Development of a Weir Design Guideline Using Sustainability and Circularity as Leading Principles

Master Thesis

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by

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Cover: The weir at Linne

Preface

This thesis is the final step towards obtaining my Master's degree in Civil Engineering with a specialisation in Hydraulic and Offshore Structures at the Faculty of Civil Engineering and Geosciences at Delft University of Technology. The research for this thesis was conducted during my internship at Royal HaskoningDHV.

I would like to sincerely thank my supervisor, Mark Voorendt, for his continuous support, guidance throughout this project and insightful feedback. I would also like to thank the other members of my committee, Sander Pasterkamp and Floris van der Ziel, for their valuable feedback and constructive criticism. I am particularly grateful to Floris for guiding me towards the topic of the Meuse weirs. Initially, my focus was on developing a sustainable design for a storm surge barrier, but Floris highlighted the relevance of the VenR project for the Meuse weirs. This led to the development of the thesis topic: creating a sustainable guideline for the design of weirs.

I also want to thank my colleagues at Royal HaskoningDHV, who supported me by answering my questions regarding sustainability and the practical considerations during the design process. Their insights were very important in advancing the progress of my work.

I hope that the findings and recommendations presented in this thesis will contribute meaningfully to the VenR project and support future sustainable design efforts for the Meuse weirs.

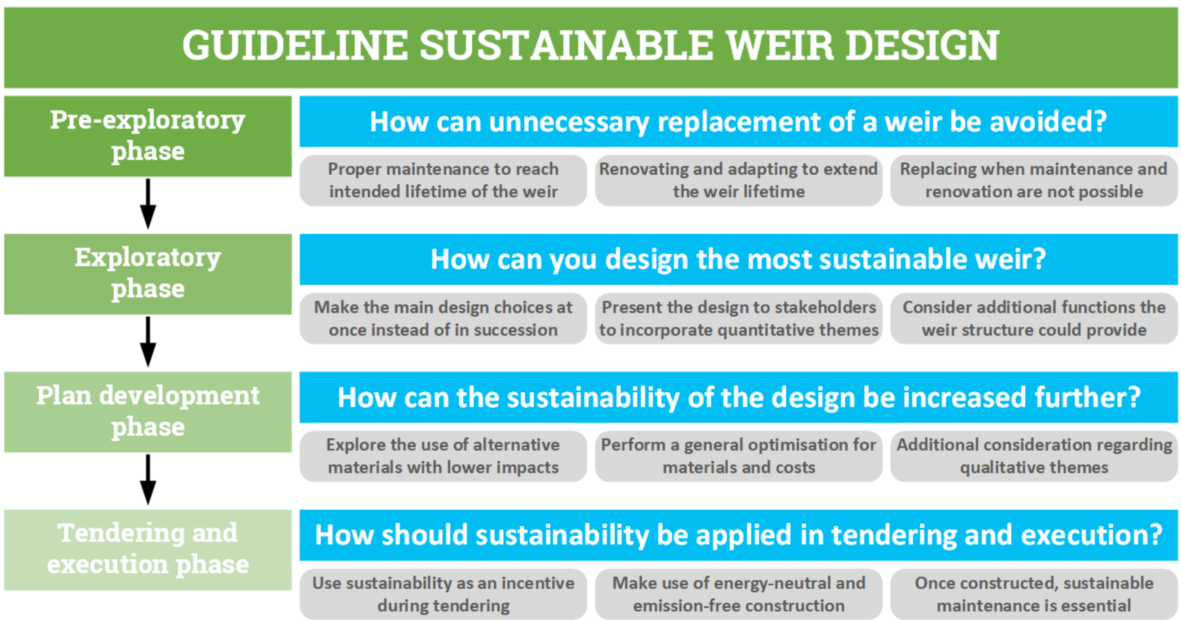
Stijn Bezooijen
Delft, February 2025

Summary

Seven large weirs are used to regulate the water level of the Dutch part of the Meuse for inland shipping. Managed by Rijkswaterstaat (RWS), these weirs were originally constructed between 1925 and 1936 to make the Meuse navigable year-round by preventing low water levels during dry periods. Nowadays, the Meuse remains one of the most important inland shipping routes in Europe, being used by over 16,000 vessels annually. However, these structures approach the end of their functional and technical lifetime and will have to be renovated or replaced between 2028 and 2035. Since their original construction both the requirements and boundary conditions of the design have changed. Nowadays the Meuse weirs are not only used for navigation, but also to buffer water in the upstream basins to use during droughts for drink water production or irrigation. Additionally, climate change is expected to impact the discharge pattern of the Meuse, leading to more frequent and intense occurrences of both droughts and floods.

Potential new weir designs must be in line with the requirements and the sustainability and circularity goals posed by Rijkswaterstaat, while considering the uncertainties due to climate change. This study aims to develop a guideline for designing sustainable weirs. This guideline is then applied through a case study covering the conceptual design of the weir at Linne.

Development of a guideline for sustainable weir design
Sustainability is divided into 10 distinct themes, ranging from materials & circularity to ecology and social relevance. These themes cover all relevant sustainability aspects encountered during weir design. They are used to analyse the sustainability challenges and solutions. This analysis forms the basis for the guideline for sustainable weir design. An overview of the guideline is provided in the figure below. The guideline is divided into four phases, offering a structured approach to integrating sustainability into the design of replacement weirs.



Overview of the four phases of the guideline sustainable weir design

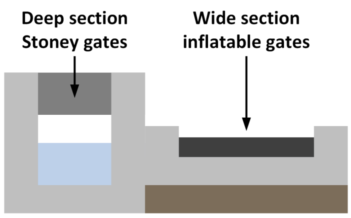
- Pre-exploratory phase: The focus of this phase is on assessing whether a new weir is necessary. This includes evaluating the current weir's lifespan, considering renovation or replacement and deciding to build a new weir. Sustainability is maximised by avoiding unnecessary construction and extending the life of existing structures. Additionally, combining the functions of multiple structures into a single one can increase the sustainability of the project by reducing the number of structures that need to be built.
- Exploratory phase: This phase involves making a design for the weir, focusing on three major decisions: gate type, main dimensions of the structure and integration of the structure in the surrounding area. These choices, along with potential additional functions like ecological improvements and renewable energy generation, are crucial for sustainability. During this phase, stakeholder input is used for addressing the themes ecology, social relevance and spatial quality. Possible design concept are evaluated on both quantifiable and qualitative sustainability criteria. Reusing elements from the existing structure provides the greatest sustainability gains.
- Plan development phase: The chosen design of the previous phase is refined. Sustainable materials usages and material reduction are investigated, as well as deciding the future of the old weir. A more detailed evaluation of sustainability is part of this phase, with adjustments based on constructibility and maintainability. Additional sustainability gains in this phase may come from the use of alternative materials, such as plastics.
- Tendering and execution phase: Although sustainability gains are limited at this stage, there is still potential to be gained by using sustainability as an incentive during tendering. Potential gains can come from using emission-free construction equipment, though this heavily depends on earlier decisions regarding materials and construction methods.

Case study Linne

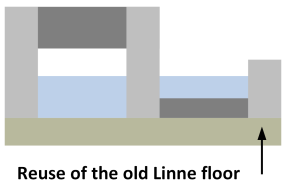
The guideline was applied in a case study for the Linne weir. The Linne weir is the oldest of the Meuse weirs, having been constructed in 1925. Four design concepts were generated and evaluated, with concepts B and D each having two variants. During the evaluation, sustainability has been taken into account using the "milieukostenindicator" (MKI) [environmental cost indicator][1] of the designs. In the table below, two of the most sustainable design concepts for the new Linne weir are presented.

Most sustainable design concepts Linne

Concept B.1: This weir is constructed at the location of the dam north of the current Linne weir. The design features a 'deep' section with Stoney gates for precise water level regulation and two 'wide' sections for increased discharge capacity. These wide sections have a high weir floor, reducing the required gate height, which allows for the effective use of an inflatable gate. This gate remains inflated during low river discharge and deflates when additional capacity is needed. Inflatable gates are significantly lighter than steel gates, resulting in a 20% reduction in MKI, making this a sustainable alternative.



Concept C: This concept involves reusing the floor of the old Linne weir, as it is assumed this floor has not reached the end of its technical lifetime. Reusing elements of the old structure contributes to circularity and a reduction of 50% in MKI, making it the most sustainable design concept.



Guideline validation

After applying the guideline to the Linne weir case study, it was validated through reviews by three specialists. This validation was used to create the final version of the guideline, which can be found at the very end of this document.

[1]The MKI is a single score used to express the environmental impact of a project in monetary terms. It combines various measurable environmental effects using weighting factors.

Contents

1 Introduction

1.1. Motivation for the present thesis

The water level in the Dutch part of the Meuse is regulated using seven large weirs. These Meuse weirs were built in order to artificially increase the water level of the Meuse to make it navigable for inland shipping even during low river discharges. Rijkswaterstaat (RWS) maintains the seven weirs and estimates that between 2028 and 2035 all of them will reach the end of their functional or technical lifetime, which RWS defines as: "the structure is worn and no longer functions" (Rijkswaterstaat, 2021). On the left side of Figure 1.1 a photo of the Meuse weir at Lith is shown. On the right side of the figure the working of a weir is schematically depicted. The weirs are still essential for shipping along the Meuse. Without the weirs the water level would drop drastically during dry months, making it impossible for ships to use the river.

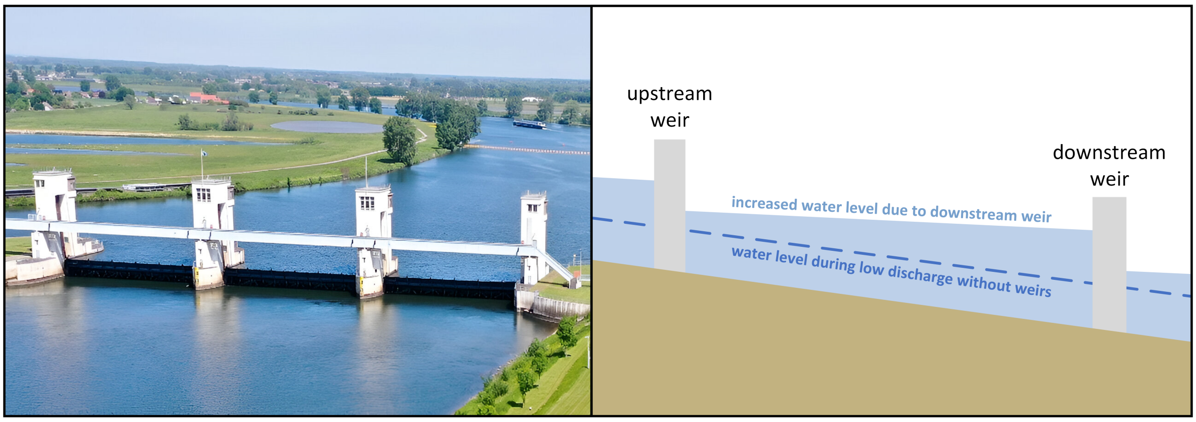


Figure 1.1: Left: a photo of the Meuse weir in Lith, adapted from (Rijkswaterstaat, 2024c). Right: schematisation of the water level increase due to the addition of multiple weirs in a river section.

When the weirs reach the end of their design lifetime, RWS will replace or renovate the weirs as part of the project "Vervanging en Renovatie" (VenR) [Replacement and Renovation] (Delbressine et al., 2023). Based on a study done by Antea Group on behalf of RWS, it can be concluded that the weirs are fully integrated in the large scale water system of region. Therefore, renovation or one-to-one replacement of the weirs is advised, instead of changing the number or locations of the weirs (van Tilburg, 2015). The new weirs will have to be designed for the next 100 years. The weirs must be adapted to the current requirements as well as the assumed requirements considering a 100 year lifespan. These requirements differ from the requirements when they were built in the 1920s.

During the renovation and replacement process of the Meuse weirs, RWS aims to work sustainably by incorporating the weirs into the Meuse river system. The weirs should not disrupt the natural processes occurring in the system. This thesis aims at providing insight in the possibilities of using sustainable and circular approaches for renovating and replacing weirs.

1.2. Problem analysis

1.2.1. Historical context

During the Industrial Revolution there was a need for a reliable shipping connection between the ports in the west of the Netherlands and the industry in Liège. The Zuid-Willemsvaart, a canal connecting Maastricht and 's-Hertogenbosch, formed the first part of this route as can be seen in Figure 1.2. The Liège-Maastricht Canal served as the second part of the route. However, by the late 19th century, the volume of ship traffic exceeded the capacity of the Zuid-Willemsvaart, leading to the need to find an alternative route between Maastricht and the west.

The Meuse forms a natural route from North Brabant through Limburg to Liège and could be used as an alternative to the Zuid-Willemsvaart. However, the Meuse is a river with a pluvial regime, leading to extensive dry periods in summer and wet periods in winter. During dry periods the water level of most of the Meuse was too low for inland ships to navigate, while during wet periods the flow velocity in the upstream parts of the river became too high for ships at that time to navigate the waterway (Delbressine et al., 2023). This prompted the Dutch government to look into the canalisation of the Meuse. However, part of the Dutch Meuse was shared with Belgium, as the river lies directly on the border.

In 1912, a joint committee of the precursor of RWS and the Belgium Department of Public Works proposed to canalise the Meuse and construct 14 weirs as a possible solution to eliminate both problems (Delbressine et al., 2023). Discussion about the realisation of the plans came to a halt due to start of World War I and it became evident that the Netherlands relied on coal from Belgium and Germany for energy. This led to an urgent need for large-scale coal mining and transportation from South Limburg, accelerating the plans for the Meuse canalisation.

