larger than the maximum desired adaptivity in that scenario in that time period, the box is marked green; if not, it is marked yellow and regional measures are required to serve that specific purpose.

Table 5-3: Feasible weir adaptations of local design alternatives 2 and 6.

Legend (A = first adaptation measure; B = second adaptation measure)
A ∪ B = union (A or B)

<table>
<tr><th>Purpose</th><th>Scenario (year) in which the purpose applies</th><th colspan="2">Weir Belfeld adaptation measure in local design alternative 2</th><th colspan="2">Weir Belfeld adaptation measure in local design alternative 6</th></tr>
<tr><td rowspan="2">Increasing the discharge capacity of the river valley</td><td>DRUK (2050)</td><td rowspan="2">Enlarging the flow opening</td><td>By 10%</td><td rowspan="2">Enlarging the flow opening</td><td>By 10%</td></tr>
<tr><td>STOOM (2050, 2100)
WARM (2100)</td><td>By 15%</td><td>By 15%</td></tr>
<tr><td rowspan="3">Preventing more frequent flooding of the river valley</td><td>DRUK (2050)</td><td rowspan="2">Enlarging the flow opening</td><td>By 10%</td><td rowspan="2">Enlarging the flow opening</td><td>By 10%</td></tr>
<tr><td>STOOM (2050)</td><td>By 15%</td><td>By 15%</td></tr>
<tr><td></td><td colspan="2">∪
shifting the set point location</td><td colspan="2">∪
shifting the set point location</td></tr>
<tr><td>Accommodating higher container vessels</td><td>DRUK (2050)
STOOM (2050)</td><td colspan="2">Lowering to maximum NAP +13.70 m
∪
shifting the set point location</td><td colspan="2">Shifting the set point location</td></tr>
<tr><td rowspan="2">Providing more freshwater storage</td><td>DRUK (2050, 2075)
STOOM (2075, 2100)
WARM (2075, 2100)</td><td colspan="2">Heightening to maximum NAP +14.80 m</td><td colspan="2">Heightening to maximum NAP +15.10 m</td></tr>
<tr><td>DRUK (2100)</td><td colspan="2">Heightening to maximum NAP +14.80 m</td><td colspan="2">Heightening to maximum NAP +15.30 m</td></tr>
<tr><td>Increasing the dynamics in dedicated natural areas</td><td>DRUK (2050)</td><td colspan="2">Shifting the set point location</td><td colspan="2">Shifting the set point location</td></tr>
<tr><td>Improving the accessibility of the Prins Willem-Alexanderport</td><td>DRUK (2100)</td><td colspan="2">Heightening to maximum NAP +14.80 m</td><td colspan="2">Heightening to maximum NAP +15.10 m</td></tr>
<tr><td>Providing more frequent flooding of the river valley</td><td>WARM (2075, 2100)</td><td colspan="2">Heightening to maximum NAP +14.80 m</td><td colspan="2">Heightening to maximum NAP +15.10 m</td></tr>
</table>

Table 5-3 focusses on the performance of the design alternatives. Besides, the present value of the life cycle costs of both alternatives can be decisive as well. The total life cycle costs of the alternatives are dependent on the adaptations, which are applied during the lifetime of weir Belfeld. Therefore, ten adaptation paths have been set up, which represent a wide range of possibly useful adaptations to weir Belfeld. The ten adaptation paths are all allocated to the most logical of the four delta scenarios, which does not imply that an adaptation path cannot occur in one of the other scenarios. The life cycle costs for both alternatives are elaborated in Appendix M.2 for all adaptation paths; the summary is shown in Figure 5-14. If a bar is outlined with an arrow on top, it means that the weir adaptivity of the alternative is smaller than the demanded adaptivity in that specific adaptation path. Thus, regional adaptation measures are required in this case, which results in higher total costs.

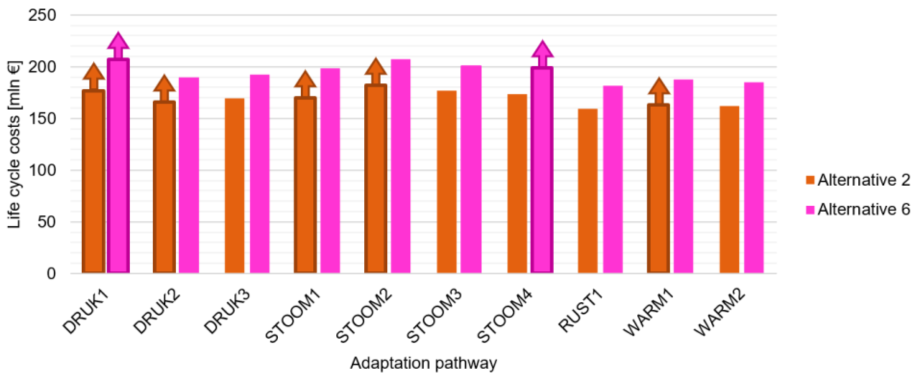


Figure 5-14: Life cycle costs for the local design alternatives 2 and 6 in the ten adaptation paths.

The life cycle costs of design alternative 6 are, on average for all ten adaptation paths, 15% larger than the life cycle costs of design alternative 2. This is explained by the additional initial investment required in the non-adaptive sub- and superstructure during establishment of the weir: in alternative 2 the concrete parts have to be able to withstand a maximum water head of 4.05 m, in alternative 6 the maximum water head is 4.55 m, since the weir gates can be adapted to a 0.5 m larger height.

5.5 Conceptual design of the adaptive weir Belfeld

Based on Table 5-3 and Figure 5-14, design alternative 6 has been selected as weir Belfeld design. As shown in Table 5-4, by selecting this alternative, the weir can be heightened with maximum 1.20 m, which is sufficient in all scenarios, except in the scenario DRUK from the year 2100. The adaptivity is therefore substantially better in comparison with design alternative 2, of which heightening is limiting the freedom of choice in three of the four scenarios. Lowering the dammed water level is economically not feasible by the selection of alternative 6, thus to enable navigation of four-layered empty container vessels, bridges have to be raised. However, the raise can be diminished by a shift of the set point location.

Table 5-4: Adaptivity regarding the dammed water level of design alternative 2 and 6.

Scenario	*Local design alternative 2*	*Local design alternative 6*
DRUK	Heightening limited by the weir from the year 2050	Lowering not possible and heightening limited by the weir from the year 2100
STOOM	Heightening limited by the weir from the year 2050	Lowering not possible
RUST	Sufficient adaptivity	Sufficient adaptivity
WARM	Heightening limited by the weir from the year 2075	Sufficient adaptivity

Regarding the shift of the location of the set point and the increase of discharge capacity, the weir adaptivity meets the maximum desired adaptivity in all scenarios. The location of the set point is easily shifted by adapting the management of the radial gates and the increase in discharge capacity is obtained by constructing identical weir openings next to the existing weir openings. On top of that, the navigation opening is beneficial: by shifting the set point location to the theoretical location, this opening enables navigation on 17 days per year on average, which is much more often than in the current situation, see Figure 5-5. If the frequency of opening is decreased in the future by for example heightening the weir, the navigation opening can be possibly replaced by three weir openings, of which one is a discharge opening. In other words, design alternative 6 can then be converted to design alternative 2 with ease.

In summary, the conceptual design of the adaptive weir Belfeld is presented on the next page in Figure 5-15, including the possible adaptation measures. To prepare the concrete sub- and superstructure for an additional water head of 1.20 m, an additional initial investment of approximately €35 mln is required for construction of the weir. This lead to a total initial investment of €150 mln to which the operational expenditures and costs of adaptation measure have to be added to end up with the total life cycle costs.

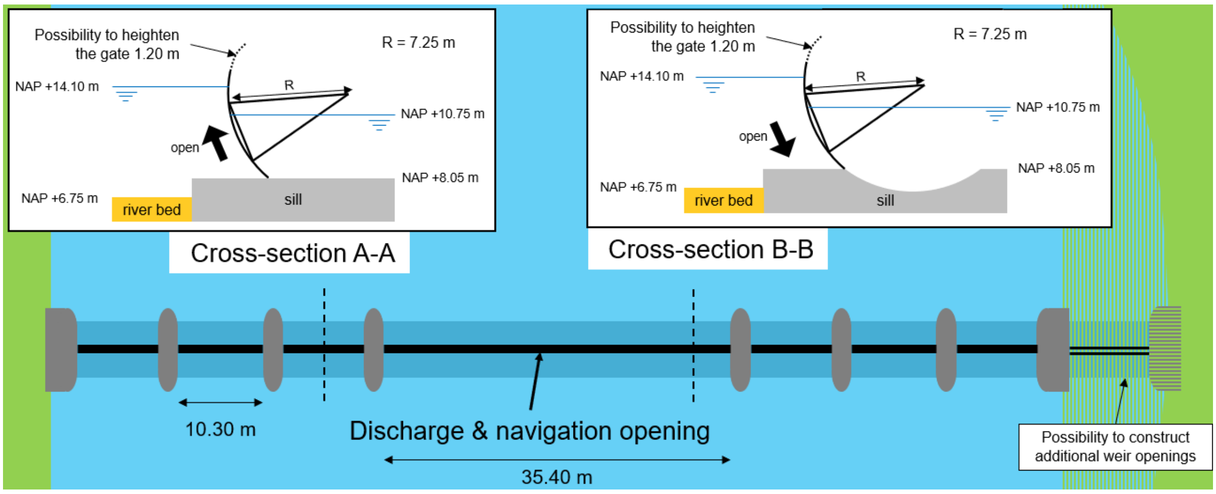
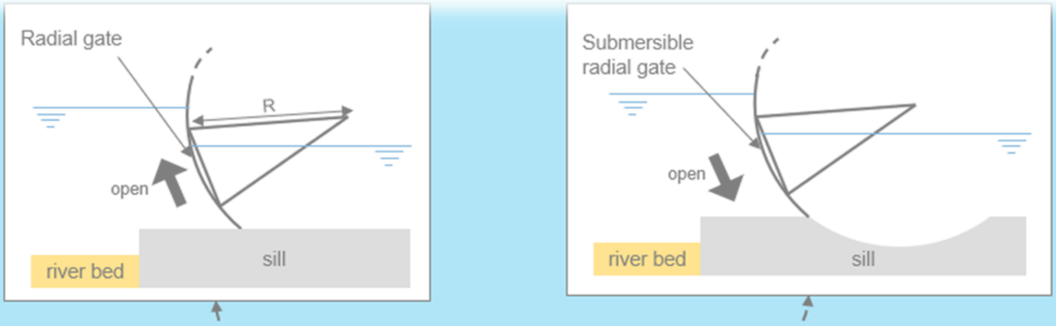


Figure 5-15: Overview of the proposed adaptive weir Belfeld.



6 Conclusions & recommendations

This chapter presents the conclusions and recommendations of this study in Section 6.1 and 6.2, respectively.

6.1 Conclusions

First, the conclusions of this study dealing with the adaptivity of the River Meuse on the global design level are listed. Thereafter, the adaptation scheme of weir section Belfeld and the adaptive design of weir Belfeld are presented, which have been set up in the regional and local design level. Regarding the adaptivity of the River Meuse, the following conclusions have been drawn from the global design level:

- The benefit of weir adaptivity is spatially dependent and, thus, varying between weir sections. Current (international) regulations and the fact that the surrounding area has adjusted to the current water system restrain the adaptivity of weir sections to cope with future developments. In the River Meuse, the section Linne-Belfeld is an exception, since commercial navigation in weir section Roermond can be restricted to the port of Roermond exclusively. The Maasplassen area is then fully allocated to recreation, ecology and freshwater storage. As nowadays, all commercial vessels can pass weir section Roermond via the parallel Lateral Canal, which is part of weir section Belfeld.
- Because the crest level of embankments and foundations of buildings are based on the current dammed water levels and groundwater table, respectively, replacement of the weirs in 2030 by weirs at the same location and the same height is an appropriate replacement strategy. For the same reasons, removal of weir Roermond without constructing a new weir is infeasible for the year 2030.

An adaptive weir has been proposed to replace the current weir Belfeld in this study, at a location just upstream of the current weir. The adaptive design consists of seven radial gates next to each other. A 35.4 m wide submersible radial gate is applied for accurate water level control and the passage of vessels during a flood wave, six 10.3 m wide radial gates close off the other weir openings. This weir design follows after the regional and local design analysis:

- The adaptation scheme shown in Table 6-1 gives an overview of adaptations required to meet the changed boundary conditions and requirements. To serve specific purposes in the future, regional and/or weir adaptation measures have to be taken. Which measure is executed, depends on the scenario and the maximum adaptivity of the weir. Besides, adaptation measures can involve additional measures if contradicting purposes apply at the same time. By the design of an adaptive weir more freedom of choice is offered to the future waterway managers: regional measures that involve undesired implications can be discarded in future instead of that they are inevitable.

Table 6-1: Adaptation scheme of weir section Belfeld after construction of the proposed design alternative.

Legend (A = regional adaptation measures; B = weir adaptation measures)
A ∩ B = intersection (A and B)
A ∪ B = union (A or B)
A ⊃ B = superset [(only A) or (minimized A + B)]

Purpose	*Scenario (year) in which the purpose applies*	*Regional adaptation measures*	*Binary operator*	*Weir Belfeld adaptation measures*	
Increasing the discharge capacity of the river valley	DRUK (2050	'Room for the River' measures	⊃	Enlarging the flow opening	By 10%
	STOOM (2050, 2100) WARM (2100)				By 15%
Preventing more frequent flooding of the river valley	DRUK (2050)	Raising the main channel embankments ∪ dredging the main channel	∪	Enlarging the flow opening ∪ shifting the set point location	By 10%
	STOOM (2050)				By 15%
Accommodating higher container vessels	DRUK (2050) STOOM (2050)	Raising bridges on the Maasroute	⊃	Shifting the set point location	
Providing more freshwater storage	DRUK (2050, 2075) STOOM (2075, 2100) WARM (2075, 2100)	Dredging a new lake ∪ enlarging an existing lake	∪	Heightening to maximum	NAP +15.10 m
	DRUK (2100)				NAP +15.30 m
Increasing the dynamics in dedicated natural areas	DRUK (2050)	-	-	Shifting the set point location	
Accommodating larger vessels to the Prins Willem-Alexanderport	DRUK (2075)	Deepening the Prins Willem-Alexanderport	-	-	
Improving the accessibility of the Prins Willem-Alexanderport	DRUK (2100)	Deepening the Prins Willem-Alexanderport	∩	Removal of weir Roermond ∪ replacing weir Roermond upstream	
			⊃	Heightening to maximum NAP +15.30 m	
Providing more frequent flooding of the river valley	WARM (2075, 2100)	Lowering the river valley	∪	Heightening to maximum NAP +15.10 m	

- The adaptivity of weir Belfeld enables to dam the water level to maximum NAP +15.30 m in the future, 1.2 m higher than the current dammed water level of weir section Belfeld. The concrete substructure is already designed in 2030 to withstand this larger water head; only heightening the superstructure and the radial gates is needed then in future. A larger flood wave in the future can be discharged by constructing an additional weir opening next to the designed weir. More weir adaptivity is provided by adjusting the management of the radial gates: in this way, the location of the set point, the location at which the dammed water level is maintained at its target value regardless of the discharge, can be shifted throughout the weir section. The frequency of an open weir can be increased from 6 to 17 days per year, which makes the weir design, including a navigation opening, more beneficial.
- The adaptivity of weir Belfeld requires an additional initial investment of approximately €35 mln, leading to a total of €150 mln. This additional investment is used to prepare the non-adaptive substructure to the possibly higher dammed water level in the future. The proposed weir design is sufficiently adaptive to serve the purposes in all scenarios, except in the scenario DRUK from the year 2100 and if higher container vessels have to be accommodated on the River Meuse. To serve

the latter purpose, bridge heightening is inevitable, since lowering the dammed water level is not possible with the proposed weir design. Although, the required bridge heightening can be decreased by a shift of the set point location.

- A method of using adaptation schemes for designing an adaptive weir has been developed for weir Belfeld. The method and approach is applicable for every weir in order to give the asset-owner a full overview of measures to be taken in the future lifetime of the asset. Design choices of today can enable easy adaptations in the future.

6.2 Recommendations

The enumeration below advices on further research subjects and the procedure to obtain a more detailed adaptive weir Belfeld:

- To put adaptivity into practise, the entire system of the River Meuse has to be considered. Adaptation schemes have to be developed for each weir section to generate designs for all weirs in the river. The performance of each section should agree and complement on global functions, such as navigation, water discharge and freshwater storage.
- This research can be improved by involving the asset-owner of the weirs and the waterway network, Rijkswaterstaat, and other stakeholders, for instance the users of the River Meuse. Their knowledge of the water system today can be employed to obtain quantitative adaptation schemes. Furthermore, the current greatly simplified geohydrological analysis has to be improved with spatial-dependent and time-dependent modelling software.
- The design of the adaptive weir Belfeld has to be elaborated by structural calculations; only a geometric design is presented in this research. During the structural design, adaptivity has to be kept in mind as well: continuously it has to be assessed if an initial investment is needed or an adaptation can be made in the future.
- The dammed water levels have to be researched in transient flow conditions. If the set point is not located at the weir itself, the combination of the downstream weir height and the discharge over the upstream weir determines the dammed water level at each location. In this case, there is a lag between the moment of weir operation and the water level change at the location of the set point. During a continuously varying river discharge, the position of the weir gates has to be adjusted continuously. Unified operation of the weirs is required to prevent counteracting weir operations and up and down swaying dammed water levels.
- Further research has to be performed to the replacement of weir Roermond by a new weir at the Louis Raemaekersbridge. This alternative enables vessels to navigate from the main navigation route on the River Meuse to the port of Roermond without lockage. Disadvantageous aspects are the more complicated weir construction and the required additional lock for recreational vessels.

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Appendix A
Delta scenarios

The four delta scenarios DRUK, STOOM, RUST and WARM are discussed below. The developments in the scenarios can all be traced back to the rate of climate change and the socioeconomic developments. In literature, the delta scenarios have been elaborated on (inter)national scale level. To apply the scenarios during the design of an adaptive weir, the scenario-dependent developments have to be known on regional scale level. The translation of the developments on (inter)national scale level to regional scale level is performed in this appendix. As starting point, a combination of Figure 1-2 and Figure 4-10 is shown below.

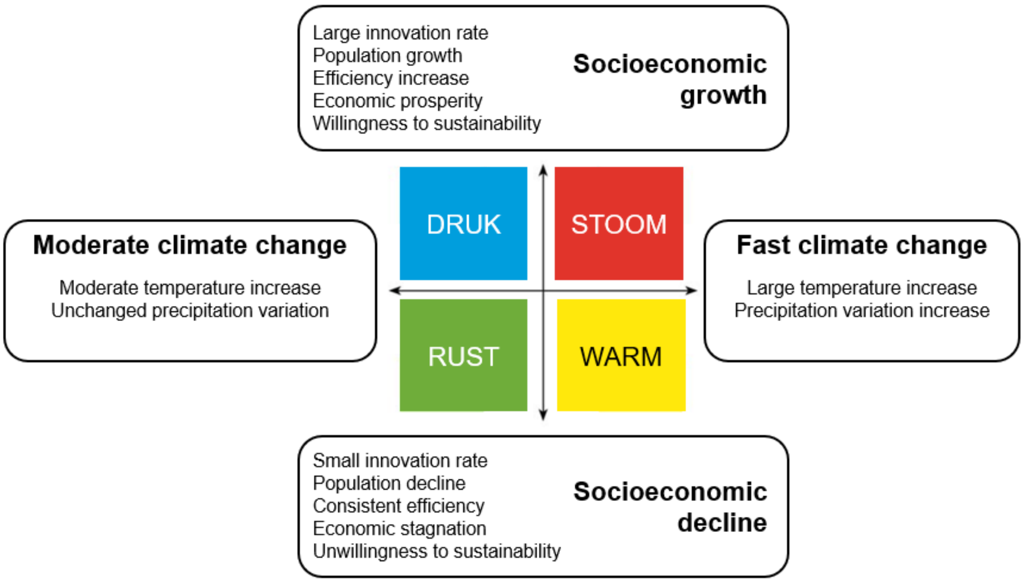

Figure A-1: Schematic overview of the (inter)national scenario developments (Wolters, Van den Born, Dammers, & Reinhard, 2018).

A.1 Regional scenario developments

The translation of the scenario developments to the regional developments is exemplified below per (sub)function. Each explanation starts with an overview of the (inter)national scenario-dependent developments which are used to derive the regional developments related to that specific (sub)function. The colours of each (sub)function agree with the colours in Figure 4-10. Thereafter, a textual explanation and a table illustrate the regional development per scenario.

Flexibility to groundwater changes

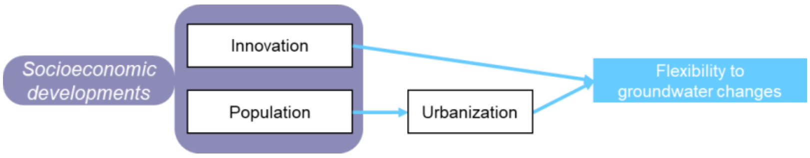

Figure A-2: Translation of the (inter)national scenario developments to the development of the flexibility to groundwater changes.

DRUK Population keeps increasing in this scenario. The economic growth attracts people to the cities, in first instance in the Randstad, later on scattered over the entire country. The population increase, however, is captured within the cities themselves or new clustered villages. The ecological value of rivers is recognized, so residing in river valleys is discouraged. Technological developments and restructuring new districts in the cities makes them flexible to maximum a 3.0 m modification of the dammed water levels.

STOOM The increasing population benefits from the economic prosperity in this scenario. The attractivity of watery and woody areas spreads the wealthy people to the outer urban areas. Urbanization is widespread and well-developed infrastructure provides fast connections between these areas. Therefore, infrastructure and more residences are built in the river valley area, not paying attention to the limits which are put on the groundwater table. Therefore, the dammed water levels can be changed with a maximum of 0.5 m.

RUST The peripheral areas perceive the largest consequences of the population decline. The employment opportunities in these regions are limited, inhabitants move to the larger cities where all social services are still provided. Old economic and residential districts are reused for living, working and recreating. The increase of natural area like parks increases the adaptivity, so maximum a 3.0 m change of the dammed water levels is allowed.

WARM Comparable with scenario RUST, the decline of population results in peripheral areas to vacant housing. The solution, however, differs; new residences are built in the outer districts, as there is enough space. This leads to impoverishment and vacant housing and offices in the current city centres. Demolition of these buildings is thought to be too expensive. The flexibility to a change of the groundwater table stays the same; the maximum allowable modification of the dammed water levels is 1.0 m.

Table A-1 shows the flexibility to groundwater changes per scenario with respect to the reference scenario in 2030.

Table A-1: Development of the flexibility to groundwater changes per scenario (Wolters, et al., 2018).

Scenario	*Innovation*	*Population*	*Urbanization*	*Flexibility to groundwater changes*
DRUK	Large rate	Increase	Clustered	***Increase***
STOOM	Large rate	Increase	Spread	***Decrease***
RUST	Small rate	Decline	Clustered	***Increase***
WARM	Small rate	Decline	Spread	***Unchanged***

Surface water use by agriculture

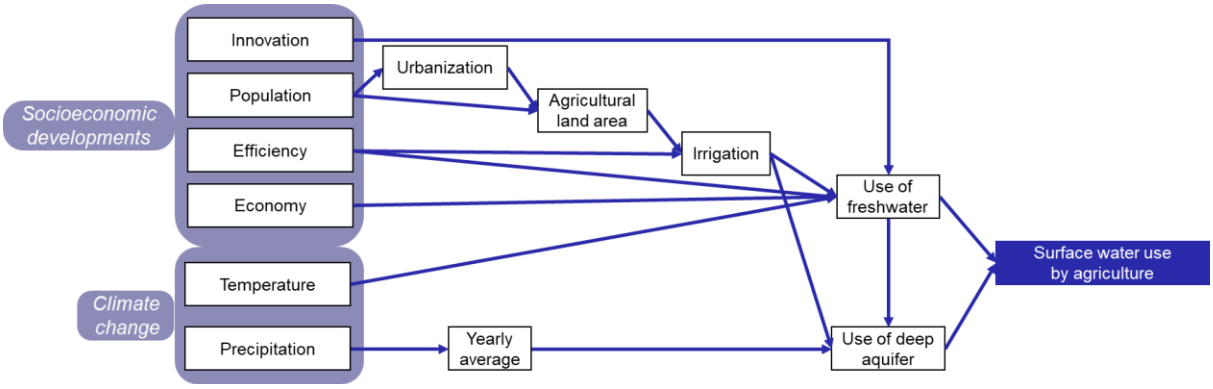

Figure A-3: Translation of the (inter)national scenario developments to the development of the surface water use by agriculture.

DRUK Although the population increase takes place in the existing cities, the agricultural acreage decrease. The competitive position of the Dutch agriculture, however, is maintained by the efficient hinterland connections of the sea ports and the application of innovations. The innovations avert a larger freshwater demand. Fresh water of good quality is required, so especially water from the deep aquifer, which stays supplied by the increasing yearly average precipitation, is extracted. In the end, the use of surface water does not change significantly.

STOOM The pressure on the agricultural sector raises in this scenario, because of the more intense dry periods and the population increase. The spread urbanization causes decrease of the agricultural acreage. Investments are done in the efficiency, among which the establishment of extra irrigation systems. These are needed to bridge the dry periods, in which the increased temperature provides favourable circumstances for cultivation. Summarizing, the use of fresh water in summer is that large that more surface water has to be stored.

RUST Internationally the agricultural sector cannot compete, so the focus is shifted towards regional and local demand. Of all scenarios, the surface water use by agriculture in this scenario is the smallest. The agricultural acreage stays the same, since population declines and new residences are built within the current cities. Innovations are rare, because the small economic growth does not provoke these. The demand of fresh water only increases a little, which can be easily extracted from the deep aquifer. Eventually, the surface water use by the agricultural sector even decreases.

WARM The products of agriculture change due to the fast climate change; Mediterranean crops better deal with the drought in summer. The position on the international market deteriorates, so the sector focusses more on regional sale. Just like in scenario RUST, population declines and urbanization leads to only limited expansion of cities. Due to the fast climate change and lack of innovations, the growth of irrigated area is enormous. Therefore, more surface water has to be stored in summer to be used by agriculture.

Table A-2 shows the surface water use by agriculture per scenario with respect to the reference scenario in 2030.

Table A-2: Development of the surface water use by agriculture per scenario (Klijn, Van Velzen, Ter Maat, & Hunink, 2012) (Wolters, et al., 2018).

Scenario	Innovation & Efficiency	Popu-lation	Economy	Temperature	Yearly average precipitation
DRUK	Large increase	Increase	Prosperity	Small increase	Increase
STOOM	Large increase	Increase	Prosperity	Large increase	Increase
RUST	Small increase	Decline	Stagnation	Small increase	Increase
WARM	Small increase	Decline	Stagnation	Large increase	Increase

Scenario	Urbanization	Agricultural land area	Irrigation	Use of fresh water	Use of deep aquifer	Surface water use by agriculture
DRUK	Clustered	Decrease	Small increase	Small increase	Increase	Equal
STOOM	Spread	Decrease	Large increase	Large increase	Increase	Increase
RUST	Clustered	Unchanged	Small increase	Small increase	Increase	Decrease
WARM	Spread	Unchanged	Large increase	Large increase	Increase	Increase

Surface water use for drinking water production

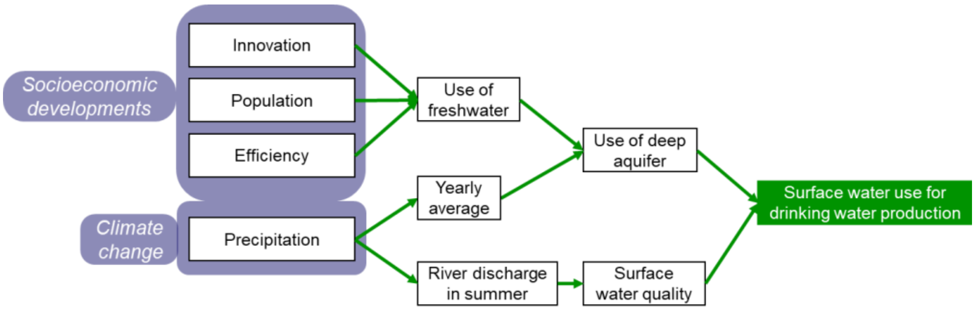

Figure A-4: Translation of the (inter)national scenario developments to the development of the surface water use for drinking water production.

DRUK Due to the population growth, the use of fresh water would increase strongly. This is counteracted by innovations and investments in efficiency. The water production at Heel has a permit to enlarge the production, it is, however, technically hindered. The large innovation rate in this scenario lead to an extended capacity of the water treatment and intake facility. Since the extreme river discharge in summer does not decrease, problems with water quality will not grow. The result is a small increase of the surface water use for drinking water production.

STOOM The base socioeconomic development in scenario STOOM are the same as in scenario DRUK. The river discharge in summer, however, is reduced in this scenario. Water quality problems become more frequent in summer, during which most drinking water is needed. Because the yearly average precipitation increases, the deep aquifer is not depleted by human extraction. The good quality water in this aquifer (Van der Aa, Tangena, Wuijts, & De Nijs, 2015) is therefore used in this scenario above the surface water.

RUST Until 2050 the demand to drinking water production stays the same. This is the result of stabilizing population growth and little innovations. After 2050, water saving measures lead to a decrease of the drinking water demand. Since the deep aquifer contains water of good quality and is supplied by more precipitation averagely, the water from the deep aquifer is sufficient to provide in the drinking water demand. The drinking water production at Heel diminishes.

WARM The fast climate change results in a smaller discharge in summer, just like in scenario STOOM. Therefore, the quality of surface water is insufficient in summer to produce drinking water from it. Besides, the stockpile of water in the deep aquifer is sufficiently large to provide drinking water for a declining population.

Table A-3 shows the surface water use for drinking water production per scenario with respect to the reference situation in 2030. The focus lies on the intake in summer, since this is the critical period from the viewpoint of surface water use.

Table A-3: Development of the surface water use for drinking water production per scenario (Snippen, Mens, Hunink, & Ter Maat, 2016) (Wolters, et al., 2018).

Scenario	*Innovation & Efficiency*	*Population*	*Yearly average precipitation*	*Use of fresh water*
DRUK	Large increase	Increase	Increase	Small increase
STOOM	Large increase	Increase	Increase	Large increase
RUST	Small increase	Decline	Increase	Small increase
WARM	Small increase	Decline	Increase	Large increase

Scenario	*River discharge in summer*	*Surface water quality*	*Use of deep aquifer*	*Surface water use for drinking water production*
DRUK	Unchanged	Equal	Small increase	***Increase***
STOOM	Decrease	Decrease	Large increase	***Stop***
RUST	Unchanged	Equal	Small decrease	***Decrease***
WARM	Decrease	Decrease	Equal	***Stop***

Surface water use by industry

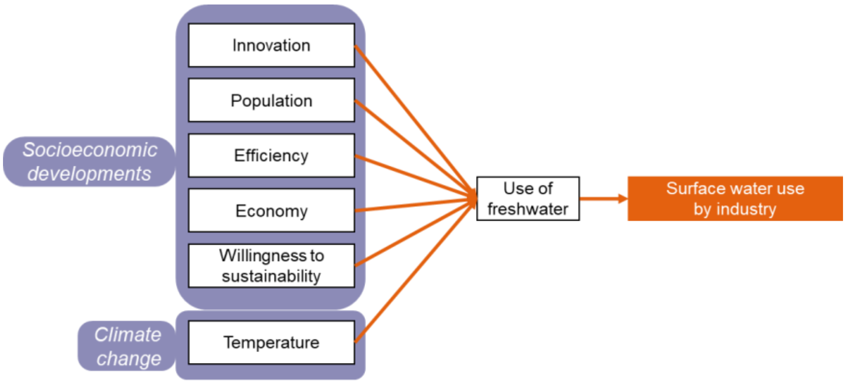

Figure A-5: Translation of the (inter)national scenario developments to the development of the surface water use by industry.

The delta scenarios, updated in 2017, split the surface water demand of the industry in two categories: cooling water for energy production and process and cooling water for other industry. In the first category, the transition to renewable energy sources is taken as an autonomous development; in 2030 wind and solar energy are the dominant energy sources in all scenarios. Looking at the evolutions since 2017, this is not realistic. Therefore, this section sticks not to the delta scenarios.

DRUK — The economic prosperity and population growth result in an increase of the production of industry. Innovation and investments in efficiency are large as well. Due to the fast transition to renewable energy sources, reopening of the power plant at Buggenum is unlikely. Cooling water is not required and, in total, the use of (surface) water by the industrial sector decreases.

STOOM — The socioeconomic development in scenario STOOM are similar to scenario DRUK except the transition to the renewable energy sources. In scenario STOOM this transition is much slower, so cooling water is required after reopening of the power plant at Buggenum. The increase in temperature leads to an even larger demand for cooling water. Therefore, more surface water storage is required to provide sufficient cooling and process water.

RUST — In this scenario, the decrease of freshwater use by the industrial sector is the largest. Economy and population growth stabilize, so the need of industrial products declines. Simultaneously, the transition to renewable energy sources is fast, so reopening of the power plant at Buggenum is unlikely. Therefore, the required cooling water stays negligible.

WARM — The fast climate change results in an increase of temperature. Because the transition to renewable energy resources is only moderate, power plant Buggenum is reopened. More surface water has to be stored to be used as cooling water. The population decline and economic hardship, however, result in a larger decrease in process water use. In the end, the surface water use in industrial activities is smaller.

Table A-4 shows the surface water use by industry per scenario with respect to the reference situation in 2030.

Table A-4: Development of the surface water use by the industrial sector per scenario (Wolters, et al., 2018).

Scenario	Innovation & Efficiency	Population	Economy	Willingness to sustainability	Use of fresh water	Surface water use by industry
DRUK	Large increase	Increase	Prosperity	Large	Small increase	Decrease
STOOM	Large increase	Increase	Prosperity	Small	Large increase	Increase
RUST	Small increase	Decline	Stagnation	Large	Small increase	Decrease
WARM	Small increase	Decline	Stagnation	Small	Large increase	Small decrease

Discharge of flood waves

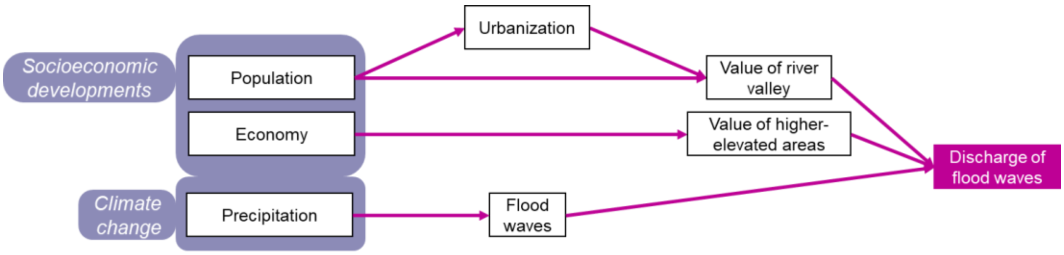

Figure A-6: Translation of the (inter)national scenario developments to the development of the discharge of flood waves.