After the war, negotiations with Belgium continued, but these stagnated before the plans could be realised. In the 1921, an alternative solution was chosen by the Dutch government: the Juliana Canal would be realised, eliminating the need to canalise the shared part of the Meuse. In addition, weirs would be constructed, see Figure 1.2. These weirs were to be used to regulate the water level of the Meuse. By artificially increasing the water level, the Meuse was made navigable for inland ships during the entire year. The first weir was constructed in Linne and completed in 1925. The final weir was built at Lith in 1936.

Figure 1.2: Overview of the catchment area of the Meuse and the weirs with their respective construction year. Based on data from Rijkswaterstaat (Delbressine et al., 2023)

According to Rijkswaterstaat (2024e), the Meuse is still one of Europe's the most important inland shipping routes. In 2018, over 16 thousand ships with more than 11 million tonnes of cargo travelled along the Meuse from Maastricht to Sambeek (Rijkswaterstaat). The CO_2 emissions from inland shipping in the EU are on average 76% lower per tonne-km than those from heavy goods vehicles, such as trucks (European Environment Agency, 2022). This makes inland shipping a more sustainable cargo transportation method.

1.2.2. Sustainability goals

Between 2028 and 2035 the seven Meuse weirs will reach the end of their functional or technical lifetime (Rijkswaterstaat, 2021). The replacement of the weirs poses a significant challenge that needs to be resolved in the upcoming years. When developing the new designs, there are multiple key considerations. Navigability remains the most important consideration. However, unlike a century ago, RWS - owner of the weirs and responsible for the Meuse river functioning - now places a strong emphasis on developing sustainable and circular projects.

RWS aims to create a sustainable living environment for future generations, while working towards a safe, liveable and accessible Netherlands. This vision is accompanied by a goal: climate neutral, energy neutral and circular operations by 2030 (2024g). Being climate neutral entails emitting no greenhouse gases or compensating for all caused emissions. Achieving energy neutrality means generating all energy they need themselves.

Operating circular is defined by RWS (2024b) as: "operating without producing waste while reusing resources". To operate without producing waste, circularity should not only be considered at the end of the lifetime of an asset, when traditionally most of the waste is produced. It should be already incorporated during the development of the construction. A distinction between different levels of circularity should be made.

These goals alone are not sufficient to form a definition of sustainability and circularity for the replacement of the weirs. They can not directly be translated to standards for the development of new designs.

1.2.3. Changed requirements and boundary conditions

Alongside a shift in emphasis, there is also a change in design requirements. In 2023 RWS released an analysis of the Dutch part of the catchment area of the Meuse with a focus on the subsystem of weir and lock complexes, which can be used to determine design requirements for individual complexes. Below, an overview is given of several causes leading to altering of design requirements.

- <u>Low water levels:</u> In the future, low discharges caused by drought are expected to occur more frequently and last for extended duration due to climate change (Delbressine et al., 2023). In order to retain enough water for other functions, such as drink water production and irrigation, water losses due to leakages must be reduced and a larger volume of water should be buffered. A higher buffer volume is achieved by increasing the retaining height of the weirs.
- <u>High water levels:</u> In addition to more frequently occurring low water levels, high water levels will also occur more frequently and reach more extreme heights. As a result, the weirs are expected to be opened more frequently and the navigation locks will be obstructed more often. To future-proof the waterway, vessels must be able to pass the weirs during the high water levels (Delbressine et al., 2023).
- <u>Larger vessels:</u> Compared to the 1920's, the normative vessel size has increased in length and draft (Delbressine et al., 2023). It is assumed that the amount of cargo transported via the Meuse will stabilise, leading to a lower frequency of larger ships on average. RWS is currently improving the Meuse shipping route to accommodate vessels with a draft of 3.50 m throughout the entire route. However, it is recommended to design the weirs for a draft of 4.00 m (Delbressine et al., 2023).

  Over the past century, there have been numerous accidents involving a collision between vessels and weirs (Delbressine et al., 2023). Therefore, mitigating this risk through appropriate design measures is something that should be considered.

- Safety standards: Safety standards have become stricter and new norms have been set. Not only standards related to marine traffic, but also safety standards during construction and maintenance. This has resulted in stricter requirements during design.
- Affecting water quality and ecosystem: Nowadays, more consideration is given to the impact of the construction, usage and maintenance of hydraulic structures on water quality and the local ecosystem when compared to during the development of the original weir complexes (Delbressine et al., 2023). After construction, the environmental impact of the weirs includes, but is not limited to, water pollution due to used chemicals, release of microplastics from plastic elements, limiting of natural habitats and disruption of fish migration.

  When developing new projects, RWS strives to prevent any negative impact on the environment. This can be incorporated into the design of the new weir complexes. This is much more feasible than adapting existing designs, which had to be done in the last decades to reduce the negative impact of the current structures. This is in line with the vision of RWS for creating a sustainable living environment.

1.2.4. State of technology

Renovation and replacement

In 2010, on behalf of Rijkswaterstaat, DHV conducted a study into possible design visions for the future of the Meuse (DHV, 2010). Based on these visions DHV looked into renovation and replacement strategies for the hydraulic structures in the Meuse with a focus on weirs, locks and bridges. One of the possible scenarios considered is the one-to-one replacement of the current weirs. In the analysis it was assumed this would have to happen between 2025 and 2030.

Since 2010, multiple studies into the renovation and replacement of the Meuse weirs have been conducted. In 2014 Antea Group conducted a study on behalf of Rijkswaterstaat to assess the remaining lifetime of the Meuse weirs and to estimate the renovation costs (de Jong, 2014). In their study they concluded that even tough all functions of the complex are linked, the renovation of a weir can be done separately from the other major structures in the complex. The followup report in 2015 advises renovation or one-to-one replacement of the weirs, instead of changing the number or locations of the weirs (van Tilburg, 2015).

The 2023 RWS analysis gives an overview of the weir system in the Dutch part of the Meuse. It can be used to determine hydraulic boundary conditions for the design of a new weir, if the current weir is to be replaced.

Adaptive design

Frijns (2019) considered the design of an adaptive weir for Belfeld, considering four different future climate scenarios. The uncertainty in these future scenarios can be taken into account by implementing an adaptive design. Frijns states that an adaptive design can only be realised if the working of the entire Meuse river system is taken into account. Three adaptive strategies for developing a functional design mentioned are: being able to construct an additional weir opening, adjusting the management of the weir gates and heightening the retaining level by extending the gate height.

Developing an adaptive design is one possible method for making a sustainable design. By adapting the design only when needed, initial impacts and costs can be prevented. Therefore, the recommendations made by Frijns should be considered during the development of the functional design. Adaptability should also be taken into account during the structural design, since the adaptations must be constructable.

Considerations regarding constructability

De Heer (2020) investigated multiple possible design variants, which could be used for the new generation of Meuse weirs. This study included a method for implementing the design into the system, replacing the current weir at Linne. The report contains several recommendations for the development of a structural design for an inflatable weir as well as recommendations for construction methods. De Heer recommends to construct the abutment and piers of the new weir directly upstream of the current Linne weir in small cofferdams. The sill beam and other elements must be fabricated near the location. The prefab elements can then be installed without the need of large cofferdams or diverting the flow.

Hydropower potential
Van Bergen (2023) explored the feasibility of implementing a hydropower plant at the Grave weir. This case study was used to determine the feasibility of large-scale implementation of hydropower plants in all Meuse weirs. Van Bergen concluded that the developed concept is applicable at each weir except Borgharen. The recommendations made regarding the feasibility of a hydropower plant should be taken into account during the development of the functional design for a future Meuse weir.

1.2.5. Problem statement

The seven Meuse weirs are near the end of their functional and technical lifetime. Thus, the navigability along the Meuse, the river-ecosystem and the water management in the region are at risk if they are not renovated or replaced. Potential new designs must be in line with the requirements and the sustainability and circularity goals posed by Rijkswaterstaat, while considering the uncertainties due to climate change. However, the set requirements could constrain the design flexibility, posing a risk to the overall sustainability of the solutions.

1.3. Thesis objective and scope

1.3.1. Thesis objective

The objective of this thesis is to develop a guideline for designing sustainable weirs.

1.3.2. Scope definition

The scope of the guideline covers the entire design process, starting with a pre-exploratory phase and ending with execution and maintenance. The guideline will address the technical aspects of the design process. Policy aspects are excluded from the scope.

The design scope of the case study covers the conceptual design of the weir at Linne. This design must be integrated in the Meuse river system. Therefore, the boundary conditions of the project location depend on the interaction between the weir and the river system as analysed by RWS (Delbressine et al., 2023).

Figure 1.3: Top: aerial photo of the Linne weir and lock complex (Beeldmateriaal Nederland, 2023). Bottom: a photo of the weir in Linne, adapted from (Rijkswaterstaat, 2024c).

The scope of the location and functional design is the entire weir complex, since all functions of the weir complex must be taken into account while making the functional design. The top of Figure 1.3 shows a single weir and lock complex, consisting of at least the following subsystems: a weir, a navigation lock, a hydroelectric power plant, a dam, a control centre, a fish ladder, scour protection, jetties and mooring structures. When a weir needs to be renovated, the functions of the entire complex need to be taken into account, since the underlying subsystems are linked. Lastly, the stability of elements is checked if these elements are reused from the old weir in the new design.

Part of the scope

- Sustainability study covering the following topics:
  - Development of a sustainability guideline
  - Potential measures for sustainable weir design
  - The circularity of construction materials for weir design
  - Methods to measure and evaluate sustainability and circularity
- Conceptual design for the weir at Linne as a case study:
  - Determine the design requirements & boundary conditions
  - Determine the location of the new weir
  - Multiple concepts focusing on different sustainability aspects
  - Functional design of a weir, taking into account the main functions of the complex
  - Stability of reused elements

Excluded from the the scope

- Analysis of the entire Meuse river system
- Structural design of the weir elements

1.4. Thesis approach and thesis outline

The approach of this thesis is based on the civil engineering design method adopted for hydraulic structures by Molenaar and Voorendt (2024), as depicted in Figure 1.4. The method consists of eight iterative design phases, together forming a design cycle. This cycle will be covered on a conceptual level during the case study, with the addition of the development of the guideline, which is done before the system analysis is performed. Additionally, after the case study is performed, the guideline is validated. The thesis approach is divided into seven steps, each directly linked to a chapter in the report.

1.4.1. Approach steps for the present thesis

Step 1: problem analysis (Chapter 1)

The first step of the approach corresponds to design phase 1 of the design method. This step consists of performing a problem analysis. The problem analysis was used to form a problem statement, which led to formulate the objective of the thesis.

Step 2: development of sustainable design guideline (Chapter 2)

In this step, a guideline for evaluating the sustainability and circularity of weir designs is created. This is supported by a sustainability study answering the following research questions:

- What definition for sustainability and circularity should be used during design?
- What criteria can be used to evaluate sustainability and circularity?
- Which materials and components can be used for a circular design given the required lifetime of different elements?
- Which steps should be taken to come to a sustainable design?

Step 3: system analysis (Chapter 3)
The third step of the approach corresponds to design phase 2 of the method. First, one of the Meuse weirs is chosen as a case study, to which the guideline created in step 2 is applied. Then, a system analysis consisting of of an area, stakeholder and function analysis is performed for the case study. These analyses will be used to create the basis of design in step 4.

Step 4: basis of design (Chapter 4)
Using step 1 to 3 the basis of design is created. This step corresponds to design phase 3 of the method and is used for all of the following steps. First, the requirements and evaluation criteria are formulated. Then, the boundary conditions for the project location are stated.

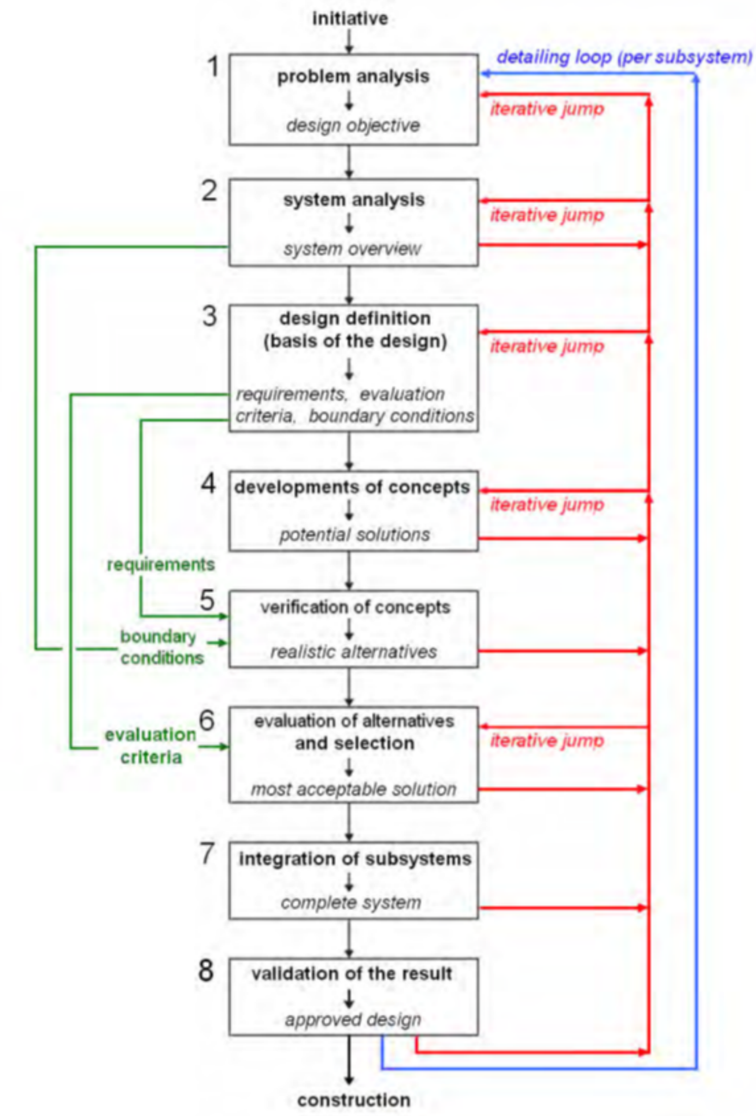


Figure 1.4: The basic engineering design cycle as applied in civil engineering (Molenaar and Voorendt, 2024). The design cycle consists of 8 design phases.