In this Section, the discharge of flood waves is split into two separate components: the discharge through the main channel and the discharge through the river valley.

DRUK The extreme precipitation events do not increase in this scenario. Therefore, the flood waves in the River Meuse do not increase significantly, certainly not after 2050. Nevertheless, the discharge of flood waves is a challenge in this scenario. The new clustered villages, economic prosperity and population growth result in larger consequences in case of a flood of the higher-elevated areas. To keep the risk the same, the probability of flooding of these areas outside the river valley has to be lowered.

STOOM The discharge of flood waves has to deal with major challenges in this scenario. Extreme precipitation events increase and the resulting increased flood waves enter the Netherlands faster. On the other hand, the spread urbanization leads to higher consequences of flooding of the river valley. Also the higher-elevated areas outside the river valley have an increased value, because of the economic prosperity. The requirements on flood frequency of the river valley and higher-elevated areas both increase the most in this scenario.

RUST The extreme precipitation events and size of flood waves in the River Meuse stay the same. The economic hardship does not lead to an increase of the area value, so no problems are expected on the discharge of flood waves in this scenario.

WARM The fast climate change puts pressure on the discharge of flood waves, despite the population and economic decline. Urbanization is limited, but takes place in the outer districts of cities. The consequence of a flooding of higher-elevated areas therefore does not change significantly; in the river valley it even decreases. To keep the risk equal in the future, discharge of flood waves in the river valley has to be improved.

Table A-5 summarizes the development of the accepted flood probability of the river valley and the higher-elevated areas outside the river valley.

Table A-5: Development of the discharge of flood waves per scenario (Wolters, et al., 2018).

Scenario	Population	Economy	Urbanization	Precipitation
DRUK	Increase	Prosperity	Clustered	Unchanged variation
STOOM	Increase	Prosperity	Spread	Increased variation
RUST	Decline	Stagnation	Clustered	Unchanged variation
WARM	Decline	Stagnation	Spread	Increased variation

Scenario	Flood waves	Value of river valley	Value of higher-elevated areas	Accepted flood probability of river valley	Accepted flood probability of higher-elevated areas
DRUK	Unchanged	Unchanged	Increase	***Unchanged***	***Decrease***
STOOM	Increase	Increase	Increase	***Decrease***	***Large decrease***
RUST	Unchanged	Unchanged	Decrease	***Unchanged***	***Unchanged***
WARM	Decrease	Decrease	Decrease	***Increase***	***Decrease***

The quantitative evolution of the governing flood waves in the River Meuse is found in literature and presented in Table A-6. The reference governing flood waves has a maximum discharge of 3800 m^3/s (Bruggeman, et al., 2011). In combination with the base socioeconomic developments, the change of the required discharge capacity of the main channel and the river valley is set for each scenario. It is assumed that the river valley can just discharge the governing flood wave of 3800 m^3/s in the reference situation in 2030.

Table A-6: The quantitative development of the governing flood waves per scenario in 2050 and 2100 (Bruggeman, et al., 2011).

Scenario	Governing flood wave in 2050 [m^3/s]		Governing flood wave in 2100 [m^3/s]	
DRUK	3900	+3%	4000	+5%
STOOM	4100	+5%	4600	+20%
RUST	3900	+3%	4000	+5%
WARM	4100	+5%	4600	+20%

Table A-7: The required discharge capacity of the river valley per scenario in 2050 and 2100.

Scenario	Required discharge capacity in 2050		Required discharge capacity in 2100	
	Main channel	River valley	Main channel	River valley
DRUK	+5%	+5%	+5%	+10%
STOOM	+15%	+15%	+30%	+30%
RUST	+0%	+0%	+0%	+0%
WARM	-5%	+0%	-5%	+15%

Ecology

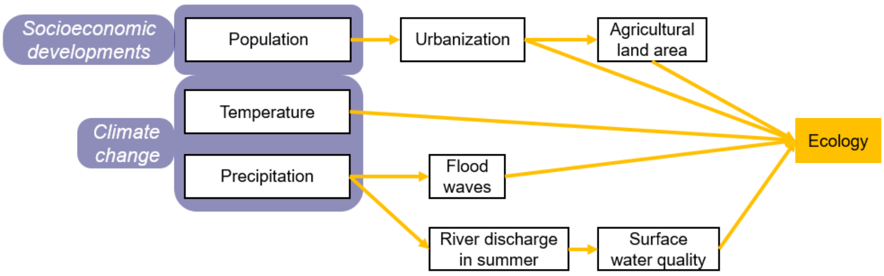

Figure A-7: Translation of the (inter)national scenario developments to the development of ecology.

DRUK — Part of the yield of the large economic growth is used for the realization of large ecosystems and habitats in the river valley. The focus lies on the Natura 2000 sites. In the intermediate (bronze green) areas, the agriculture land and nature is combined in circular or nature-inclusive agriculture. Near the cities the area has an important function as recreation area. During wet periods the area, as well as agricultural land, serves as water retention area.

STOOM — Natural areas are important for outdoor recreation. Walking, biking and events are popular activities in nature to elude the hectic life in the urban areas. It is tried to preserve the biodiversity and natural area, but this is difficult due to the lack of area, more extreme weather conditions and the intensive use by recreation. Moreover, space is limited by the agriculture acreage and spread urbanization. The European legislation on Natura 2000 sites is annulled later on.

RUST — Funds for nature development are small. Maintenance is overdue leading to overgrown open areas. The agricultural areas slowly change to extensive natural-managed areas. In urban areas removal of houses provides space for parks and water retention. Summarizing, less attention and finances are paid to the maintenance of ecosystems.

WARM — Limited investments and climate change cause a decrease of productivity in the agricultural sector. The agricultural acreage in regularly flooded areas is given back to nature. Flood waves become more frequent, since the climate change is fast, thus contributing to this development. Without human interventions new ecosystems develop as a long band in the river valley. Outdoor recreation is only located near the cities.

Table A-8 shows the development of ecology per scenario from the reference situation in 2030.

Table A-8: Development of the ecology per scenario (Wolters, et al., 2018).

Scenario	Population	Urba-nization	Agricultural land area	Precipitation
DRUK	Increase	Clustered	Decrease	Unchanged variation
STOOM	Increase	Spread	Decrease	Increased variation
RUST	Decline	Clustered	Unchanged	Unchanged variation
WARM	Decline	Spread	Unchanged	Increased variation

Scenario	*Flood waves*	*River discharge in summer*	*Surface water quality*	*Ecology*
DRUK	Unchanged	Unchanged	Equal	***Large nature sites in the river valley***
STOOM	Increase	Decrease	Decrease	***Decreased attention to nature sites***
RUST	Unchanged	Unchanged	Equal	***Overgrown nature sites***
WARM	Increase	Decrease	Decrease	***Development of watery nature sites***

Navigation

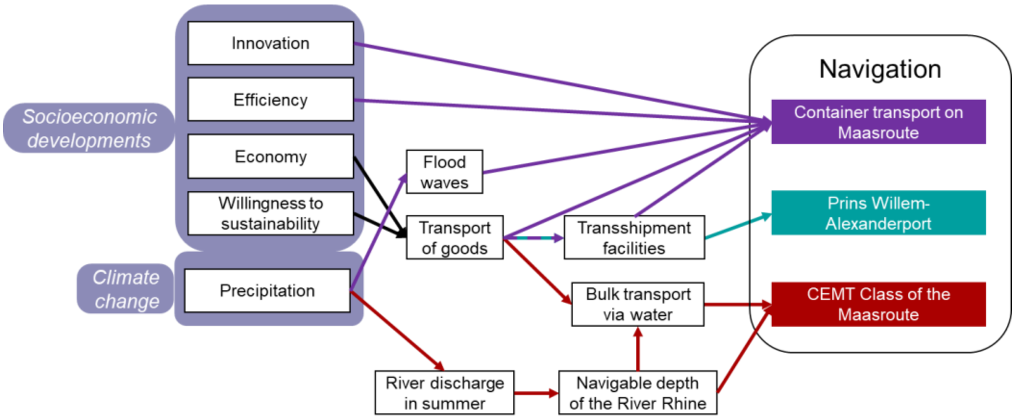

Figure A-8: Translation of the (inter)national scenario developments to the development of navigation.

Before the evolution of the navigation is addressed per scenario, first the influence of climate change and the willingness to sustainability is explained.

Climate change involves changing river discharge in summer and winter, which hampers the availability of the waterway network. From the viewpoint of safety, navigation can be forbidden during flood waves, leading to economic loss to the transport sector. Moreover, more or larger flood waves reduce the availability of the waterway due to the bridge clearances. On the other hand, lack of water supply leads to small water depths, which results in unnavigable rivers. Especially for the free flowing part of the River Rhine this can become a problem. Since the governing vessels on the Maasroute use the River Rhine as well, a depth limitation on the River Rhine effects the navigation on the Maasroute as well.

The willingness to create a sustainable environment is decisive to mitigate these effects and the increase of the market share. Transport on water is relatively sustainable and includes economy of scale. To successfully transfer the container transport from road to water, investments are needed in the waterway system. One can think on heightening of bridges and better transhipment facilities to stimulate multimodal transport. The rise of the pallet-wide high-cube 45 ft container, called the continental containers, is worth highlighting. The conventional containers, 20 ft and 40 ft, have American dimensions, which just do not fit the European pallets. Therefore, continental containers have been developed with a larger width, length and height to increase the loading efficiency with European pallets. However, the efficiency of container vessels loading with 45 ft containers is low nowadays. The width of the Class V vessels is just not sufficient to accommodate four continental containers next to each other. Therefore, 45 ft containers are mostly transported by truck and train. Investments in the waterway network and the container vessels itself determine the transfer of transport of these containers from road and rail to water. The extent to which this will happen, is dependent on the scenario.

DRUK The transhipment in the large sea ports increases due to the economic prosperity. The transport on water increases significantly, since the climate change does only affect the system a little and industry settles near waterways and inland terminals. The large willingness to sustainability involves large investments in the waterway system before 2050 to allow transport of four layers of containers on vessels. Structures are replaced bearing in mind that container vessels become 0.5 m wider in the future to increase the loading efficiency of vessels with continental containers.

STOOM Although the transhipment in the large sea ports increases due to the economic prosperity, the throughput to the inland waterways increases less. Until 2050 the inland navigation remains an important sector for the transport of bulk and continental containers, but after 2050 the effects of climate change affect the sector. The low willingness to sustainability only involves limited investments; bridge heightening is limited, so the transport of continental containers over water is therefore restricted. In the end of this century, the availability of the River Rhine decreases in low water periods.

RUST The growth of transhipment in the large sea ports is, just like the economic growth, limited. From 2050 a decrease of the total volume is expected. The inland navigation sector keeps the leading sector regarding the bulk transport; the continental container transport is limited. Nevertheless, the large willingness to a sustainable environment involves investments in the waterway system to enable transport of four layers of containers on vessels. Hereby, a vessel's beam of 12.5 m instead of 12.0 m is taken into account in the second half of the 21st century.

WARM The growth of the transhipment in seaports is limited until 2050; after that a decrease is expected. This is caused by the deteriorated availability of the inland waterways and the economic hardship. The negative climate change effects are not counteracted by investments in the system. Therefore, the continental containers are still transported by truck and train. The market share in bulk transport is kept until 2050, but also decreases afterwards.

Table A-9 shows the development of navigation per scenario from the reference situation in 2030.

Table A-9: Development of navigation per scenario (Wolters, et al., 2018) (Van Dorsser, 2012).

Scenario	***Innovation & Efficiency***	***Economy***	***Willingness to sustainability***	***Precipitation***	***Transport of goods***
DRUK	Large increase	Prosperity	Large	Unchanged variation	Large increase
STOOM	Large increase	Prosperity	Small	Increased variation	Large increase
RUST	Small increase	Stagnation	Large	Unchanged variation	Small increase
WARM	Small increase	Stagnation	Small	Increased variation	Large increase

Scenario	*Flood waves*	*River discharge in summer*	*Navigable depth of the River Rhine*	*Bulk transport via water*	*Transshipment facilities*
DRUK	Unchanged	Unchanged	Unchanged	Unchanged	Large improvement
STOOM	Increase	Decrease	Decrease	Unchanged	Limited improvement
RUST	Unchanged	Unchanged	Unchanged	Decrease	Large improvement
WARM	Increase	Decrease	Decrease	Decrease	No improvement

Scenario	*Container transport on Maasroute*	*Prins Willem-Alexanderport*	*CEMT-Class of the Maasroute*
DRUK	*Increase*	*Increased importance*	*Unchanged*
STOOM	*Increase*	*Unchanged*	*Decrease in maximum depth*
RUST	*Unchanged*	*Unchanged*	*Unchanged*
WARM	*Unchanged*	*Decreased importance*	*Decrease in maximum depth*

The result of Table A-9 is insufficiently specific to take into account as evolution in the scenarios. Moreover, the time dimension is not addressed yet. With the help of Figure A-9, Figure A-10, Figure A-11 and Figure A-12, the evolution of the navigational subfunctions is made quantitatively and the evolution rate is addressed. In these figures, two extra scenarios are presented, namely DOORSTOMEN and WATERDRUK. Since these scenarios are not elaborated for the other subfunctions, these are not applied in this project.

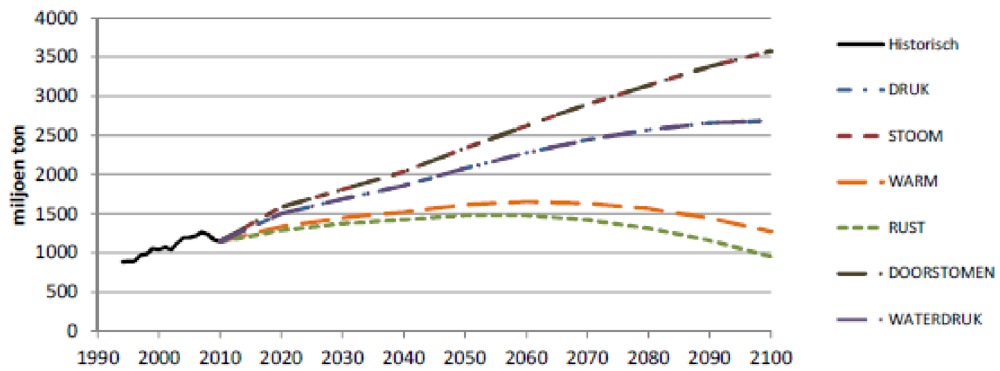

Figure A-9: Development of the total domestic transport volume per scenario (Van Dorsser, 2012).

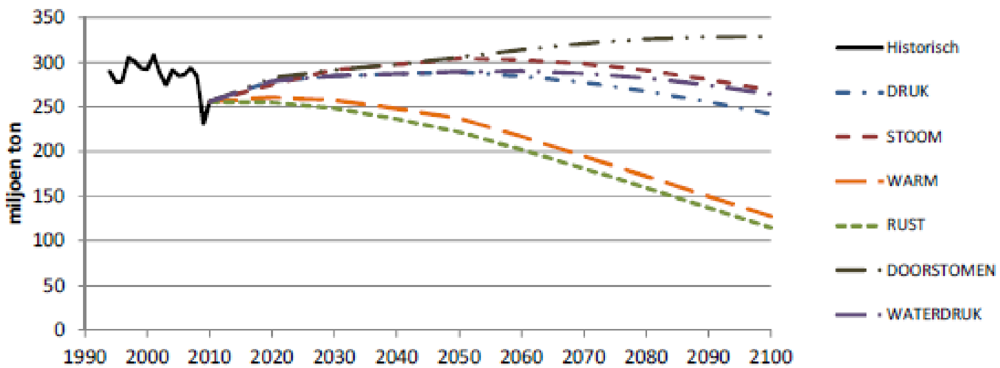

Figure A-10: Development of bulk transport via the inland waterway network per scenario (Van Dorsser, 2012).

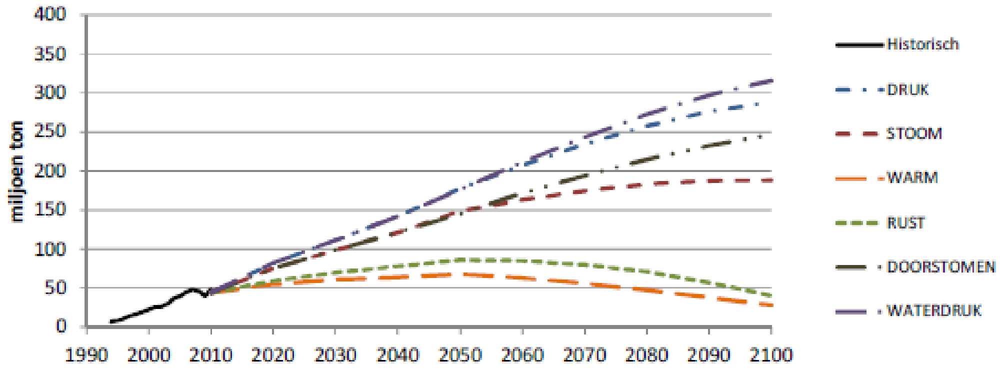

Figure A-11: Development of conventional container transport via the inland waterway network per scenario (Van Dorsser, 2012).

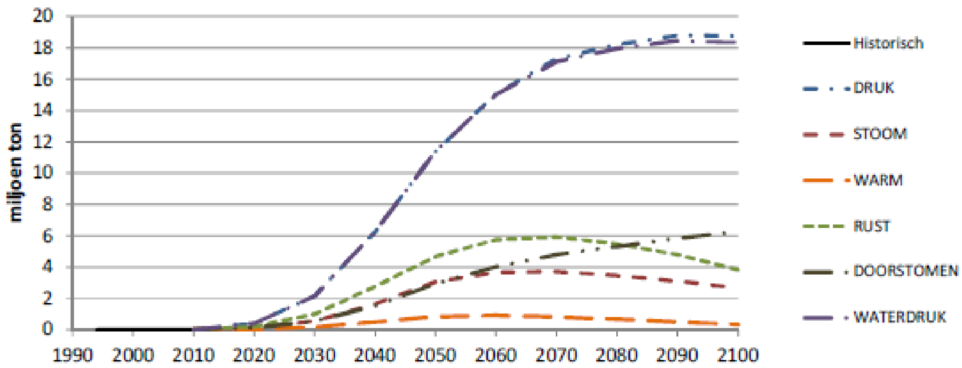

Figure A-12: Development of continental container transport via the inland waterway network per scenario (Van Dorsser, 2012).

Table A-10 includes the translated developments which are considered during the rest of the project.

Table A-10: Specific, time-related development of navigation per scenario (Wolters, et al., 2018) (Van Dorsser, 2012).

Scenario	*Maximum layers of high-cubes containers*		*Prins Willem-Alexanderport*	*CEMT-Class Maasroute*	
Year	*2050*	*2100*		*2050*	*2100*
DRUK	*4 empty containers*	*4 empty containers*	*Increase of governing draught to 3.0 m*	*Vb*	*Vb*
STOOM	*4 empty containers*	*4 average loaded containers*	*Unchanged*	*Vb*	*Va*
RUST	*3 empty containers*	*4 average loaded containers*	*Unchanged*	*Vb*	*Vb*
WARM	*3 empty containers*	*3 empty containers*	*Port closed*	*Vb*	*Va*

A.2 Evolution of boundary conditions and requirements per scenario

On basis of Appendix A.1, the evolution of the boundary conditions and requirements are set up per scenario. In Figure A-13 to Figure A-16, the developments are summarized per scenario per (sub)function as mentioned in Section 4.2 and Appendix A.1. The time dimension of the developments is partly based on information found in literature and partly based on the innovation rate in that particular scenario; in general, if the technological innovation rate is large, the boundary conditions and requirements evolve faster than if the technological innovation rate is small.

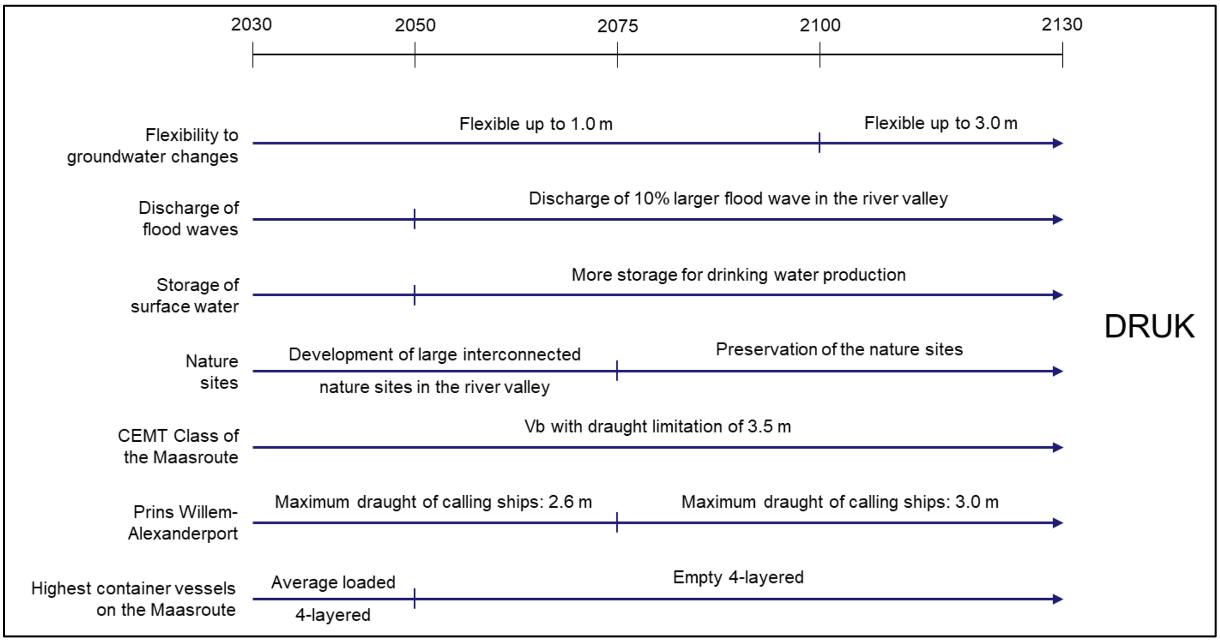

Figure A-13: Evolution of boundary conditions and requirements in scenario DRUK.

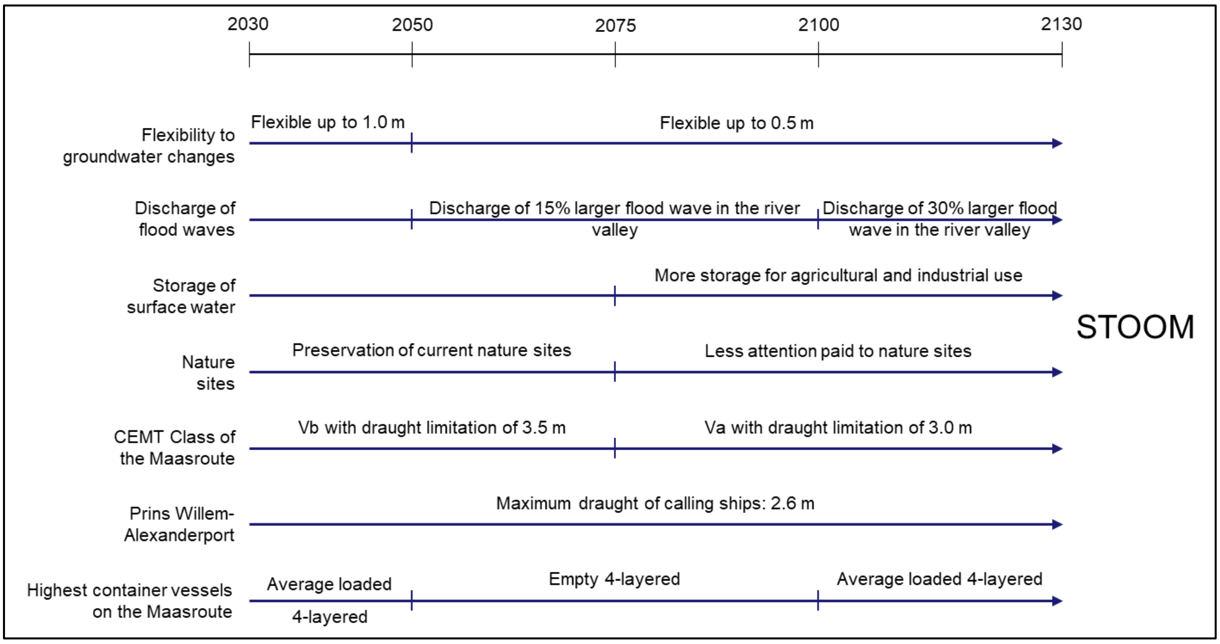

Figure A-14: Evolution of boundary conditions and requirements in scenario STOOM.

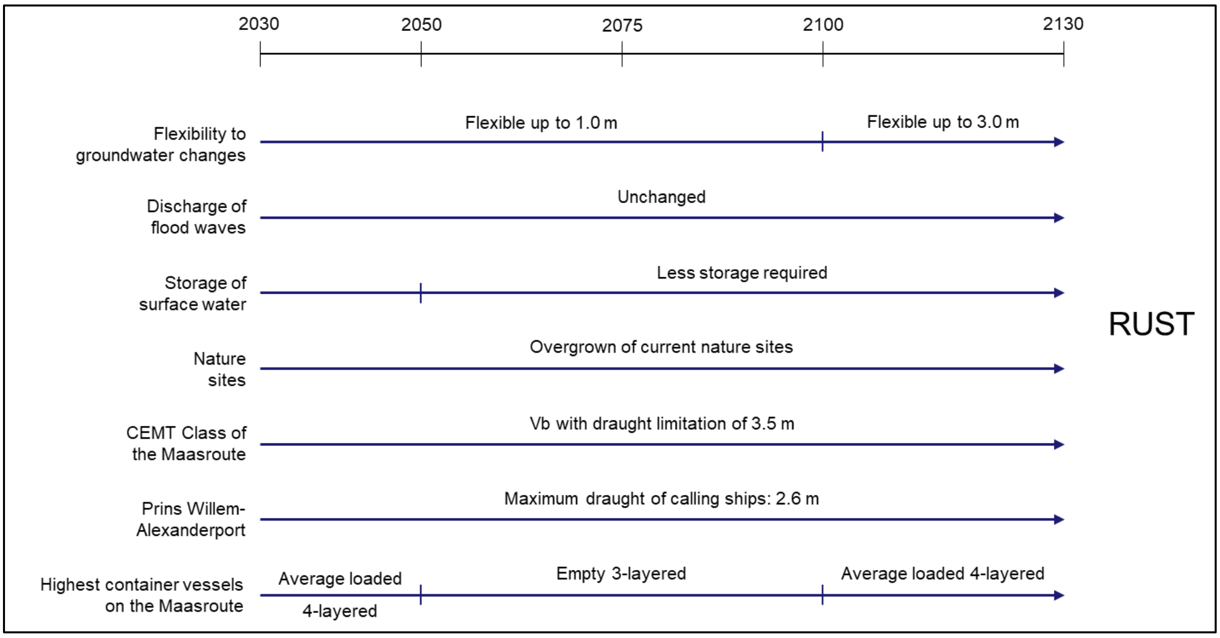

Figure A-15: Evolution of boundary conditions and requirements in scenario RUST.

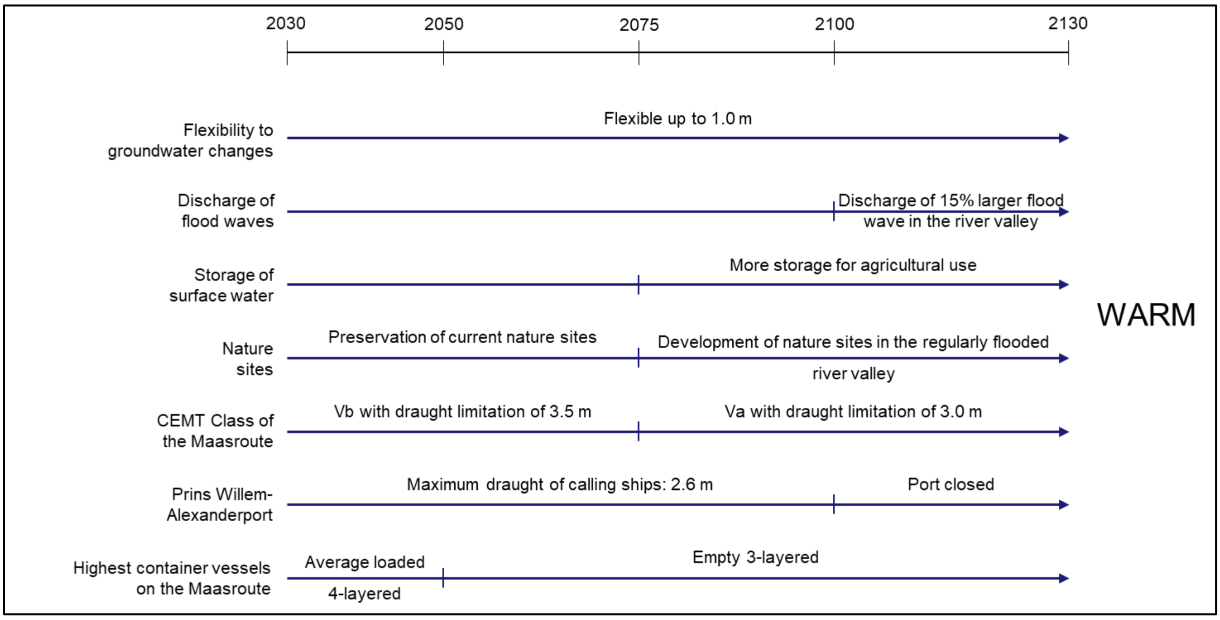

Figure A-16: Evolution of boundary conditions and requirements in scenario WARM.

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Appendix B
System of the River Meuse

This appendix describes the system of the River Meuse elaborately. This starts with an overview of the current system of the River Meuse and its tributaries, after which Appendix B.2 addresses the variation of the River Meuse's discharge. Appendix B.3 includes the chronological development of the waterway network. It covers the establishment and human interventions in the River Meuse and the connected waterways. For completeness, Figure 2-1 of the main report, is repeated below.

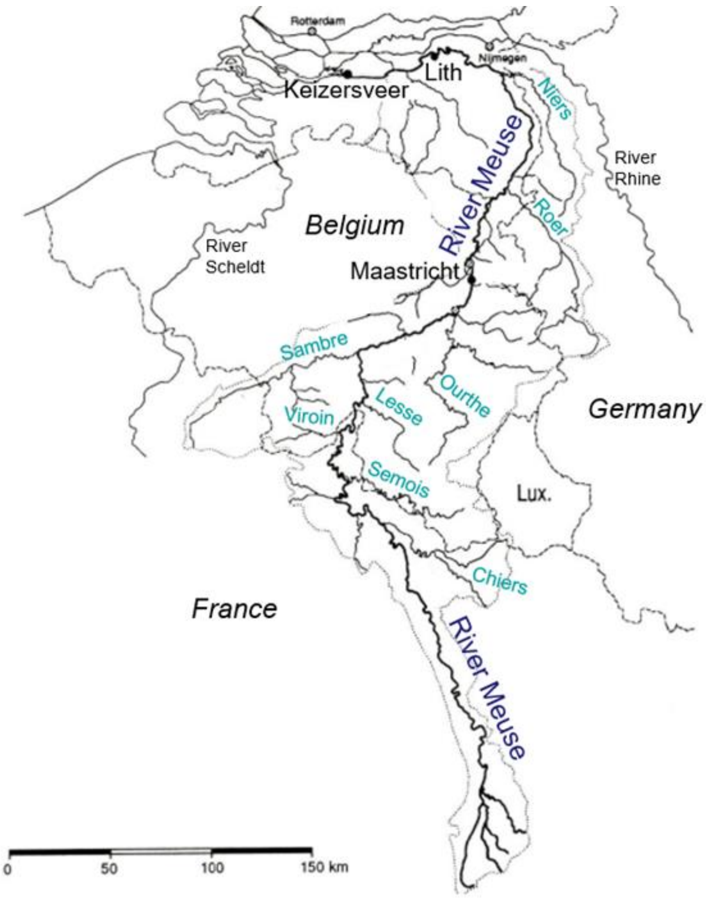

Figure B-1: Overview of the catchment area of the River Meuse (Rijkswaterstaat, 1992).

B.1 Hydrological system

The source of the River Meuse is located at the Plateau of Langres near Pouilly-en-Bassigny at an elevation of NAP +400 m. Near the source, the river, called the Meuse Lorraine, flows calm through a wide, flat valley with parallel to it a canal. The river and the canal confluence and bifurcate a couple of times; downstream of the bifurcations weirs control the water level and discharge of the river and the canal. The subsoil consists of limestone and alluvial deposits which both have a high permeability. Consequently, in dry periods the River Meuse here is mainly fed by groundwater. During these periods, the groundwater flow in this area is a non-negligible contribution to the total river discharge in the Netherlands.

At Sedan the first main tributary, the Chiers, confluences with the River Meuse, which changes the nature of the river: the subsoil is very impermeable unto Namur and the gradient increases significantly downstream as shown in Figure B-2.

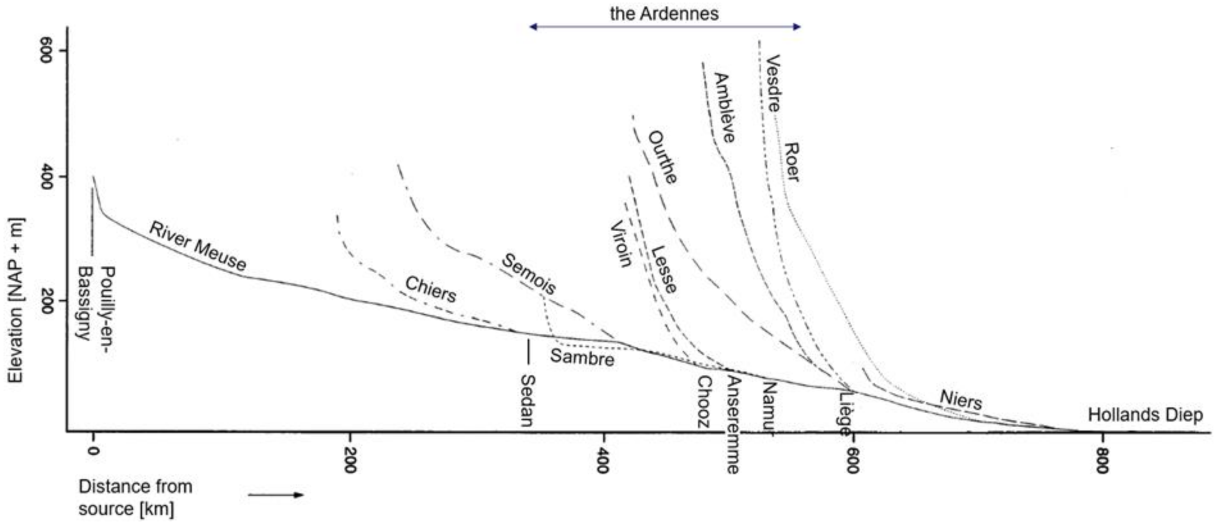

Figure B-2: Longitudinal overview of the River Meuse and its tributaries (Rijkswaterstaat, 1994).