Step 5: location selection (Chapter 5)
Using the basis of design a suitable location for the new weir can be determined. The precise location will be determined once the dimensions of the functional design are known.

Step 6: functional design (Chapter 6)
After the location of the weir is determined, the functional design of weir is made. During this step the following design questions must be answered:

- What is the retaining height needed to ensure navigability during low discharge extremes?
- What type of retaining element(s) should be used to regulate both the water level during dry periods and discharge during wet periods?
- What are the main dimensions of the weir?

The information gathered in the previous steps is essential to answering these questions and the basis of design must be finished before this step can be started. However, it is possible that in a later stage the basis of design must be adapted to include oversights. In this step a loop through design phase 4 to 8 of the method is performed:

- Design phase 4: The development of multiple concepts. Each concept is a possible functional design for a Meuse weir. Additionally, a reference design, based on the current weir is made.
- Design phase 5: The concepts generated in phase 4 must be verified. It is checked whether all concepts meet the requirements set in the basis of design. If a concept does not meet a requirement, the concept can be adapted and discarded. It is possible that the concept is accepted nonetheless, if the value of the concepts outweighs failing the requirement. The requirement itself should also be reviewed. If the requirement does not suit the design objective, it might be changed or removed.
- Design phase 6: The concepts that passed the verification of phase 5 are evaluated based on the criteria specified in the basis of design. Additionally, the concepts are compared to the reference design. The best suited concept is chosen as the functional design.

Step 7: generalisation and validation (Chapter 7)
In this step, the created sustainability guideline is generalised and validated. It is checked whether the guideline can be applied to other weir replacement projects, not only the Meuse weirs, but also to the construction of completely new weirs.

1.4.2. Case study

In step 3 of the approach, the case study is started with a system analysis of one of the seven Meuse weirs: Borgharen, Linne, Roermond, Belfeld, Sambeek, Grave or Lith. The sustainability guideline is then applied to this case study. The Linne weir, built in 1925 and the oldest of the Meuse weirs, is selected for the case study. The Roermond, Belfeld and Sambeek weirs, constructed shortly after Linne, share a similar design. The findings from the case study are used to evaluate and reflect on the sustainability guideline.

1.4.3. Structural safety approach

Structural safety is an integral part of the design approach, addressing both the serviceability limit state (SLS) and ultimate limit state (ULS). This is directly tied to flood risk management of the Meuse, which has, alongside with the navigability of the Meuse, the highest priority in the renovation project (van Tilburg, 2015). All variables used during design have a certain level of uncertainty. These uncertainties should be taken into account by using a safety margin. Techniques to incorporate a safety margin can be classified using the following levels (Molenaar and Voorendt, 2024):

- Level 0: Deterministic design
- Level I: Semi-probabilistic design
- Level II: Simplified probabilistic design
- Level III: Full probabilistic design

The objective of this thesis is to perform a study to support the development of a conceptual design. For this design purpose the usage of a level I method is suitable. Therefore, the design will be tested using the partial factor method, which is a level I method. Using this method it should be verified that both the SLS and ULS are not exceeded during all critical design situations. This method can be classified as a form of semi-probabilistic design (Molenaar and Voorendt, 2024).

2
Development of a sustainable design guideline

The goal of this chapter is to create a guideline for evaluating the sustainability and circularity of weir designs. Sustainability and circularity are broad terms that cover a multitude of different aspects of design. Therefore, definitions used during the creation of the guideline are specified in Section 2.1. Additionally, these definitions are used to identify sustainability challenges encountered during weir design and to formulate criteria for evaluating the sustainability of weir designs in Section 2.2. This is structured around a set of sustainability themes. Section 2.3 contains the guideline itself and Section 2.3.6 gives an overview of the potential sustainability measures suitable for weir design.

2.1. Definition of sustainability and circularity

2.1.1. Sustainable development

In 1987, the United Nations' Brundtland Commission defined sustainability as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment & Development, 1987). This definition forms the essential basis for numerous of the definitions used in this sector and other sectors.

The Brundtland Commission's definition mainly captures the concept of sustainability from a social viewpoint. It emphasises the current generation's ethical responsibility to ensure equity across multiple generations. This involves preserving resources, opportunities and safe living environments for future generations. While the definition does not explicitly include an ecological aspect, it implies that ecological sustainability is part of meeting the needs of people. However, ecological aspects are so crucial that they should be directly considered; otherwise, there is a risk of overlooking them, which could undermine sustainability efforts.

Rijkswaterstaat (2024d), CROW (Hekker et al., 2011) and Platform CB'23 (2020), have all based their guidelines on the insights of the Brundtland Commission. For this project, an adapted Brundtland Commission definition, suited for the development of (civil) projects, will be used (Platform CB'23, 2020):

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs"

Using this definition, the most sustainable design is one that optimally fulfils the needs of the present generation while minimally hindering the ability of future generations to satisfy their own needs. It is important to note that what constitutes "needs" can be subjective and vary based on context and circumstances. Some needs might even be conflicting. Therefore, both the social and ecological needs, considering the design of new Meuse weirs, should be clearly specified. This can be done with help of sustainability themes.

2.1.2. Sustainability themes

The social and ecological needs related to the design of the Meuse weirs are closely linked to the functions of the weir complex. The weir complexes in the Meuse have multiple functions, of which an overview will be given in Section 3.4. These function can can be conflicting, as an example:

To maintain enough water for ships during a drought, the weir is fully closed, practically damming the river. However, this conflicts with the function of the complex to preserve the fish migration routes, as the fish won't be able to pass the weir. In this case, the conflict might be solved by installing a fish ladder next to the weir. Regardless of whether a single fish ladder is sufficient to resolve the conflict, more design choices arise when all functions and needs of the complex are taken into account.

To create a sustainable design, which suits all functions and fulfils all needs, trade-offs must be made. However, it is not immediately apparent what design choices will result in the most sustainable design. The given definition of sustainable development can not directly be applied to the design of the weir. As a solution, the different social and ecological aspects of sustainability will be categorised in themes. Then, an inventory of the possible design choices and strategies is made.

CROW is a Dutch knowledge platform in the "Grond-, weg- en waterbouw" (GWW) [ground, road and hydraulic construction] sector. CROW has developed the ambition web, a tool used to analyse sustainability ambitions during GWW projects (2024). The ambition web can be used to define the sustainability ambitions of a design project in the concept phase using specific themes. It is not an evaluation tool because it does not provide criteria for evaluating a design. The following 10 themes from the 2024 version of the ambition web are used:

Materials and circularity
(Section 2.2.1)

Energy and climate mitigation
(Section 2.2.2)

Climate adaptation
(Section 2.2.3)

Environmental effects
(Section 2.2.4)

Ecology
(Section 2.2.5)

Social relevance
(Section 2.2.6)

Spatial quality
(Section 2.2.7)

Accessibility
(Section 2.2.8)

Well-being and health
(Section 2.2.9)

Utilisation of space
(Section 2.2.10)

The themes from the ambition web are used to categorise the different aspects of sustainability for the design of weirs. In Section 2.2, the relevance of each of the 10 themes for weir design is analysed. For each theme the sustainability challenges encountered are explained and an inventory of sustainability strategies and criteria is created. These criteria are also used for the guideline in Section 2.3, as this guideline will contain evaluation criteria as well as requirements based on the themes. The applicability of the themes also depends on the specific details of a weir design project. Therefore the created guideline is applied to the case study in Chapter 3.

2.1.3. Circular construction

Working circular contributes to sustainable development. Circularity is a specific aspect of sustainability. Throughout this report, sustainability is assumed to encompass circularity. Circular construction is defined for this project, as it plays a crucial role during the design process. This definition is used in Section 2.2.1 to determine what design choices and strategies regarding circularity can be used to make a sustainable weir design.

For this project the definition of circular construction as stated by Platform CB'23 is adopted. Platform CB'23 is a Dutch initiative focused on establishing national, industry-wide standards for sustainable building practices. The definition used (Platform CB'23, 2023):

> *"Developing, using and reusing buildings, areas and infrastructure without unnecessarily depleting natural resources, polluting the living environment and affecting ecosystems. Carrying out construction such that it is economically justifiable and contributes to the welfare of people and animals. Here and there, now and later"*

Alongside the definition of circular construction, Platform CB'23 also developed seven circular design strategies (Platform CB'23, 2023). These strategies can be interpreted as the general methods to achieve circularity. Not all strategies have the same relevancy considering the weir replacement project. Below, an overview of the strategies is given.

- Prevention: A distinction is made between two types of prevention. Firstly, preventing the construction of additional structures could be considered. This is not relevant for the case study, since one-to-one replacement for all Meuse weirs is deemed necessary. The second strategy entails optimisation. Efficient use of elements or material types can lead to a reduction in the total amount of materials needed. Using fewer materials can also result in lower emissions, also contributing to the overall sustainability of the project.
- Designing for quality and maintenance: Protecting existing value by extending the lifespan of structures, elements and materials. Structures that outlast their intended technical lifespans are more sustainable. However, if this extended lifespan is achieved through maintenance or other interventions, the impact of these activities must be considered, as they could reduce the overall sustainability of the structure.
- Designing for adaptability: If a structure is designed for spatial-functional adaptability, it can be modified over time to meet changing needs or boundary conditions. This strategy aligns with the need for structures to adapt to climate change.
- Designing for disassembly and reusability: This strategy considers technical adaptability. When the elements of a structures can be disassembled, the elements themselves can be adapted to new requirements. In addition, the elements could also be reused for a different function without the need of remanufacturing.
- Design with reused elements of structures: Elements of structures can be reused on multiple levels: directly reused for the same function, reused for the same function when repaired or refurbished at the end of design life, reused as a product in the manufacturing process or repurposed for a different function.
- Design with secondary resources: Secondary resources are resources that have been used before or are a waste product from another process. These resources are used as an alternative for primary resources. Thus, protecting natural sources from depletion and preventing waste.
- Design with renewable resources: Using renewable raw materials or resources reduces the use of non-renewable resources and their potential depletion. A renewable resource is a resource that is grown, naturally replenished or naturally cleaned on a human timescale. These resources can be depleted, but sustainable management prevents this. A structure built from renewable resources does not always have the lowest environmental impact, since multiple other factors such as transportation should be taken into account.

These strategies fall into two categories: designing with sustainable materials and minimising material use. Both aspects are applied in Section 2.2.1.

2.2. Inventory of sustainability challenges and criteria per theme

2.2.1. Materials and circularity

This theme emphasises the use of sustainable materials and circular strategies in the design process. It includes reusing and recycling materials, reducing waste and CO_2 emissions during production and minimising the unnecessary consumption of natural resources. The detailed definition of circular construction and the seven circular design strategies provided in Section 2.1.3 form the basis for this section.

Using secondary and renewable materials
Based on the two material properties mentioned in the seven circular design strategies stated in Section 2.1.3, a distinction between four types of resources or raw materials can be made. Firstly, a material can either be primary, a material that has never been used before, or secondary, a material that has been used at least once before. Secondly, a material can either be renewable or non-renewable. A material is renewable if it is replenished naturally over a relatively short period. One human generation (approximately 25 years) is a suitable time frame, aligning with the definition of sustainable development in Section 2.1.3. Grown materials such as wood, bamboo, or natural rubber are all considered renewable. These materials are sourced from plants that can be replanted and regrown within a relatively short period. In addition to these grown materials, certain non-plant-based materials can also be considered renewable. For example, dredged sediment can be replenished naturally through sedimentation processes. This makes it a renewable resource, especially when managed sustainably. In contrast, a non-renewable material is one that cannot be replenished naturally within this time frame, such as fossil fuels, metals and minerals.

Combining both two properties, four types of materials can be distinguished. In Figure 2.1 the materials types have been ranked from most preferred (+) to least preferred (-) type. This preference is a general assumption, which does not always hold true. For example, building using a renewable resource does not automatically guarantee a lower environmental impact than building using a non-renewable resources. Therefore, it could be the case that the design using a non-renewable resource scores better during evaluation.

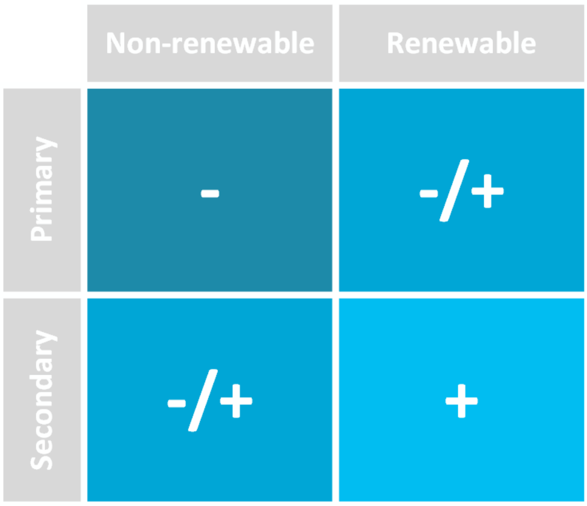


Figure 2.1: Distinction made between four types of circular materials.