At Chooz a nuclear power station uses some of the river discharge as cooling water. Also the parallel canal ends here; navigation downstream to Belgium takes place over the dammed River Meuse. As a result, upstream of Namur the River Meuse is 100 m wide, flowing in a narrow valley; downstream of Namur the river width increases even to 130 m, as the valley itself is wider too. In this middle part, many tributaries drain towards the River Meuse. The tributaries mentioned in Figure B-2 are slightly touched below.

- Chiers
  The spring of this tributary is located in Luxemburg and it confluences with the River Meuse just upstream of Sedan. The drainage of its catchment area is much larger than that of the upstream part of the River Meuse. During dry periods, the discharge of the Chiers was half of the total River Meuse's discharge at Sedan, but this portion has been declined, since the iron mines are closed nowadays.
- Semois
  The drainage of this tributary goes slower than the other ones having their spring in the Ardennes. In de 1960s a reservoir was considered to enlarge the minimum discharge of the River Meuse, but the socioeconomical aspects turned out non-profitable. Nowadays, a significant part of a flood wave in the River Meuse can originate from the Semois.
- Viroin
  This tributary, mainly flowing in France, shows, in combination with the calcareous soil, karst phenomena. However, most water, whether or not by subsurface flow, confluences with the River Meuse some kilometres upstream of Chooz.
- Lesse
  The Lesse is a typical river in the Ardennes with its mouth just downstream of the weir of Anseremme. Just like the Viroin, karst phenomena have created caves and subsurface flows. The Lesse and its tributaries all start with a large gradient, declining towards the mouth, which results in very large discharge peaks during wet periods and very low discharges during dry periods.
- Sambre
  This tributary deviates from the others by its considerable navigational function. It connects the navigable River Meuse at Namur with the Brussels-Charleroi Canal. The discharge and water levels of the Sambre are therefore completely controlled by weirs and locks. The absence of flood plains

results in fast propagation of the flood wave, although the most downstream weirs can slow it down by damming a higher water level in these situations without causing significant upstream floods. A complex of reservoir dams guarantees via the River Eau d'Heure a minimum discharge of 5 m^3/s in the Sambre, enabling the usage of the locks in dry periods.

- Ourthe
  The catchment area of the Ourthe comprises the northern part of the Ardennes. Rapidly varying discharge and its mouth located near Liège causes the Ourthe to be the most important tributary of the River Meuse for the water level prediction in the Netherlands. Next to the Ourthe, its tributaries Amblève and Vesdre make up more than half of the catchment area of the Ourthe. The nature of the area, impermeable soil, large river gradients and steep slopes, causes rapidly increasing and large discharges. The presence of reservoirs, also built for generation of energy and recreational purposes, barely flattens the discharge peaks into the River Meuse.

After confluence with these tributaries, the River Meuse enters Dutch territory at Eijsden. North of Maastricht, the River Meuse forms the natural border between Belgium and the Netherlands for a couple of kilometres, which is why this gravel section is called Grensmaas (in English: Border Meuse). More downstream, its gradient reduces significantly. The river is named after the sediment which is found on the riverbed: the Zandmaas (in English: Sandy Meuse). Two tributaries in this area are worth mentioning:

- Roer
  The Roer confluences with the River Meuse in Roermond. The Roer flows from Germany to the River Meuse via a graben of the local tectonic plates. The German catchment area includes some reservoirs, which sizes are equal to the sum of all Belgium reservoirs within the catchment area of the River Meuse. In combination with effluent discharges, a minimum discharge of the Roer is maintained.
- Niers
  The catchment area of the most northern main tributary comprises German territory as well. The Niers flows in a relatively flat area with little precipitation and much ground infiltration. The vast majority of the discharge enters the River Meuse at Goch, the other part just north of Venlo via the Niers Canal. The contribution to the total discharge of the River Meuse is small.

Via the Zandmaas, the Bergsche Maas and the Amer water flows to the Hollands Diep which is indicated as the mouth of the River Meuse, see Figure B-3. The Hollands Diep is also fed by water from the River Rhine via the River Waal and the Merwede. Via The Haringvliet sluices the water enters the North Sea.

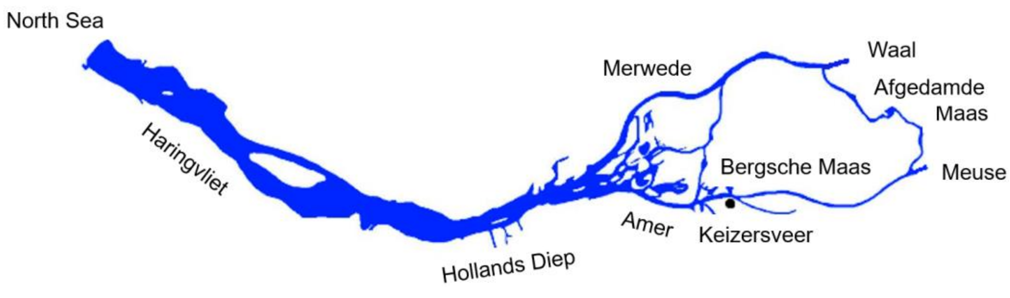

Figure B-3: Overview of the mouth of the River Meuse (Sportvisserij Zuidwest Nederland, 2013).

B.2 Discharge of the River Meuse

The described catchment area in Appendix B.1 determines the discharge of the River Meuse. The area is relatively low-lying, so the river is not fed by melting glaciers. The supply of rain water is highly varying; per season as well as per year. Discharge measurements at Borgharen, near Maastricht, result in the discharge variation within a hydrological year as shown in Table B-1.

Table B-1: Average number of days a specific discharge is exceeded at Borgharen in a year (Geerling, Buijse, & Van Kouwen, 2010).

Discharge [m³/s]	Winter	Spring	Summer	Autumn	Total	
50	87.1	88.6	54.9	54.5	285.0	78%
75	84.5	83.7	39.6	44.5	252.3	69%
100	81.5	76.6	25.5	37.0	220.6	60%
150	74.5	59.3	12.3	26.6	172.6	47%
200	64.9	44.6	6.6	20.0	136.1	37%
300	49.6	28.0	2.8	12.7	93.1	25%
400	38.2	18.0	1.4	7.9	65.4	18%
500	28.9	11.7	0.7	5.1	46.3	13%
600	21.2	7.2	0.3	3.2	31.9	9%
700	15.8	4.7	0.2	2.0	22.6	6%
800	11.5	3.0	0.1	1.3	16.0	4%
900	8.7	2.0	0	1.0	11.7	3%
1,000	6.4	1.2	0	0.8	8.3	2%

The catchment area is narrow and elongated, so it can rain simultaneously in a large part of the catchment area, which results in large flood waves. The discharge is amplified by the little water storage in the area. Averagely, in the Ardennes the amount of precipitation is the largest of the catchment area as well. The drainage of this area is also the fastest, which leads to the discharge variety shown in Figure B-4. The yearly average river discharge is 230 m³/s, but the variation from year to year is significant. For example, between 1969 and 1979 the average discharge was only 160 m³/s. In summer, the period of May until October, discharges of 10 m³/s are not exceptional, because of the small precipitation volumes and the evaporation in the area (Rijkswaterstaat, 1992).

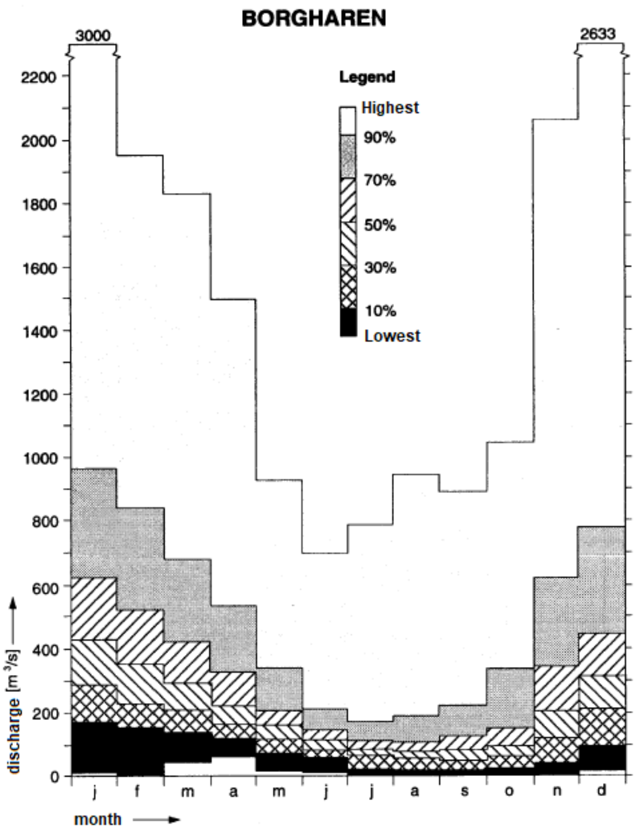

Figure B-4: Variety of the discharge of the River Meuse measured at Borgharen (Rijkswaterstaat, 1994).

Flood wave size

The discharge of the River Meuse has been measured since 1911. The highest measured discharge at Borgharen equals 3,000 m^3/s, measured in 1926 as a result of heavy rainfall and melting snow in the Ardennes. More than 100 years of measurement data have been applied to derive extreme value distributions by fitting the distributions to the data. In this way, the peak discharges of much larger return periods are known, which is important for flood safety. Table B-2 shows the return periods and size of large flood waves in the River Meuse.

The fitting of the distributions does include some unavoidable inaccuracies. The system of the River Meuse has been changed in the last century, so the behaviour of flood waves as well. In former times, multiple areas flooded which stay dry now during an equally sized flood wave. On top of that, river bend cut-offs decreased the distance between the area of precipitation and the point of interest. The course of a peak discharge of 3,000 m^3/s will be completely different from the situation in 1926 (Rijkswaterstaat, 1994). Therefore, the discharge peaks of the past are homogenized to the present situation. A new relation between discharge and resulting water levels has been proposed after the flood waves in 1993 and 1995. The flood of 1926 is comparable with a present flood wave of 3,175 m^3/s. The homogenized discharges of the flood waves are used to determine the extreme discharges, but these do not account for the effect of climate change or climate variations (Van Schrojentstein Lantman, 2004). This enlarges the uncertainty of the extreme discharges, which is supported by the wide 95% confidence interval in Table B-2.

Table B-2: Return periods with corresponding discharges and uncertainties (Chbab, Den Bieman, & Groeneweg, 2017).

Return period [y]	Discharge [m^3/s]	95% confidence interval	
		Lower limit [m^3/s]	Upper limit [m^3/s]
2	1,440	1,270	1,610
5	1,970	1,740	2,200
10	2,300	2,010	2,590
50	2,970	2,430	3,510
100	3,220	2,650	3,800
250	3,520	2,950	4,090
1,250	3,910	3,210	4,290

Propagation speed of flood waves

The short-term prediction of flood waves and the corresponding water levels is of large importance nowadays to guarantee the flood safety in the Netherlands. Numerical models, which include the characteristics of the river (area), are used to predict the river water levels. Predictions far ahead in time are problematic, since the flood wave at Borgharen is hugely impacted by the tributaries in the Ardennes. In Figure B-5 the travel time of flood waves unto Borgharen is shown. Within 48 hours water runs from France to Borgharen; if water levels have to be predicted more in advance, rainfall prediction has to be added. The accuracy reduces drastically in this case.

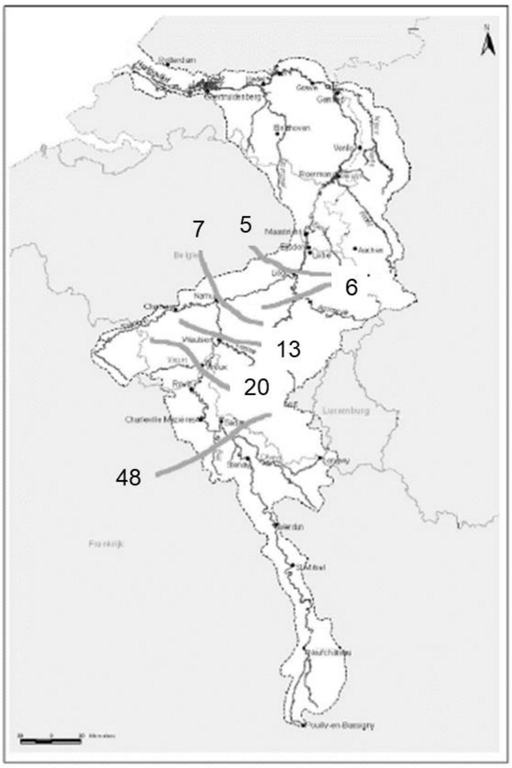

Figure B-5: Flood wave propagation (Van Schrojentstein Lantman, 2004).

The flood wave propagation is slightly different for each flood wave, because the shape of the flood wave differs. This shape changes during the propagation of the flood wave. Sharp-crested flood waves are topped off by the Maasplassen, an area with many lakes and a wide river valley. Therefore, blunt flood waves cause higher water levels downstream than sharp-crested flood waves. Consequentially, the travel time from Borgharen to Lith ranges from 56 to 86 hours (Van Schrojentstein Lantman, 2004). Because of all these variabilities, the standard tables, which are used to calculate the water levels downstream based on the discharge near Borgharen, have to be applied with great care (Rijkswaterstaat Zuid-Nederland, 2013).

In contrast to the River Rhine, floods do not play a role before the flood waves reach the Netherlands. Near Liège, the River Meuse flows in a natural valley, so floods are constrained to this area; downstream of Maastricht, flood waves are for the first time significantly affected by the Maasplassen. The exact decrease of the peak discharge is the result of a complex interaction of floods and water supply from these flooded areas and tributaries. In general, the peak discharge at Lith is 50 m^3/s smaller than the peak discharge at Borgharen. This is mainly caused by the flooding of the subsided Flemish mine areas adjacent to the Grensmaas (Silva, Slomp, Stijnen, & Van Velzen, 2005).

B.3 Historical development of the waterway network

Due to the rapid changing water levels, the nature of the River Meuse was unsuitable for navigation purposes in the 18th century. During the reign of Napoleon navigation increased, because borders were abolished and trading increased. Therefore, Napoleon instructed to connect the River Scheldt (from Antwerp) with the River Meuse (via Venlo) and the River Rhine (to Neuss). Supply of water had to be guaranteed by constructing an additional canal from Maastricht to this so-called Canal du Nord. Though, only a small part has been constructed. In the following decades, more and more other waterways have been constructed. An overview of the present waterway system in Flanders and the Netherlands is given in Figure B-6. In the text below, the development of this network is chronologically explained (Rijkswaterstaat, 1994) (Burgers, 2014).

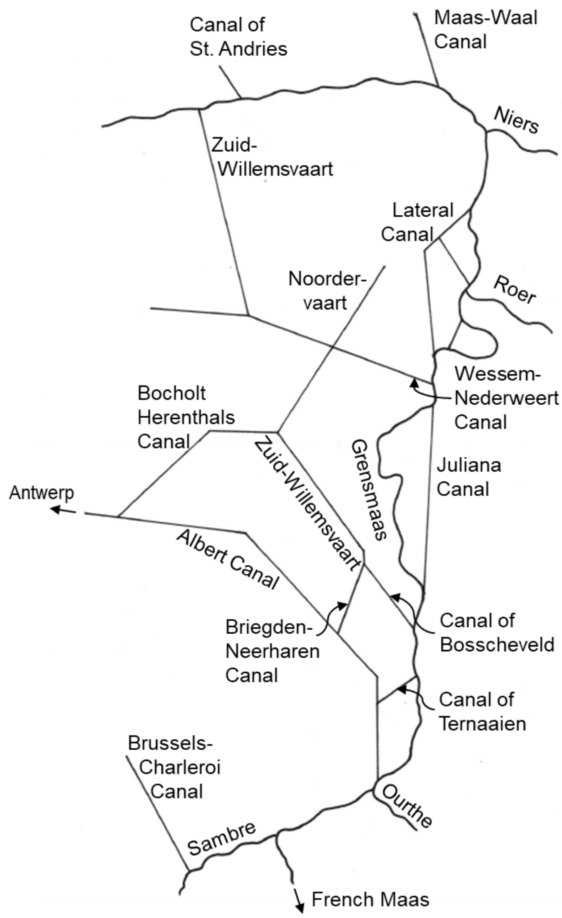

Figure B-6: Overview of the waterways connected to the River Meuse in Flanders and the Netherlands.

After the period of Napoleon, the United Kingdom of the Netherlands was formed (1815) and William I decided to construct the Zuid-Willemsvaart. This canal still connects Maastricht via the former supply canal and parts of the Canal du Nord to 's Hertogenbosch, after if flows into the Dieze. 20 locks were constructed, the most upstream one in Maastricht to provide the canal with water and to connect the canal with Liège. Upstream of Liège, in the Sambre, canalization started in 1824. In the decennium thereafter, the connection with Paris via the Canal de la Sambre à l'Oise and with Brussels via the Brussels-Charleroi Canal was realized. This completed the first waterway connection between Liège and Antwerp in 1832.

In the same period, the Belgian Revolution, which eventually has led to establishment of the Kingdom of Belgium, was going on. In the independence statement, the sea entrance of the port of Antwerp has been set as Dutch territory and in the east a River Meuse section, now called the Grensmaas, has been indicated as border between Belgium and the Netherlands. Abruptly, the Zuid-Willemsvaart became property of two conflicting countries.

In the following decades, the improvement of the waterway network went on by the constructing of canals:

- Improvements in France started in 1835 with the realization of the Canal des Ardennes. The River Meuse is connected with the River Seine and the cities of Reims and Paris via this canal. Ore mining was the main reason to improve the French part of the River Meuse; Belgian and Luxembourgish ore and coal was to be used in the French industry. Somewhat later, in 1868, the Marne-Rhine Canal provided the connection between the industry of Lorraine and the rest of France. Simultaneously, the Canal de l'Est was constructed, which includes canalized River Meuse sections and canals parallel to the river. By completing this, it was possible to transport coal from Belgium to the industry of Lorraine. The location of the waterway network in northern France is shown in Figure B-7.

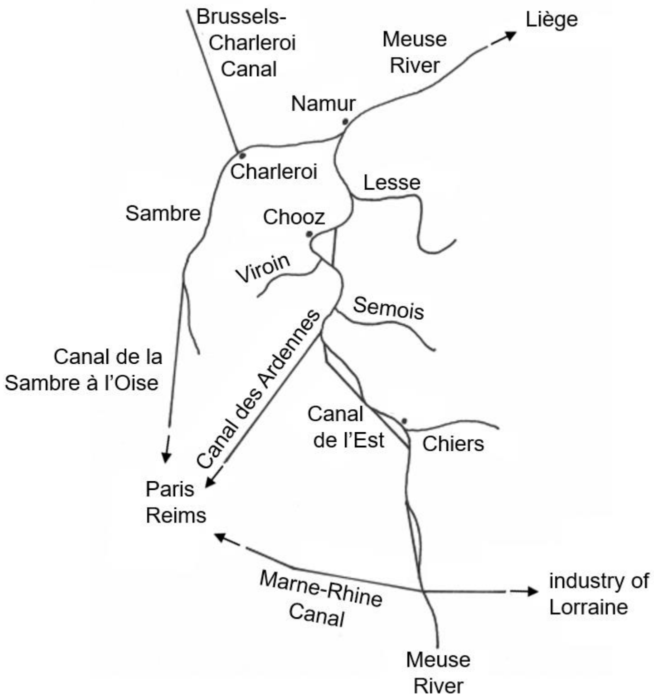

Figure B-7: Overview of the waterways network to the River Meuse in Wallonia and France.

- The aim of the Canal du Nord was partly reached in 1846 by connecting the Zuid-Willemsvaart to Antwerp by digging the Bocholt-Herentals Canal. The expansion of the canal between Herentals and Antwerp, finished in 1859, resulted in more inland navigation from and to Antwerp.
- A canal with 6 locks between Liège and Maastricht enabled navigation of vessels unto 450 tons in 1850. A transverse canal at Visé has been dug to connect the mines on the eastern bank of the River Meuse. A weir in the River Meuse has been built to manage the water inlet of the Zuid-Willemsvaart and the other Flemish waterways.
- The first canalization of the River Meuse itself started in Liège in 1853. The section between Liège and Namur was made suitable for vessels unto 600 tons within 12 years.

The measures in Wallonia and France did not result in much noise, but this does not apply to the extension of the waterway network in Flanders. The position of the port of Antwerp was very important for the just established Belgium; all domestic canals had been dug focussing on the hinterland connection of this port. The competitive ports in the Netherlands regarded these canals as a threat for their market position. The relationship between the neighbouring countries was already not too good, the port competition made it even worse. Soon the countries had issues on the water inlet of the Flemish canals. Much water of the River Meuse was directed into the Liège-Maastricht Canal. Moreover, the Belgian agricultural sector drained water from the Grensmaas. During dry periods, the users of the Dutch River Meuse had to deal with largely reduced water levels, during wet periods navigation in Flanders struggled with large flow velocities. After several conflicts between both nations, an agreement was signed in 1863. An inlet structure at Bosscheveld (in the Netherlands) replaced the inlet structure of the Zuid-Willemsvaart at Hocht (in Belgium). The water distribution over the canals and the River Meuse was regulated to solve the existing problems; a minimum discharge for the Dutch River Meuse and a maximum discharge for the Flemish canals and agriculture was agreed upon. Part of the discharge diverted to the Flemish canals had to flow back to the Netherlands via the Zuid-Willemsvaart. Last, Belgium agreed to pay for the canalization of the Dutch River Meuse.

Until 1900, less progress was made in the latter project, in contrast with the section upstream of Liège. Due to the canalization project here, vessels unto 1,150 tons were able to sail from Liège unto the French border at the end of the nineteenth century.

In 1906, a mixed Dutch-Belgian commission was installed to address the canalization project. A couple of starting points and set requirements of this commission are still visible in the current waterway network. Among them, the 60 m wide navigable opening of the weirs during a flood wave. At the same time, the continuing growth of the navigation sector led to undesirable long transport times at the Zuid-Willemsvaart and the other Flemish Canals, caused by their numerous locks. Simultaneously, the Dutch mines arose and therewith the need for a better transport system than the national railway network. The disagreement between the Netherlands and Belgium returned; the Dutch focus lied on transport to sea via Rotterdam, but Belgium insisted on improved waterways between the mouth of the River Scheldt and the River Rhine. Eventually, a plan of 15 weirs in the River Meuse has been proposed, of which 10 between Eijsden and Maasbracht, because of the large gradient of the Grensmaas. The politicians in Belgium were not convinced of this idea; the benefits for the port of Rotterdam were much larger than for the port of Antwerp. A connection between Antwerp and the River Rhine or Liège was, however, technically not feasible in that time.

World War I impeded the negotiations and execution of the canalization project; the Grensmaas became a border of Germany and the neutral Netherlands. The Netherlands imported mine products from neighbouring countries before the war, since these were cheaper than its own mining products. WW1 put pressure on an improved transport of the own mine products from the South of Limburg. It was proposed to transport the mine products from the mines to Maasbracht by train, from where the mine products had to transported by vessel. The gradient of the River Meuse north of Maasbracht is much lower than that of the Grensmaas, so less weirs were needed here. The canalization of the Dutch River Meuse started in 1918. The result is shown in Figure B-8.

Figure B-8: Canalization of the Zandmaas (Burgers, 2014).

The weirs at Linne, Roermond, Belfeld, Sambeek and Grave have all been facilitated with locks to enable passage of vessels. More downstream, many river bends increased the transport route significantly. Damming water level by weirs over here was not possible, since the surrounding areas drain surplus water towards the River Meuse. Another solution has been thought out, which was the construction of the Maas-

Waal Canal. This canal connected the River Meuse in 1927 with the North Sea via the River Waal. The first four weirs had been mentioned in the proposal of the Dutch-Belgian commission, the weir at Grave has been added to control the water level of the Maas-Waal Canal. The location of the most upstream one, weir Linne, is selected to just not influence the shared Grensmaas. In 1929 the main navigation route to Rotterdam via the Maas-Waal Canal was suitable for vessels unto 2,000 tons. Maasbracht was an important transhipment hub in this time, also because of the construction of the Wessem-Nederweert Canal, which provides a domestic connection to the Zuid-Willemsvaart.

Simultaneously with the canalization of the Zandmaas, the disagreement between Belgium and the Netherlands about the navigability of the Grensmaas dragged along. The Netherlands eventually constructed a canal, parallel to the Grensmaas, with only three locks. Besides, a new inland port on this so-called Juliana canal was more profitable for the access of the Dutch mines. Weir Borgharen, completed in 1928, controlled the water levels in the canal and the River Meuse section upstream of the Grensmaas. In Maastricht faster waterway connections were added between the River Meuse and the Flemish canals by the construction of locks at Bosscheveld and St. Pieter.

Belgium reacted by construction of the Albert Canal in Flanders in the 30s. This canal connects the southern part of the Liège-Maastricht Canal and the Herentals-Antwerp Canal and was suitable for vessels unto 2,000 tons. The other Flemish Canals, except the Liège-Maastricht Canal, were enlarged to accommodate vessels unto 600 tons. The weir of Monsin determines the water level at the bifurcation of the River Meuse and the Albert Canal. During World War II, the first vessels used the six locks in the Albert Canal to navigate to Antwerp. Upstream of Liège, improvements of earlier canalization works started. Near Maastricht, the Briegden-Neerharen Canal formed a connection between the Albert Canal and the Zuid-Willemsvaart.

By construction of the Juliana Canal, the Briegden-Neerharen Canal and the lock at Bosscheveld, the agreement of 1863 has been violated. Both countries developed their own navigation routes for vessels up to 2,000 tons. The connection between these two navigation networks at Ternaaien, however, was only suitable for vessels up to 450 tons. In 1961 a lock complex for larger vessels and the Canal of Ternaaien solved this problem. The Liège-Maastricht Canal through the centre of Maastricht was damped. Figure B-9 shows the weirs and locks in or adjacent to the Dutch River Meuse.

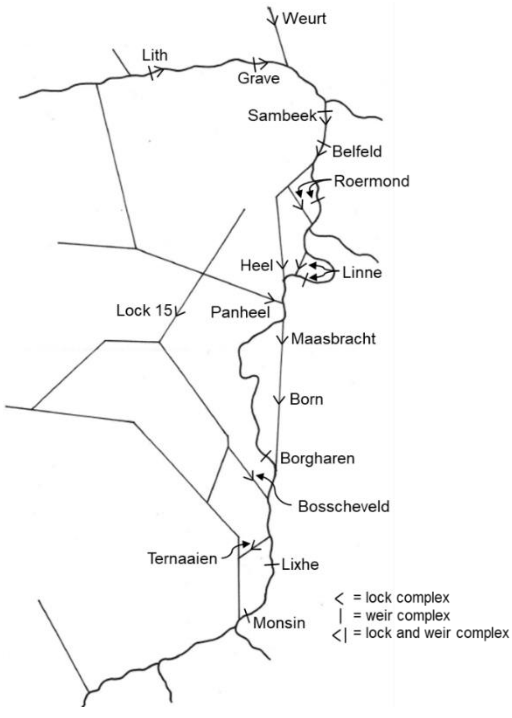

Figure B-9: Overview of locks and weirs in or adjacent to the Dutch part of the River Meuse.

After World War II navigation increased even more, so these decades have been dominated by enlargement of the waterways and structures:

- Extension of the Juliana Canal was demanded and executed. The locks at Roosteren have been demolished, the locks of Maasbracht have been renewed and now form the downstream boundary of the canal. A little downstream, construction of the Lateral Canal have shortened the main navigation route by five kilometre.
- The Canal Antwerp-Brussels-Charleroi has been enlarged to accommodate vessels unto 1,350 tons with the number of locks decreasing from 13 to 8.
- In the canalized River Meuse in Belgium, the 5 locks between Namur and Huy have been replaced by 2 large locks (9,000 tons) in the seventies. Weirs have been replaced as well; weir Lixhe replaced weir Visé in 1980 for example. The section upstream of Liège unto the French border has been made suitable for vessels unto 1,350 tons. The French part has not been modernized, because navigation has not improved much in that region.

Besides the measures to improve navigation, the floods in the history have played an important role in the development of the river system. In the past, many spillways were constructed to lower the effects of the floods on the living environment of inhabitants. Among the spillways west of Roermond and near Maastricht, the one from Cuijk (near Grave) to 's-Hertogenbosch was the largest. In this area, the River Waal and River Meuse confluence, which has led to multiple floods. During flood periods the water level in the River Waal was higher than in the River Meuse, so water, even more than the own discharge of the River Meuse, flowed to the River Meuse. This caused floods of the River Meuse and the spillways. A couple of interventions have been realized for a better safety against floods in this area:

- The connection between the River Meuse and the River Waal at St. Andries was replaced by a lock in 1856.
- The distribution of water from the River Rhine over the River Waal and River IJssel has been regulated at the Pannerdensche Kop.
- Construction of the New Merwede in 1860 created an own discharge canal for the Waal, see Figure B-3.
- In 1904 the Bergsche Maas was opened, which completed the separation of both rivers. The old course of the River Meuse is now called the Afgedamde Maas (in English: Dammed Meuse), see Figure B-3.

These interventions resulted in a River Meuse which was partly able to discharge flood waves by its own. After the flood wave in 1926 additional measures started, to increase flood safety. This included deepening of the main navigation channel, shortening of the groins and cutting off some river bends. Water levels decreased, which induced the construction of weir Lith in 1936. The large spillway was closed in 1942, the spillways in the south were closed too, after the construction of the Juliana Canal and Lateral Canal. The gravel extraction in the valley of the River Meuse since 1950 have created the Maasplassen, which also has increased flood safety by lowering the peak discharge of flood waves.

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Appendix C
Weir hydraulics and weir management

In this appendix, first, in Appendix C.1, the general hydraulics of a dammed river are elaborated. The applied hydraulic model is derived and presents the formula, which is evaluated numerically to calculate the water level in a weir section. The local flow conditions at the weir itself are subject of Appendix C.2. Thereafter, Appendix C.3 addresses all weirs within the study area. It starts with the weirs in Belgium, followed up by the weirs in downstream direction of the River Meuse. The focus lies on the type of gates and operation of these gates to obtain the desired water level. The secondary functions of the weir complexes are mentioned as well.

C.1 Steady gradually-varying flow

The water depth of a free-flowing river is dependent on the river characteristics and the discharge. The relation between water depth and discharge is described by the Chézy formula:

$$Q = A \cdot u = B \cdot d_e \cdot C \cdot \sqrt{d_e \cdot i_b} \tag{C.1}$$

The river characteristics that influence the water depth are the width, the gradient and the roughness. These parameters are not constant over the entire stretch; the width is even changing for varying water depths. If the water level rises, the river valley and/or floodplains may flood. Buildings, roads and trees all result in a larger flow resistance to the flow in case of flooding. In other words, the roughness of the river valley in total is larger than that of the main channel. Thus, the Chézy value is dependent on the water level as well.

Additionally, from this formula the need of weir Lith becomes clear. To prevent floods, river bends have been cut-off, by which the gradient of the river section has been increased. As a result, for each discharge the corresponding water depth decreases as well. Flood safety is increased, but in dry periods it also lowers the water level, leading to problems for the navigation sector. Construction of weir Lith solved this problem.

To calculate the resulting water levels, an hydraulic model is set up (ARCADIS, 2015). The river is simplified as a rectangular prismatic channel, as shown in Figure C-1. This figure shows the definition of the used parameters as well.

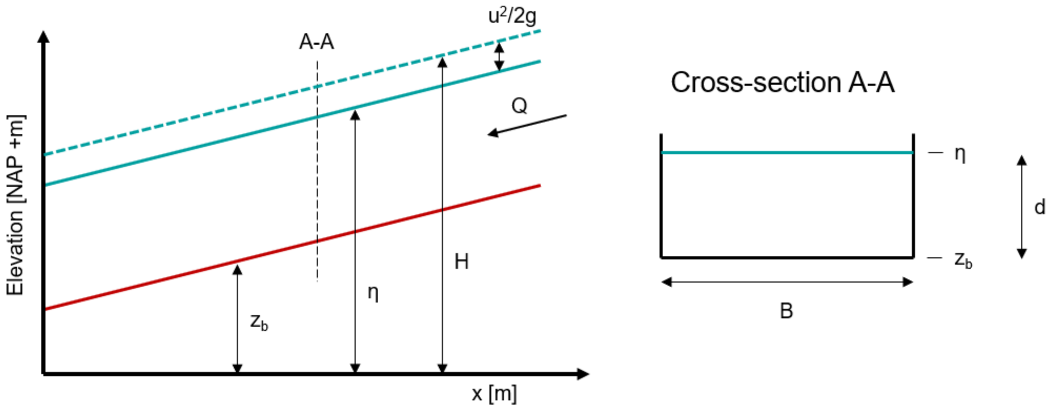

Figure C-1: The definition of the parameters used in the hydraulic model.

The basis of this model is the conservation of energy which is presented by Bernoulli's law:

$$H = \eta + \frac{u^2}{2g} \tag{C.2}$$

This law is rewritten as function of the water level. The course of the water level is obtained by differentiating this function.

$$\frac{d\eta}{dx} = \frac{dH}{dx} - \frac{u \cdot du}{g \cdot dx} \tag{C.3}$$

Now equation (C.1) comes into play to obtain an expression for the course of the energy head. It is assumed that the course of the energy level is equal to the bed slope.

$$u = C \cdot \sqrt{d \cdot i_b} = C \cdot \sqrt{(\eta - z_b) \cdot \frac{dH}{dx}} \tag{C.4}$$

The flow velocity can also be expressed as function of the discharge, see equation (C.5).

$$u = \frac{Q}{B \cdot d} = \frac{Q}{B \cdot (\eta - z_b)} \tag{C.5}$$

Combining equations (C.4) and (C.5) leads to the expression for the course of the energy head.

$$\frac{dH}{dx} = \frac{Q^2}{((\eta - z_b)B)^2 \cdot (\eta - z_b) \cdot C^2} \tag{C.6}$$

An expression for the change of the flow velocity is obtained by differentiating of equation (C.5).

$$\frac{du}{dx} = \frac{A \cdot {}^{dQ}\!/_{dx} - Q \cdot {}^{dA}\!/_{dx}}{A^2} \tag{C.7}$$

Only the steady situation is analysed, so ${}^{dQ}\!/_{dx}$ is equal to zero. The change of the river's cross-section is presented by equation (C.8).

$$\frac{dA}{dx} = \frac{dB}{dx} \cdot (\eta - z_b) + B \cdot (\frac{d\eta}{dx} - \frac{dz_b}{dx}) \tag{C.8}$$

For a prismatic channel holds $\frac{dB}{dx}=0$. Filling in equations (C.5) and (C.6) and the reduced equations (C.7) and (C.8) results in the expression for the course of the water level.

$$\frac{d\eta}{dx}=\frac{[\frac{Q^2}{((\eta-z_b)\cdot B)^2}\cdot(\frac{1}{C^2\cdot(\eta-z_b)}+\frac{B}{g\cdot(\eta-z_b)\cdot B}\cdot\frac{dz_b}{dx}]}{[1-\frac{B\cdot Q^2}{g\cdot((\eta-z_b)\cdot B)^3}]} \tag{C.9}$$

This expression is numerically evaluated at all locations for various discharges.

C.2 Weir flow conditions

To obtain the desired water level in the entire weir section, the weir has to regulate the water level and discharge by operation of the weir gates. Several designs have been applied which are split into two categories from the viewpoint of water level control: overflow weirs and underflow weirs. Both weirs are addressed in this appendix.

C.2.1 Overflow weirs

The discharge over a weir gate or weir sill is dependent on the water levels upstream and downstream. If the water level downstream is relatively large, it reduces the discharge over the weir. This situation, called submerged overflow, is schematically shown in Figure C-2. A broad-crested weir is shown in this figure, which means that the flow lines on top of the weir are parallel. Weirs in rivers, however, are mostly classified as sharp-crested weirs, but the hydraulics of both weirs are similar.

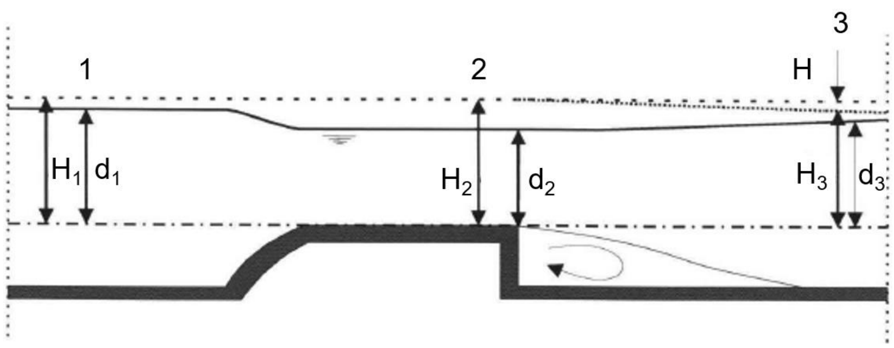

Figure C-2: Submerged overflow conditions for a broad-crested weir (Bezuyen, Stive, Vaes, & Zitman, 2012).

Again, the conservation of energy is applied by use of Bernoulli's law. Contrary to equation (C.2), the energy head H is expressed with respect to the top of the gate or the sill instead of to the reference level NAP. The elevation of the water level η is therefore equal to the water depth d. Conservation between cross-section 1 and 2 leads to the following equation:

$$d_1+\frac{u_1^2}{2g}=d_2+\frac{u_2^2}{2g} \tag{C.10}$$

Rewriting this equation, results in the flow velocity and discharge on top of the weir.

$$Q=B_2\cdot h_2\cdot u_2=B_2\cdot d_2\cdot\sqrt{2g(H_1-d_2)} \tag{C.11}$$

The water depth on top of the weir's sill or gate and energy head are, however, often unknown. That's why the upstream and downstream water level are desired as input. The water depth d_2 is converted to d_3 and the energy head H_1 into the water depth d_1; the accompanied deviation in the outcome is obviated by introducing a discharge coefficient. This coefficient takes the loss of energy between cross-section 2 and 3 into account, too. Moreover, this coefficient considers the differences between a broad-crested and sharp-crested weir. The discharge over a sharp-crested weir is slightly larger than the discharge over similar broad-crested weirs like shown in Figure C-2. Finally, the discharge, in case of submerged overflow, is calculated by equation (C.12).

$$Q = c_{overflow} \cdot B_2 \cdot d_3 \cdot \sqrt{2g(d_1 - d_3)} \tag{C.12}$$

From this equation it becomes clear that the discharge increases if the downstream water level subsides. The water level on top of the weir itself subsides as well unto the submerged flow turns into critical flow. The Froude number, calculated with equation (C.13), has then risen to 1.0. The threshold is reached when the downstream water level d_3 has subsided to two-third of the upstream energy head H_1.

$$Fr = \frac{u}{\sqrt{gd}} \tag{C.13}$$

In critical flow, the discharge is maximum for a given width. If the downstream water level subsides even more, the flow on top of the weir will not change. This means that the downstream water level does not influence the flow and discharge over the weir. This situation, called free overflow, is shown in Figure C-3.

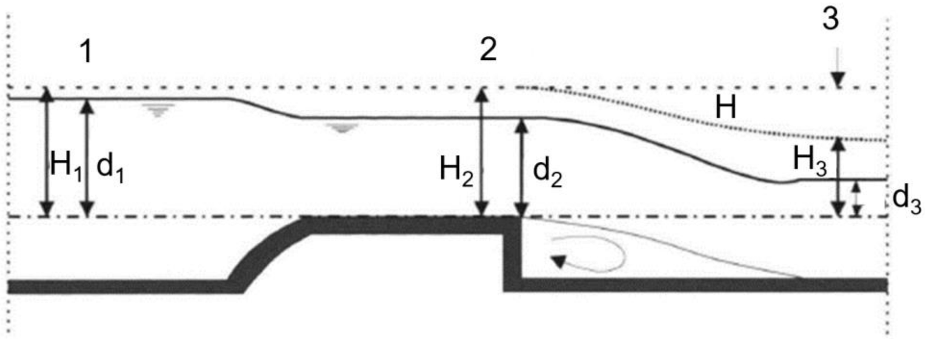

Figure C-3: Free overflow conditions for a broad-crested weir (Bezuyen, Stive, Vaes, & Zitman, 2012).

Again, equation (C.10) is taken as starting point. Since the Froude number is equal to 1.0 during free overflow, equation (C.13) can be combined with equation (C.10). This results in the following expression for the water depth on top of the weir, in case of free overflow.

$$d_2 = \tfrac{2}{3} \cdot H_1 \tag{C.14}$$

The discharge, in case of free overflow, is then:

$$Q = \tfrac{2}{3} \cdot c_{overflow} \cdot B \cdot \sqrt{\tfrac{2}{3} \cdot g} \cdot d_1^{3/2} \tag{C.15}$$

C.2.2 Underflow weirs

As for overflow, underflow conditions are also split into a submerged and a free situation. Bernoulli's law is applicable for these situations as well and is used to obtain the discharge formulas. Since the derivation is the same as for overflow weirs, this is not repeated here.

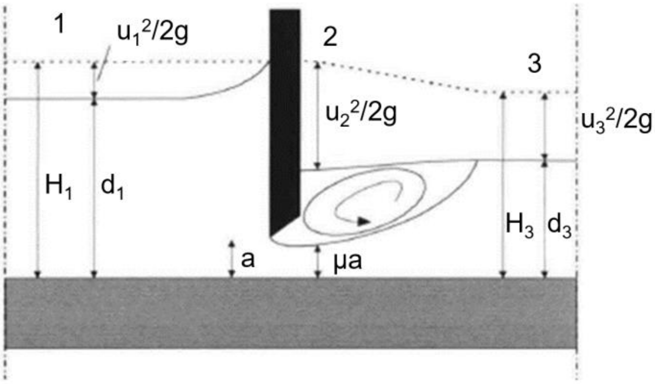

Figure C-4: Submerged underflow conditions for an underflow weir (Bezuyen, Stive, Vaes, & Zitman, 2012).

Figure C-4 shows the flow for an underflow weir, in case of submerged flow. The downstream water level covers the underflowing jet; the water jump is located directly behind the weir. In this way, the downstream water level determines the discharge partly, as can be seen in the following expressions:

$$Q = c_{subunderflow} \cdot B_2 \cdot a \cdot \sqrt{2g(d_1 - d_3)} \tag{C.16}$$

Again, after derivation with help of the Bernoulli's law, the upstream energy head H_1 and water depth at cross-section 2 μa are part of the expression and, again, this is undesired. For convenience, these are replaced by the upstream water depth d_1 and the opening between the sill and the weir gate a, respectively. The deviation is accounted for by the discharge coefficient $c_{subunderflow}$.

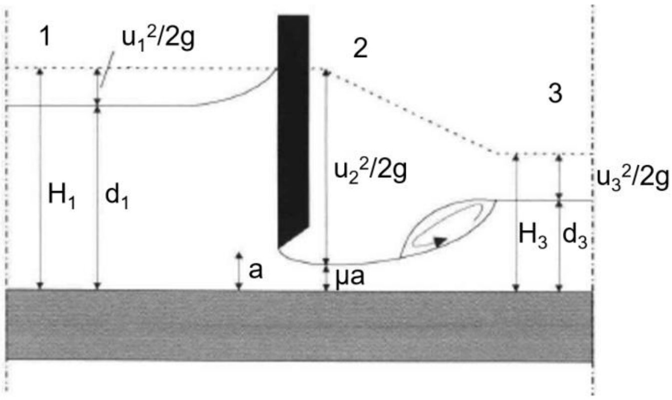

Figure C-5: Free underflow conditions for an underflow weir (Bezuyen, Stive, Vaes, & Zitman, 2012).

In case of free underflow, the water jump is located more downstream, as in Figure C-5. According to equation, the discharge in case of free overflow is not hampered by the downstream water level, but by the water depth of the jet.

$$Q = c_{freeunderflow} \cdot B_2 \cdot a \cdot \sqrt{2g(d_1 - a)} \tag{C.17}$$

For underflow weirs, the discharge coefficient for submerged and free flow is different, in contrast to the discharge coefficient of the overflow weirs.

Analysis of the discharge formulas for underflow weirs shows that in both situations, the discharge is dependent on the root of the upstream water level. The discharge of an overflow weir is, in case of free overflow, dependent on the upstream water level to the power 1.5. This means that a small adjustment of the position of an overflow weir gate leads to a larger discharge adjustment than a small adjustment of the position of an underflow weir gate. Figure C-6 show the elevation of the bottom of the underflow gate and the crest of the overflow gate which are required to maintain a water level at NAP +14.10 m. The discharge coefficients have been taken equal to 1.0, the width to 10 m and the sill's elevation to NAP +8.05 m to obtain this figure. The crest of the overflow gate is adjusted more than the bottom of the underflow gate in this plotted discharge range. Thus, an overflow gate is able to regulate the water level more accurately than an underflow gate.

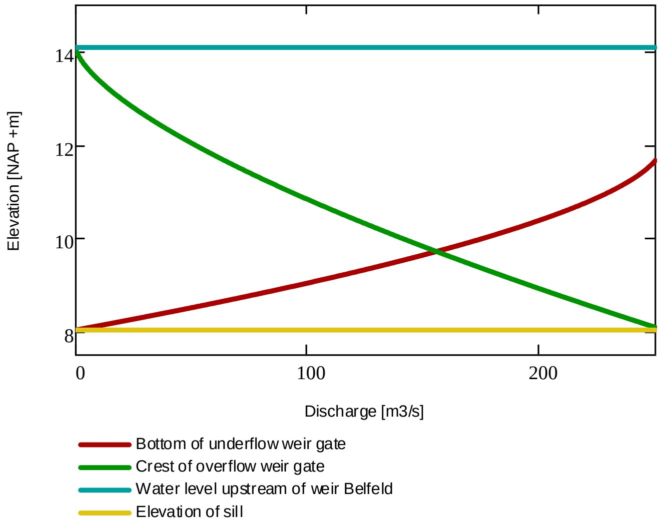

Figure C-6: Water level regulation by an overflow and underflow weir.

C.3 Characteristics of the weir structures in the project area

The weirs in the project area are discussed in streamwise direction in this appendix.

Weirs in Belgium

The most upstream weir in the project area is weir Monsin. It is combined with a bridge; in each of the six bridge spans a 27 m wide Stoney gate is placed. With the help of small flap gates on top of the Stoney gates the water level upstream is regulated accurately. The water level is maintained at NAP + 60.00 m, which is demanded for navigation on the Albert Canal (Santilman, 1939).

The second Belgian weir in the project area is situated near Lixhe. The weir itself, however, does not affect the Dutch part of the River Meuse. The hydropower station does; the 3 turbines are each designed for a discharge of 85 m^3/s, so the discharge through this hydropower station varies with steps of 85 m^3/s as well. Especially in dry periods, the management of this hydropower station determines the discharge and discharge peaks downstream (Rijkswaterstaat, 1992).

Borgharen

The weir of Borgharen is the most upstream Dutch weir in the River Meuse. It consists of four openings. The widest opening is 30 m wide, equipped with only a fixed-wheel gate and was constructed as passage opening for vessels during a flood wave. The width is much smaller than the width of the Poirée weirs more downstream, because the Grensmaas was not part of the main transport route of coals during period of construction (Schot, Lintsen, Rip, & De la Bruhèze, 1998). The wheels are fixed to the gate and slide up and down to operate the gate. Drawback of this gate type is the lift of the total dead weight in case of opening. A crane which runs on top of the weir over a steel bridge is needed for this. For accurate water level control, the other three openings, each 23 m wide, are closed off by a fixed-wheel gate with a flap on top, see Figure C-7. Adjustment of the flap enables accurate water level regulation and the disposal of floating material (Erbisti, 2014).

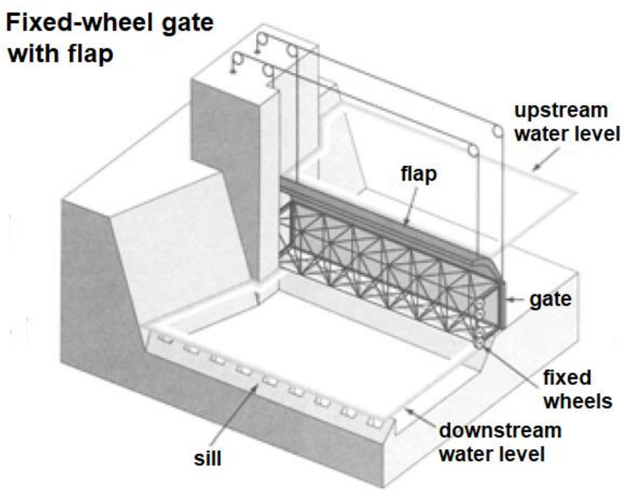

Figure C-7: Fixed-wheel gate with flap (Schot, Lintsen, Rip, & De la Bruhèze, 1998).

The water level upstream of weir Borgharen is maintained at NAP + 44.00 m, variating from NAP + 43.90 to NAP+ 44.10 m. The weir operation is summarized in Table C-1. Overflow is only accepted over the fixed-wheel gates with flaps; underflow occurs at all four gates (Kranenbarg & Kemper, 2006).

Table C-1: Operation of weir Borgharen.

Discharge [m³/s]	*Water level regulation*
0 – 230	Fixed-wheel gates rest on foundation, regulation by flaps
230 – 300	Fixed-wheel gate in widest opening lifted 0.20 m
300 – 1200	All fixed-wheel gates are lifted by steps of 0.10 m
> 1200	All fixed-wheel gates completely lifted

Adjacent to the weir a small lock and a fish passage is situated (Antea Group, 2014).

Linne, Roermond, Belfeld and Sambeek

The weirs of Linne, Roermond, Belfeld and Sambeek are all very similar, so they are treated simultaneously. The weirs consist of the mentioned combination of a Stoney weir and a Poirée weir, see Figure C-8.

The Stoney weir is divided into discharge openings of 17 m width each. The lifting procedure of Stoney gates is comparable with the transport of heavy material on cylinders. The rolling mechanism is not coupled to the gate itself; it rolls half of the shifted distance of the gate itself. In this way, slip is prevented. The lifting mechanism is located on a bridge on top of the concrete pillars. The period of construction was decisive for choosing Stoney gates, since no other gate types were available by then which enabled water level control as accurate as Stoney gates. In the weirs in the River Meuse, double Stoney gates have been applied to only allow overflow. Underflow was undesired in that time, because this resulted in more severe scour of the riverbed in contrast to overflow (Schot, Lintsen, Rip, & De la Bruhèze, 1998).

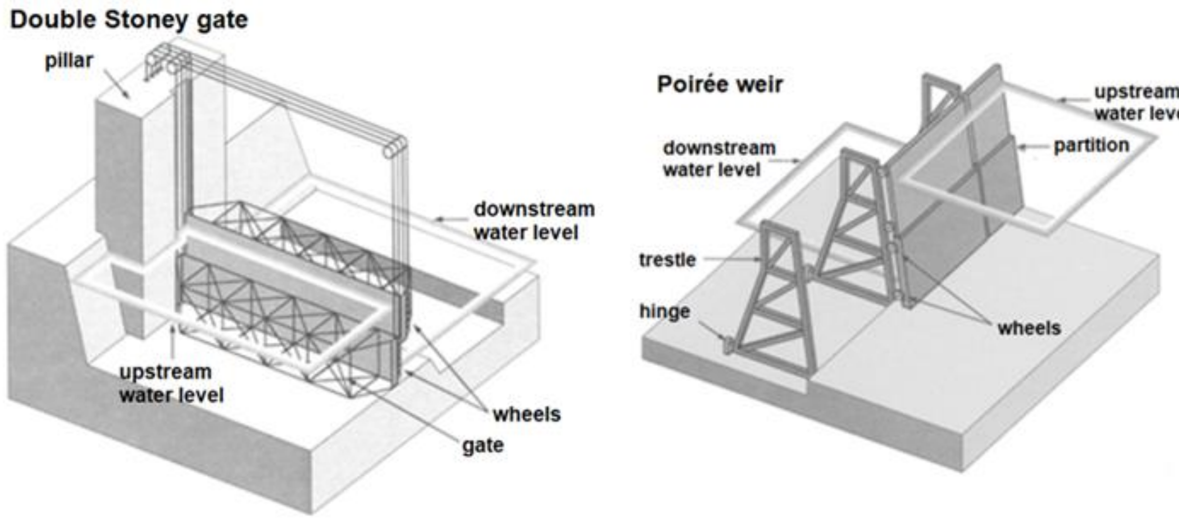

Figure C-8: Double Stoney gate (left) and Poirée weir (right) (Schot, Lintsen, Rip, & De la Bruhèze, 1998).

The Poirée weir consists of partitions which are supported by trestles. The concept of the Poirée weirs has been adopted from the earlier constructed weirs in Belgium and France. Erecting and lowering of the Poirée weir is done manually and is specialist workmanship. First, the partitions are lifted by rolling its wheels upward over the framework of the trestles. The lifting crane moves over a rail on top of the connected trestles and stows the partitions one-by-one and row-by-row at the river bank. Subsequently, the trestles are disconnected and laid down on the foundation, which is possible because of the hinged connection at the foundation (Schot, Lintsen, Rip, & De la Bruhèze, 1998). In this way, flood waves can pass. The opening, created by the lowering of the trestles, is used for passage of vessels.

The exact dimensions of both weir parts and the dammed water levels of the weirs are mentioned in Table C-2. The way these water levels are maintained is summarized in Table C-3.

Table C-2: Dimensions and dammed water levels of combined weirs (Kranenbarg & Kemper, 2006).

	Linne	*Roermond*	*Belfeld*	*Sambeek*
Stoney weir	3 x 17 m	2 x 17 m	2 x 17 m	2 x 17 m
Poirée weir	15 partitions, each 4.00 m wide	17 partitions, each 4.00 m wide	13 partitions, each 4.85 m wide	13 partitions, each 4.85 m wide
Upstream water level	NAP + 20.80 m	NAP + 16.85 m	NAP + 14.10 m	NAP + 10.75 m
Tolerance of water level	NAP +20.70 – 20.90 m	NAP + 16.70 – 16.85 m	NAP + 13.90 – 14.20 m	NAP + 10.70 – 10.90 m

Table C-3: Operation of combined weirs (Kranenbarg & Kemper, 2006).

Discharge [m³/s]	*Weir*	*Water level regulation*
0 – 200	All	All Poirée partitions are lowered, regulation by the double Stoney gates
200 – (800, 1000 or 1070)	All	Some Poirée partitions are pulled out to enable regulation by the double Stoney gates as long as possible
> 800	Belfeld	
> 1000	Linne and Roermond	All Poirée partitions are pulled out, trestles are laid down, the double Stoney gates are completely lifted
> 1070	Sambeek	

Weir Linne is an exception, since vessels can never use the weir opening, since the cyclist bridge still spans the opening created by the erection of the Poirée weir and limits the air clearance in high water conditions. All weir complexes include a fish passage. On top of that, the weir complex of Linne includes a hydropower station (Antea Group, 2014).

Grave

At Grave, the weir is combined with an important river crossing which connects the cities of 's Hertogenbosch and Nijmegen. The weir is a reversed version of the Poirée weir, see Figure C-9. Using standard trestles and partitions was not possible, because of the large water level difference (3.50 m). The trestles are substituted by stiles, which rotate around a horizontal hinge axis at the bridge deck, although it can move vertically a little. To dam the river, the stiles rotate downwards in opposite direction of the flow. When in vertical position, a small vertical downward translation ensures that the stiles are supported by the abutment blocks on the riverbed. The partitions are lowered by cables between the stiles, with a maximum of three partitions above each other. The bridge weir at Grave is divided into 20 segments, which means that at most, during low water levels, 60 partitions are employed to maintain the upstream water level. The costs of service and maintenance are high because of the many partitions. In wet periods, the stiles rotate to their upward horizontal position at the bottom side of the bridge deck to create a navigable opening, although the air clearance is limited by the stiles (Schot, Lintsen, Rip, & De la Bruhèze, 1998).

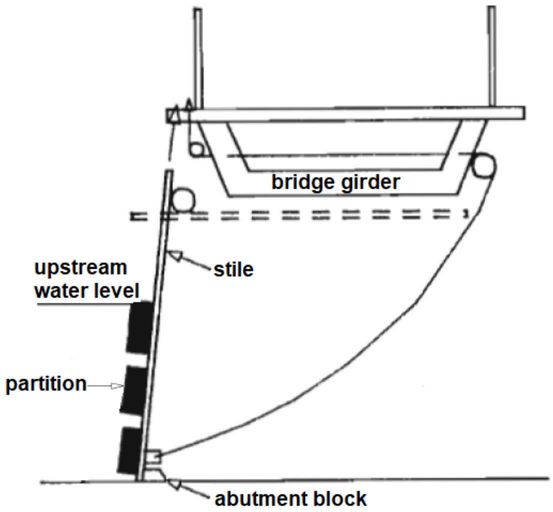

Figure C-9: Reversed Poirée weir (Kranenbarg & Kemper, 2006).

The water level upstream of weir Grave is maintained at NAP +7.50 m with a small tolerance of 0.05 m. The weir operation is summarized in Table C-4. Because lowering and lifting of partitions takes a long time, the weir operation is based on the operation of the first upstream weir Sambeek. As long as the bottom row is located at the sill, overflow conditions occurs. If the discharge is even larger, the bottom row is partially lifted and the water flow underneath the partitions as well (Joustra, Muller, Van Asselt, & Verheij, 2018).

Table C-4: Operation of weir Grave (Kranenbarg & Kemper, 2006).

Discharge [m³/s]	*Water level regulation*
0 – 800	Partitions are lifted one by one, row by row. Each partition of the top row lifted out of the water results in a discharge increase of 20 m³/s.
>1650	All stiles are rotated to the bottom of the bridge deck.

The weir of Grave is accompanied by a fish passage and a lock complex. The lock dimensions are smaller than at the upstream weirs, since large vessels use the Maas-Waal Canal to navigate to Rotterdam and therefore not have to pass weir Grave.

Lith

Just like weir Linne, weir Lith has many secondary functions: the pedestrian bridge connects both banks, the hydropower station generates electricity, the fish passage is used by migrating animals and the Prinses Maxima Locks enable passage of vessels. The weir itself is built some years later than the upstream weirs in the River Meuse. It was needed after the upstream section has been made suitable for discharging large flood waves by bend cut-offs. During small discharges, the water depth was not sufficient anymore for navigation. The closing mechanism is comparable to the one of weir Borgharen. Weir Lith consists of three 38 m wide openings, all equipped with fixed-wheel gates with flaps, see Figure C-7. Table C-5 shows that the gates are lifted completely to the level of the steel bridge when the river discharge exceeds 1000 m^3/s. The created openings are used by vessels to pass the structure. The upstream water level is maintained at NAP + 4.90 m. This is done automatically by registration of water levels and gate movements each 5 minutes (Biemans, 2007).

Table C-5: Operation of weir Lith.

Discharge [m^3/s]	*Water level regulation*
0 – 1000	Fixed-wheel gates rest on foundation, regulation by flaps
> **1000**	Fixed-wheel gates completely lifted

Appendix D
Reference projects

In other countries, weirs are also approaching the end of their lifetime. In this appendix, the deficiencies of these weirs are mentioned. More important, the approach of upgrading of these structures is addressed. This gives a clear overview of the methods applied in neighbouring countries to maintain the functions of the weirs.

France

The canalization of the River Meuse in France took place 50 years before the canalization in the Netherlands. The weirs in this area are completely replaced now. Just like the Dutch Poirée weirs, the French weirs are operated manually; this operation takes much time and money. The 29 weirs in the River Meuse and the River Aisne are replaced by inflatable rubber weirs. The operation is updated to a modern, automated and reliable system. The large replacement project is used to install some hydropower plants as well. Besides, attention is given to fish migration by the construction of fish traps (Chapital, 2015).

Germany

A joint venture worked on the maintenance and upgrading of the weirs in the River Main. The project started with material analyses, inspections and recalculations just like is done in the Netherlands within the national replacement programme. In the end, five weirs in this river have been prioritised. The locations of the weirs has been revised, but a new layout of the river system with relocated weirs or removal of weirs was not thought to be feasible. At the oldest one, weir Viereth, the upgrade has been started already. The gates of the 80-year-old weir have been replaced by modern gates to regulate the water levels more accurately. Refurbishment of the old gates was economically disproportionate, because the lifetime of the gate was almost reached. The ability to discharge flood waves during execution has been a tough requirement, since all weir openings are needed for this. With the help of an innovative, floatable gate it was possible to discharge a considerable amount of water via the building pit.

At Würzburg, the weir, finished in 1954, has been combined with a monumental bridge, which complicates the renovation activities and upgrade of the weir (Würzburg Weir and Lock, n.d.). As at weir Viereth, a new modern gate has been constructed. At weir Limbach, only repair works have been done, since the gate has been damaged by a ship collision.

15 years ago, in the River Rhine on the border of Switzerland, the weir of Rheinfelden has been completely substituted by a new one, 130 m downstream. The old weir of Rheinfelden had been constructed in the end of the nineteenth century and thus was the oldest weir in the upper section of the River Rhine (Fust & Reif, 2015). Also the hydropower station has been renewed, although it still uses the same inlet canal. After construction of the new weir was finished, the old weir has been dismantled.

In the River Weser, in total 5 weirs have been addressed. As in the River Main, the project has been focussed on the weir complexes itself starting with structural and material inspections. Due to their old age and degraded status of the structures, replacement of the gates has been proposed. For one weir, already renovated 25 years ago, adaptations to the design have been proposed to eliminate the vibrations.

Last, the Horkheim and Neckarsulm weir in the River Neckar have been replaced. Like the other projects mentioned before, the gates were in need of complete renewal. Feasibility studies regarded the complete replacement of the weir gates and a new construction of the weir. At weir Horkheim, built in the same period as the weirs in the River Meuse, a modern gate type has been installed and new monitoring equipment and structural reinforcements have been added to the structure to be able to check and catch up the deterioration of the elements. At Neckarsulm, a new weir structure just upstream of the present one has been proposed, because the mechanical elements have been replaced in 1950 and the gate vibrations cannot be eliminated by a renovation (Krebs+Kiefer, 2019).

Belgium

The waterway network in Belgium is, just like in the Netherlands, very extensive. Currently, a project on a new connection between the River Scheldt and River Seine is going on. 7 waterways, which form the connection between the waterway network in Belgium and the Netherlands and the network in northern France, are extended to accommodate larger vessels. The first plans have been developed at the end of the 20th century; nowadays execution has been started. In contrast to the replacement projects in Germany, within this project the focus lies more on the improvement of the total network, including the natural values of the area, the adjacent cities, the local economy and recreational activities. To improve the inland navigation, the canals are widened and deepened, air clearances are enlarged and new locks are constructed, as well as weirs and fish passages. More than 70 activities can be identified at dozens of locations. Most of the improvements are required because of structural degradation and increase of navigation since the construction of the network.

Relatively little activities deal with weirs, since most of the waterways are canals. In the Upper-Scheldt, three weirs are renewed to increase the reliability of this waterway. In the past, an undesirable sequence of small adaptations have been applied to these weirs. In the River Leie, an old weir is replaced by a new one. The most feasible location turned out to be the current location. Before removal of the current weir and construction of the new weir, a temporary weir is built to take over the water level regulation for the execution period of the project. The opportunity of a new weir is taken to include a hydropower station into the structure (De Vlaamse Waterweg nv, 2019).

Austria

In a suburb of Vienna, a weir has been built in 1872 as part of the improvement of the River Danube and the Danube Canal. A floating gate was used to protect the Danube Canal against ice and floods. Even before the start of the 20th century, this gate type has been replaced by a needle weir, like the Poirée weirs. Moreover, a lock has been added during this gate replacement. The locks and weirs lasted thereafter for approximately 75 years. By then, a second gate replacement took place; two radial gates have been installed, which are still operative nowadays. From 2005 on, a hydropower plant uses the water head to generate electricity (ANDRITZ Hydro GmbH, 2013).

Appendix E
Navigation on the River Meuse

This appendix addresses the navigation on the River Meuse. Since the River Meuse is part of the European waterway network, Appendix E.1 shows the classification of the River Meuse according to the European classification system. Appendix E.2 focusses more on the navigation in the regional design area and the related requirements to the waterways, locks, bridges and ports.

E.1 Classification and intensity of global navigation

Table E-1 and Table E-2 show the governing dimensions of vessels according to the CEMT-classification as well as the subclasses defined by Rijkswaterstaat.

Table E-1: First part of European and Dutch classification of commercial vessels (Rijkswaterstaat, 2017).

CEMT-Klasse	Motorvrachtschepen (Motorvessels)							Duwstellen (Barges)			
	RWS Klasse	Karakteristieken maatgevend schip**				Classificatie		RWS Klasse	Karakteristieken maatgevend duwstel**		
		Naam	Breedte	Lengte	Diepgang (geladen)	Laad-vermogen	Breedte en lengte		Combinatie	Breedte	Lengte
			m	m	m	t	m			m	m
	M0	Overig				1-250	B<= 5,00 of L<= 38,00				
I	M1	Spits	5,05	38,5	2,5	251-400	B= 5,01-5,10 en L>=38,01	BO1		5,2	55
II	M2	Kempenaar	6,6	50-55	2,6	401-650	B=5,11-6,70 en L>=38,01	BO2		6,6	60-70
III	M3	Hagenaar	7,2	55-70	2,6	651-800	B=6,71-7,30 en L>=38,01	BO3		7,5	80
	M4	Dortmund Eems (L < = 74 m)	8,2	67-73	2,7	801-1050	B=7,31-8,30 en L=38,01-74,00	BO4		8,2	85
	M5	Verl. Dortmund Eems (L > 74 m)	8,2	80-85	2,7	1051-1250	B=7,31-8,30 en L>=74,01				
IVa	M6	Rijn-Herne Schip (L <= 86 m)	9,5	80-85	2,9	1251-1750	B=8,31-9,60 en L=38,01-86,00	BI	Europa I duwstel	9,5	85-105
	M7	Verl. Rijn-Herne (L > 86 m)	9,5	105	3,0	1751-2050	B=8,31-9,60 en L>=86,01				
IVb											
Va	M8	Groot Rijnschip (L <=111 m)	11,4	110	3,5	2051-3300	B= 9,61-11,50 en L=38,01-111,00	BII-1	Europa II duwstel	11,4	95-110
	M9	Verlengd Groot Rijnschip (L >111 m)	11,4	135	3,5	3301-4000	B= 9,61-11,50 en L>= 111,01	BIIa-1	Europa IIa duwstel	11,4	92-110
								BIIL-1	Europa II Lang	11,4	125-135
Vb								BII-2l	2-baksduwstel lang	11,4	170-190
VIa	M10	Maatg. Schip 13,5 * 110 m	13.50	110	4,0	4001-4300	B=11.51-14.30 en L=38.01-111.00	BII-2b	2-baksduwstel breed	22,8	95-145
	M11	Maatg. Schip 14.2 * 135 m	14.20	135	4,0	4301-5600	B=11.51-14.30 en L>= 111.01				
	M12	Rijnmax Schip	17,0	135	4,0	>= 5601	B>= 14.31 en L>= 38.01				
VIb								BII-4	4-baksduwstel (incl. 3-baks lang)	22,8	185-195
VIc								BII-6l	6-baksduwstel lang (incl 5-baks lang)	22,8	270
VIIa								BII-6b	6-baksduwstel breed (incl. 5-baks breed)	34,2	195

Table E-2: Second part of European and Dutch classification of commercial vessels (Rijkswaterstaat, 2017).

CEMT-Klasse	Duwstellen (Barges)				Koppelverbanden (Convoys)							Doorvaart-hoogte*
	RWS Klasse		Classificatie		RWS Klasse	Karakteristieken maatgevend koppelverband**				Classificatie		
		Diepgang (geladen)	Laad-vermogen	Breedte en lengte		Combinatie	Breedte	Lengte	Diepgang (geladen)	Laad-vermogen	Breedte en lengte	incl. 30 cm schrikhoogte
		m	t	m			m	m	m	t	m	m
	M0											
I	M1	1,9	0-400	B<=5,20 en L= alle	C1l C1b	2 spitsen lang 2 spitsen breed	5,05 10,1	77-80 38,5	2,5 2,5	<= 900 <= 900	B<= 5,1 en L=alle B=9,61-12,60 en L<= 80,00	5,25* 5,25*
II	M2	2,6	401-600	B=5,21-6,70 en L=alle								6,1
III	M3 M4 M5	2,6 2,7	601-800 801-1250	B=6,71-7,60 en L=alle B=7,61-8,40 en L=alle								6,4 6,6 6,4
IVa	M6 M7	3,0	1251-1800	B=8,41-9,60 en L=alle								7,0* 7,0*
IVb					C2l	Klasse IV + Europa I lang	9,5	170-185	3,0	901-3350	B=5,11-9,60 en L=alle	7,0*
Va	M8 M9	3,5 4,0 4,0	1801-2450 2451-3200 3201-3950	B=9,61-15,10 en L<=111,00 B=9,61-15,10 en L<=111,00 B=9,61-15,10 en L=111,01-146,00								9,1* 9,1* 9,1*
Vb		3,5-4,0	3951-7050	B=9,61-15,10 en L>=146,01	C3l	Klasse Va + Europa II lang	11,4	170-190	3,5-4,0	3351-7250	B=9,61-12,60 en L>=80,01	9,1*
VIa	M10 M11 M12	3,5-4,0	3951-7050	B=15,11-24,00 en L<=146,00	C2b C3b	Klasse IV + Europa I breed Klasse Va +Europa II breed	19,0 22,8	85-105 95-110	3,0 3,5-4,0	901-3350 3351-7250	B=12,61-19,10 en L<=136,00 B>19,10 en L<=136	7,0* alleen voor klasse IV koppelverband 9,1*
VIb		3,5-4,0	7051-12000 (7051-9000)	B=15,11-24,00 en L=146,01-200	C4	Klasse Va + 3 Europa II	22,8	185	3,5-4,0	>=7251	B>12,60 en L>=136,01	9,1*
VIc		3,5-4,0	12001-18000 (12001-15000)	B=15,11-24,00 en L>=200,01								9,1*
VIIa		3,5-4,0	12001-18000 (12001-15000)	B>=24,01 en L=alle								9,1*

On basis of this vessel classification, waterways have been classified as well, see Figure E-1 on the left. The classification of the waterway is equal to the largest CEMT-Class of vessels that is allowed on that waterway. The right part of Figure E-1 shows the vessel intensity at each location per CEMT-Class. The coloured circle diagrams show the distribution of the passing vessels over the CEMT-Classes in terms of load capacity. Data are used to generate these diagrams; some deviations from reality are possible, since

- the number and size of vessels in the Maas-Waal Canal is counted at lock Weurt, which is the lock which connects the Maas-Waal Canal with the River Waal. Part of the counted vessels is sailing towards the inland port of Nijmegen along the canal and therefore does not really contribute to the navigation intensity on the River Meuse.
- in contrast to all other counts, the counts in Maastricht are not performed at a lock, but at a bridge. At all other locations the average of the counts from 2005 until 2008 is used; in Maastricht data is missing. Also, recreational vessels have not been counted here. Eventually, the total number of commercial vessels is taken as two-third of the number counted at lock Born (Zomer, Harmsen, Buter, & Schilt, 2007).