<u>Concrete</u>
Concrete is not a renewable resource. However, it can be recycled by crushing the old concrete into aggregate, referred to as recycled concrete aggregate (RCA), which can then be used as a base material for new concrete. This recycling process reduces the demand for new raw materials, lowers waste generation and decreases the environmental impact of concrete production, contributing to a more sustainable construction practice. RCA, however, differs from natural aggregates in both physical and mechanical properties due to the presence of residual mortar attached to the original concrete. The quality of RCA is influenced by factors such as the source of the concrete and the effectiveness of the treatment process used to remove the adhered mortar (Ismail and Ramli, 2013).

One method to enhance RCA quality involves treating it with low-concentration acid, which helps remove loose particles of mortar and improves its physical performance. Studies have shown that treated RCA can produce concrete with higher compressive strength compared to untreated RCA (Ismail and Ramli, 2013; Chauhan and Singh, 2023). However, it will not reach the same strength as concrete made from primary materials.

In the Netherlands, the concrete superstructure of hydraulic structures is designed for a lifetime of 100 years. Weirs consist of several concrete components: the foundation, which includes the floor and possibly the piles; the abutments on both sides of the waterway; the piers between the abutments and openings; potential lift towers; a stilling basin downstream and a sill beam in each opening. These parts are constructed from either concrete or reinforced concrete. Additionally, the gates of some hydraulic structures are constructed using concrete. However, concrete is not a suitable material for most gate types (Daniel and Paulus, 2019). Below, several advantages and disadvantages of concrete as a construction material for weir design are given:

Advantages

- High durability and long lifetime
- High strength
- Low maintenance

Disadvantages

- Large carbon footprint
- Partly recyclable with lower quality
- Very brittle
- Not suitable for most gate types

In some cases, it might be possible to reuse some of the elements, when an old weir is replaced by a new structure. This depends on multiple factors, but most importantly, the quality and remaining lifespan of said elements. This should be investigated before developing a new design, as reusing old elements should be taken into account from the start of the process to create the most sustainable structure. If elements cannot be reused, recycling is a secondary option. However, this is less preferred due to the lower quality of recycled concrete.

<u>Steel</u>
The main component of steel is iron ore, a non-renewable resource. However, steel is highly recyclable and can be recycled multiple times without significant loss of quality, thereby reducing CO_2 emissions and energy consumption during production (Daniel and Paulus, 2019). Additionally, some steel elements can be reused without the need for recycling, further minimising the environmental impact. One of the biggest challenges in reuse, is separating the steel elements from the concrete superstructure.

In weir design, most steel is used for several elements and components: the weir gate and gate mechanism, sheet piles, rebar in the reinforced concrete, possibly a traffic bridge and accessibility features such as stairs, walkways and guardrails. Most individual elements are designed for a lifetime of up to 50 years and thus have to be replaced before the superstructure reaches the end of its lifetime. In addition, steel is more susceptible to degradation than concrete. To mitigate this, coatings can be applied to protect the steel elements. However, this increases the maintenance requirements, environmental impact and overall costs.

<u>Wood</u>
Wood is a renewable resource, but is must be sourced from sustainably managed forests. For each tree harvested, a new one must be planted. Wood also stores carbon, which helps mitigating climate change in the short term. This carbon storage can offset emissions generated during project development. Using timber as a construction material for hydraulic structures has several advantages and disadvantages:

Advantages

- Fully renewable
- Can be used to store carbon
- Lightweight
- Aesthetic appealing

Disadvantages

- Low strength
- Susceptible to water damage and rot
- Requires a lot of maintenance
- Could pose a fire risk, even for weirs

Glued laminated timber (glulam) has increased strength compared to regular timber and is used for construction. However, it is still not sufficient to make it suitable for the primary structural components of the weir. The low durability and limited strength of wood are significant drawbacks, making it unsuitable as a construction material for most types of hydraulic gates and the superstructure of the weir (Daniel and Paulus, 2019). It is suitable as a material for some of the jetties and mooring structures at the complex. Wood can also be utilised for benches, fences and signage, though this represents only a very small fraction of the total material needed.

Saving materials
In addition to using sustainable materials, materials can be used sustainably. Two major methods for material savings are preventing material usage and extending the lifetime of components. Firstly, the design of the weir should be optimised to reduce the total amount of material needed. The less material used, the lower the environmental footprint of the weir. The total strength of an element depends on its size and the characteristics of the material used. Thus, an optimal balance between the type and amount of material used should be found to reduce the environmental footprint while ensuring the element is sufficiently strong. This optimisation can be achieved during the structural design, but it is heavily influenced by the choices made during the functional design, such as the type and size of the gates. Therefore, these design steps should be iterated to find the best solution. Secondly, extending the lifetime of components can significantly reduce material consumption. This can be done by using durable materials, applying protective coatings and designing for easy maintenance.

Fibre-reinforced polymer
Fibre-reinforced polymer (FRP), also known as fibre-reinforced plastic, is a composite material made of a polymer matrix reinforced with fibres. The polymer is a thermoset, a material that is obtained by irreversibly hardening ('curing') a viscous liquid, such as a polyster resin. During the curing process, chemical reactions result in links forming between polymer chains, giving the material its rigidity. The fibres used in FRP are usually made of glass, carbon or aramid. Using polyester based FRPs has several advantages and disadvantages (Mosleh, 2024):

Advantages

- Inexpensive when used with glass fibres
- Creep resistant
- Great strength/weight ratio
- Low volumetric weight
- Chemical resistant

Disadvantages

- Rather brittle
- Can not be reshaped
- Recycling can be major problem
- Toxicity during production

Depending on the type of retaining element or gate used in the design of a new weir. It might be possible to construct it using a FRP. The material has already been used in hydraulic structures as an alternative to traditional materials. In 2016 the gates of Sluis III, a navigation lock in the Wilhelmina Canal near Tilburg, were replaced by gates made from FRP. These mitre gate doors can turn a head difference of 7.90 m. (Kunstof en Rubber, 2016). The mitre gates are produced by FiberCore Europe using their InfraCore® Inside technique. According to FiberCore Europe, their product has several advantages compared to steel gates (FiberCore Europe, n.d.):

- Low self-weight
- Low maintenance (no need to apply coatings)
- Long design life (more than 100 years)
- Ability to be recycled into new FRP elements

Among the advantages listed, the ability to be recycled is the most important sustainability aspect. Traditional FRP products are difficult to recycle due to the curing process during production. However, FiberCore Europe claims that their FRP products can be recycled into new FRP elements. It is important to investigate the potential limitations of this recycling process.

Scour protection
Erosion can occur both upstream and downstream of the weir, either due to flow contraction or plunging, as illustrated in Figure 2.2. This erosion results in the formation of scour holes. To prevent the soil bed from eroding and to avoid the instability of the foundation, which could lead to structural failure, scour protection is implemented. A stilling basin is constructed downstream of the weir to dissipate the

energy of the flowing water. However, erosion can still occur beyond the basin. Therefore, additional scour protection is placed behind the basin, as shown in Figure 2.2. This scour protection is more cost-effective to construct and has a lower environmental impact compared to extending the basin. It consists of multiple granular layers consisting of small rocks, gravel or coarse sand.

Scour protection at weirs can still fail during high river discharges. If the protection fails, scour holes may form too close to the weir, posing a risk to the foundation. Therefore, regular maintenance of the protection is essential, which includes sediment depositions. According to an RWS expert, sections of weirs with underflow are particularly prone to degrading scour protection compared to overflow. Thus, overflow weirs can be considered more sustainable, as they require fewer material depositions.

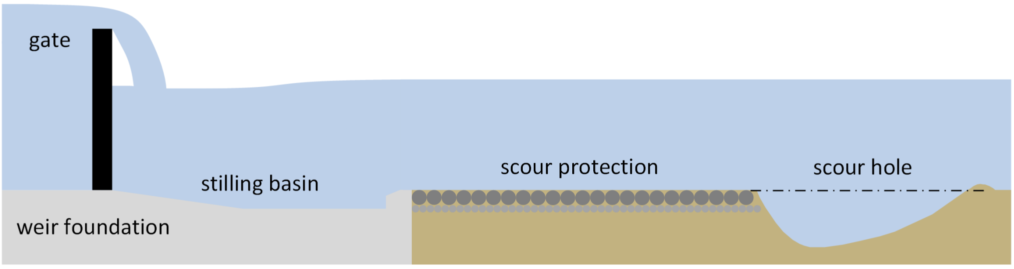


Figure 2.2: Formation of a scour hole behind the weir due to flow over the weir.

Gate types Several gate types should be considered during the functional design phase as their suitability depends on numerous factors. In section D.1 an overview of gate types for weir design is given. However, two gate types are explicitly mentioned:

- Visor gates: On average, these gates have a lower material usage than lifting or radial gate, while suitable for great spans (Daniel and Paulus, 2019). However, they cannot be used for precise water level control.
- Inflatable gates: These gates consist of large bellows filled with air, water or a combination of both. Made from rubber and plastic materials (U.S. Army Corps of Engineers, 2001), they have a relatively low mass. Additionally, inflatable gates are supported from below, meaning they have no theoretical limit on span width. However, they can also not be used for precise water level control and are vulnerable to puncturing loads.

Criteria for materials and circularity

Several indicators can be used to measure sustainable material usage and circularity. These include: CO_2 emissions during the production of materials and elements, the total mass of renewable materials in the structure, the total mass of secondary materials in the structure and the total mass of recyclable materials in the structure. These indicators can be estimated during the conceptual design using characteristic values.

The Milieukostenindicator (MKI) [Environmental Cost Indicator] is a single score used to express the environmental impact of a project in monetary terms. It combines various measurable environmental effects using weighting factors. The MKI covers CO_2 emissions during the production of materials and elements, as well as several quantifiable criteria of other sustainability themes.

The input data for the MKI calculation includes detailed information about all raw materials used in the project. This data includes production processes, energy consumption and transportation of materials. A Life Cycle Analysis (LCA) is performed to determine all emissions and the total environmental impact throughout the object's entire lifetime. The LCA creates an environmental profile, which is used to show how the object scores on various environmental impact categories.

Lastly, the scores are multiplied by conversion factors and added together to calculate a single price, the MKI. The lower the MKI, the more sustainable the project. The data used for the MKI calculation can also be used to determine the amount of renewable and secondary materials used, as well as the amount of waste at the end of the object's lifetime.

2.2.2. Energy and climate mitigation

The theme of energy and climate mitigation is concerned with energy use and the CO_2 or CO_2-equivalent emissions during transportation, construction and maintenance. This theme excludes all CO_2 emissions caused during the production of materials and elements.

Reducing energy consumption

RWS has the ambition to operate energy-neutral by 2030 (Rijkswaterstaat, 2024g). To achieve this goal, the energy consumed during all life stages of an object should be minimised. Additionally, energy must be generated to achieve energy-neutrality. The weir has two main sources of energy consumption: operating the gate and using the electrical installations around the weir, such as lighting. The most effective strategy is to limit the energy consumption of the gate. This can be achieved by optimising gate operations. The weir gates are adjusted based on water levels and discharge. By developing predictive models to control these adjustments, unnecessary movements of the gate can be avoided, thereby reducing energy consumption.

Generating green energy

A weir complex can be used to generate green energy by accommodating a hydroelectric power plant (HPP). These plants generate electricity with turbines by using part of the discharge through the complex. In the Netherlands, there are already multiple weir complexes housing HPPs, such as those in Amerongen, Linne and Lith. Based on the report by Van Bergen (2023), it can be concluded that constructing hydroelectric power plants at most of the weirs in the Meuse is feasible.

When designing a new weir, the potential addition of a hydroelectric power plant (HPP) should be considered. The amount of green energy an HPP can produce depends on the product of the head difference over the weir and the discharge through the HPP. In the Netherlands, the head difference is typically small, while the discharge is relatively high. However, the discharge will fluctuate and not the entire discharge of a river will flow through the HPP. Therefore, it is critical to analyze the relationship between head difference and available discharge for the HPP to determine whether it is sustainable to construct the HPP.

Reducing CO_2 emissions

The environmental footprint of the new weir can be expressed as the total equivalent amount of CO_2 emitted during the construction, usage and demolition phases. This theme excludes CO_2 emissions from the production of materials and elements, as these are considered under the theme of materials and circularity. For this theme, multiple sources of CO_2 emissions should be taken into account:

- Emissions from transporting materials and elements to the site
- Emissions from energy production
- Emissions from equipment used during construction
- Emissions from operating the weir
- Emissions from maintenance works

These emissions highly depend on the type and amount of materials used during construction. Another key consideration is the location of the new weir. If the new weir is constructed directly in the main flow of the existing waterway, where the current weir is located, no bypass will be needed. Constructing a bypass would require digging, constructing earthworks and the transportation of large volumes of soil, all of which generate emissions. These emissions can be partly avoided by building the new weir within the same waterway.

Lastly, net CO_2 emissions can be reduced by carbon offsetting, which involves compensating for the emissions caused. For a weir design project, this could include planting trees, which absorb CO_2 from the atmosphere. Depending on the available space, this can help reduce the carbon footprint and contribute to a more sustainable project.

Criteria for energy and climate mitigation

The two most important measurable indicators for this theme are the total CO_2 emissions caused during the life cycle of the object and the net energy consumption on a yearly basis. Both indicators are incorporated into the MKI value. In section 2.2.1 the MKI calculation process is explained.

2.2.3. Climate adaptation

Climate change is expected to increase the frequency and intensity of weather extremes. This theme focuses on managing these impacts. In the context of weir design, this involves two main applications: mitigating the effects of prolonged droughts and managing higher water levels during extreme weather events. Both challenges should be taken into account from the start of the design process.

Overcoming droughts and water shortages
Weirs can play an important role during droughts by providing water for crop irrigation or drinking water production. By increasing the retaining height of the weir, a higher water level can be realised upstream of the weir. If the banks and dike on both sides of the waterway are also heightened accordingly, more water can be stored when the weir is closed, which can be used during water shortages.

There is no need to immediately increase the retaining height of the weir to its final height at the end of the design lifetime. This is particularly important given the shorter design lifespan of the gates, around 50 years, compared to the superstructure, which is around 100 years. The old gates can be replaced by adapted gates at the end of their lifespan, or possibly, the gates themselves can be adapted during maintenance. However, since the superstructure will most likely consist of reinforced concrete, which is difficult to heighten, the abutments and piers of the weir should already be adjusted to future needs.

The water stored during extended periods of drought must be retained. Leakage losses can significantly hinder the buffering effort. The type of weir gate used plays an important role in preventing leakage (Daniel and Paulus, 2019). Therefore, a gate type that is resistant to leakage should be selected.

Adapting to high water levels
Due to climate change, high water levels will occur more frequently and reach more extreme heights. As a result, the weirs are expected to open more often and the structures must be able to withstand higher loads. The exact implications should be investigated during the preliminary works to obtain the boundary conditions for the design. These boundary conditions and their uncertainty must be taken into account using an appropriate structural safety approach.

Additionally, frequenter extreme high water levels will also result in the navigation locks being obstructed more often. When the navigation locks of a weir complex are obstructed, shipping is halted. This will lead to economic losses, unreliable shipping routes and idle vessels consuming fuel. To future-proof the waterway, vessels must be able to pass the weirs during high water levels (Delbressine et al., 2023). This creates a window in which vessels can still use the waterway by traversing over the weir instead of via the navigation lock.

Criteria for climate adaptation
Climate adaptation can be quantified, but setting specific design requirements is more effective for addressing the discussed challenges. This allows for a practical application of climate adaptation strategies. The first aspect, droughts and water shortage, can be managed by setting a requirement for the amount of water buffered and specifying a maximum leakage loss over the weir. The buffered capacity must be adapted to the expected future needs. Secondly, to maintain reliable shipping routes, it is required that vessels can pass over the weir when it is fully opened.

2.2.4. Environmental effects

The environmental effects covered in this theme include impacts on water, air and soil quality. As described in Section 1.2.3, the construction and maintenance of weirs can directly pollute the river water. Additionally, equipment used for the construction and maintenance of weirs can cause pollution, such as nitrogen emissions, which negatively impact air quality. However, there is no direct relation between the weirs and soil quality.

Preserving water quality
The weirs should not negatively impact water quality. Water quality is directly linked to other river functions such as drinking water production, recreational activities like swimming and its use as an aquatic habitat for local fauna. The degradation of coatings is a source of pollution. Coatings are applied to steel elements, such as the gates of a weir, to protect them from corrosion. Over time,

these coatings can wear down, causing particles to end up in the water. Another source of pollution is the leakage of lubricant used for the gate mechanism. Coatings and lubricants are applied during maintenance. Measures must be taken during maintenance to prevent pollution from reaching the water. The maintenance of the weirs should be considered during the design to facilitate this. Not only to prevent pollution, but also to increase the maintainability of the weir. An additional strategy is to remove the sources of pollution. For example, to use a bio-based lubricant instead of a petroleum-based lubricant for the mechanisms (Delbressine et al., 2023).

Preserving air quality
Construction of the weir involves various activities using construction equipment, which results in nitrogen and particulate emissions, among others. Part of these emissions can be mitigated by using zero-emission construction equipment. Small electric equipment is already widely utilised, but larger equipment, such as pile drivers, is not yet available (Buyer group zero emissie bouwmaterieel, 2022).

Criteria for environmental effects
Laws and regulations dictate the permissible levels of emissions, setting an upper limit that must not be exceeded. Additionally, reducing emissions beyond these requirements results in a more sustainable design. Therefor, this theme can both be taken into account using requirement for the design as well as an evaluation criteria. The measurable sources of pollution are incorporated into the MKI value. In section 2.2.1 the MKI calculation process is explained.

2.2.5. Ecology

This theme specifically addresses the flora and fauna in the environment of a project. As stated in Section 1.2.3, the addition of the weirs in the Meuse significantly impacted fish migration and aquatic habitats. The situation has improved in the last decades. Although the situation has improved over the past decades, both ecological connectivity and the quality of aquatic habitats remain important concerns.

Preserving ecological connectivity
Weir complexes form barriers in fish migrations routes. Since 2007 the accessibility for fish is increased along the entire Dutch part of the Meuse due to the construction of fish ladders at all weirs (CLO, 2022). In new weir complexes the fish ladders will also play an important part in preserving the fish migrations routes. However, only the construction of fish ladders is not sufficient.

The addition of hydro power plants in the Meuse led to severe problems for downstream migrating fish. Species such as salmon and eel follow the main flow downstream. When the hydro power plants are in operation, the main flow and thus the fish pass through the turbines, leading to a high mortality rate (CLO, 2022).

In the 2021 report 'Stromend habitat en connectiviteit in de Maas' (Flowing habitat and connectivity in the Meuse) ATKB proposes several measures to improve the connectivity and habitat quality (Vriese et al., 2021). An overview of all promising measures related to the renovation of the weir complexes and its component is given:

- Removing a weir from the river system is considered the most effective option for restoring natural fish migration and creating habitats.
- Construction of new fish ladders or optimisation of existing ones, provided they continue to be used and are not replaced. The report states multiple possible adaptations that should be considered. Some of these adaptations are locations specific. An extra fish ladder in the weir complex in addition to the current fish ladder will also greatly increase the ecological connectivity.
- The turbines in hydro power plants pose a threat to fish migrating downstream, potentially harming or killing them. Modifying the turbines can increase the safety of these fish. For instance, replacing the turbine blades with rounder ones can allow fish to pass through more safely.

- A weir bypassing channel (”stuwpasserende nevengeul”) can be constructed to improve the connectivity by allowing a continuous flow and allowing fish to pass the weir. The channel spans the height difference of several meters, depending on the weir, over a distance of a few kilometres. The potential construction of a weir bypassing channel can be considered during the functional design. Sufficient free space is needed to create the channel.

Improving aquatic habitat quality
In addition to forming migration barriers, weir complexes also deteriorate the quality of aquatic habitats in the Meuse. This is mainly due to altering the flow and sediment transport and due to the fragmentation of the available habitats. ATKB also proposed several measures to increase the habitat quality in several sections of the Meuse.

- Removing the weirs and constructing weir bypassing channels are both mentioned above as possible measures to increase the ecological connectivity. These measure also improve the habitat quality. Both measures result in a flowing habitat, which is essential to certain fish species.
- Two additional measures to improve the quality of aquatic habitats include adding fine gravel nourishments downstream of the weirs and placing dead wood along the riverbanks. Since these measures are not directly related to the design of the new weirs, they will not be considered.

Criteria for ecology
Fish migration due to increased ecological connectivity can be measured at a specific location through observations. Fish can be tagged and their movements tracked. Alternatively, the number of fish passing through a waterway can be counted in a survey. The effectiveness of potential measures can also be predicted based on earlier projects, fish migration data and characteristics of the waterway.

The effect of potential measures to improve the quality of aquatic habitats can be assessed both qualitatively and quantitatively. A qualitative assessment involves expert reviews and an evaluation of habitat conditions, while a quantitative assessment can be done using biodiversity surveys after the construction of the project.

2.2.6. Social relevance

The theme of social relevance involves considering the interests and wishes of all stakeholders in a project. By actively seeking out stakeholders to inventory their wishes before the start of the project, stakeholders become involved and awareness is created. This can increase support for the project. It is particularly important to engage local stakeholders, as they are directly affected by the project’s outcomes. Understanding their needs and concerns can lead to more sustainable solutions.

Criteria for social relevance
Social relevance is not a quantifiable theme; it is expressed through the opinions of stakeholders. These opinions can be gathered using various methods, such as direct conversations, interviews or residents’ meetings. To maximise social relevance, this should be done as early in the design process as possible, when design responsiveness is still high. As the process progresses, fewer aspects of the design can be changed and costs will increase, resulting in a less sustainable design.

2.2.7. Spatial quality

The theme of spatial quality focuses on improving the experiential, utility and future value of spatial development in projects. This involves integrating the design in the surrounding environment and adapting to changes within this environment. An important factor to consider during the replacement of a weir, is the cultural and historical value of the original structure.

Increasing future value
A weir complex can have a positive future value if it can be adapted to changing requirements. For weirs, the most likely changing requirements are those related to climate change. The weirs should be adaptable to a changing climate, as explained in Section 2.2.3. This is especially relevant due to the high uncertainty associated with climate change. Adaptability will lead to a more robust design with greater future value.

Increasing social safety
A socially safe environment is one that is designed to make people feel secure and protected from threats posed by human actions. This is not a main priority during the design of a weir, as the direct interaction between the weir and users is very limited. However, this interaction increases if the weir gains an additional function, such as providing a fixed connection over the waterway (see Section 2.2.8). Possible methods to increase social safety include creating clear sight lines and ensuring good lighting.

Maintaining cultural and historical value
Hydraulic structures from the 20th century often have some level of protection as monuments. In the Netherlands, RWS manages 185 hydraulic structures with the status of national protected monuments (Rijkswaterstaat, 2024a). Some Dutch weirs fall into this category. Special guidelines outline what must be considered when these weirs are renovated or replaced (Delbressine et al., 2023). Although other weirs and structures might not have national monument status, they are still recognised as monuments and are considered to have high cultural-historical value.

Criteria for spatial quality
Most of the future value of a weir depends on its ability to adapt to the changing climate, which is addressed under the theme of climate adaptation. The other aspects, social safety and cultural and historical value, are closely linked to the opinions of the structure's users. Similar to the theme of social relevance, spatial quality is difficult to quantify. However, it can be expressed through the opinions of stakeholders. These opinions can be gathered using various methods, such as direct conversations, interviews or residents' meetings. These opinions should be gathered early in the design process, when design responsiveness is still high. As the process progresses, fewer aspects of the design can be changed and costs will increase, resulting in a less sustainable design.

2.2.8. Accessibility

The accessibility theme is concerned with the ability to move people and goods over infrastructure. Several aspects influence the accessibility, such as time, reliability, effort and costs. Optimising a current route for these aspects or by providing an alternative route, the accessibility is increased, which can contribute to the sustainability of a project. In the case of the weirs, this is relevant for the navigability of the weir for ships, the addition of a fixed bridge over the weir and the accessibility during the construction and maintenance.

Weir navigability
As stated in Section 2.2.3 it is expected that high water levels will occur more frequently due to climate change. Frequenter high water levels will result in the navigation locks being obstructed more often. When the navigation locks of a weir complex are obstructed, shipping is halted. This will lead to economic losses, unreliable shipping routes and idle vessels consuming fuel. Each weir has a maximum discharge for which it can still operate. If that maximum is surpassed, the weir is fully opened. Allowing vessels to pass over a weir when it is opened can mitigate these issues.

Fixed connection
A weir can also serve as a fixed connection between the two sides of a waterway. For example, a bridge could be installed over the weir, using parts of the same superstructure as the weir itself. If this connection is accessible for public traffic, the complex gains an additional use, eliminating the need to construct another structure to fulfil this function. However, the addition of a permanent connection, such as a bridge, can interfere with the ability of vessels to traverse a fully opened weir, which can also be beneficial as discusses above. For the design of new weirs, the added value of additional functions must be weighed against the increased costs to accommodate these functions.

Accessibility during construction and maintenance
For a large structure like a weir, it is essential that the project site is easily accessible for heavy construction equipment. Large piles, prefab elements or sheet pile walls may need to be delivered, or large amounts of soil moved from the site. Additionally, after construction, the weir must remain readily accessible for maintenance.

Criteria for accessibility

The accessibility theme can be measured by travel time or route length. This applies to both the weir navigability and the addition of a fixed connection across the waterway. However, since transportation is not the primary function of weirs, these measurements are less relevant during design. Additionally, it is a binary choice when comparing different concepts: either there is a bridge or there is not and either vessels can pass the weir or they cannot. Thus, it is more practical to set requirements for both aspects. A weir must be navigable for vessels if it is on a shipping route. Additionally, a weir must include a permanent bridge if it replaces an old weir that is part of an existing route. Lastly, the aspect of accessibility during construction and maintenance must also be incorporated as a requirement, as the weir must be accessible during construction and maintenance. However, this aspect can also be taken into account as a qualitative criteria, as it has an influence on both the nuisances during construction and the ease of maintenance.

2.2.9. Well-being and health

This theme focuses on creating a healthy and safe living environment to contribute to the well-being and health of the structure's users. When designing a weir, it is essential to consider constructional, technical and organisational (BTO) choices that contribute to safety. Additionally, the impact of the weir on the flood defence system should taken into account.