- the counted vessels are only classified by their load capacity. Based on this information and the help of Table E-1 and Table E-2, these data have been converted to the CEMT-classification. This might involve some additional deviations, but the dimensions of the vessels using the waterways can thereby be related more easily to the dimensions of the waterways.

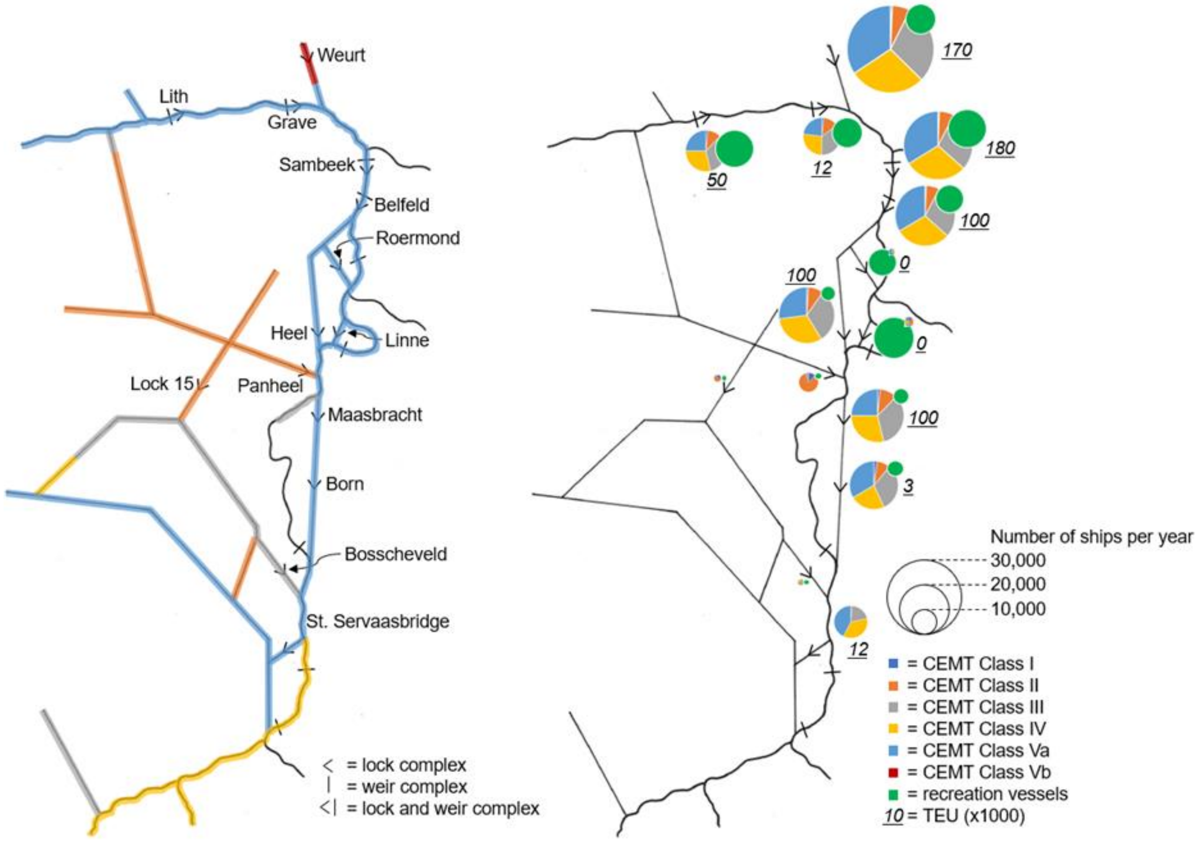

Figure E-1: Classification (left) and intensity (right) of the waterways in the global design area.

E.2 Regional navigation and limitations

Since the ports of Born and Stein are the main destinations and origins of the Class Va vessels using the Maasroute between Belfeld and Heel, the activities in these ports involve the requirements to this navigation route. The port of Born was opened to transport coal products, but after the mines were closed the port of Born made a transition to a logistical node. Multimodal transport of goods is facilitated by good connections via road and a barge and rail terminal, which was opened in the 90s. This terminal has grown to one of the largest inland terminals of the Netherlands. The local petrochemical industry Chemelot, the car manufacturer NedCar and other industry using bulk products use the port intensively. Besides, the waterway connections with the ports of Antwerp and Rotterdam are used for container transport. Daily, hundreds of containers are transported from and to these sea ports, see Figure 3-3 as well (Rijkswaterstaat, 2009). The port of Stein is largely owned by Chemelot. The port supplies dry and liquid bulk for the production of chemical products. The bulk is transported by road, rail and pipe lines to the right factory (Kortweg & Kuipers, 200).

As mentioned earlier, the characteristics of the Maasroute are limiting the navigation sector. The water depth is governing for the bulk transport, the air clearance for the container transport. This appendix deals with both aspects in Sections E.2.1 and E.2.2.

E.2.1 The required water depth for commercial navigation

The water depth has been addressed earlier in Appendix C.1, in which the hydraulic model is set up. In this model, the water depth equals the difference between the water level and the bed level. Therefore, this appendix first addresses the bed level simultaneously with the water depth requirements for navigation. The bed level in the calibrated model of ARCADIS is not right, so other data are applied to find out the bed level.

The present elevation of lock sills is presented in Table E-3.

Table E-3: Present elevation of lock sills (Geerling, Buijse, & Van Kouwen, 2010).

Lock sill	Elevation [NAP + m]	Dammed water level [NAP + m]	Water depth [m]
Belfeld upstream	+7.25	+14.10	6.85
Roermond upstream	+11.90	+16.85	4.95
Roermond downstream	+10.70	+14.10	3.40
Heel downstream	+10.00	+14.10	4.10
Linne downstream	+13.40	+16.85	3.45

Nowadays, all these locks accommodate Class Va vessels of 3.0 m draught maximum. After the upgrade of the Maasroute, the CEMT-Class is enlarged to Class Vb with a maximum draught of 3.5 m. The corresponding minimum dimensions are different for a cross-section in a waterway, in a lock and in an inland port. Since weirs dam the water level, Figure E-2 shows only the minimum required water depth in relation to the vessel's draught. Table E-4 applies these requirements to the locks and waterways in the Maasroute (Rijkswaterstaat, 2017).

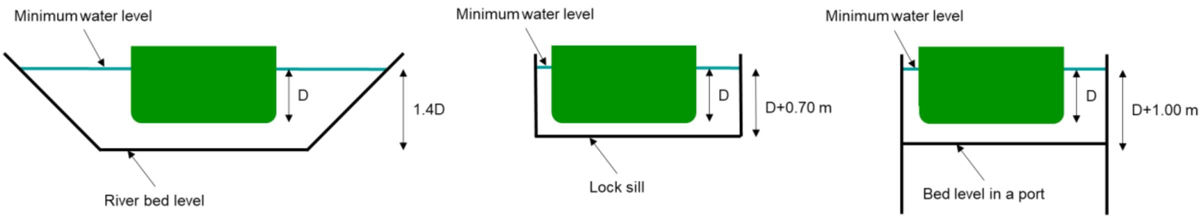

Figure E-2: The water depth requirements in a commercial navigation waterway in a cross-section of a river (left), a lock (middle) and an inland port (right) (Rijkswaterstaat, 2017).

Table E-4: The minimum required water depths for various vessel's draughts (Rijkswaterstaat, 2017).

CEMT-Class	Maximum draught [m]	Minimum water depth in waterway [m]	Minimum water depth at lock sill [m]
Va	3.00	4.20	3.70
Vb	3.50	4.90	4.20

Comparing Table E-4 with the last column of Table E-3, it stands out that the locks of Roermond and Linne do not meet the national guideline. The use of these locks is restricted in periods of low discharge (Rijkswaterstaat, 2019). Taking into account the keel clearance of 0.70 m, the maximum draught is equal 2.70 m at lock Roermond and 2.75 m at lock Linne in a zero-discharge situation. The restriction only holds if the river discharge is low; in the current way of damming, if the discharge increases, water levels increase and vessels of larger draught are allowed to use these locks.

It is assumed that the present bed levels of the waterway do not restrict the maximum draught more than lock sills do. Thus, near lock Belfeld and lock Heel, the bed level is elevated 0.50 m lower than the lock sill, since this is the difference of the minimum water depths in the first row of Table E-4. The current bed level near lock Linne is calculated in the same way with the following formula:

$$z_b = \eta_{sill,lock} + (D + 0.7) - D \cdot 1.4 \tag{D.1}$$

The results are summarized in Table E-5. The bed level near lock Roermond is not calculated, since it follows after interpolation of the bed level from the upstream and downstream locks. The bed slope of the Lateral Canal and the lock canals is negligible and taken as zero.

Table E-5: Calculation of the current bed elevation.

Location	Maximum draught [m]	Elevation of the lock sill [NAP + m]	Current bed elevation [m]
Belfeld	3.00	+7.25	+6.75
Heel	3.00	+10.00	+9.50
Linne	2.75	+13.40	+13.00

The calculated bed level near lock Heel corresponds with the current bed level of the Lateral Canal found in literature (Douben & Maris, 1994).

The current bed level is, however, not necessarily starting point of this project. The Maasroute is upgraded in these years to a Class Vb waterway. In literature is found that the dredging of the summer bed is not needed for this upgrade (De Vries, 2000). Setup of the dammed water level is not discussed as well. These findings do not agree if one applies the current bed levels as presented above. For example, the water depth in the Lateral Canal is 4.60 m, but, for a Class Vb waterway, this has to be 4.90 m. The water depth at the downstream sill of lock Heel is also just not sufficient. Since the upgrade of the Maasroute is finished before the weirs are replaced, in this project, deepening of the Lateral Canal and lock Heel is taken as starting point. In this way, the water depth is just sufficient for Class Vb vessels without a change of the dammed water level. The locks of Linne and Roermond stay untouched, since they are not part of the Maasroute. Figure E-4 shows the bed level along the River Meuse from weir Belfeld to weir Linne after the upgrade to a Class Vb waterway.

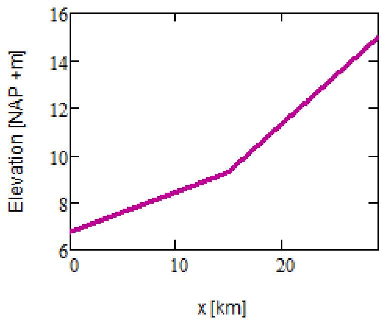

Figure E-3: Bed level along the River Meuse from weir Belfeld (x = 0 km) to weir Linne (x = 29 km).

Besides the locks and waterways part of the Maasroute, the regional project area encompasses a commercial port. The bed of the Willem-Alexanderport is situated at NAP +13.25 m (Rijkswaterstaat, 2019); according to the national guidelines a keel clearance of 1.00 m is taken into account in commercial ports. Assuming that the port meets the national guidelines, the maximum allowable draught of vessels calling this inland port is then 2.60 m.

E.2.2 Required air clearance for container transport

The required air clearance for container transport depends on the loading of container vessels and the dimensions of the stacked containers. Conventional 20 and 40 ft containers have a height of 8 ft and 6 inch, high-cubes are 9 ft and 6 inch high. The difference of approximately 30 cm results in a higher container vessels. In this appendix, the target value stated in the SVIR (Structuurvisie Infrastructuur en Ruimte) (in English: Strategy Infrastructure and Spatial Planning) is compared with three other methods in this appendix for three-layered and four-layered container vessels. These methods include new calculations, measurements and high-cubes. Table E-6 shows the minimum air clearance for all of these methods, all including a safety margin of 30 cm. An averagely loaded container vessel is loaded to 65% of its capacity, of which 65% of the containers is loaded and 35% empty (Brolsma, Rapportage containerhoogtemetingen, 2013).

Table E-6: Minimum air clearance for 3- and 4-layered container vessels and several determining methods (Brolsma, Rapportage containerhoogtemetingen, 2013) (Brolsma, Corridoranalyse containers, 2015).

Method	Three layers of conventional containers	Three layers of high-cube containers	Four layers of conventional containers	Four layers of high-cube containers
Target according to SVIR	7.00 m	-	9.10 m	-
Calculation: average loading	7.06 m	7.88 m	9.20 m	10.29 m
Calculation: 100% empty containers	7.51 m	8.43 m	9.88 m	11.10 m
Measurements 2012: 10% exceedance	8.50 m		10.85 m	

Note that the minimum air clearances apply to the water level which is exceeded 1% of the time. Since weirs are open in this situation, this situation is less important for this project. Therefore, in the subsequent, the minimum air clearances in Table E-6 are applied to the zero-discharge situation.

The required air clearances are compared with the bridge clearances on the Maasroute, without taking into account the high-cubes. Table E-7 mentions the limiting bridges per section with its air clearance from the Maas-Waal Canal to the port of Born, which contains the large container terminal. The rail bridge Buggenum, Hornerbridge and the bridge over lock Heel are situated within the weir section of Belfeld. Bridges over the Juliana Canal, north of port Born, have been heightened in the past to accommodate 4-layered container vessels, taking into account the translation waves in the canal. Translation waves in canals are not considered in this project.

Table E-7: Limiting bridges on the Maasroute unto the port of Born (Vreeker & Heijster, 2016).

Bridge	*Elevation [NAP + m]*	*Dammed water level [NAP + m]*	*Air clearance [m]*
Lowest bridge over Maas-Waal Canal	+17.46	+7.50	9.96
Rail bridge Mook	+17.49	+7.50	9.99
Lowest bridge near Venlo	+22.10	+10.75	11.35
Rail bridge Buggenum	+24.80	+14.10	10.70
Hornerbridge (road N280)	+25.60	+14.10	11.50
Bridge lock Heel	+24.90	+14.10	11.00
Bridge Wessem (road A2)	+30.13	+20.80	9.33
Lowest bridge over Juliana Canal	+40.43	+33.30	10.03

It is concluded that the bridges over the Maasroute do just fulfil the target value according to the SVIR and the calculated air clearance with average loading in the zero-discharge situation. In the current waterway network, vessels with four layers of containers which are all empty, cannot sail to the port of Born. The air clearance of bridge Wessem (9.33 m) is smaller than required height (9.88 m). If high cubes come into play, the air clearance of multiple bridges is too small to accommodate four-layered container vessels.

E.2.3 Classification and requirements to recreational waterways

Like for commercial navigation, classes have been set for the recreational navigation. Distinction is made between waterways only accessible for motor vessels and waterways accessible for motor vessels as well as sailing vessels. Sailing vessels require more water depth and ideally a very large air clearance, as can be seen in Table E-8. The large air clearance is only achieved at a so-called standing mast route. At all other waterways, the height on a waterway is restricted by some bridges and the height of motor vessels is governing for the waterway design.

Table E-8: Classification of recreational vessels (Waterrecreatie Nederland, 2019).

	Zeil- en Motorbootroute (ZM)			Motorbootroute (M)		
	Categorie	**Masthoogte**	**Diepgang**	**Categorie**	**Opbouwhoogte**	**Diepgang**
Verbindingswater	AZM	30	2,10 (2)	AM	Hwjh (1) (3)-per route beoordelen met een minimum 3,40 m.	1,5
Ontsluitingswater	BZM	30	1,9	BM	Hwjh (1)-per route beoordelen met een minimum 2,75 m.	1,5
Ontsluitingswater met doorvaart-beperkingen	CZM (4)	30 (5)	1,7	CM	Hwjh (1)-per route beoordelen met een minimum 2,75 m.	1,4
	DZM	Wordt niet gehanteerd		DM	Hwjh (1)-per route beoordelen met een minimum 2,4 m.	1,1

As mentioned in the main report, the Maasplassen area is classified as Class BZM waterway with a restricted air clearance. The counts of recreational vessels at lock Linne and Roermond, see Figure 3-3, approximately 20,000 passing recreational vessels per year, show that recreational navigation in this area is of normal intensity. A waterway is classified as high intensity recreational waterway if more than 30,000 recreation vessels pass the locks per year.

The depth and air clearance requirements on a recreational waterway differ from waterways suited for commercial navigation. In general, as shown in Figure E-4, the keel clearance is smaller, except in recreational lakes, at which a margin of 30 cm is added to compensate for wind set-up and waves.

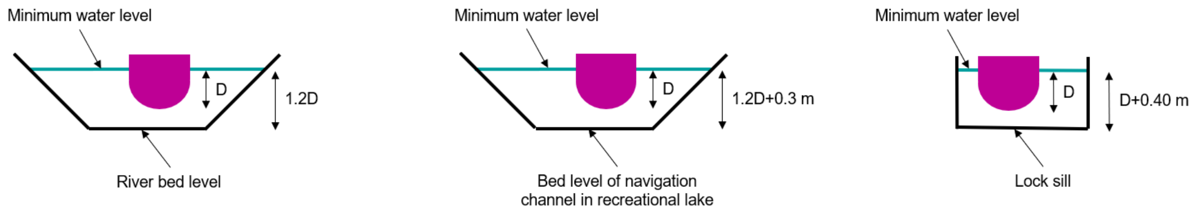

Figure E-4: The water depth requirements in a normal-intensity recreational navigation waterway in a cross-section of a river (left), a navigation channel in a recreation lake (middle) and a lock (right) (Rijkswaterstaat, 2017).

The air clearance of sailing routes has to be 30.0 m. Since this is not feasible for the Afgesneden Maas, the air clearance is based on the air clearance needed for recreation motor vessels, which is 4.0 m.

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Appendix F
Global design area

The boundaries and interfaces of the global design area are made clear in this appendix. Figure F-1 shows the global design area, followed by the system's boundaries, components and interfaces.

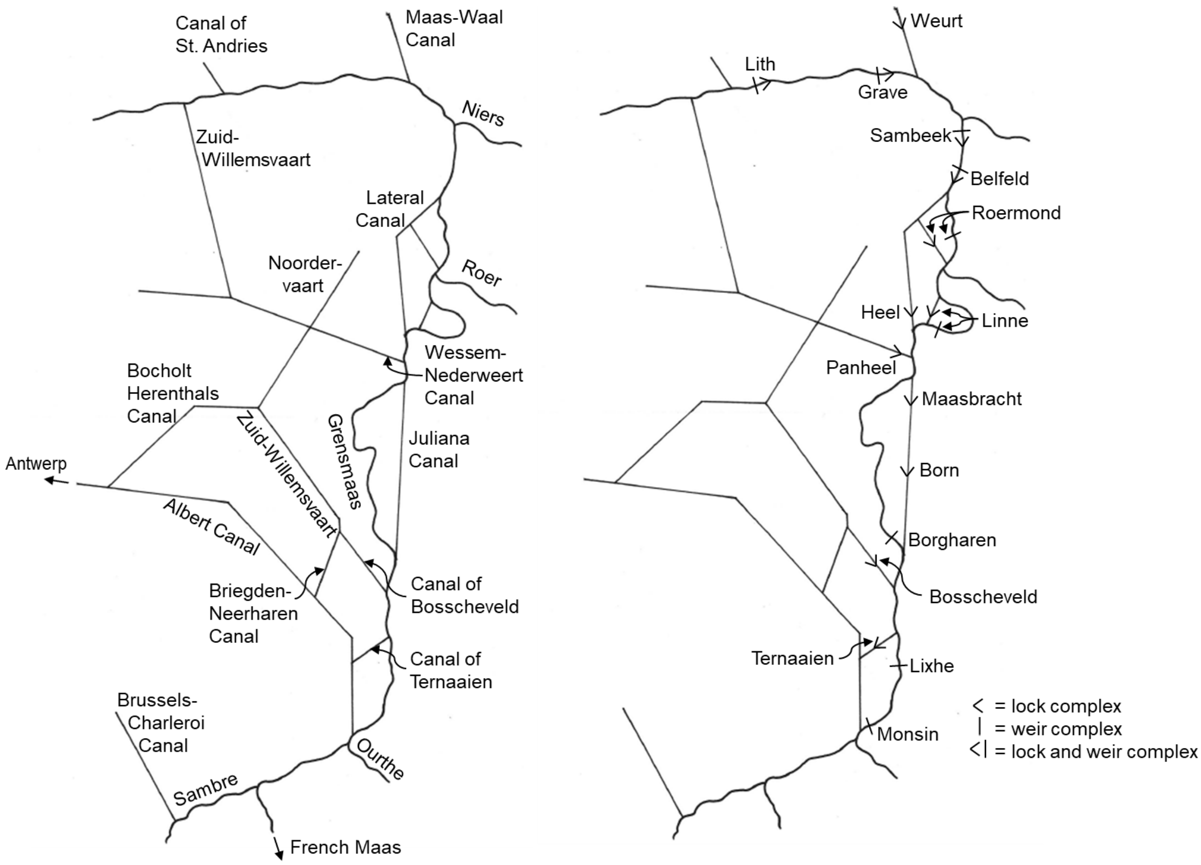

Figure F-1: Overview of the waterway network in the global design area.

System's boundaries	System's components
• weir Monsin • lock Ternaaien (Canal of Ternaaien) • lock Bosscheveld (Canal of Bosscheveld) • lock Panheel (Wessem-Nederweert Canal) • Roer • Niers • lock Weurt (Maas-Waal Canal) • weir Lith	• the Bovenmaas • the Grensmaas • the Juliana Canal • the Plassenmaas • the Lateral Canal • the Zandmaas • the Bedijkte Maas

System's external interfaces	System's internal interfaces
• confluence of Canal of Ternaaien and Bovenmaas • bifurcation of Canal of Bosscheveld and Bovenmaas • bifurcation of Wessem-Nederweert Canal and Plassenmaas • confluence of Roer and Plassenmaas • confluence of Niers and Zandmaas • bifurcation of Maas-Waal Canal and Zandmaas	• bifurcation of Juliana Canal and Grensmaas • confluence of Juliana Canal and Grensmaas • bifurcation of Lateral Canal and Plassenmaas • confluence of Lateral Canal and Plassenmaas

Appendix G
Global design: requirements analysis

This appendix elaborates the requirements analysis, which is done as proposed by H.G. Tuin in his thesis (Tuin, 2013). Not all steps are important by definition on this scale level, so only the useful steps are presented in this appendix.

Customer expectations

Rijkswaterstaat, the executive agency of the Ministry of Infrastructure and Water Management, is responsible for the functioning of the waterway network. Rijkswaterstaat has to provide a water system which has been adjusted to the users of this system. Starting point is a cooperation between Rijkswaterstaat, local governments and users to obtain a flexible system which adapts to the changing circumstances and new opportunities.

The main tasks of Rijkswaterstaat have been derived from inter(national) legislation. In the Netherlands, the Articles of the European Directives have been implemented in national legislation. In Figure G-1 the main European Directives are shown on top. The Waterwet (in English: Water Act), the Wet Milieubeheer (in English: Environmental Protection Act) and Scheepvaartverkeerswet (in English: the Ships Act) are the three most important national acts concerning the quantity and quality of water. The Waterwet is an assembly of former acts on groundwater, water management, water pollution and flood protection. The Scheepvaartverkeerswet regulates the traffic on water, addressing safety, pollution and maintenance of waterways. Especially the Waterwet and the Wet Milieubeheer include the relevant Articles from European legislation (Kenniscentrum InfoMil, n.d.).

The national acts are not that specific to obtain directly the main tasks of Rijkswaterstaat. Concrete measures of the national acts can be found in the underlying documents. For the Waterwet this can be found in the Waterbesluit (in English: Water Decree) and the Waterregeling (in English: Regulations governing Water). These address the application of permits, the distribution of management activities over Rijkswaterstaat and local administrators and the procedure and framework of the national management plan. In the management plan of national waters, the main tasks of Rijkswaterstaat are mentioned. These have been taken over into Figure G-1. The tasks are numbered with a reason: the first task is the most important, the fifth one the least. Rijkswaterstaat first focusses on the most important tasks and, if possible, extra functions to the system are added, in consultation with local authorities and investors (Rijkswaterstaat, 2015).

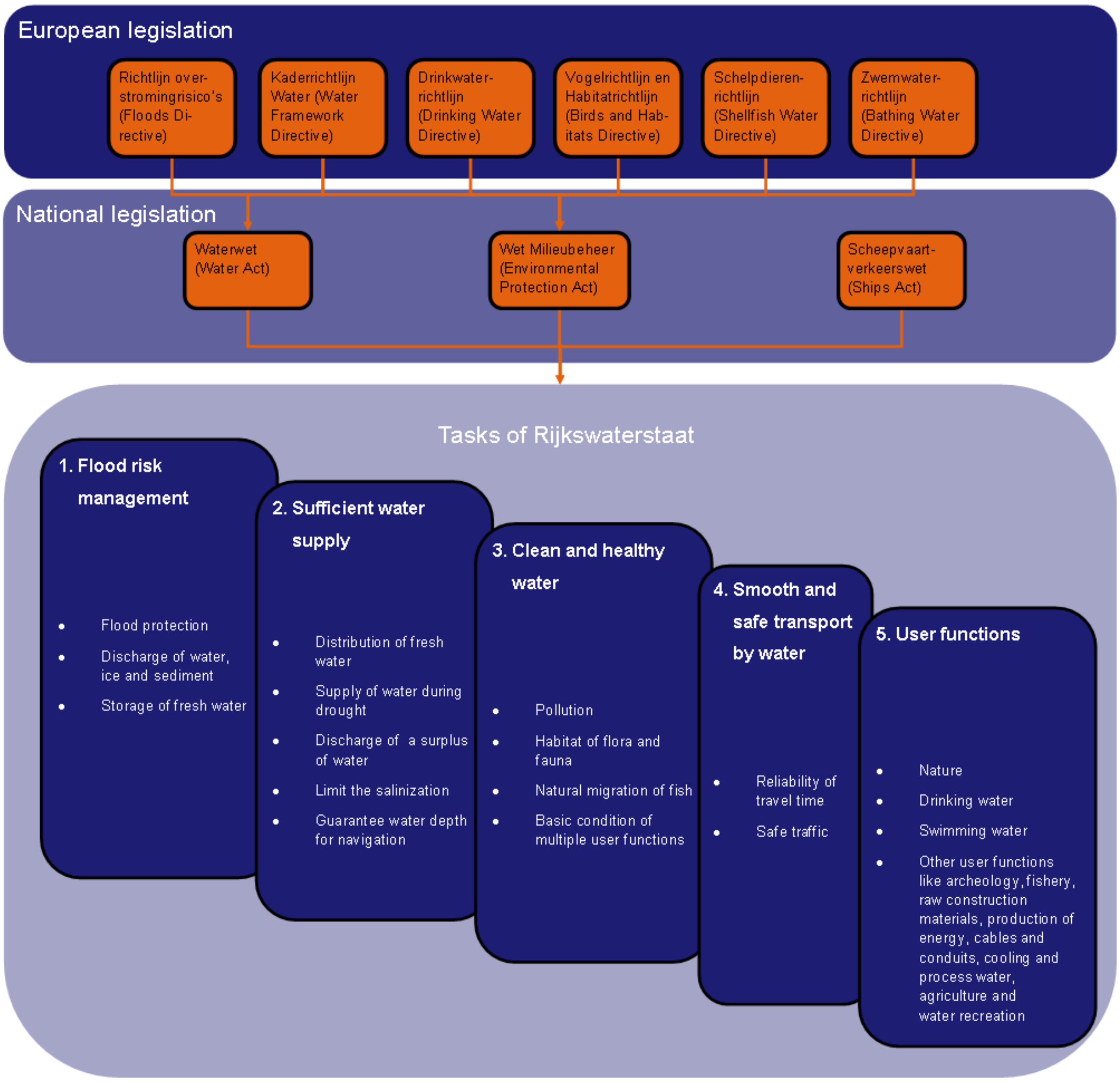

Figure G-1: Legislation of water issues and tasks of Rijkswaterstaat.

Besides, another fixed sequence has been set by the Waterbesluit. In this document, it is stated which functions have to be maintained in the event of freshwater shortage. They are as well ordered from high to low priority on receiving water (Kenniscentrum InfoMil, n.d.).

1. flood protection and irreversible damage;
    a) stability of flood defences
    b) settlements
    c) nature
2. user functions;
    a) drinking water
    b) production of energy
3. small-scaled, high-valued usage such as;
    a) capital intensive agriculture and process water
4. Remaining interests.
    a) navigation, agriculture, industry, recreation and fishery

The water supply in low water periods is regulated by the sequence above and the agreement between the Netherlands and Belgium. Since 1996 this bilateral agreement has not been changed. The starting point of the agreement is an equal distribution of fresh water over Dutch and Flemish use. The discharge of the Grensmaas is a common responsibility of both countries. The main items, addressing the water distribution, are listed below (Koninkrijk der Nederlanden, Vlaams Gewest, 1995):

- At Maastricht at least 8 m^3/s is directed towards Flanders via the intake structure at Bosscheveld.
- At most 10 m^3/s flows via the Zuid-Willemsvaart back towards the Netherlands.
- If there is shortage of water, the two first bullet points do not apply. In these periods the starting point is an equal distribution of water over both areas. More specific, three phases are defined:
    - The start-up phase: discharge between 60 and 100 m^3/s. Maximum water use in the Netherlands and Flanders each is 25 m^3/s. The surplus is discharged via the Grensmaas downstream.
    - The alarm phase: discharge between 30 and 60 m^3/s. The minimum discharge of the Grensmaas is 10 m^3/s. This requirement is combined with a reduction of discharge variations which is important from the viewpoint of ecology and water quality of the Grensmaas. Water savings in both countries are even in this phase.
    - The crisis phase: discharge below 30 m^3/s. The requirement of minimum discharge of the Grensmaas is cancelled. The available discharge is equally distributed over the Grensmaas and the users in Flanders and the Netherlands.

Constraints

The system of waterways includes a couple of constraints which are imposed by either external or internal factors. The internal constraints are a result of the present system and decisions in the past. Recalling these constraints is only possible with a complete change of the system and/or cancellation of agreements. This is beyond the scope of this project, so for this study the layout of the system and the weirs itself is restricted by them. They are listed below:

- internal constraints;
    - the bilateral agreement on the distribution of water over Flanders and the Netherlands and the discharge of the Grensmaas for several discharge volumes.
- external constraints.
    - the discharge of water, ice and sediment. The main inflow takes place at Monsin; by tributaries (of which the Roer and the Niers are the largest) the discharge is increased a little. Water, ice and sediment exits the project area downstream at Lith.
    - the water supply to connected canals. This is of great importance to the freshwater supply of the sandy areas in the Province of Noord-Brabant (Rijkswaterstaat, 2015).

Operational scenarios

The scenarios, considered in the global design level, only address the changes of the discharge volumes. The other developments, important for the adaptive design, come into play in the lower scale levels.

The development of the peak discharge of flood waves has been analysed with help of the historical discharge data. This is done to make a long-term prediction of flood waves and low water periods. Climate change is one of the main contributors to the development of the discharge. Historically, the average discharge of the River Meuse does not change significantly. Figure G-2 shows that in the spring the discharges slightly increase; in the autumn a slight decrease is observable.

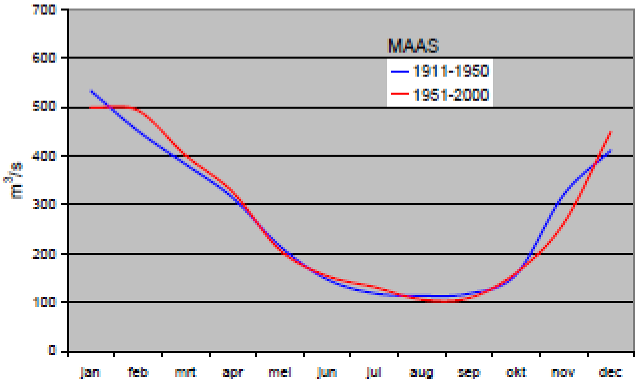

Figure G-2: Average monthly discharge of the River Meuse in the first and second half of the 20th century (De Wit, Buiteveld, & Van Deursen, 2007).

If the average discharge development, however, is analysed more accurately, three periods of approximately 30 years can be distinguished. The first 30 years of measurements after 1911 is characterized by many flood waves. The period thereafter until 1980 shows less flood waves, the period after 1980 again shows many flood waves. This variation can be caused by natural variation and/or climate change, but currently this pattern is thought to be a natural variation with a period of 30 years. The numerical increase of flood waves since 1980 is not caused by climate change (De Wit, Buiteveld, & Van Deursen, 2007).

The current numerical models predict an increase of the peak discharge of the normative flood wave. Nowadays, this normative flood wave, with a return period of 1,250 years, has a peak discharge of 3,800 m³/s. Table G-1 shows the peak discharges in 2050 and 2100 for each scenario. These are calculated according the KNMI'14 climate scenarios which already change from the KNMI'06 scenarios. This indicates that the mentioned numbers, especially for 2085, contain large uncertainty. The last two columns show the change of the discharge during dry periods. The deviation between the scenarios is remarkable; they do not even agree on an increase or decrease (Klijn, Hegnauer, Beersma, & Sperna Weiland, 2015).

Table G-1: Long-term development of peak discharges of normative flood waves and 7-days lowest discharge (Bruggeman, et al., 2011) (Klijn, Hegnauer, Beersma, & Sperna Weiland, 2015).