Making BTO choices

Constructional choices involve selecting durable, water-resistant materials and ensuring safe access points for maintenance. Technical choices include integrating monitoring systems for water levels and flow rates, installing safety barriers and emergency lighting. Organisational choices involve developing clear maintenance procedures, providing regular training for staff on safety protocols and scheduling routine inspections of the weir and its components. These choices must be incorporated into the design of the weir.

Flood defence system

Although weirs are not primarily built as flood defence structures, they become integral parts of the broader flood defence system in which they are constructed. Failure of a weir could impact this system significantly and could even lead to flooding. Therefore, weirs must adhere to strict structural requirements.

Criteria for well-being and health

The effect of weirs on user well-being and health is not quantifiable. Therefore, requirements must be set to take this theme into account during the design, as it can not easily be evaluated. Firstly, like any structure of similar significance, weirs must adhere to strict structural requirements. Additionally, the design must include safety features such as secure access points for maintenance and water level monitoring systems. Most of these requirements are mandated by regulations and must be followed.

2.2.10. Utilisation of space

Efficient use of above-ground and underground space is essential, especially in densely populated areas. The necessity of new construction should always be thoroughly analysed, as explained in Chapter 1. For the weir replacement project, new construction is deemed necessary. The value of the weir complex can also be increased by serving additional functions without expanding its area. For example, adding a permanent traffic-accessible connection between the two sides of a waterway enhances the complex's utility and eliminates the need for another structure.

Additionally, this theme involves preserving archaeological objects in the project's subsoil. Before construction, the subsoil at the project location should be investigated to determine the presence of items like pottery, tools or structures. If any objects are found, their presence must be documented and an archaeology-friendly building plan should be developed. This can include removing the objects from the ground or ensuring that construction activities won't damage the findings.

Criteria for utilisation of space
The theme of utilisation of space can be assessed by measuring the total area in m^2 required for the weir complex, with a preference for lower land usage. The extra space needed during the construction phase can also be considered as an indicator. Lastly, requirements must also be established to preserve archaeological objects, based on existing regulations.

2.3. Guideline sustainable weir design

2.3.1. Overview of the guideline

This guideline provides a structured approach to integrating sustainability into the design of new weirs and evaluating the sustainability of made designs. When designing a replacement for an old weir, various choices impacting the project's overall sustainability are made. The goal of this guideline is to support making the most sustainable decisions.

This guideline is based on the analysis in Section 2.2, which forms an overview of sustainability challenges and solutions relevant for weir design. These are categorised using 10 distinct themes from the ambition web as developed by the knowledge platform CROW and elaborated upon in Section 2.2. The guideline is divided into four phases, as presented in Figure 2.3.

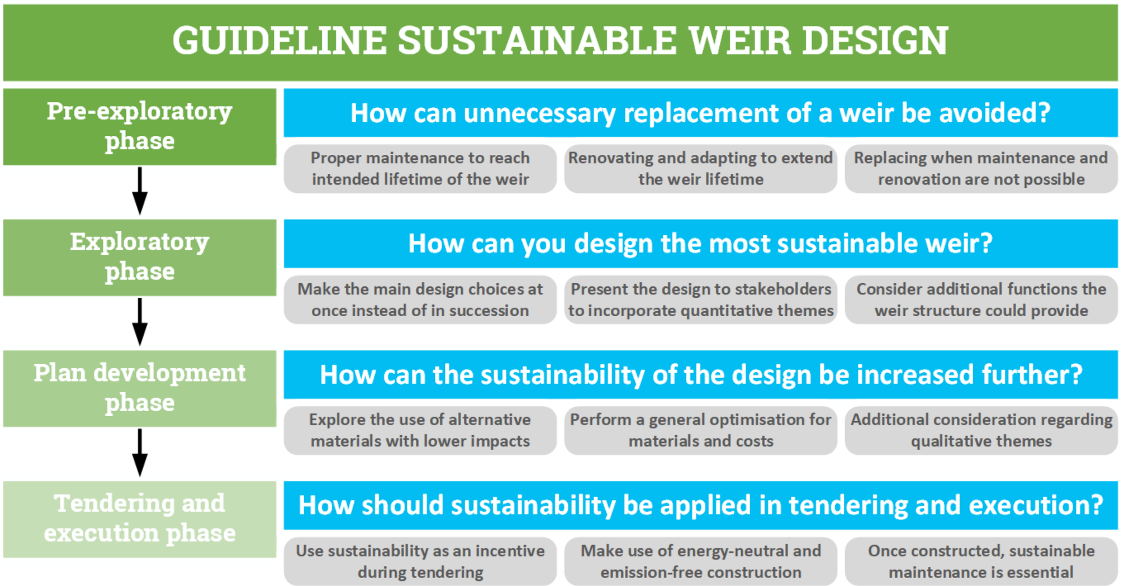


Figure 2.3: Overview of the four phases of the guideline sustainable weir design

- Pre-exploratory phase: During this phase the most sustainability value can be gained, as it determines whether a new structure is necessary. Deciding to not construct a new structure can be seen as the most sustainable option.
- Exploratory phase: In this phase different design alternatives are explored. The most value can be gained by identifying the best combination of design decisions leading to a low environmental impact. In addition, quantitative sustainability themes must be taken into account by incorporating stakeholder input regarding these themes.
- Plan development phase: During plan development the design is refined and additional value can be gained by exploring the use of alternative construction materials and performing general optimisations.
- Tendering and execution phase: Tendering and execution form the final stage, where some sustainability value can still be gained. However, effective measures during this phase rely on having considered construction and maintenance earlier in the design process.

At the start of each phase, a central question is posed, which is answered during that phase. This approach helps maintain an overview of design choices impacting sustainability. Some decisions cannot be made independently and must be addressed in mutual coherence within the design process. For each phase, the guideline outlines how to incorporate the relevant sustainability aspects into the design. This also includes requirements for the design and criteria to evaluate the sustainability of the design. At the end of the guideline, an overview of potential sustainability measures is provided.

In Chapter 7 the guideline has been validated through reviews by three specialists. The updated version of the guideline can be found at the very end of this document.

2.3.2. Guideline for the pre-exploratory phase

This phase of the design process is mostly outside the scope of the thesis' case study

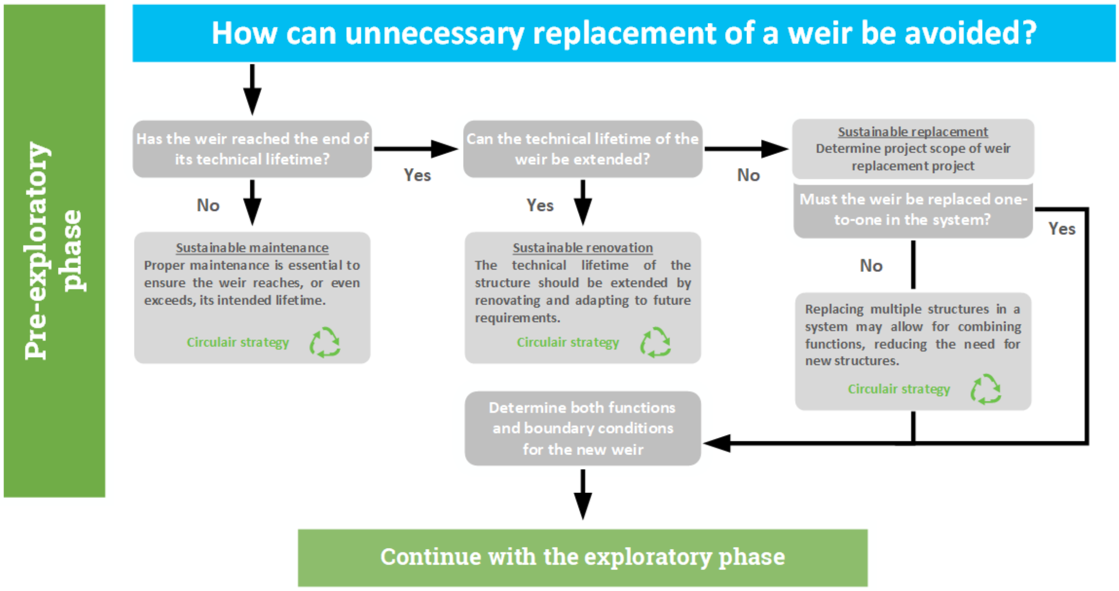


Figure 2.4: Guideline for the pre-exploratory phase

The most sustainability value can be gained by incorporating sustainability from the very start of the design project during the pre-exploratory phase, rather than trying to retrofit sustainability into an existing design. The central question to be answered in this phase is: "Is it necessary to replace the existing weir with a new structure?" as it is most sustainable to avoid building a new structure. To answer this question, the following steps must be followed:

- **Investigate whether the weir has reached the end of its functional or technical lifetime**
  If the weir has not yet reached the end of its functional or technical lifetime, there is no immediate need for a sustainable replacement. However, sustainability can still be considered. The weir must be well-maintained to ensure it reaches, or possibly exceeds, its intended lifetime. Protecting existing value is a circular strategy (Platform CB'23, 2023). If the weir has reached the end of its lifetime, renovation must be considered.
- **Investigate whether the lifetime of the weir can be extended**
  If the weir has reached the end of its lifetime, it should be investigated whether the lifetime can be extended by renovating the structure and adapting it to future requirements, thereby preventing the need to build a new structure. This is also a circular strategies (Platform CB'23, 2023). If it is not possible to renovate the weir, it must be replaced.
- **Determine the scope of the replacement project**
  When there is a need to replace an old weir, the scope of the project must first be determined. This includes creating an overview of all structures in the same water system as the weir. If other structures also need replacement, this presents opportunities to work sustainable.

- **Investigate the possibility to replace multiple structures with one**
  When multiple structures in the same water system need to be replaced, it might be possible to combine the functions of several structures. This can reduce the need for new structures and minimise environmental impact. For example, raising the water level of one or several weir basins, might allow for the removal of one of the weirs from the system. This would result in the need to construct one less replacement weir.
- **Determine the functions and the boundary conditions for the new weir**
  The last step of this phase is to determine both the function and boundary conditions for the new weir structure, as these are needed in order to make concept designs. The following investigations are necessary:
  - Investigate implications of climate change (climate adaptation)
    Effect of climate change on discharge pattern of the waterway must be investigated before the conceptual design can be made, as this effects several of the requirements for the weir.
  - Investigate reusability of old weir elements (materials and circularity)
    Reusing elements from the old weir can help reduce emissions and contribute to a more sustainable design. Therefore, it should be assessed whether any elements of the old weir can be reused before choosing the location of the new weir, as this may allow for different design choices.

2.3.3. Guideline for the exploratory phase

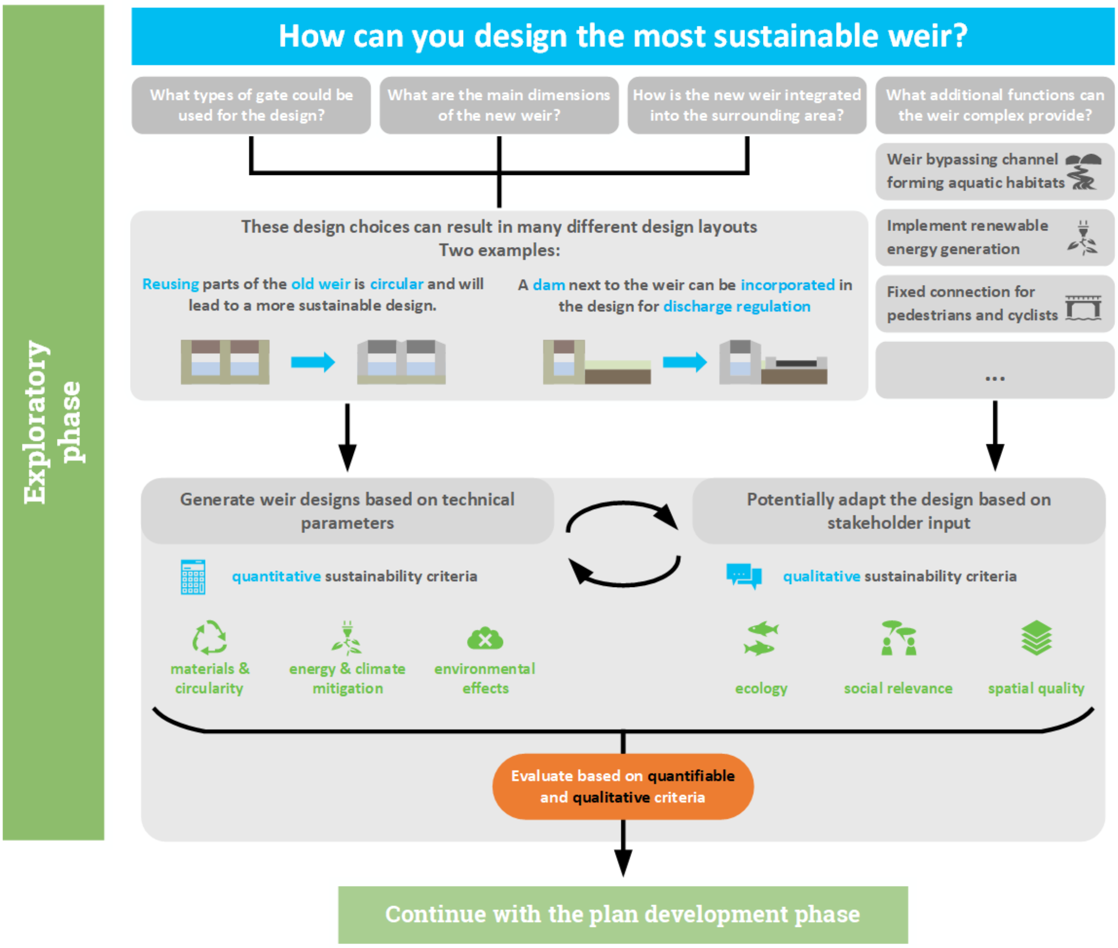


Figure 2.5: Guideline for the exploratory phase

During the exploratory phase the design of the weir itself is given shape. Three design choices with a big impact on the sustainability of the weir design must be made. As these choices are highly interdependent, they must be considered together to create the most sustainability value.

- **What type of gate could be used for the design?**
  The gate contributes significantly to the total material use of the weir. Reducing the amount of material used for the gates or using alternative materials with lower impacts compared to traditional materials is an effective method to increase the sustainability value.
- **What are the main dimensions of the weir (width, length, height and opening size)?**
  The superstructure of the weir will consist mostly of concrete. Reducing the dimensions of the weir and thus the volume of concrete, while maintaining its functionality, will result in a lower environmental impact. These dimensions also determine the amount of water that can flow through the weir and the type and size of the gates that can be used.
- **How is the new weir integrated into the surrounding area?**
  The position of the weir determines what construction methods can be used as well as influencing the suitability of gate types.

By making these design choices, the basis for the conceptual design for the new weir is developed. This process may result in various design layouts. However, if these design choices are made sequentially rather than simultaneously, the design will be limited, which could likely result in sustainable options being overlooked. Additionally, the weir complex could offer several additional functions. These functions are not the motivation for constructing the weir, but they do increase its sustainability value.

- Constructing a weir bypassing channel (ecology)
  A weir bypassing channel can improve ecological connectivity by allowing continuous water flow and enabling fish to pass the weir. Additionally, it provides additional aquatic habitats.
- Implementing renewable energy generation (energy and climate mitigation)
  Hydropower plants (HPPs) generate renewable energy, contributing to sustainability of the weir complex. However, constructing an HPP requires a considerable amount of resources, leading to environmental impacts. Although it may be feasible to integrate an HPP within the weir complex, its sustainability should not be presumed. To avoid green washing, a detailed analysis is needed.
- Including a permanent connection at the weir complex (accessibility)
  If the weir replaces an old weir that is part of an existing road connection, the new design must retain this function. This is efficient use of the land, as no other additional structure is required. Additionally, if the bridge uses the piers of the weir, it does not need its own supports. Thus, reducing material usage.

Sustainability evaluation criteria
To evaluate the sustainability value of weir concepts, specific sustainability evaluation criteria must be formulated. These evaluation criteria encompass the most important sustainability aspects that need to be assessed during this phase. The criteria should be supplemented by non-sustainability criteria typically used for evaluating hydraulic structures. A distinction is made between quantitative and qualitative criteria:

- **Quantitative criteria**
  Circularity and materials, energy and climate mitigation and environmental effects: **MKI value**
  Each of these themes includes a measurable indicator that contributes to the total Milieukostenindicator (MKI) [Environmental Cost Indicator] of the design. The MKI is a single score used to express the environmental impact of a project in monetary terms. It combines various measurable environmental effects using weighting factors and can be calculated using software tools, such as DuboCalc. Alternatively, an initial estimate can be made using a hand calculation. The MKI covers material usage, CO_2 emissions and various environmental impacts. A lower value indicates a more sustainable design.

- **Quantitative criteria**
  Ecology, social relevance and spatial quality
  These three themes are hard or impossible to quantify, while needing to be evaluated during this phase of the design process to gain the most sustainability value. Addressing these themes later in the process not only increases costs but also reduces sustainability. The themes also share a reliance on stakeholder input to maximise their impact, as they are not quantified.

To incorporate stakeholder input effectively, it is recommended to generate weir designs based on technical parameters first and then present these designs to stakeholders for feedback. This approach provides a basis for discussion, allowing the design to be adapted as needed to balance stakeholder input with technical requirements. This cycle repeats until the designs meet all requirements and can be evaluated on both quantitative and quantitative criteria.

Financing as condition for creating sustainability value
After evaluating the design variants, financing can be considered, as it does not add value to the project. The costs of a design are a condition that must be met in order to create the corresponding value. By comparing the costs to the created value, financing is taken into account. The value of each proposed design is divided by its estimated costs to determine the value-cost ratio. The variant with the most favourable value-cost ratio could then be selected. Additionally, a budget can be established to set a maximum limit on the costs, ensuring that the project remains financially feasible.

2.3.4. Guideline for the plan development phase

This phase of the design process is mostly outside the scope of the thesis' case study

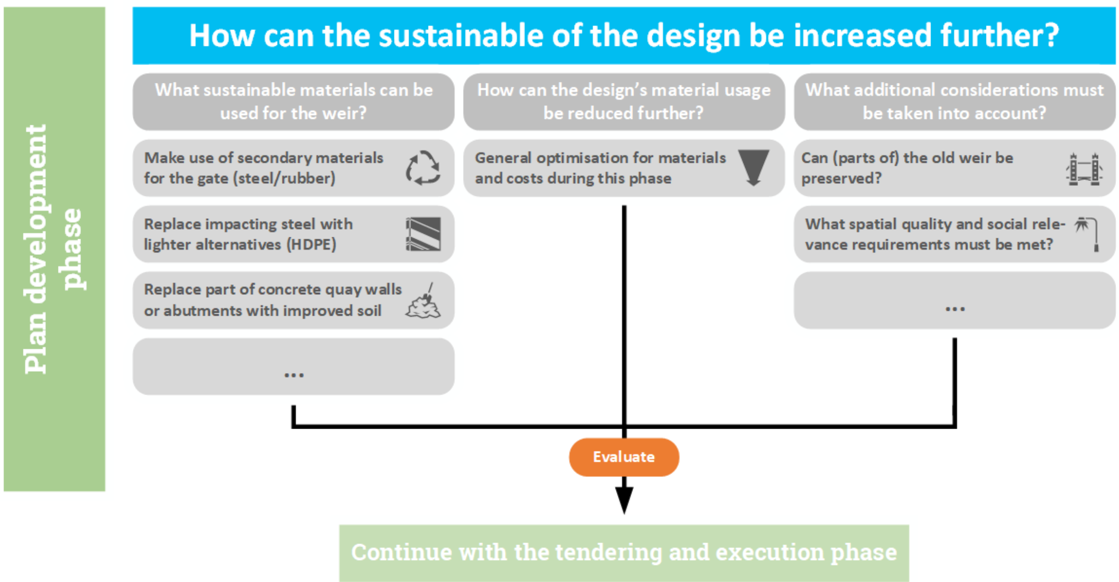


Figure 2.6: Guideline for the plan development phase

During this phase the selected concept is refined and detailed. The design's responsiveness is low, meaning that opportunities for significant changes are limited. Some key considerations can still be addressed, such as material usage, though with less impact on the weir's overall sustainability.

Sustainable material usage
Building on the highest-scoring concept design from the exploratory phase, the potential use of alternative sustainable materials should be investigated. Key elements contributing significantly to environmental impact include the concrete used in the superstructure, the steel in the gates and sheet piling, and the earthworks involved in constructing the weir itself and shaping the waterway. For each of these elements, feasible alternatives should explored.

Reducing materials usage
In addition to exploring alternative materials, the potential to reduce material usage should also be assessed. This involves optimising the design for both materials and costs during this phase. Various materials should be assessed, as some may have a higher environmental impact per unit but enable design optimisations that reduce overall material use, resulting in a more sustainable design.

Additional considerations weir design
During this stage, there also some additional considerations to be made:

- Decide future of old weir (spatial quality)
  Also this theme involves engaging stakeholders, particularly in recognising the cultural and historical significance of old weirs if they are to be replaced. A sustainable approach should be taken to decide the future of the old weir. Possible options include: repurposing the structure, preserving parts for heritage purposes or visibly reusing elements in the new design. In the conceptual design stage, a decision must be made regarding the future of the old weir. Therefore, this theme must be considered during the preliminary works.
- Improving social safety (spatial quality)
  Spatial quality also includes social safety, which must be taken into account during the final design. Requirements must be set to ensure there is good lighting at the complex.

Evaluation detailed design
During this phase, the design is further detailed and should be re-evaluated using both quantitative and qualitative criteria. It is important to consider constructibility and maintainability, as certain sustainable methods are only compatible with specific elements and materials. For example, emission-free equipment often has lower power compared to equipment using fossil fuels, meaning it may not be capable of handling the same size of structural elements that fossil-fuel-powered equipment can manage.

2.3.5. Guideline for the tendering and execution phase
This phase of the design process is outside the scope of the thesis' case study

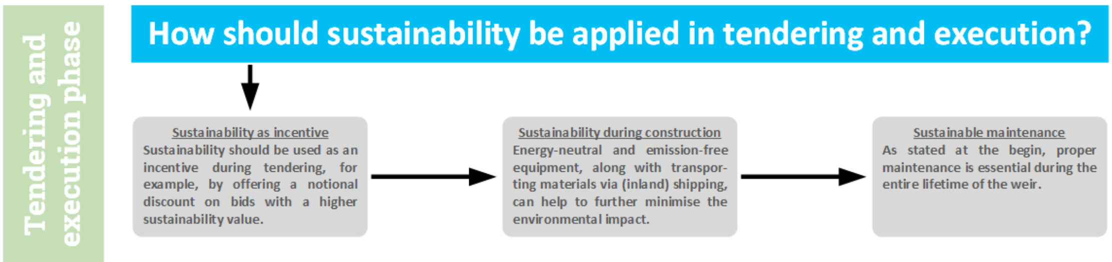


Figure 2.7: Guideline for the tendering and execution phase

This is the final phase covered in the guideline, where the design is translated into construction and operation plans. While some sustainability value can still be realised at this stage, its potential is significantly reduced compared to earlier phases. The success of these sustainability measures, however, largely depends on decisions made during the earlier stages of the design process.

2.3.6. Potential sustainability measures for the conceptual design
This section provides an overview of the most suitable potential measures for creating a sustainable weir design. These measures should be applied during the development of the conceptual design. The measures are organised into three categories: location selection measures (LM), functional design measures (FM) and structural design measures (SM).

Location selection

- LM.1 (Section 2.2.4): Construct the new weir in an existing waterway.
  If possible, the new weir should be constructed in the existing waterway without creating a bypass. This can also include a parallel channel or a section of a floodplain. Building within an existing waterway minimises the required earthworks, thus reducing emissions and environmental impact.

Functional design

- FM.1 (Section 2.2.1): Reuse elements from the old weir
  If a new weir is replacing an old one, it should be assessed whether the following elements from the old weir can be reused: the foundation, the piers, the abutments and the gates. The reusability is entirely dependent on the specific project and its location.
- FM.2 (Section 2.2.1): Use an overflow weir
  Using an overflow weir instead of underflow weir, can help protect the scour protection in the waterway. Therefore, the weir should be designed using gates that primarily facilitate overflow.
- FM.3 (Section 2.2.2): Use a visor gate or inflatable gate
  Both a visor gate and inflatable gate are suggested to use for the weir. These gates generally have a lower weight and therefore might lead to a sustainable design. Thus, both these gate types should be considered as an alternative during the functional design.
- FM.4 (Section 2.2.2): Include a hydroelectric power plant
  The addition of a HPP to the weir complex should be considered. A HPP could help in generating green energy and achieving energy neutrality. This benefit should be weighted against the environmental impact of constructing the HPP.
- FM.5 (Section 2.2.3): Increase the retaining height of the weir
  Climate change is expected to lead to extensive droughts. To address this challenge, additional water can be buffered. One potential measure is to increase the retaining height of the weirs, which increases the volume of water buffered in the upstream weir basin.
- FM.6 (Section 2.2.3): Use an adaptable gate type
  Building upon measure FM.5, increasing the retaining height of the weirs to buffer water can be done adaptively in response to climate change. Choosing a gate type that can be adjusted to accommodate this, is a sustainable choice.
- FM.7 (Section 2.2.5): construct a weir bypassing channel
  Constructing a weir bypassing channel can improve ecological connectivity by allowing continuous water flow and enabling fish to pass the weir. Additionally, it increases the quality of aquatic habitats.

Structural design

- SM.1 (Section 2.2.1): Construct the gate using a fibre-reinforced polymer
  The weir gates could potentially be made using a durable plastic. This depends on requirement material properties and the type and shape of the gate. However, it will lead to both a lower gate mass and a lower environmental impact than a fully steel gate.
- SM.2 (Section 2.2.4): Use bio-based lubricant
  For the weir mechanisms the usage of a bio-based lubricant is preferred over a petroleum-based lubricant. If that is not possible, all possible leakages should be prevented.

3
System analysis

The goal of this chapter is to perform a system analysis for the case study. First, one of the seven Meuse weirs is selected. Then, an area analysis, stakeholder analysis and function analysis are performed. The results of these analyses form the foundation for the design in Chapter 4.

3.1. Case selection

As stated in Section 1.4, one of the seven Meuse weirs (Borgharen, Linne, Roermond, Belfeld, Sambeek, Grave or Lith) must be chosen for the case study. Among these, the Linne, Roermond, Belfeld and Sambeek weirs share a similar design, having been constructed in the same time frame. The Linne weir is the oldest of these. Therefore, it has been selected for the case study.

Figure 3.1 shows a photo of the weir. The first part of the case study involves a system analysis of the Linne weir complex, which includes an area analysis, a stakeholder analysis and a function analysis. These analyses will be incorporated into the design process by translating them into requirements, evaluation criteria and boundary conditions in the basis of design in Chapter 4. Using the basis of design, a conceptual design for a new weir, replacing the current weir at Linne, will be made. This design is divided into three parts: location selection, Chapter 5) and functional design, Chapter 6.