Scenario	*Peak discharge of normative flood wave in 2050 [m³/s]*	*Peak discharge of normative flood wave in 2100 [m³/s]*	*7-days lowest discharge in 2050 [relative to 2017]*	*7-days lowest discharge in 2085 [relative to 2017]*
DRUK	3,900	4,000	+5%	+3%
STOOM	4,100	4,600	-45%	-60%
RUST	3,900	4,000	+5%	+3%
WARM	4,100	4,600	-45%	-60%

Appendix H
Global design: synthesis and verification

This appendix presents the synthesis and verification on the global design level. For each weir in the Dutch part of the River Meuse, the modifications are treated in the same sequence as set in the main report:

1. removal of a weir and replacing the first downstream weir by a new, higher weir;
2. replacing a current weir by a new weir at a different location; either for several kilometres or to a preceding or subsequent section of Figure 3-4.
    a. downstream
    b. upstream
3. replacing a current weir at the same location by a new weir with a differing height.
    a. lowering
    b. heightening

Borgharen

At weir Borgharen the boundary conditions from the Belgian weirs are most influential. One of these conditions considers the peak discharges on the Bovenmaas. These have to be flattened to avoid negatively effects to the ecological value of the Grensmaas (see Section 3.3). The current weir section of Borgharen takes this indispensable function. Furthermore, weir Borgharen dams up the water level to NAP +44.00 m in the Bovenmaas and the southern part of the Juliana Canal, both part of the Maasroute.

1. If weir Borgharen is removed, the water level cannot be dammed by weir Linne; the height difference between these locations is that large that this causes permanent flooding of embankments. Moreover, in this way, the water level (variation) in the Grensmaas is modified, which is not conform the bilateral agreement.
2.
    a. Replacing weir Borgharen by a new weir some kilometres downstream does not meet the requirements, since the water level (variation) in part of the Grensmaas is modified.
    b. Construction of a new weir upstream meets the requirements. It forms, however, a new obstacle in the Maasroute. As additional measure, a new canal has to connect the new weir section and the Juliana Canal; the additional lock lengthens the travel time. Enabling north-south navigation of Class Vb vessels via the Briegden-Neerharen Canal, Zuid-Willemsvaart and Wessem-Nederweert Canal is thought to be infeasible within a construction time of 10 years. Moreover, it lengthens the travel time significantly and the accessibility of the ports at the Juliana Canal is questionable, since the locks of Born have to withstand a reversed water level difference.
3.
    a. Replacement by a lower weir at the same location does not meet the requirements, since it limits the navigational depth of the Bovenmaas and the southern part of the Juliana Canal.
    b. Replacement by a higher weir could contribute to the storage of fresh water for prolonged periods of small discharge. But then, less buffer is left to flatten the discharge peaks resulting from the hydropower station of weir Lixhe. The risk on ecological damage in the Grensmaas is increased by this modification.

Linne

Weir Linne provides a navigable connection between the Juliana Canal, Lateral Canal and to a lesser extent the Wessem-Nederweert Canal. The Wessem-Nederweert Canal is the main supplier of fresh water for the Province of Noord-Brabant. The Maasroute runs for a short section on the River Meuse from the locks of Maasbracht in the south to the locks of Heel in the north. The lock of Linne is especially used by recreational vessels, see Figure 3-3.

1. The dammed water level has to be maintained at NAP +20.80 m, because of the functions mentioned above. If weir Linne is removed, this water level has to be maintained by a higher weir Roermond. Since embankments and recreation facilities in the Maasplassen would flood (ESRI Nederland, 2019), this does not meet the requirements. Connecting the Juliana Canal and Lateral Canal by a new canal would provide an uninterrupted canal as part of the Maasroute. The new canal has to cross the River Meuse and, in addition, the room in the river valley is limited: on the east, the power plant of Maasbracht is located and, on the west, the Wessem-Nederweert Canal and the southernmost Maasplassen. Thus, a new canal is infeasible.
2.
    a. Replacement of weir Linne by a new weir downstream can meet the requirements, but it forms a new obstacle in the busy navigation route of recreational vessels in the Maasplassen area. An additional lock is needed to link the southernmost lakes with the lakes near Roermond.
    b. Replacement by a new weir upstream is not an option at all: the backwater curve moves onto the Grensmaas, which is not allowed according to bilateral agreement.
3.
    a. Like for weir Borgharen, construction of a new, lower weir Linne does limit the maximum draught of the navigation on the Maasroute.
    b. Replacement by a higher weir at the same location modifies the water levels on the Grensmaas by which the bilateral agreement would be violated.

Roermond

The weir of Roermond is valuable from the viewpoint of the recreation in the Maasplassen area, the storage of fresh water and the accessibility of the port of Roermond. Commercial shipping in this weir section is negligible with respect to the Maasroute, see Figure 3-3.

1. If the current weir section Roermond is restricted to recreational vessels (except the navigation channel to the port of Roermond), a heightened weir Belfeld can take over the mentioned functions without flooding of surrounding areas. The lock of Linne and the Maasplassen area may be only used by recreational vessels, which have a smaller draught with respect to commercial vessels. Navigation from the port of Roermond to the Maasroute and vice versa is possible without lockage.
2.
    a. Replacement of weir Roermond at a location downstream does meet the requirements as well. It is, however, not beneficial: a new obstacle is formed on the Maasroute. Travel times increase to pass the new weir by the adjacent new locks.
    b. Replacement at an upstream location, on the other hand, is beneficially for the commercial navigation. Again, navigation from the port of Roermond to the Maasroute and vice versa is possible without lockage. Lakes north of the new weir have to be connected with the recreational area on the south side by an adjacent new lock, so costs will be a little higher.
3.
    a. A lower weir at Roermond is feasible if only recreation vessels are allowed to the majority of weir section Roermond. Although, it does not score well on one of the criteria.
    b. A new, higher weir Roermond is a possible modification, meeting the requirements, and contributing to supply and storage of fresh water. By heightening of the dammed water

level in weir section Roermond, pumping water to the weir section of Linne becomes more affordable. The new pumping station can play an important role in the freshwater supply to Noord-Brabant and the Juliana Canal, in combination with the pumping stations of Maasbracht and Panheel. Reservoirs in Germany guarantee a minimum discharge of the Roer of 10 m^3/s, which is why the water shortage of weir section Roermond is less severe than of weir section Linne (Rijkswaterstaat, 1992) (Rijkswaterstaat, 1994). On top of that, by a higher weir at Roermond, the large area of the Maasplassen is used to store a considerable amount of fresh water.

Belfeld

The River Meuse near Belfeld is part of the Maasroute. Weir Belfeld dams up the water level of the Lateral Canal and part of the River Meuse to NAP +14.10 m. Via lock Heel in the south and the locks next to weir Belfeld navigation on the Maasroute is enabled.

1. If weir Belfeld is removed, the navigation depth on the Maasroute has to be maintained by weir Sambeek. The needed dammed water level of weir Sambeek in this case leads to permanent flooding of the lowest terraces on both sides of the Zandmaas (ESRI Nederland, 2019). Thus, removal of weir Belfeld does not meet the requirements.
2. Replacement of weir Belfeld by a new weir at a different location always has to involve the construction of a new lock to facilitate navigation on the Maasroute.
    a. Replacement at a downstream location is feasible, but does not include advantages related to the criteria.
    b. Replacement at an upstream location causes dehydration of the environment (Heijkoop, Wils, & Van de Kerk, 2008), since the water levels fall over the entire length of displacement. Thus, it does not meet the requirements.
3.
    a. Replacing weir Belfeld by a lower weir does not meet the requirements, since the dammed water levels are lowered in a sandy area and navigation on the Maasroute has to be facilitated.
    b. Replacing weir Belfeld by a higher weir meets the requirements. It is needed if weir Roermond is removed and it provides more freshwater storage, too.

Sambeek

The analysis of weir Sambeek is very similar to the weir of Belfeld. The weir section Sambeek is part of the Maasroute and does not contain any confluence or bifurcation.

1. Weir Grave cannot take over the dammed water levels if weir Sambeek is removed, because it leads to permanent flooding of the floodplains (ESRI Nederland, 2019).
2.
    a. Replacement by a new weir downstream is feasible, but does not include advantages related to the criteria.
    b. Replacement by a new weir upstream causes dehydration of the environment (Heijkoop, Wils, & Van de Kerk, 2008), since the water levels fall over the entire length of displacement. Thus, it does not meet the requirements.
3.
    a. A lower weir Sambeek does not meet the requirements, since the dammed water levels are lowered in a sandy area and navigation on the Maasroute has to be facilitated.
    b. A higher weir Sambeek meets the requirements. It provides more freshwater storage for prolonged periods of small discharge.

Grave

The main function of weir Grave is, just like the other weirs on the Maasroute, concerned with the navigation sector. There is, however, a difference, since most of the vessels using this weir section do not pass the weir itself. The Maas-Waal Canal forms the main waterway between the River Meuse, the River Waal and the German industry, which is why this canal is used intensively. Weir Grave dams up the water level to NAP +7.50 m in this canal. If the water level at the bifurcation of the River Meuse and the Maas-Waal Canal exceeds NAP +8.30 m, the flood gate and lock are operative to keep the water level in the canal below the dike crests. For water levels on the River Meuse higher than NAP +12.15 m navigation via the canal is obstructed (Van Aubel, 2016).

1. The function of weir Grave cannot be taken over by a heightened weir Lith, since this, again, causes permanent flooding of the floodplains (ESRI Nederland, 2019). Thus, removal is not feasible.
2.
   a. Replacement by a new weir downstream does meet the requirement, but it does not provide advantages besides.
   b. Replacement at an upstream location causes dehydration of the environment, since the water levels fall over the entire length of displacement. Thus, it does not meet the requirements and, moreover, it would form an additional obstacle in the navigation route from the Maas-Waal Canal to the south and vice versa.
3.
   a. A new, lower weir Grave does not meet the requirements, since the dammed water levels are lowered in a sandy area and navigation on the Maasroute has to be facilitated.
   b. Replacement of weir Grave by a new, higher weir meets the requirements. It provides more freshwater storage for prolonged periods of small discharge.

Lith

Weir section Lith is not part of the Maasroute. Therefore, the number of vessels navigating in this weir section is considerably lower, see Figure 3-3.

1. Removal of weir Lith does not meet the requirements, since there is no weir downstream which can take over its functions. In dry periods, the water depth is insufficient for navigation of Class Va vessels due to bend cut-offs in the past.
2.
   a. Replacement of weir Lith at a downstream location does meet the requirements. The extent of displacement is limited by the height of the main channel embankments downstream of the current location.
   b. In case of replacement at an upstream location, the navigability of the Getijdenmaas has to be guaranteed. Since this is not part of the global design area, this is beyond the scope of this project.
3.
   a. Replacing weir Lith by a lower weir at the same locations does not meet the requirements, since navigation of Class Va vessels has to be facilitated in the weir section.
   b. Replacing weir Lith by a higher weir meets the requirements. It provides more freshwater storage for prolonged periods of small discharge.

Appendix I
Regional design area

This appendix gives an overview of the regional project area. First, all lakes, structures, creeks, bifurcations and confluences are listed in Table I-1.

Table I-1: Location of objects in the regional design area.

Object	*Type*	*Distance to weir Belfeld [km]*
Zandmaas		
Weir Belfeld	Hydraulic structure	0.0
Bifurcation River Meuse and lock canal Belfeld	Bifurcation	0.9
Schelkensbeek	Creek	3.0
Marina WSV Poseidon	Marina	3.3
Tasbeek	Creek	4.2
Old riverbend	Desolated river course	4.8
Port of Kessel	Marina	5.7
Huilbeek	Creek	6.8
Sand extraction Kessel-Eik	Lake	7.8
Rijkelse Bemden	Lake	9.8
Snepheiderbeek	Creek	9.9
Dode Maasarm	Lake	10.9
Marina WH Hanssum	Marina	11.1
Neerbeek	Creek	11.3
Sand extraction Heel	Lake	11.3
Swalm	Tributary	11.9
Asseltse Plassen	Lake	13.2
Drainage channel of power plant Buggenum	Drainage channel	14.5
Lateral Canal		
Confluence River Meuse and Lateral Canal	Confluence	14.8
Rail bridge Buggenum	Bridge	15.4
Power plant Buggenum	Port	15.8
Confluence lock canal Roermond and Lateral Canal	Confluence	16.0
Hornerbridge (N280)	Bridge	18.6
Bridge Heel	Bridge	22.5
Lock Heel	Hydraulic structure	22.7

Object	*Type*	*Distance to weir Belfeld [km]*
Afgesneden Maas		
Confluence River Meuse and Lateral Canal	Confluence	14.8
Rail bridge Buggenum	Bridge	15.4
Weir Roermond	Hydraulic structure	17.0
Bifurcation River Meuse and lock canal Roermond	Bifurcation	17.8
Prins Willem-Alexanderport	Port	18.0
Doevesbeemd + Doncker Nack	Lake	18.3
Louis Raemaekersbridge (N280)	Bridge	18.4
Roer	Tributary	18.5
La Bonne Aventure	Marina	19.2
De Rosslag	Marina	20.3
Noorderplas + Plas Hatenboer Nieuwe Nack + Zuidplas	Lake	20.8
Ooldergreend	Lake	22.3
Isabellegreend	Lake	22.6
Confluence canal lock Linne and Loop of Linne	Confluence	23.5
Lock Linne	Hydraulic structure	24.1
Oolderplas	Lake	24.4
Gerelingsplas + Spoorplas	Lake	25.7
Weir Linne	Hydraulic structure	29.0

The last column is applied as input in the hydraulic model described in Appendix C.1. With this model, the water level at each location can be calculated for various discharges. To simplify the model, not all objects are taken into account and simplifications have been made, among which:

- The characteristics of the weir section Belfeld and weir section Roermond are based on a calibrated model of ARCADIS (ARCADIS, 2015). The used parameters are (for both weir sections):
$$B = 130\ m$$
$$C = 50\ \sqrt{m}\ /\ s$$
Both parameters are independent of the water level, which is not the case in reality.
- The bed level in the calibrated model is not right, so other data have been applied to obtain the right level. The bed level is based on the current navigation in the regional design area; the resulting bed level as shown in Figure I-1 is derived in Appendix E.2. Two sections of constant bed slope are identified: the boundary is located at the confluence of the Lateral Canal and the River Meuse.

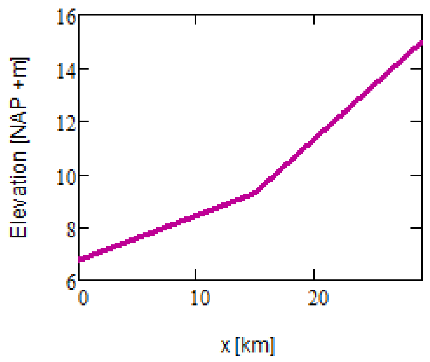

Figure I-1: Bed level along the River Meuse from weir Belfeld (x = 0 km) to weir Linne (x = 29 km).

- The bed slope of all canals is thought to be negligible and taken as zero. The discharge via these canals (and thus via the locks) is also neglected. As a result, the water levels in the canals calculated by the hydraulic model are horizontal.
- Connected lakes are modelled with the small-basin approach; the water level in the lake is equal to the water level at the connection with the River Meuse. The distance in the last column of Table I-1 indicates the distance between the connection and weir Belfeld.
- The layout of the lakes is simplified as well. The recreation function of the northern part is taken by two lakes: the recreational lakes of Roermond (at km 18.4) and lake Hatenboer (at km 20.8). The natural lakes are represented by the Oolderplas (at km 24.4).

Figure I-2 shows the modelled design area after applying these simplifications. The parts indicated in red do not have a bed slope and have, resultingly, an horizontal water level for each discharge. The bed level and the elevation of the lock sills is indicated in the right overview.

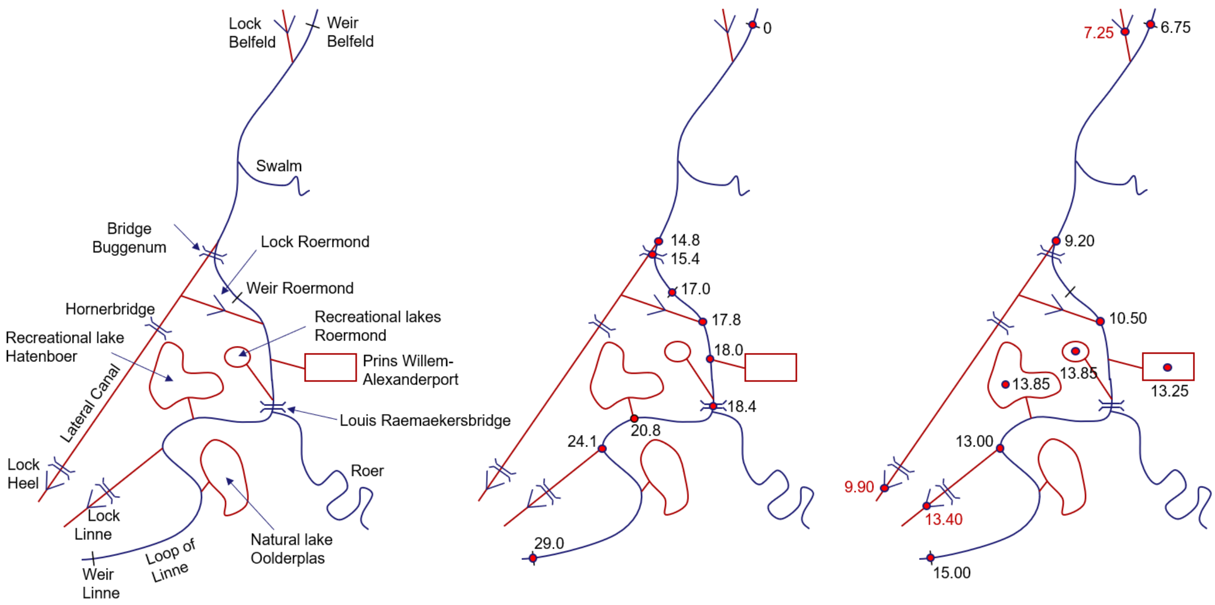

Figure I-2: The simplified modelled regional design area: elements (left), kilometre set (middle) and bed elevation (right).

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Appendix J
Regional water management

This appendix focusses on the exchange of River Meuse water with water volumes perpendicular to the streamwise direction. Section J.1 focusses on the interaction of the river with groundwater flow. The model which is applied to calculate the effects of a changed dammed water level on the groundwater table is elaborated. Furthermore, Section J.2 elaborates on the interaction between the River Meuse and the connected creeks and tributaries.

J.1 Geohydrology

A modification of the dammed water levels of the River Meuse involves a direct change of the groundwater table in the surroundings of the river. In this subsection, the extent of this change is addressed.

Groundwater flow is described by Darcy's law; water flows from high potential to low potential. The discharge is dependent on the flow area, the potential difference, the distance between these potentials and the permeability of the soil k. The general law of Darcy is applicable in multiple situations, for which, depending on the situation, the formula simplifies. In the regional project area, the top layers of soil consist of sand and gravel layers. Groundwater data show that the shallow groundwater table fluctuates in these layers (Waterschap Limburg, 2019). As earlier mentioned, the deep groundwater table in the area is of large importance as well. The deep aquifer is supplemented by rainfall and the effect of a modification of the dammed water levels to the groundwater flow in this layer is assumed to be negligible. The focus in this appendix lies on the shallow groundwater flow.

In general the groundwater table in the surrounding of the River Meuse lies higher than the dammed water levels in the river itself. This means that groundwater flows towards the River Meuse, which acts as a drain. Schematically, the River Meuse is a long chain of drains in sequence. The groundwater flow is dealt with per meter width; a cross-section of the River Meuse and the groundwater is shown in Figure J-1.

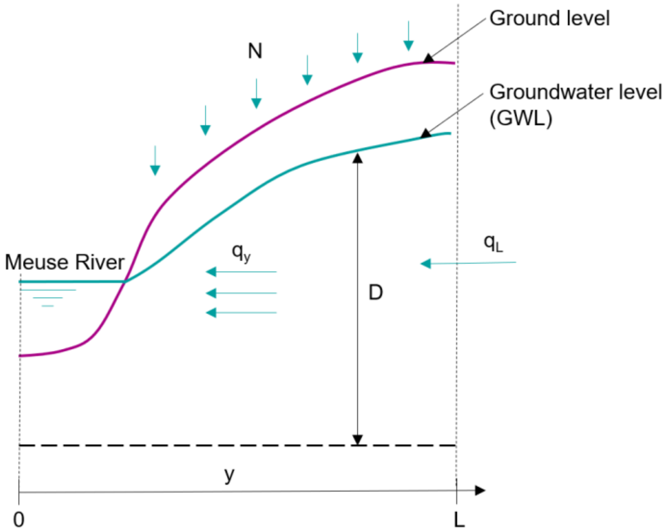

Figure J-1: Schematisation of the groundwater flow.

A volume balance is set up for this area.

$$N \cdot L = q_0 - q_L \tag{I.1}$$

To quantify the influence of the dammed water levels in the River Meuse, it is important to find out unto which distance a modification of the dammed water level has effect on the groundwater table. This influence length is indicated with L. As a first indication, L is equal to the distance from the river to the location where the groundwater flow q_L is equal to zero (grootte intrekgebied, 2019). This means that all rain water infiltrated, in the Netherlands approximately 0.001 m/day (Bakker, 2019), in the influence area flows towards the River Meuse via the aquifer.

The groundwater flow at each location is calculated with Darcy's law:

$$q_y = -k \cdot D_{aquifer} \cdot \frac{d\eta_{GWL}}{dy} \tag{I.2}$$

At $y=L$, the groundwater flow is zero; at $y=0$, the groundwater flow is maximum. The course of the groundwater flow is described by the corresponding differential equation:

$$\frac{dq_y}{dy} = N \tag{I.3}$$

Combining equation (I.2) and (I.3) leads to the differential equation for the elevation of the groundwater table.

$$\frac{d^2\eta_{GWL}}{dy^2} = -\frac{N}{k \cdot D_{aquifer}} \tag{I.4}$$

Since this is a non-homogeneous differential equation, the solution is a combination of a particular solution and the solution to the homogeneous solution.

$$\eta_{GWL}(y) = -\frac{N}{2 \cdot kD_{aquifer}} \cdot y^2 + \left(\frac{N}{2 \cdot kD_{aquifer}} \cdot L + \frac{\eta_{GWL}(L) - \eta_{GWL}(0)}{L}\right) \cdot y + \eta_{GWL}(0) \tag{I.5}$$

The groundwater level elevation is a parabolic function of y, the perpendicular distance to the River Meuse. The data in Table J-1, retrieved by groundwater surveys at four different locations, are applied to find the best parabolic fit at each location. The locations of Belfeld, Neer, Heel and Roermond are selected, since recent data (summer 2018) was available at various distances to the River Meuse. The average elevation of the groundwater table in summer is presented in the table below; choosing this time period excludes significant changes in dammed river water level, wherein the systems reaches (or approaches) a steady-state.

Table J-1: Retrieved groundwater data (Waterschap Limburg, 2019).

Belfeld		**Neer**		**Heel**		**Roermond**	
y [m]	η_{GWT} [NAP + m]	y [m]	η_{GWT} [NAP + m]	y [m]	η_{GWT} [NAP + m]	y [m]	η_{GWT} [NAP + m]
40	15.2	-	-	-	-	0	16.9
270	17.7	550	15.3	300	15.1	230	17.3
700	20.2	1700	19.3	1050	17.1	550	18.1
1900	24.0	2400	21.0	1700	18.3	3300	22.0

In Figure J-2 the best parabolic fit at each location is shown. The groundwater table is plotted from $y=0$, at the River Meuse, unto $y=L$. At the latter location, the groundwater table is horizontal; the potential head difference and the discharge are zero. The influence length of the River Meuse ranges between 1.9 and 4.7 kilometres.

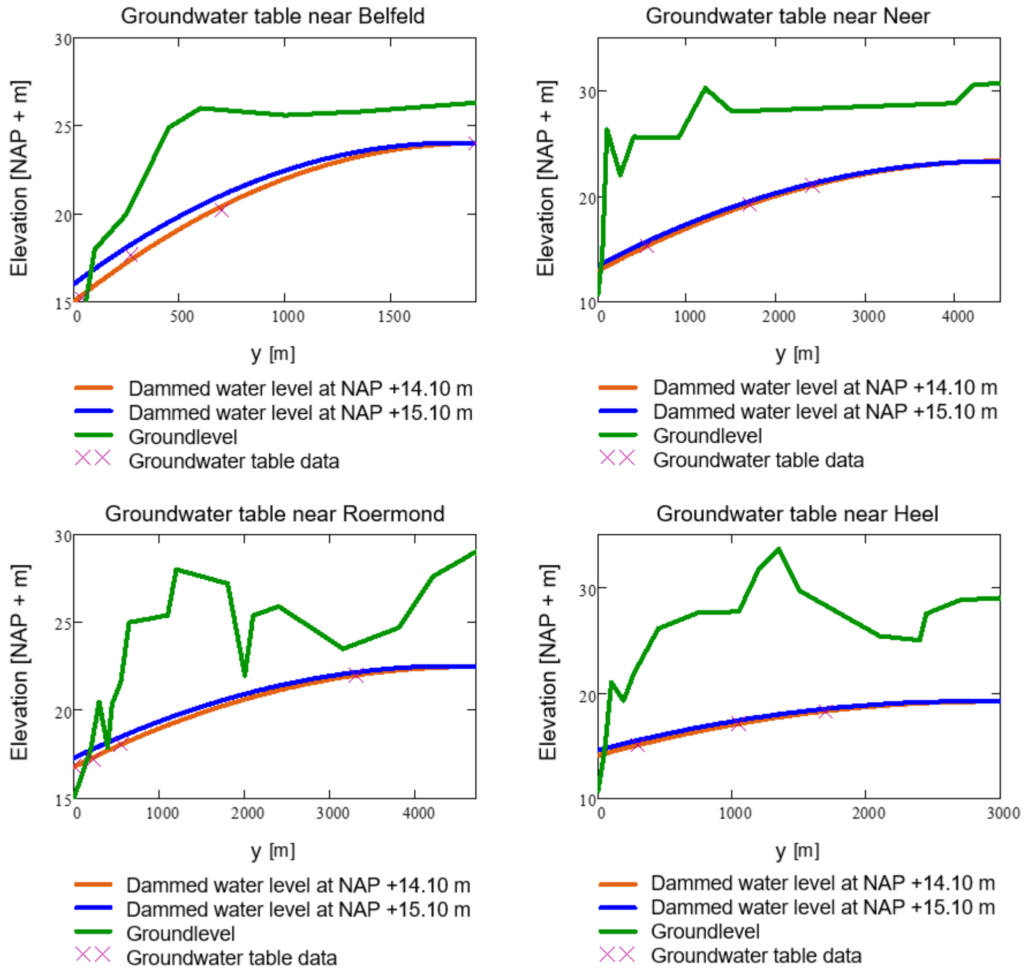

Figure J-2: Best parabolic fit of the groundwater data at four locations.

Validation

To validate the fit, the parabolic fit is compared with equation (I.5). From the graphs in Figure J-2 the influence length L, $\eta_{GWL}(0)$ and $\eta_{GWL}(L)$ can be retrieved; the only unknowns of equation (I.5) are the horizontal permeability k and saturated thickness $D_{aquifer}$ of the aquifer. These two parameters multiplied results in the transmissivity of the aquifer, a measure for the amount of water which is transmitted horizontally to a drain. At each data location, the transmissivity is found by equalizing the graph resulting from equation (I.5) and the parabolic fit. The obtained transmissivity is compared with the results of the REGIS II model in Table J-2. The REGIS II model gives a global overview of the transmissivity of soil layers with the help of bore hole data. The wide range of transmissivity of the REGIS II model is caused by the uncertainty within a layer and the appearance of multiple aquifers above each other. The transmissivity of the theoretical fit lies within the boundaries of the REGIS II model, so they are applied to quantify the effects of a changed dammed water level.

Table J-2: Transmissivity of the aquifer (Ondergrondmodellen, n.d.).

Method	*Belfeld*	*Neer*	*Heel*	*Roermond*
Theoretical fit [m²/day]	200	1000	850	1900
REGIS II model [m²/day]	100-500	250-1000	>500	>1000

Current groundwater tables in residential areas

Since the impact of a groundwater table change is dependent on the difference between the current groundwater table and the ground level, Table J-3 sums this difference at each village located in the river valley in the regional design area.

Table J-3: The ground level and groundwater table at villages near the River Meuse.

Village	y [m]	*Nearest data location*	η_{GL} [NAP + m]	η_{GWt} [NAP + m]	η_{GL}-η_{GWt} [m]
Belfeld	600	Belfeld	25.0	19.7	5.3
Reuver	900	Belfeld	25.0	21.5	3.5
Kessel	300	Belfeld	23.0	17.6	5.4
Beesel	800	Neer	21.5	16.3	5.2
Neer	1,000	Neer	26.0	17.0	4.0
Buggenum	600	Neer	20.0	15.5	4.5
Horn	900	Heel	25.0	16.8	8.2
Beegden	700	Heel	31.0	16.2	14.8
Heel	1,500	Heel	27.0	18.0	9.0
Roermond	500	Roermond	24.0	18.0	6.0
Herten	700	Roermond	22.0	18.4	3.6
Linne	400	Roermond	27.0	17.7	9.3

J.2 Water management of creeks and tributaries

A change of the dammed water levels in the River Meuse also influences the free drainage of creeks, drainage channels and tributaries to the river. Because of the elevation differences, water freely drains towards the River Meuse. This section takes a closer look at the draining creeks and tributaries in the regional project area. First, the Tasbeek, Huilbeek and Snepheiderbeek are analyzed, see Figure J-3. All three creeks are located between weir Roermond and weir Belfeld, ranked with increasing distance from Belfeld. The red lines indicate the location of the cross-sections.

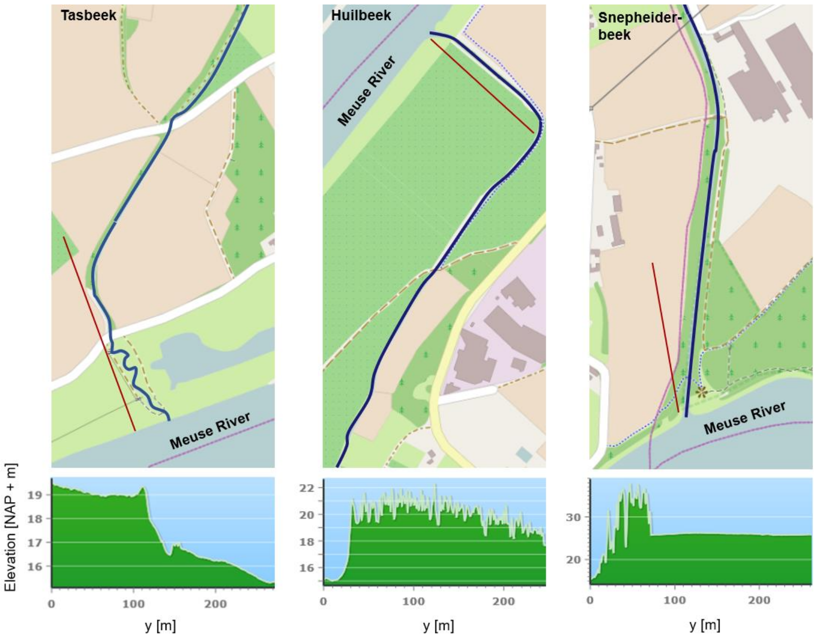

Figure J-3: The creeks Tasbeek, Huilbeek and Snepheiderbeek (OpenStreetMap Nederland, n.d.) (ESRI Nederland, 2019).

The Tasbeek and Huilbeek are small creeks of limited length. Only the Tasbeek includes some meanders and a small nature site along the River Meuse. At the bottom part of Figure J-3, the elevation along the creeks is shown; the terraces of the Zandmaas are clear. The irregularities in these graphs are caused by the wooded landscape. For both the Tasbeek and Huilbeek applies that heightening of the River Meuse's water level does not induce floods. It is also assumed that drainage of these small creeks will not be a problem. If the River Meuse's water level is lowered, these creeks could fall dry. A sluice gate prevents this.

The Snepheiderbeek differs from the previous two creeks since it forms a connection between the Noordervaart and the River Meuse. Via the Snepheiderbeek, part of the Natura 2000 site De Peel drains water to the River Meuse (Ministerie van Landbouw, Natuur en Voedselkwaliteit, n.d.). The ecological value in the creek itself is small, but the creek plays a considerable role in the water management of the protected nature site. If a changed dammed water level affects this management negatively, an intake facility in the Snepheiderbeek is a possibility to counteract this. The manager of this intake facility can adjust this intake facility to stimulate ecology in De Peel.

In this project, the change of these three creeks are out of scope, since the effects are limited or can be reduced on a local scale.

The Neerbeek and Schelkensbeek are shown in Figure J-4. Both creeks do drain in the weir section Belfeld as well, but they are larger than the previous three creeks and have more ecological value as well. The Neerbeek is a confluence of the creeks Leubeek, Zelsterbeek and Haelensche beek. The several creeks and the surrounding natural environments form the Natura 2000 site Leudal (Ministerie van Landbouw, Natuur en Voedselkwaliteit, n.d.). Despite that Leudal lies closer to the River Meuse than De Peel, the influence via the Neerbeek is negligible. As can be seen in Figure J-4 a mill with a sluice gate is located approximately 1.5 kilometre upstream of the mouth. The River Meuse's water level does only influence the downstream part if the water level rises above the top of the sluice gate at NAP +17.10 m (Waterschap Limburg, 2019). Otherwise, the water level upstream of the mill is controlled by the sluice gate and changes of the dammed water levels in the River Meuse do have negligible effects on Leudal. Hereby, it is assumed that the sluice and mill are able to withstand a larger water head or are easily strengthened in case of lowered dammed water levels in the River Meuse.

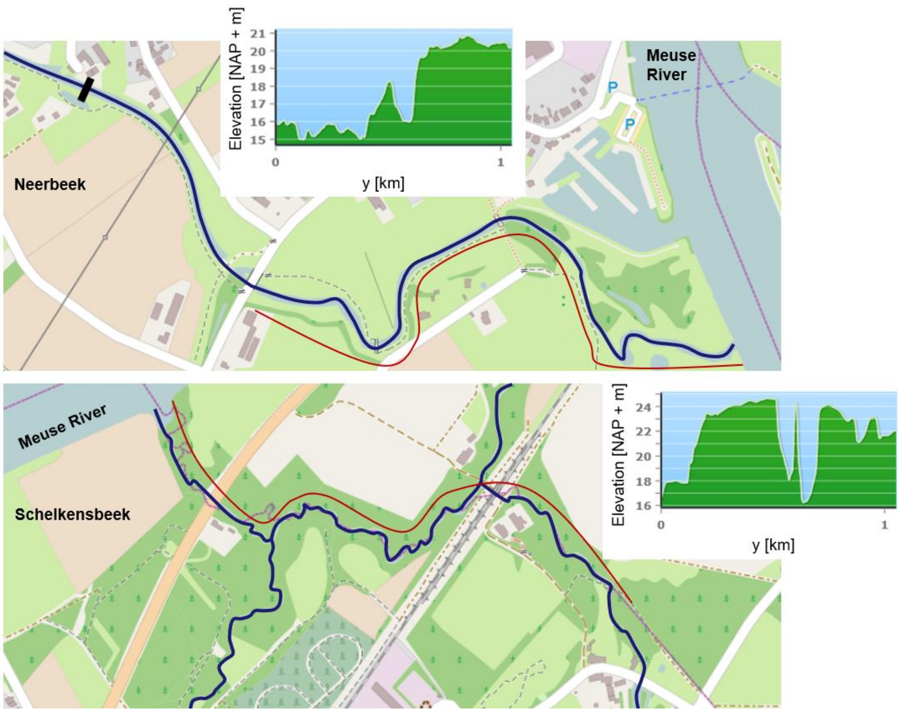

Figure J-4: The creeks Neerbeek and Schelkensbeek (OpenStreetMap Nederland, n.d.) (ESRI Nederland, 2019).

The Schelkensbeek is not part of a protected nature site, but nature developed along the meandering creek. The terraces are clearly visible in the cross-section. Although, the gradient of the creek is small, so a change of the River Meuse's water level affects the nature area in either positive or negative way over a significant length. An increase could lead to waterlogged nature; a decrease to dehydration. If the latter is unwanted, a sluice gate can be thought of.

Figure J-5 shows the Roer and Swalm, which both drain water from a Nature 2000 site to the River Meuse (Ministerie van Landbouw, Natuur en Voedselkwaliteit, n.d.). The Roer mouths just upstream of weir Roermond; the Swalm in a lake of the River Meuse downstream of weir Roermond.

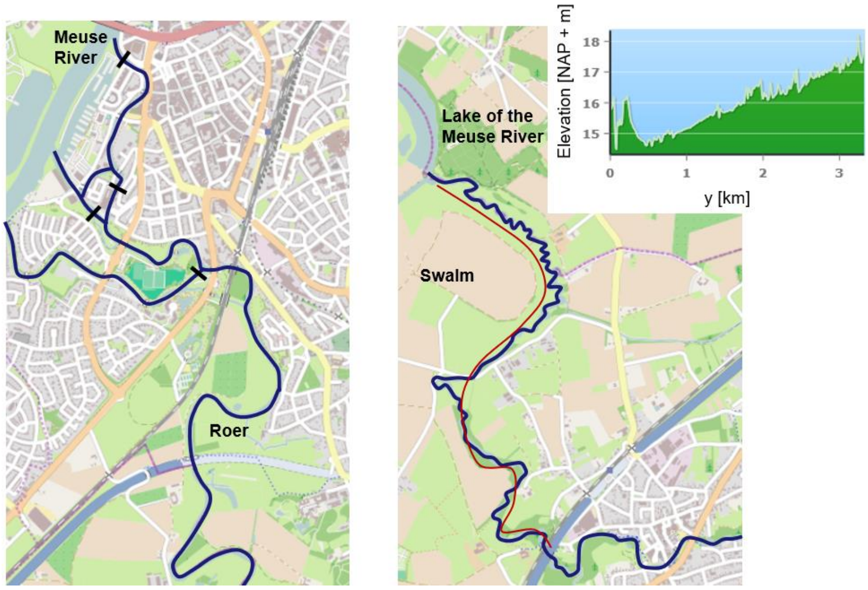

Figure J-5: The tributaries Roer and Swalm (OpenStreetMap Nederland, n.d.) (ESRI Nederland, 2019).

The situation of the Roer is comparable with the one of the Neerbeek. The protected nature site Roerdal is from ecological viewpoint valuable, but the influence of the River Meuse is limited via this tributary by the construction of sluice gates. The most northern sluice gate in Figure J-5 only closes during flood. Upstream of the two sluices in the middle the water level in the Roer is dammed at NAP +19.20 m (Waterschap Limburg, 2019). As long as the dammed water level in the River Meuse is lower than this level, the effects are small. Hereby, it is assumed that the sluices in the Roer are able to withstand a larger water head or are strengthened in case of lowered dammed water levels in the River Meuse.

The effects of changing River Meuse's water levels on the tributary Swalm is most decisive of all creeks and tributaries. The protected nature site Swalmdal includes the course of the tributary unto its mouth at the lake of the River Meuse. The gradient of the Swalm is relatively small, so a change of the River Meuse's dammed water level affects a large part of the Swalmdal.

Appendix K
Additional measures in regional design alternatives

This appendix gives an overview of the additional measures required to take to meet the requirements in 2030 for two global design alternatives: firstly, the design alternative which includes replacement of weir Roermond by a new weir upstream at the Louis Raemaekersbridge and secondly, the design alternative which includes replacement of weir Roermond by a new weir at the current location.

Table K-1: Additional measures needed in weir section Belfeld if weir Roermond is replaced by a new weir at the Louis Raemaekersbridge.

Weir Belfeld	*Current location of set point*	*Theoretical location of set point*
NAP +13.10 m	Dredging the Lateral Canal 1.00 m Dredging 6 km of the Zandmaas on average 0.50 m Deepening the downstream lock sill of Heel 1.00 m Dredging a large new lake for freshwater storage Dredging the navigation channels in the recreational lakes of Roermond 3.15 m Deepening the Prins Willem-Alexanderport 3.75 m Constructing a new lock for recreational vessels	Dredging the Zandmaas and Lateral Canal 1.00 m Deepening the downstream lock sill of Heel 1.00 m Dredging a large new lake for freshwater storage Compensating the loss of ecological value of nature sites Dredging the navigation channels in the recreational lakes of Roermond 3.15 m Deepening the Prins Willem-Alexanderport 3.75 m Constructing a new lock for recreational vessels
NAP +13.60 m	Dredging the Lateral Canal 0.50 m Dredging 3 km of the Zandmaas on average 0.25 m Deepening the downstream lock sill of Heel 0.50 m Dredging a new lake for freshwater storage Dredging the navigation channels in the recreational lakes of Roermond 2.65 m Deepening the Prins Willem-Alexanderport 3.25 m Constructing a new lock for recreational vessels	Dredging the Zandmaas and Lateral Canal 0.50 m Deepening the downstream lock sill of Heel 0.50 m Deepening lock Roermond 0.40 m Dredging a new lake for freshwater storage Compensating the loss of ecological value of nature sites Dredging the navigation channels in the recreational lakes of Roermond 2.65 m Deepening the Prins Willem-Alexanderport 3.25 m Constructing a new lock for recreational vessels

NAP +14.10 m	Dredging the navigation channels in the recreational lakes of Roermond 2.15 m Deepening the Prins Willem-Alexanderport 2.75 m Constructing a new lock for recreational vessels	Compensating the loss of ecological value of nature sites Dredging the navigation channels in the recreational lakes of Roermond 2.15 m Deepening the Prins Willem-Alexanderport 2.75 m Constructing a new lock for recreational vessels
NAP +14.50 m	Raising embankments of the Zandmaas 0.40 m Dredging the navigation channels in the recreational lakes of Roermond 1.75 m Deepening the Prins Willem-Alexanderport 2.35 m Constructing a new lock for recreational vessels	Compensating the loss of ecological value of nature sites Dredging the navigation channels in the recreational lakes of Roermond 1.75 m Deepening the Prins Willem-Alexanderport 2.35 m Constructing a new lock for recreational vessels
NAP +15.10 m	Raising embankments of the Zandmaas 1.00 m Raising rail bridge Buggenum 0.60 m Raising bridge Heel 0.50 m Dredging the navigation channels in the recreational lakes of Roermond 1.15 m Deepening the Prins Willem-Alexanderport 1.75 m Constructing a new lock for recreational vessels	Compensating the loss of ecological value of nature sites Raising rail bridge Buggenum 0.60 m Raising bridge Heel 0.50 m Dredging the navigation channels in the recreational lakes of Roermond 1.15 m Deepening the Prins Willem-Alexanderport 1.75 m Constructing a new lock for recreational vessels

Table K-2: Additional measures needed in weir section Roermond if weir Roermond is replaced by a new weir at the Louis Raemaekersbridge.

Weir Belfeld	***Current location of set point***	***Theoretical location of set point***
NAP +13.10 m	Dredging the Lateral Canal 1.00 m Dredging 6 km of the Zandmaas on average 0.50 m Deepening the downstream lock sill of Heel 1.00 m Deepening the downstream lock sill of Roermond 0.90 m Dredging a large new lake for freshwater storage	Dredging the Zandmaas and Lateral Canal 1.00 m Deepening the downstream lock sill of Heel 1.00 m Deepening the downstream lock sill of Roermond 0.90 m Dredging a large new lake for freshwater storage Compensating the loss of ecological value of nature sites

NAP +13.60 m	Dredging the Lateral Canal 0.50 m Dredging 3 km of the Zandmaas on average 0.25 m Deepening the downstream lock sill of Heel 0.50 m Deepening lock Roermond 0.40 m Dredging a new lake for freshwater storage	Dredging the Zandmaas and Lateral Canal 0.50 m Deepening the downstream lock sill of Heel 0.50 m Deepening the downstream lock sill of Roermond 0.40 m Dredging a new lake for freshwater storage Compensating the loss of ecological value of nature sites
NAP +14.10 m		Compensating the loss of ecological value of nature sites
NAP +14.50 m	Raising embankments of the Zandmaas 0.40 m	Compensating the loss of ecological value of nature sites
NAP +15.10 m	Raising embankments of the Zandmaas 1.00 m Raising rail bridge Buggenum 0.60 m Raising bridge Heel 0.50 m	Compensating the loss of ecological value of nature sites Raising rail bridge Buggenum 0.60 m Raising bridge Heel 0.50 m

Table K-3: Additional measures needed in weir section Belfeld if weir Roermond is replaced by a new weir at the current location.

Weir Roermond	***Current location of set point***	***Theoretical location of set point (also of weir Belfeld)***
NAP +15.85 m	Dredging a large new lake for freshwater storage Dredging the navigation channels in the recreational lake Hatenboer 0.60 m	Dredging a large new lake for freshwater storage Dredging the navigation channels in the recreational lake Hatenboer 1.50 m Compensating the loss of ecological value of nature sites
NAP +16.45 m	Dredging a new lake for freshwater storage	Dredging a new lake for freshwater storage Dredging the navigation channels in the recreational lake Hatenboer 1.00 m Compensating the loss of ecological value of nature sites
NAP +16.85 m		Dredging the navigation channels in the recreational lake Hatenboer 0.50 m Compensating the loss of ecological value of nature sites
NAP +17.35 m	Raising embankments of the Afgesneden Maas 0.50 m	Compensating the loss of ecological value of nature sites
NAP +17.85 m	Raising embankments of the Afgesneden Maas 1.00 m	Raising 4 km embankments of the Afgesneden Maas 0.5 m Compensating the loss of ecological value of nature sites

Table K-4: Additional measures needed in weir section Roermond if weir Roermond is replaced by a new weir at the current location.

Weir Roermond	*Current location of set point*	*Theoretical location of set point (also of weir Belfeld)*
NAP +15.85 m	Dredging a large new lake for freshwater storage Deepening the Prins Willem-Alexanderport 1.00 m Dredging the navigation channels in the recreational lake Hatenboer 0.60 m	Dredging a large new lake for freshwater storage Deepening the upstream lock sill of Roermond 0.70 m Deepening the Prins Willem-Alexanderport 1.75 m Dredging the navigation channels in the recreational lakes of Roermond 2.00 m Dredging the navigation channels in the recreational lake Hatenboer 1.50 m Compensating the loss of ecological value of nature sites
NAP +16.45 m	Dredging a new lake for freshwater storage Deepening the Prins Willem-Alexanderport 0.40 m	Dredging a new lake for freshwater storage Deepening the upstream lock sill of Roermond 0.50 m Deepening the Prins Willem-Alexanderport 1.50 m Dredging the navigation channels in the recreational lakes of Roermond 1.75 m Dredging the navigation channels in the recreational lake Hatenboer 1.00 m Compensating the loss of ecological value of nature sites
NAP +16.85 m		Deepening the upstream lock sill of Roermond 0.10 m Deepening the Prins Willem-Alexanderport 1.60 m Dredging the navigation channels in the recreational lakes of Roermond 1.30 m Dredging the navigation channels in the recreational lake Hatenboer 0.50 m Compensating the loss of ecological value of nature sites
NAP +17.35 m	Raising embankments of the Afgesneden Maas 0.50 m	Deepening the Prins Willem-Alexanderport 1.00 m Dredging the navigation channels in the recreational lakes of Roermond 0.70 m Compensating the loss of ecological value of nature sites

NAP +17.85 m	Raising embankments of the Afgesneden Maas 1.00 m	Raising 4 km embankments of the Afgesneden Maas 0.50 m Deepening the Prins Willem-Alexanderport 0.50 m Dredging the navigation channels in the recreational lakes of Roermond 0.15 m Compensating the loss of ecological value of nature sites

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Appendix L
Types of gates

This appendix elaborates on the types of gates applied in weir structures. As mentioned in the main report, gates moving horizontally or rotating around a vertical axis are not included, since widening of the weir is infeasible if these gates are applied.

Flap gates

A flap gate regulates the upstream water level by rotating around an horizontal axis at the weir's sill. Water is discharged by an overflowing nappe. In open state, the flap gate rests on the sill, not disturbing the flow. If water levels have to be dammed up, a hoisting mechanism lifts the flap to the desired elevation. The work done by the hoisting mechanism in each pier can be reduced by the application of floats or counterweights. If lifted not completely, severe oscillations can occur due to the low-pressure zone under the overflowing nappe, which is why steel strips are added on top of the flap gate to make the overflow instable. Spans up to 50 m can be achieved if a fish-belly shape like in Figure L-1 is applied. This is feasible, since the forces are transferred to the sill; the torsion resistance of the closed shell structure is the limiting factor (Erbisti, 2014).

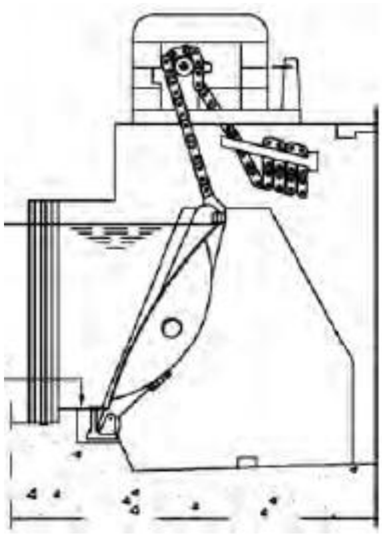


Figure L-1: Cross-section of a fish-belly flap gate (Erbisti, 2014).

Flap gates are extremely suitable to combine with other types of gates as roller, radial and fixed-wheel gates. In this case, operation of the small flap gates on top is used for the discharge of floating material and debris and fine regulation of the water level. Only large discharge variations need motion of the total gate.

Roller gates

Roller gates have been applied much in northern countries, where operation of other gates is hindered by large mass of floating ice. Roller gates have a cylindrical shape on the outside, which is supported by stiffeners on the inside. In closed position, the gate rests on the sealings, which only allows water, ice and debris to float over the gate. Opening is realized by lifting the gate along the toothed rail. Figure L-2 shows a cross-section of a roller gate (Erbisti, 2014).

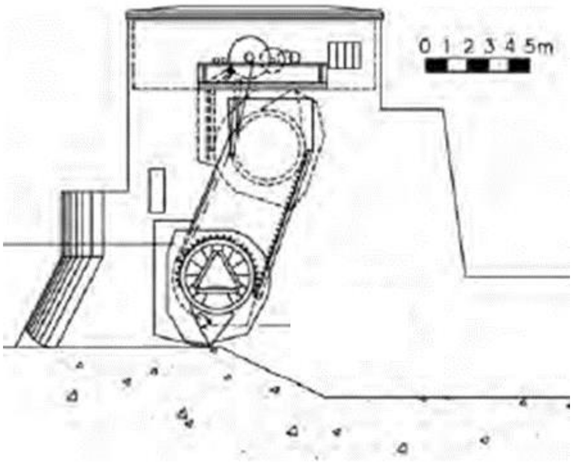


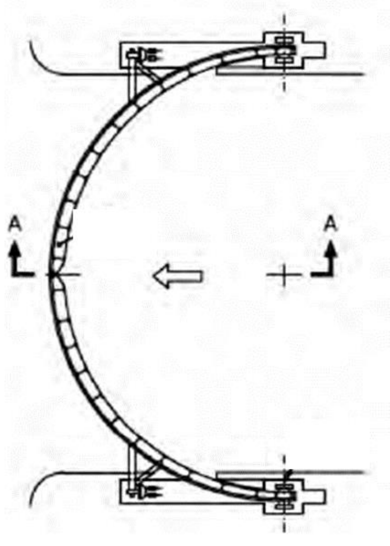
Figure L-2: Cross-section of a roller gate (Erbisti, 2014).

Thanks to the large stiffness of the steel cylinder spans up to 50 m and gate heights up to 8 m are feasible. In comparison with all other gate types, the roller gates are the heaviest and most expensive. This last, and since discharge of large floating ice masses is not a primary function of the weir at Belfeld, the application of roller gates is not further researched.

Visor gates

Visor gates are a more rare type of gate, but in the Netherlands experience has been gained by the installation of these gates in the Nederrijn and Lek. A visor gate has a semi-cylindrical shape, see Figure L-3, to prevent bending moments in the gate structure. The higher water level on the concave side pushes the gate outward, only causing tension. The forces are transferred from the gate to the sill and the piers. The gate is opened by rotation around a horizontal axis. The hoisting mechanism, located at the top of the piers, pulls the gate upward via the connected wire ropes. Completely lifting the gates creates a navigable opening on the intensely used navigation route.

By the absence of bending moments, the amount of material is more efficiently used. This makes this type of gate really competitive to other gate types for large spans. For small spans, the advantage of this gate type is less, since the length of the semi-circle is significantly longer than a flat gate and bending moments in flat gates are much smaller for small spans. In the Nederrijn and Lek, the navigable opening is 48 m wide; in the River Meuse this has to be only 35.40 m (Erbisti, 2014). Therefore, it is assumed that a visor gate is not competitive in the River Meuse.



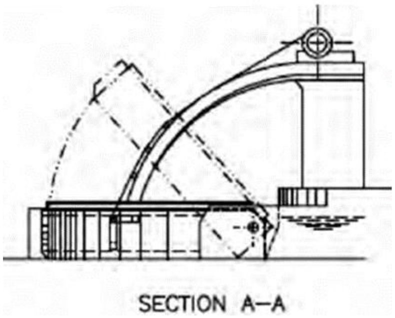


Figure L-3: Top view and cross-section of a visor gate (Erbisti, 2014).

Radial gates

Radial gates dam the water level by a curved skin plate supported by vertical and horizontal stiffeners. On the sides of both piers a radial truss structure transfer the forces from the skin plate and beams to the bearing points. Opening of radial gates is done by rotation around a horizontal axis which intersects with the bearing points. Radial gates rotate upward if the weir has to be opened as in Figure L-4; submersible radial gates rotate downward into the designed recess chamber in the sill as in Figure L-5.

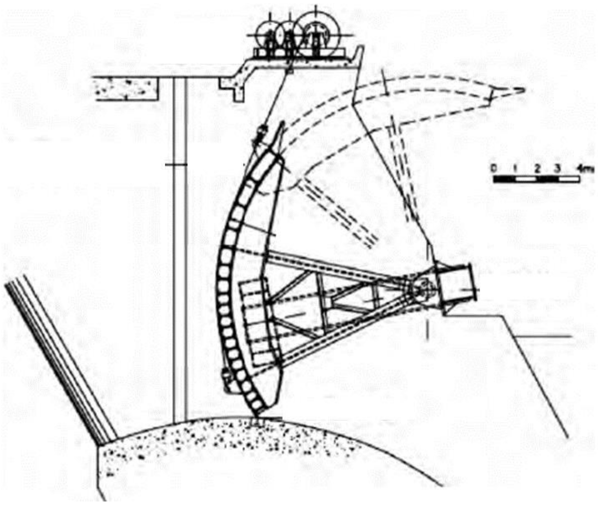


Figure L-4: Cross-section of a radial gate (Erbisti, 2014).

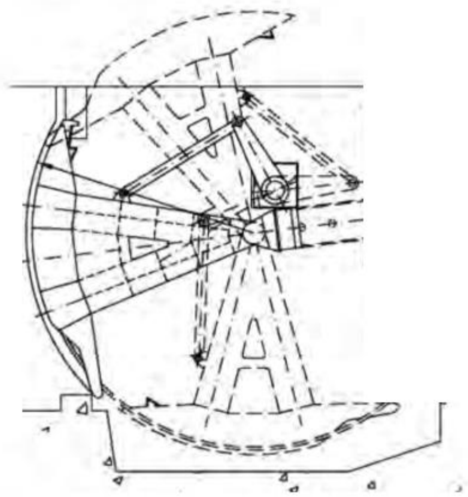


Figure L-5: Cross-section of a submersible radial gate (Erbisti, 2014).

By designing the curvature of the skin plate such that the resultant force of the water head passes through the rotation axis, the resulting moment on the entire gate is zero; there is no tendency of the gate to open or close. Another option is to design the centre of curvature a little above the rotation axis, by which opening of radial gates requires less lifting power. Also counterweights do decrease the power usage during gate operation.

When focussing on radial gates, these can be combined with flap gates on top. This allows the discharge of floating material and debris and fine regulation of the water level. Radial gates are the least expensive type of gate; the operation is easy by only lifting its own light weight and overcoming the friction forces and the maintenance is simple because of the emerged parts. A submersible radial gate is more expensive, since its maintenance is more complex. These can be combined with flap gates on top as well, which are rotated horizontally in open state. In this way, the bottom of the recess chamber can be less deep. Submersible radial gates create a navigable opening with an unrestricted air clearance.

To end up with an economical design, however, the width, radius and elevation of the bearing points of the radial gate should be conform Figure L-6. Ideally, the bearing points are located 1.0 m above the water level during the governing peak discharge, but in the River Meuse this is infeasible.

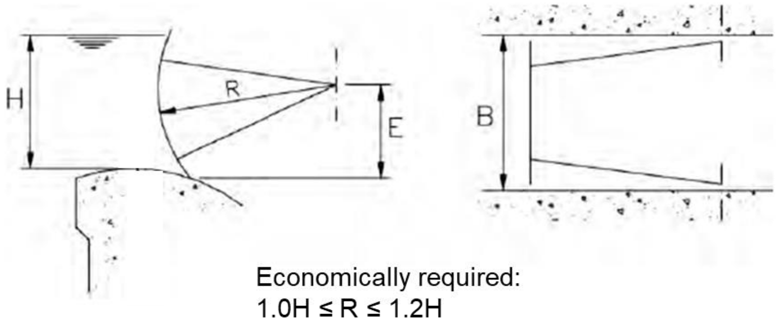


Figure L-6: Economical dimensions of a radial gate (Erbisti, 2014).

Sector gates

Sector gates look similar to radial gates by the curved skin plate. The skin plate, however, continues on the back face to create a closed recess chamber. Just like the submersible radial gate, this gate opens by subsiding into the recess chamber. Operation takes place completely hydraulically via the in- and outflow of water to the recess chamber. The water pressure inside is precisely regulated by this system, which pushes the gate upward to the closed position. If water flows out of the recess chamber, the water pressure inside the recess chamber decreases and the water above the gate pushes the sector gate into its recess chamber, like indicated in Figure L-7.

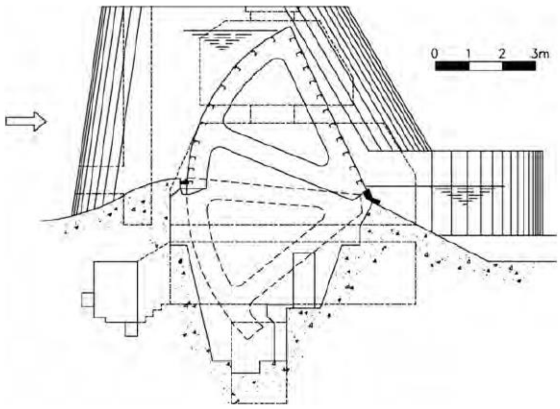


Figure L-7: Cross-section of a sector gate (Erbisti, 2014).

Since the gate transfer its forces to the rotation point at the sill, the width of this gate is unlimited. The height is limited to 8 m (Erbisti, 2014).

Drum gates

Drum gates look similar to sector gates on their turn. The operation principle is similar: movement of the gate is done by regulation of the water pressure in the recess chamber. Instead of a circular upstream skin plate, the drum gates have a triangular cross-section, as can be seen in Figure L-8. The largest difference with the sector gate is the location of the horizontal rotation axis, which is located at the upstream side for the drum gate and at the downstream side for the sector gate.

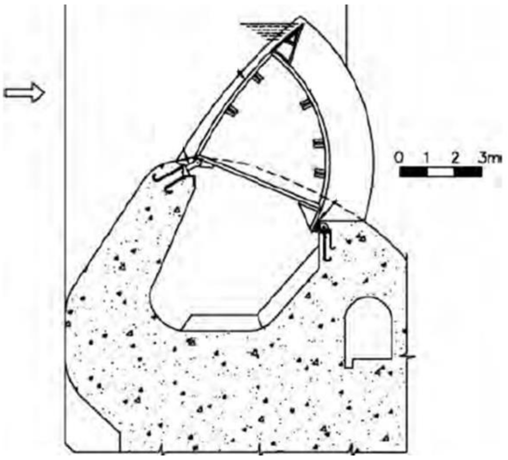


Figure L-8: Cross-section of a drum gate (Erbisti, 2014).

Again, the width of the gate is unlimited, but economical designs are only achieved for heights of maximum 4.0 m. Larger heights require much more steel and a larger recess chamber. Therefore, drum gates are unsuitable for the new weir at Belfeld.

Bear-trap gates

The bear-trap gate is operated hydraulically, too. It consists of two flat plates, which form an inverted V in closed position. The plates are pushed upwards by, again, the pressure regulation of the recess chamber. This recess chamber is much smaller and less deep with this type of gate than for the sector and drum gates. The flat plates do not rotate downwards, but are folded over each other, see Figure L-9, which requires less space. This folding, however, implies disadvantages as well: the pressure needed in the recess chamber to push the flat plates upward is larger than the upstream water pressure. A separate structure to increase the upstream water level or pump is needed to initiate the upward motion of the bear-trap gate itself.

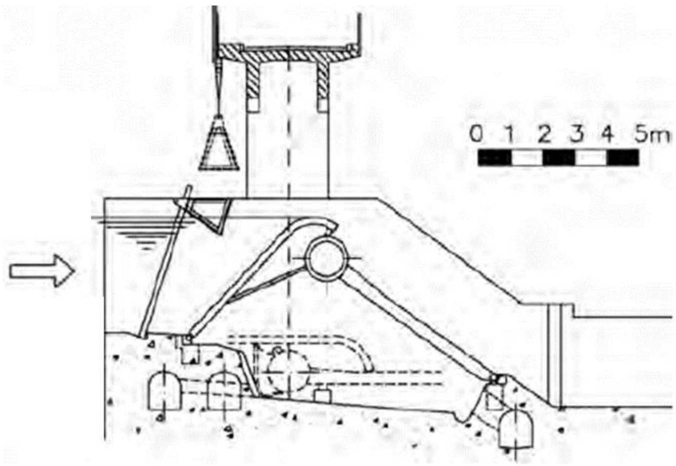


Figure L-9: Cross-section of a bear-trap gate (Erbisti, 2014).

Looking to the limits of the bear-trap gates, it is concluded that is not applicable at Belfeld, since the height is even restricted more than the drum gates (Erbisti, 2014).

Fixed-wheel gates

The most applied type of gate is the fixed-wheel gate. This type of gate consists of a flat skin plate supported by horizontal and vertical beams. These beams can be situated either on the upstream or downstream side. Designs with the beams situated downstream, however, are preferred, since the skin plate protects the beams against collision with floating objects, reduces corrosion of the beams and allows maintenance above water. Moreover, this design does not lead to significant down pull forces if the gate is partially lifted, in contrast to fixed-wheel gates with beams situated upstream. Wheels on both sides at the piers transfer the forces to the pier and provide smooth operation of the gate. The piers towers above the water level, since the fixed-wheel gates have to be lifted vertically out of the water in case of a flood wave. At top of the piers the hoisting mechanism is placed, which has to overcome the deadweight of the gate and the friction between the wheels and the wheel track. Subsidence of the entire gate into a recess chamber is thought to be infeasible, because of the considerable required depth of the recess chamber. Figure L-10 shows a fixed-wheel gate in an outlet of high-head dam.

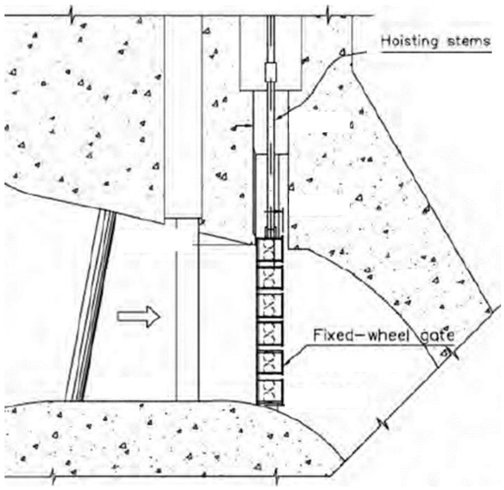


Figure L-10: Cross-section of a high-head fixed-wheel gate in an outlet (Erbisti, 2014).

To reduce the hoisting capacity and frequency of hoisting several alternatives have been designed:

- multiple-leaf fixed-wheel gates. These fixed-wheel gates have been divided into multiple vertical sections. Regulation of the water level during small discharges is done by lifting only the upper section instead of the entire fixed-wheel gate
- double-leaf fixed-wheel gates. These fixed wheel-gates consist of two elements behind each other just like the double Stoney gates. The upper leaf can be lowered to regulate the water levels accurately. If complete opening is required both leaves are lifted upwards. Because they are located behind each other, the required height of the lifting tower is less than in case of regular fixed-wheel gate. Several sub alternatives have been designed in the last century, but eventually the double-leaf fixed-wheel hook gates, see Figure L-11, turned out the best. One single wheel track is used by the wheels of the upper and lower gate. The upper gate transfers its forces to the lower gate via small rollers and protects the lower gate from the overflowing force. The top of the upper gate is curved downstream in which way it guides the overflowing nappe over the lower gate.

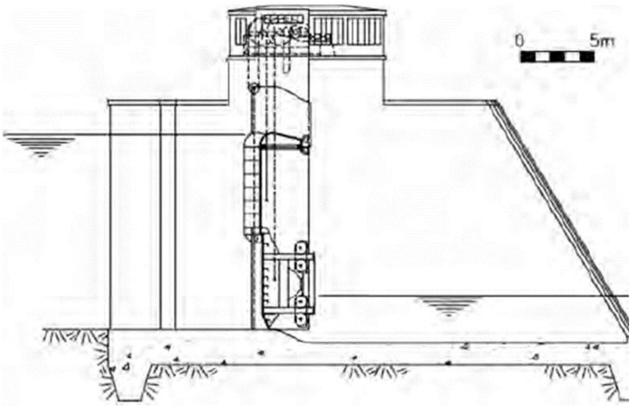


Figure L-11: Cross-section of a double-leaf fixed-wheel hook gate (Erbisti, 2014).

- fixed-wheel gates with flaps on top, see Figure L-12. Again, operating the flaps on top enables accurate water level regulation and discharge of floating material and debris without lifting the entire fixed-wheel gate.

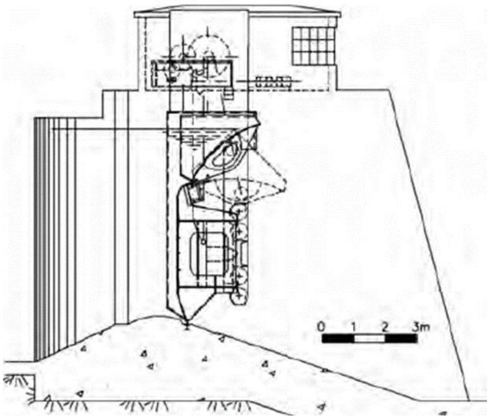


Figure L-12: Cross-section of a fixed-wheel gate with flap (Erbisti, 2014).

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Appendix M
Evaluation of local design alternatives

This appendix elaborates on the evaluation of the local design alternatives. The assessment is executed with help of Figure M-1. To apply this figure, first the score and the life cycle costs have to be known. In Appendix M.1 the score of each weir design alternative is determined by a multi-criteria analysis. Subsequently, in Appendix M.2 the life cycle costs are addressed. Appendix M.3 includes the weighted assessment of the local design alternatives.

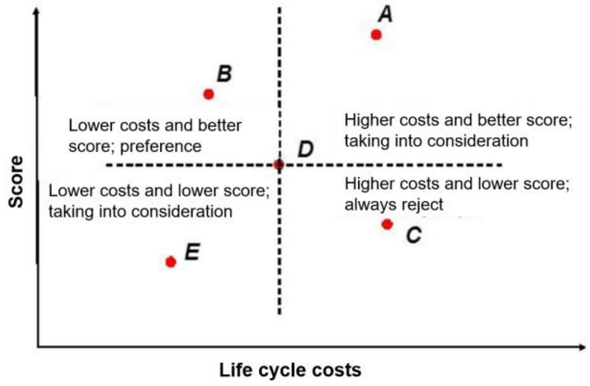

Figure M-1: Assessment of design alternative based on their score and life cycle costs (Tuin, 2013).

M.1 Multi-criteria analysis

5 criteria have been applied to assess the alternatives. First, the content of each criterion is addressed, after which the scoring of each gate type on that criterion is explained. The last section of this appendix shows the unweighted and weighted assessment of the design alternatives.

Maintainability

The maintainability of a design alternative is determined by the score on the following sub-criteria (PIANC, 2006):

- maintainability of all areas and details;
- access to maintenance sensible components;
- maintainability under operation conditions.

Considering these aspects, the maintainability of a radial gate without flap on top is the best. The gate can be rotated above water to be maintained and does not consists of many sensible components. Moreover, the bearing points and part of the radial gate are located above water under operation conditions. By adding a flap gate on top, the maintainability diminish, since an extra maintenance sensible component is added. A submersible radial gate is rotated above water as well during maintenance. Maintenance of the somewhat more complicated connection between the gate and the recess chamber lowers the score on maintainability of this gate type.

The maintainability of (double-leaf) fixed-wheel gates is good as well: the gates can be lifted out of the water for maintenance. In comparison with radial gates, the maintainability is a little more complicated due to the maintenance of the wheels and wheel tracks. By setting the downstream side dry, the lower gate of the double-leaf fixed-wheel can be maintained under operation conditions.

Flap gates score the worst on maintainability of the involved gate types. The rotation axis and sealing is located at the top of the sill, which complicates the accessibility of these maintenance sensible components. The gate cannot be lifted out of the water, so maintenance under operation conditions is impossible.

The maintainability of each local design alternative is based on the maintainability of the gates part of the alternative.

Operationality

The operationality of a design alternative is determined by the score on the following sub-criteria (PIANC, 2006):

- capacity and accuracy of river control;
- unavailability for operation due to maintenance;
- convenience of operation.

The capacity and accuracy of river control is not a distinctive sub-criterion of the design alternatives, since all alternatives include an overflow gate by which the water level is controlled accurately. The second sub-criterion is dependent on the layout of the entire weir. If a function of the weir, like water level control or navigability, is only realized by one gate, this function is just partially or not realized during maintenance of this gate. Therefore, accurate water level control by multiple weir gates score better on this sub-criterion. The same is true for alternative with two navigable openings instead of one.

The convenience of operation of the radial gates is the best by the small gate weight and small friction. Hydrodynamic forces are absent during operation. The operation of (double-leaf) fixed-wheel gates is comparable with that of the radial gates. Again, hydrodynamic forces are absent, since the skin plate is located at the upstream side. The weight of these gates is somewhat larger than the weight of radial gates. The operation of a flap gate can involve some inconvenience: vibrations when the weir is in an intermediate position are not unlikely.

Reliability

The reliability of a design alternative is determined by the score on the following sub-criteria (PIANC, 2006):

- vulnerability to sediments, floating debris and ice;
- sensitivity to malfunctions, human errors and ship collision;
- vulnerability to foundation distortions.

Just like for the criterion operationality, the first sub-criterion is not distinctive, since all local design alternatives are a combination of over- and underflow gates. The second sub-criterion is partially dependent on the layout of the entire weir. The probability of a ship collision is thought to be larger if the alternative includes a navigable opening.

The sensitivity to malfunctions and vulnerability to foundation distortions is closely related to the type of gates. Two factors are decisive for the score on these sub-criteria: opening of the gate under or above water and the connection between the gates and the piers and/or foundation. Opening of the gates under water, as submersible radial gates and flap gates, involve a smaller reliability, since the recess chamber can be obstructed by sediments or other not observable objects. By distortions of the lateral slots and wheel tracks, the transfer of forces of fixed-gate wheels can be significantly distorted. The total force can be redistributed and concentrated at only a part of the wheels, which makes these fixed-wheel gates more vulnerable to foundation distortions as radial and flap gates, which do not include wheel tracks.

Social impact

The criterion social impact includes the following two sub-criteria:

- aesthetics;
- possibility to add a river crossing.

The aesthetics of the new weir are determined by the presence of lift towers. These become remarkable elements in the environment, which is experienced as visual pollution by the inhabitants and users of the area.

Addition of a river crossing is possible for all local design alternatives without a navigation opening. If it includes a navigation opening, it must not limit the air clearance. The river crossing, therefore, has to be elevated on top of the lift towers. If lift towers are absent, a river crossing at large height is infeasible.

Navigability

The navigability of the design alternatives is not directly dependent on the gate type, but on:

- number of navigation openings;
- availability of the navigation openings.

The number of navigation openings of the local design alternatives ranges from zero to two. Of course, alternatives including two navigation openings score the best. Alternatives with only one navigation opening can create some delay to the individual vessels, since encounters have to be prevented in the stretch of the weir by communication means and local regulations, like an overtake prohibition.

A limited air clearance and water depth can reduce the availability of the navigation openings. It is assumed that lift towers are constructed sufficiently high to not limit the air clearance when the weir is about to open. During a large flood wave, however, the water level still raises after opening of the navigable opening and fixed-wheel gates do restrict the height of container vessels. On the other hand, a high elevated sill limits the maximum draught of the vessels when the weir is about to open. This limitation plays a role particularly if the location of the set point is located at the theoretical location, since the weir opens in this case at a lower water level.

Unweighted scoring of local design alternatives

Based on the Sections above, the design alternatives have been assessed. The scores on the criteria range from 1 to 5; a high score indicates a good performance of the design alternative on that criterion. The score of all design alternatives is shown per criterion in Table M-1. In the unweighted assessment all design criteria are equally important. The total score only has to be divided by the number of criteria to end up with the unweighted score of the design alternative.

Table M-1: Score of the design alternatives per design criterion.

Design alternative	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Maintainability	3	5	1	5	3	5	4	2	4	1
Operationality	2	4	1	4	2	4	3	4	5	2
Reliability	4	5	4	5	3	5	4	2	3	1
Social impact	5	5	3	2	3	3	2	2	3	3
Navigability	1	1	1	1	3	4	3	4	5	4
Total	*15*	*20*	*10*	*17*	*14*	*21*	*16*	*14*	*20*	*15*

M.2 Life cycle costs of local design alternatives

The costs of the local design alternatives are compared on their life cycle costs. These life cycle costs consists of capital expenditures (CAPEX) and operational expenditures (OPEX), see Figure M-2. The percentages are based on a cost expert (Emmen, 2019); the construction costs of a weir, gates and lift towers on literature (Jonkeren, Rietveld, & Van der Toorn, 2010) (Erbisti, 2014) (ARCADIS, 2015). The CAPEX are the initial investments to establish the weir and investments needed for renovation or upgrade of the structure. The OPEX on the other hand, include the (yearly) returning costs to keep the structure running in the way it should do. In the following, the calculation of CAPEX and OPEX are elaborated.

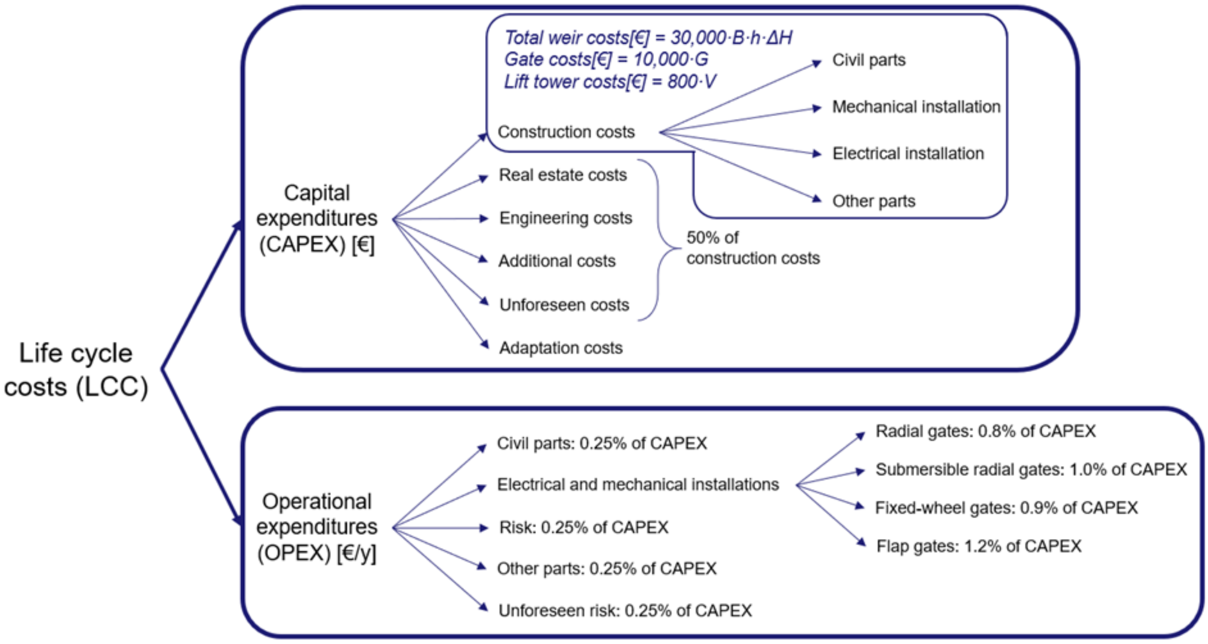

Figure M-2: Subdivision of the life cycle costs (Emmen, 2019).

CAPEX

The CAPEX mainly consist of the construction costs of the weir. Since it is impossible to determine the construction costs of each local design alternative accurately in the preliminary design phase, the construction costs are approximated by index numbers. A first indication of the total construction costs is given by the following formula, which is based on eight reference weirs (Jonkeren, Rietveld, & Van der Toorn, 2010):

$$\text{Total weir construction costs [€]} = 30{,}000 \cdot B \cdot h \cdot \Delta H \qquad \text{(L.1)}$$

In this formula, B is the total width of the weir, h the height of the weir and H the head over the weir. As stated in the main report, the average construction costs of the local design alternatives are, according to equation (L.1), €79.0 mln.

The total construction costs of a weir consist of the costs of the gates, the foundation, the concrete superstructure and substructure, the seepage screens, the bed protection and the construction costs. Only the gates and the concrete superstructure do vary significantly between the local design alternatives; variation in the total construction costs of the design alternatives is therefore based on the applied gate type and the presence of lift towers.

The gate construction costs are based on the weight of the gates, which is shown in Table M-2. Not surprisingly, the gate weight is dependent on the width B, height h and head ΔH as well. A flap gate on top of another type of gate transfers its forces to this gate, so the underlying gate still has to be able to withstand the total head. The head over the flap gate itself ΔH_{flap} is equal to the height of the flap h_{flap} if the $h_{flap}<\Delta H$, which is mostly the case.

Table M-2: Gate weight per gate type (Erbisti, 2014).

Gate type	*Gate weight G [kN]*
Radial gate	$0.640(B^2 h_{segment} \cdot \Delta H)^{0.682}$
Radial gate with flap	$0.640(B^2 h_{segment} \cdot \Delta H)^{0.682} + 2.387B(h_{flap} \cdot \Delta H_{flap})^{0.643}$
Submersible radial gate	$3.688(B^2 h_{segment} \cdot \Delta H)^{0.521}$
Submersible radial gate with flap	$3.688(B^2 h_{segment} \cdot \Delta H)^{0.521} + 2.387B(h_{flap} \cdot \Delta H_{flap})^{0.643}$
Fixed-wheel gate	$0.735(B^2 h_{fixed-wheel} \cdot \Delta H)^{0.697}$
Fixed-wheel gate with flap	$0.735(B^2 h_{fixed-wheel} \cdot \Delta H)^{0.697} + 2.387B(h_{flap} \cdot \Delta H_{flap})$
Double-leaf fixed-wheel gate	$0.913(B^2 h_{2fixed-wheel} \cdot \Delta H)^{0.669}$
Flap gate	$2.387B(h_{flap} \cdot \Delta H)^{0.643}$

Using Table M-2 and a unit price of €10,000 per kN (ARCADIS, 2015), results in the gate construction costs per local design alternative, as shown in Table M-3.

Table M-3: Gate construction costs of local design alternatives.

Local design alternative	*Number and type of gates*	*Gate weight G [kN]*	*Gate construction costs [mln €]*
1	9 radial gates + 1 flap gate	9 x 116.8 + 1 x 103.5 = 1,155	11.55
2	9 radial gates + 1 submersible radial gate with flap	9 x 116.8 + 1 x 118.2 = 1,169	11.69
3	9 fixed-wheel gates + 1 flap gate	9 x 150.4 + 1 x 102.5 = 1,456	14.56
4	10 double-leaf fixed-wheel gates	10 x 142.9 = 1,429	14.29
5	7 radial gates + 1 flap gate	7 x 104.3 + 1 x 514.2 = 1,244	12.44
6	6 radial gates + 1 submersible radial gate	6 x 119.9 + 1 x 723.3 = 1,443	14.43
7	6 fixed-wheel gates + 1 double-leaf fixed-wheel gate	6 x 154.5 + 1 x 807.8 = 1,735	17.35
8	2 fixed-wheel gates + 2 fixed-wheel gates with flap	2 x 218.4 + 2 x 851.3 = 2,139	21.39
9	2 radial gates + 2 submersible radial gates with flap	2 x 168.2 + 2 x 724.0 = 1,784	17.84
10	3 radial gates + 2 flap gates	3 x 119.3 + 2 x 487.0 = 1,332	13.32

The construction costs of the lift towers are calculated by multiplying the additional volume of concrete with the index number of €800/m³ (ARCADIS, 2015). The length of a lift tower (in streamwise direction) is taken equal to 5 m. To estimate the width and height of a lift tower, a distinction has to be made between lift towers next to a non-navigable and next to a navigable opening. Next to a non-navigable opening, a width of 3 m is assumed and the height has to be sufficient to lift the fixed-wheel gate above the water level during a governing flood wave (plus 0.5 m safety margin). Next to a navigable opening, a width of 6 m is assumed to accommodate the larger lifting equipment. The height has to be sufficient to lift the fixed-wheel gate to not limit the desired air clearance when the weir is about to open.

During estimation of the construction costs, it is assumed that the height of the lift towers cannot be adapted easily in the future. The height constructed in 2030 has to be sufficient for the entire lifetime, including all uncertainties in each scenario. Furthermore, it is assumed that the top of the piers of design alternatives without lift towers are elevated at NAP +15.60 m, which is equal to the elevation of the top of the lock walls. Then, the height of the lift towers can be calculated by equation (L.2).

$$h_{lifttower} = (h_{gate,initial} + h_{max\,adaptation}) + 20.5 - 15.6 \quad \text{for a non-navigable opening}$$
$$h_{lifttower} = (h_{gate,initial} + h_{max\,adaptation}) + 11.1 + (14.1 + h_{max\,adaptation}) - 15.6 \quad \text{for a navigable opening}$$

(L.2)

The height of lift towers of double-leaf fixed-wheel gates is less, because the smaller of the two gates can be adapted without requiring a larger lifting height. as l construction costs of the lift tower have been specified per local design alternative in Table M-4.

Table M-4: Construction costs of lift towers of local design alternatives.

Local design alternative	Number of lift towers	Volume V [m³]	Construction costs of lift towers [mln €]
1	0	0	0
2	0	0	0
3	10 next to a non-navigable opening	10 x (5 x 3 x 12.4) = 1,860	1.49
4	11 next to a non-navigable opening	11 x (5 x 3 x 9.65) = 1,592	1.27
5	0	0	0
6	0	0	0
7	6 next to a non-navigable opening + 2 next to a navigable opening	6 x (5 x 3 x 13.95) + 2 x (5 x 6 x 18.35) = 3,612	2.89
8	2 next to a non-navigable opening + 3 next to a navigable opening	2 x (5 x 3 x 13.95) + 3 x (5 x 6 x 21.65) = 2,165	1.89
9	0	0	0
10	0	0	0

On average, the construction of the gates and the lift towers costs €15.4 mln. This means that the constant costs of weir Belfeld are €63.6 mln. To end up with the CAPEX, the real estate costs (like land reclamation), the engineering costs of the engineering firm and contractor, additional costs like piping and cables and unforeseen costs, which are all together approximately equal to 50% of the construction costs, have to be added. The adaptation costs are left out at first instance, since these are highly variable on the adaptation path. The capital expenditures for weir establishment per design alternative are shown in Table M-5.

Table M-5: Calculation of the capital expenditures for the weir establishment of each local design alternative.

Local design alternative	*Constant construction costs [mln €]*	*Gate construction costs [mln €]*	*Construction costs of lift towers [mln €]*	*Total construction costs [mln €]*	*Initial CAPEX [mln €]*
1	63.6	11.55	0	75.2	112.7
2	63.6	11.69	0	75.3	112.9
3	63.6	14.56	1.49	79.7	117.2
4	63.6	14.29	1.27	79.2	116.8
5	63.6	12.44	0	76.0	114.1
6	63.6	14.43	0	78.0	117.0
7	63.6	17.35	2.89	82.7	121.4
8	63.6	21.39	1.89	86.7	127.5
9	63.6	17.84	0	81.5	122.2
10	63.6	13.32	0	76.9	115.4

OPEX

The operational expenditures are representing the recurring costs during the lifetime of a weir. In Figure M-2, it can be seen that the yearly operational and maintenance costs are approximately 2% of the CAPEX. The variance of the OPEX is only small, since the OPEX of civil parts (like maintenance of concrete parts and the painting of steel parts), other parts (like replacement of cables and cleaning) and the (unforeseen) risk is the same for every alternative. The operational and maintenance costs of the electrical and mechanical installations are significant, but the variance between the different gate types is small, because, regardless of the gate type, inspections and replacements have to be carried out according to legislation. For example, inspections by divers have to be executed for all gate types every year (Emmen, 2019).

The yearly OPEX of the local design alternatives in Table M-6 are based on the types of gates which are applied in that specific alternative.

Table M-6: Calculation of the operational expenditures of each local design alternative.

Local design alternative	*Number and type of gates*	*OPEX [% of CAPEX]*	*Initial CAPEX [mln €]*	*OPEX [mln €/100 year]*
1	9 radial gates + 1 flap gate	1.84	112.7	2.07
2	9 radial gates + 1 submersible radial gate with flap	1.82	112.9	2.06
3	9 fixed-wheel gates + 1 flap gate	1.93	117.2	2.26
4	10 double-leaf fixed-wheel gates	1.90	116.8	2.22
5	7 radial gates + 1 flap gate	1.85	114.1	2.11
6	6 radial gates + 1 submersible radial gate	1.83	117.0	2.14
7	6 fixed-wheel gates + 1 double-leaf fixed-wheel gate	1.90	121.4	2.31
8	2 fixed-wheel gates + 2 fixed-wheel gates with flap	1.90	127.5	2.42
9	2 radial gates + 2 submersible radial gates with flap	1.90	122.2	2.32
10	3 radial gates + 2 flap gates	1.96	115.4	2.26

Weir adaptation costs

The weir adaptation costs highly depend on the adaptation path. The weir adaptation costs are only calculated for ten distinctive adaptation paths for the design alternative 2 and 6. To calculate the weir adaptation costs, some starting point have been taken into account:

- To calculate the weir adaptation costs, the same equations as shown in Figure M-2 have been applied.
- It is assumed that during the establishment of the weir, investments in the concrete sub- and superstructure of the weir are done to prepare the structure for a larger water head ΔH. The size of this investment is adjusted to the maximum adaptivity of the gates. Thus, if the gates are more adaptive, the investment in 2030 in the non-adaptive weir parts has to be larger.
- If the discharge capacity of the weir has to be increased to discharge a larger flood wave, the weir is widened by constructing an additional weir opening. This weir opening is as wide as and the sill is elevated as deep as the existing non-discharging and/or non-navigable weir openings. In this way, an identical, reserve weir gate can be placed to close off the additional weir opening. The concrete sub- and superstructure is also as strong and high as the existing weir. The dimensions of the non-discharging weir openings of both alternatives are approximately the same, so the required widening is equally dependent on the changing requirement:
    - Enlarging the discharge capacity 0-10%: 1 additional weir opening
    - Enlarging the discharge capacity 10-20%: 2 additional weir openings
    - Enlarging the discharge capacity: 20-30%: 3 additional weir openings
- If the dammed water level has to heightened, the water head ΔH and height h increase. Both parameters result in larger gate adaptation costs. The adaptation costs of the concrete superstructure only consist of investments in the height, since investments to withstand the larger water head are done in 2030 (see bullet 2 of this summation).
- The operational expenditures are calculated with help of the percentages in Table M-6. The applied value of the CAPEX is the summation of the initial investments and the adaptation costs.

The ten adaptation paths are selected such that a wide range of desired adaptivity is created. The adaptation paths are allocated to the most logical of the four delta scenarios. An adaptation path can also occur in other scenarios than the scenario to which it is allocated. If the adaptivity of the weir is insufficient to meet the desired adaptivity of that adaptation path, regional adaptation measures are needed. These are not taken into account, since these regional adaptation measures have possibly already been executed for other purposes, before these measures are needed according to the adaptation path.

The ten adaptation paths are shown in Figure M-3 to Figure M-6, including the life cycle costs of the design alternatives 2 (orange) and 6 (pink) for each adaptation path. The life cycle costs are split into the initial investment for the establishment of the weir, the adaptation costs, the gate replacement cost and the operational expenditures. If the bar in the diagram is only outlined, the weir adaptivity is insufficient the meet the evolved requirements. The costs of regional adaptation measures have to be added to end up with the life cycle costs in the entire regional design area.

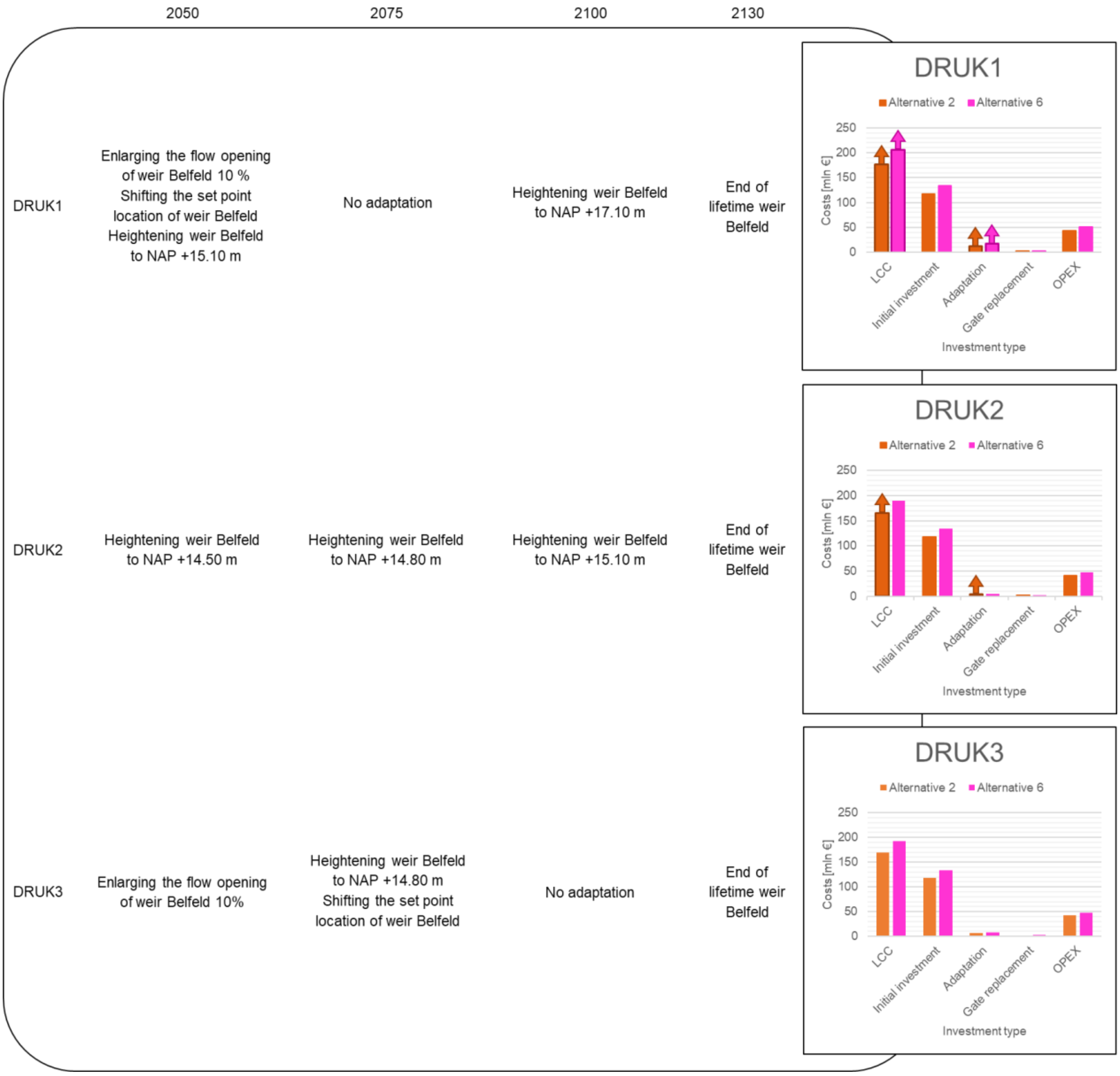

Figure M-3: Adaptation paths in the scenario DRUK, including the life cycle costs of the local design alternatives 2 and 6.

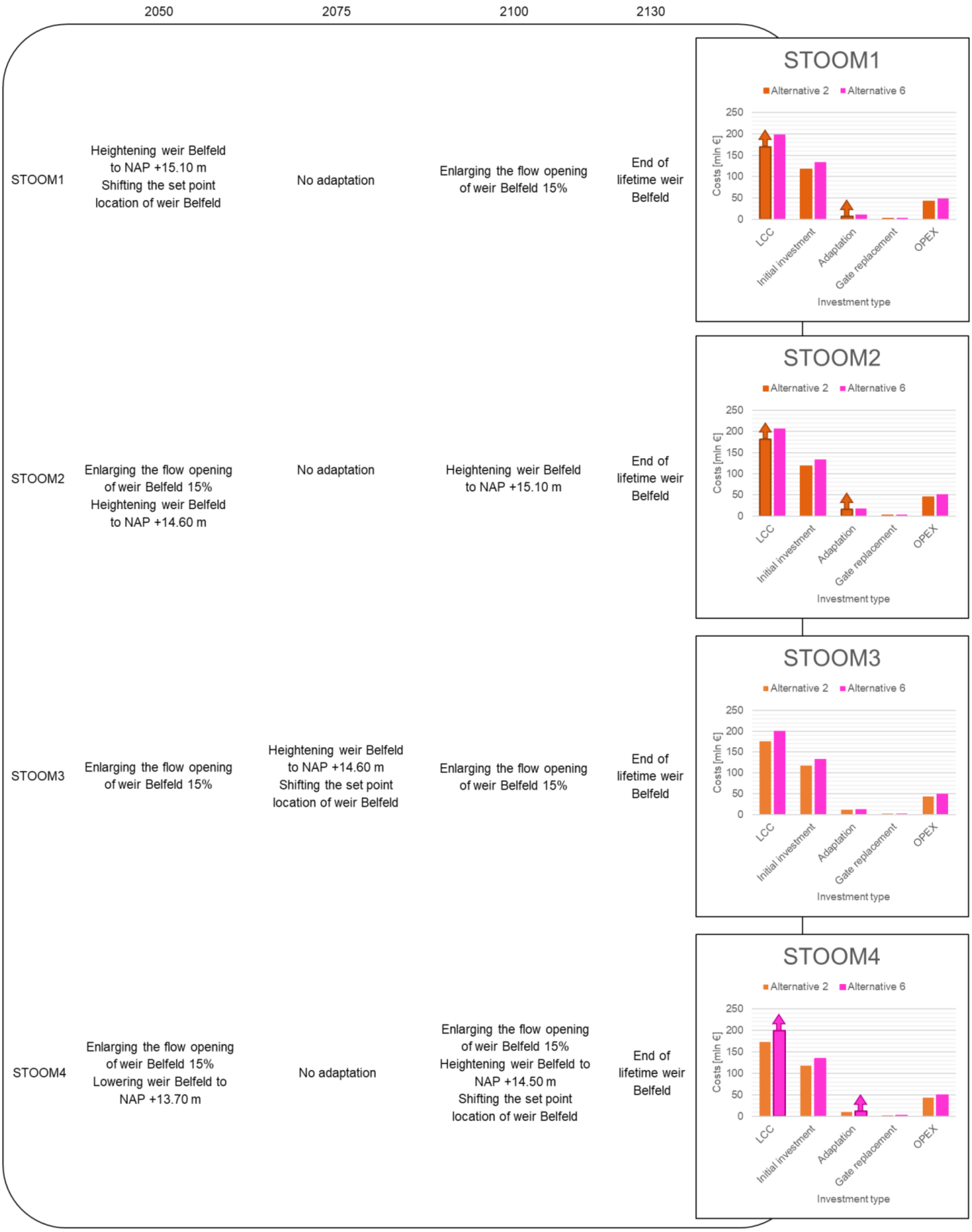

Figure M-4: Adaptation paths in the scenario STOOM, including the life cycle costs of the local design alternatives 2 and 6.

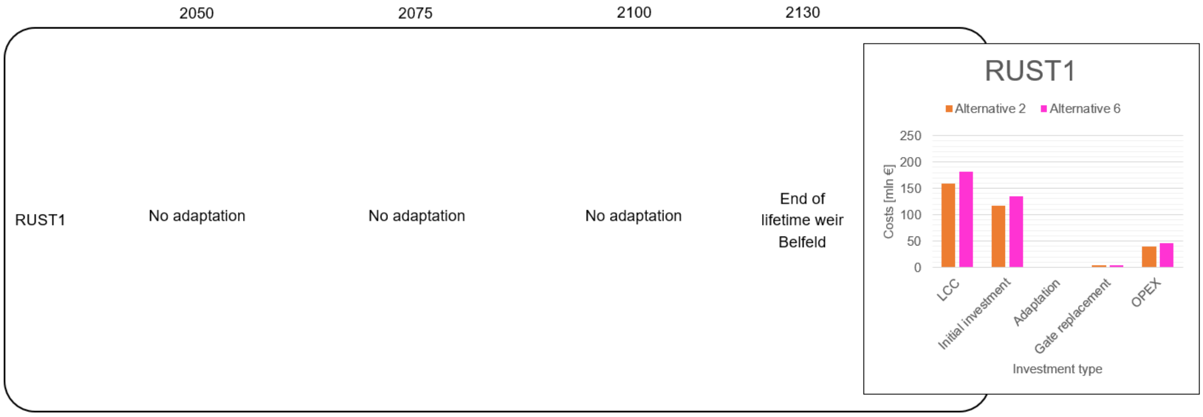

Figure M-5: Adaptation paths in the scenario RUST, including the life cycle costs of the local design alternatives 2 and 6.

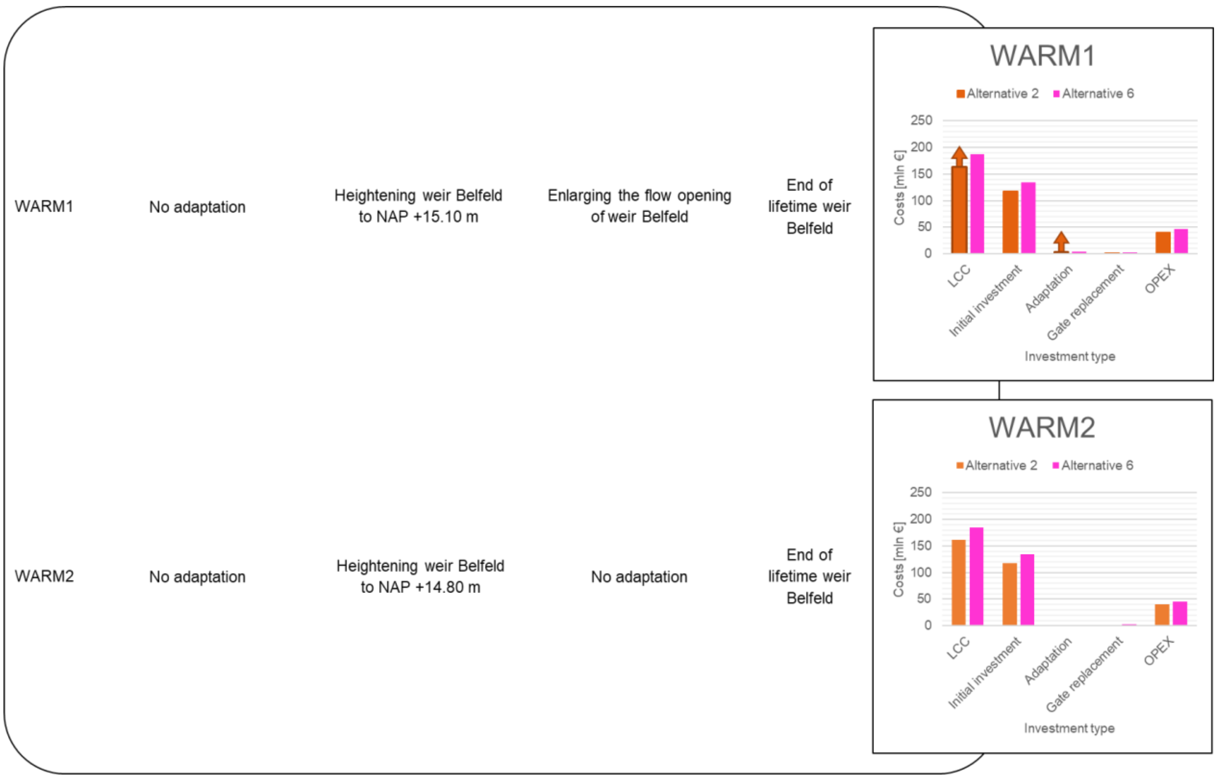

Figure M-6: Adaptation paths in the scenario WARM, including the life cycle costs of the local design alternatives 2 and 6.

M.3 Weighted evaluation

The client, which would be Rijkswaterstaat in this project, does mostly not agree on the unweighted assessment: some design criteria are more important than other, which is taken into account by multiplication of the score of each criterion (see Table M-1) by its weight factor. The summation of the weight factors have to be equal to 1.0. The larger the weight factor is, the larger the importance of the design criterion. The size of the weight factors is determined by the client, but in this project the ratio of weight factors is adopted from literature (PIANC, 2006).

Table M-7: Weight factors of each design criterion (PIANC, 2006).

Design criterion	*Weight factor*
Maintainability	1/11
Operationality	3/11
Reliability	3/11
Social impact	2/11
Navigability	2/11

As Table M-8 shows, the differences in unweighted and weighted score are small. As the costs in both assessments are equal, the weighted assessment shown Figure M-7 only has minor difference with respect to the unweighted assessment in Figure 5-11.

Table M-8: Assessment of local design alternatives.

Design alternative	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Unweighted score	3.0	4.0	2.0	3.4	2.8	4.2	3.2	2.8	4.0	3.0
Weighted score	3.0	4.0	2.2	3.5	2.7	4.2	3.2	2.9	4.0	2.2

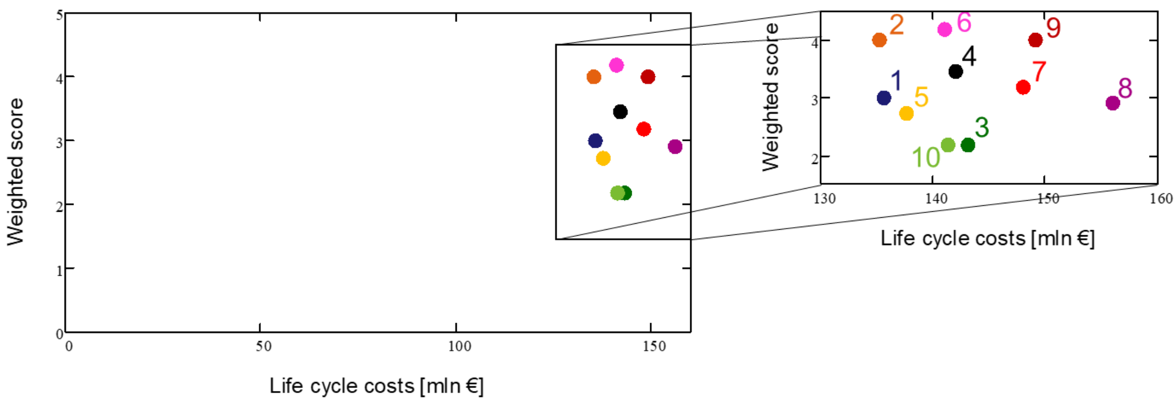

Figure M-7: Weighted assessment of the local design alternatives.

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