Figure 3.1: Photo of the Linne weir with the Poirée section in the front (right side) and the Stoney section in the back (left side).

3.2. Area analysis

3.2.1. Overview of the weir system

The Meuse forms a natural boundary between North Brabant and both Gelderland and the north of Limburg, as can be seen on the map in Figure 3.2. The Dutch part of the Meuse can be split in 6 sections with each different characteristics (Rijkswaterstaat, 2024c):

- 1. Bovenmaas: a relatively narrow valley with a hard bed. This section has the highest flow speed of the Dutch Meuse. It is also the section where the Meuse crosses the border into the Netherlands
- 2. Grensmaas: a natural border between Belgium and the Netherlands. The water level is not regulated using weirs and ships use the parallel Juliana Canal instead.
- 3. Plassenmaas: in this area gravel was mined and these pits have been filled with water, creating several small lakes, which are nowadays used for recreational purposes. The Linne weir complex is located in this section.
- 4. Zandmaas: the river bed is less steep and the Meuse has a lower flow speed, resulting in deposited sand. The landscape is characterised by terraces on the river banks.
- 5. Bedijkte Maas: the Meuse reaches the lowland and multiple cut-off meanders can be found. This entire area is protected by dikes along the river section.
- 6. Getijdenmaas: the water level of this part of the river is influenced by the tide from the North Sea. The average water level difference between the North Sea and the Meuse at Borgharen is 45 m (Rijkswaterstaat, 2024c).

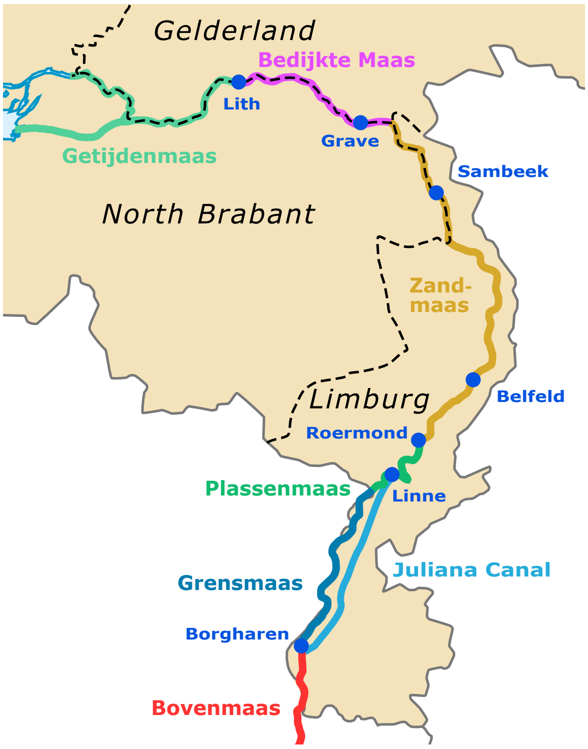


Figure 3.2: Map of the Dutch Meuse marked with the weir locations and divided in 6 sections, adapted from Rijkswaterstaat (2024c)

In Figure 3.3 the longitudinal profile of the Meuse is shown. The difference in slope between the upper part (Bovenmaas en Grensmaas) and the lower part (Plassenmaas, Zandmaas, Bedijkte Maas and Getijdenmaas) is clearly depicted. The Juliana Canal runs from Linne to Borgharen, parallel to the Grensmaas. Two navigation locks, located at Maasbracht and Born, are used to overcome the water level difference in the canal.

Each weir in the Meuse is accompanied by at least one navigation lock, which is used by ships to pass the weir and enter the next part of the river. In addition to the locks, each weir complex also has a fish ladder, which allows fish to migrate upstream past the weir. The complex in Lith and Linne both also contain a hydroelectric power plant. Table 3.1 contains some additional information about the weirs, such as the year in which they were built, the number of shipping locks in the weir complex and the type of mechanism the weir uses.

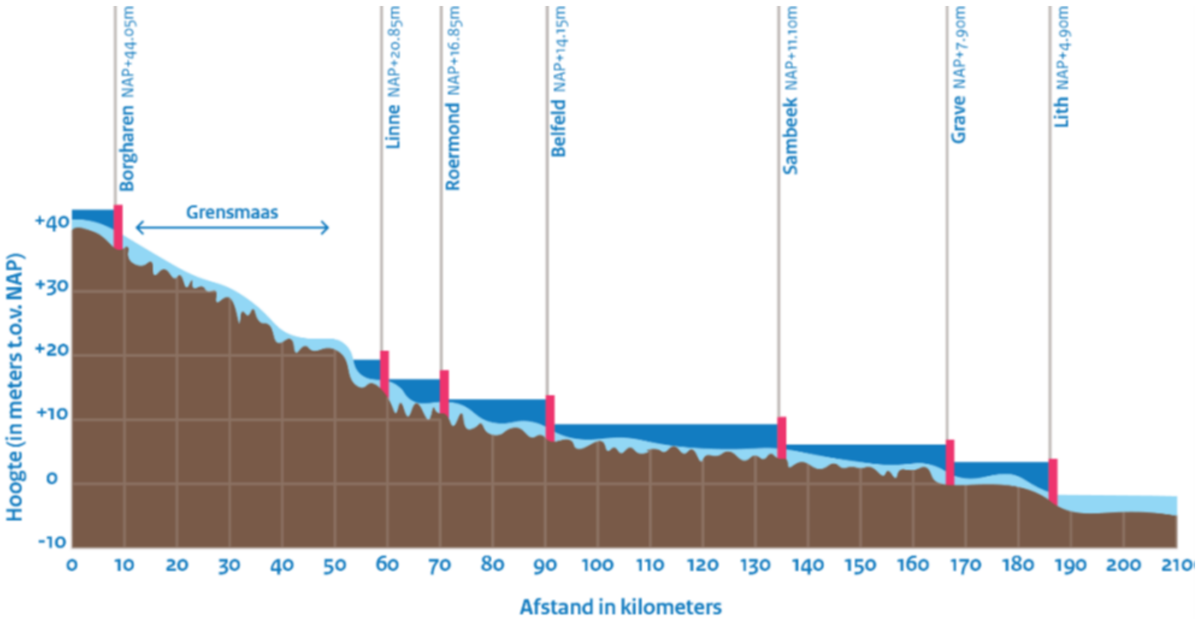


Figure 3.3: Longitudinal profile of the Meuse in the Netherlands with the weir levels and the six sections, adapted from (Delbressine et al., 2023)

Table 3.1: Basic information of the weir complexes

	Borgharen	Linne	Roermond	Belfeld	Sambeek	Grave	Lith
upstream level [NAP +]	44.05 m	20.85 m	16.85 m	14.15 m	11.10 m	7.90 m	4.90 m
max Q [m^3/s]	1600	1400	1100	1100	1300	1500	1200
Δh [m]	6	4	3	3	3	3	4.5
build year	1928	1921	1926	1926	1929	1929	1936
weir types	sliding flap	Poirée & Stoney	Poirée & Stoney	Poirée & Stoney	Poirée & Stoney	bridge with partitions	sliding flap
# locks in use	0	1	1	3	3	1	2
power plant	no	yes	no	no	no	no	yes

3.2.2. Effect of climate change

The Meuse is a river with a pluvial regime, where discharge is characterised by the amount of precipitation in the catchment area, see Figure 3.4. The precipitation pattern and thus the discharge pattern will both change due to the effects of climate change.

KNMI'23 climate scenarios

In March 2024 the Royal Netherlands Meteorological Institute (KNMI) published the second version of their revised climate scenarios. These climate scenarios replace the scenarios they published in 2014 (van Dorland et al., 2024). The KNMI developed models to analyse the effect of climate change on the area of the Netherlands in combination with the upstream catchment areas of the Rhine and Meuse. This climate analysis has three main sources of uncertainty: uncertainty in the model itself, uncertainty in anthropogenic activities and uncertainty in the response of the climate. These last two categories are crucial in determining the effect of climate change on the Meuse.

Future emissions are uncertain, so the KNMI considers three future emission scenarios in their analysis: development towards low emissions, moderate emissions and high emissions. In addition, a distinction is made between a wet (n) and a dry (d) scenario variant to take the uncertainty in regional climate response into account. Each combination of an emission scenario with a wet/dry variant is evaluated for multiple future time-horizons (2033, 2050, 2100 and 2150).

Implications for the Meuse
Deltares made an assessment of the implications of the KNMI climate scenarios for the discharge of both the Meuse and Rhine (Buitink et al., 2023). In addition, Deltares is working on an assessment of the impacts of the climate scenarios on discharge extremes for high return periods. This report is to be released in 2024. In Table 3.2 an overview of future scenarios considered by Deltares is given.

Deltares analysed the effect of these climate projections for the flow at the Belgian-Dutch border. Here the Meuse enters the Netherlands. In Figure 3.4 the part of the catchment area analysed is marked. Using a hydrological model, considering the most important processes, the climate projections have been translated into discharge projections. The graph on the left of Figure 3.5 shows the average annual 7 day minimum discharge of the Meuse at the Dutch border. The 7 day minimum is the lowest mean discharge for 7 consecutive days. For all scenarios considered, the simulated 7 day minimum decreases with reference to the current discharge pattern. The biggest decrease is about 30% (35 m^3/s) in 2150 and corresponds to dry variant of the high emission scenario (H_d).

Figure 3.4: Overview of the catchment area of the Meuse. Based on data from Deltares (Buitink et al., 2023)

Table 3.2: Overview of future scenarios considered by Deltares (Buitink et al., 2023)

Time Horizon	Low	Moderate	High
2033	2033L (Paris)		
2050		2050M_n / 2050M_d	2050H_n / 2050H_d
2100	2100L_n / 2100L_d	2100M_n / 2050M_d	2100H_n / 2100H_d
2150		2150M_n / 2150M_d	2150H_n / 2150H_d

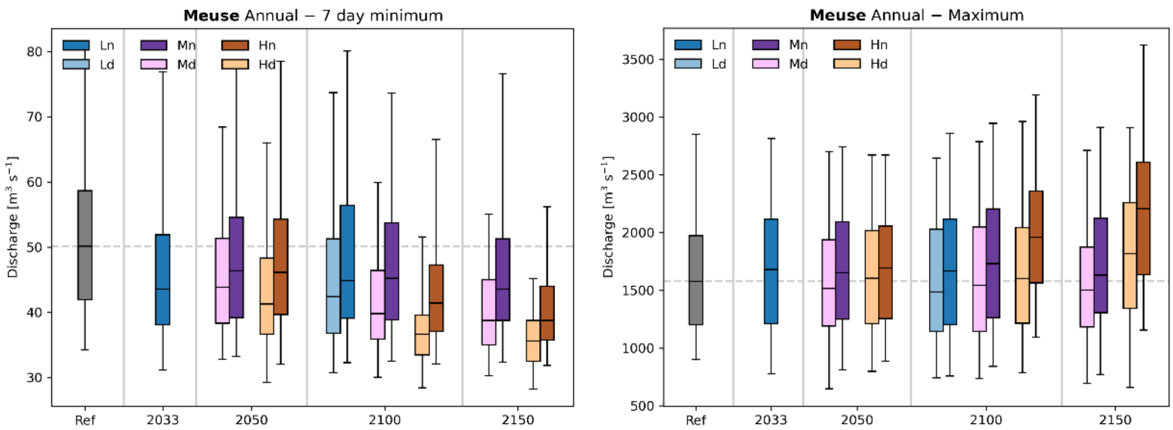


Figure 3.5: Left: annual 7 day minimum discharge of the Meuse at the Dutch border & Right: annual maximum discharge of the Meuse at the Dutch border (Buitink et al., 2023)

The graph on the right of Figure 3.5 shows the annual maximum discharge of the Meuse at the Dutch border. Most scenarios show only a small change in annual maximum. The exception is the wet variant of the high emission scenario (H_w). In 2100 it projects and increase of 20% (1950 m^3/s) and by 2150 it projects an increase of 35% (2200 m^3/s).

The annual maximum discharge can not be used as a design discharge. Deltares' analysis of high return period discharges will provide better insight, but since the report is not yet released, an assumption must be made. In 2015, Deltares performed a similar analysis for the KNMI'14 climate scenarios (Klijn et al., 2015). In that analysis the governing discharge at the Dutch border in 2085 - the furthest time horizon considered in the report - was determined to be 4750 m^3/s for a return period of 1250 years. The new weir will have a design lifetime of 100 years, for which the discharge characteristic in 2130 would have to be known. The discharge through the Plassenmaas section and the Linne weir complex is not equal to the discharge at the border. For regular conditions the discharge through the Plassenmaas is lower, since part of the discharge at the border is diverted to other waterways. For design purposes, a discharge of 5000 m^3/s for a return period of 1250 years in 2130 at Linne is assumed.

3.2.3. Weir complex Linne

Waterways surrounding the weir

The Linne weir, part of the original 1912 plan, will be the first Meuse weir to reach 100 years in 2025. Located in the Plassenmaas, the Meuse has large meanders here, visible in Figure 3.6. The navigation Lock of the complex is not situated directly next to the weir, which is the case for all other weirs in the Meuse. The lock is in a smaller adjacent waterway, forming a bypass for the meander with the weir.

The Lateral Canal Heel-Buggenum and the navigation lock Heel opened in 1972, form a bypass for Linne and Roermond weirs and locks, see Figure 3.6. The shipping industry prefers the lateral canal for its efficiency over the Plassenmaas meanders. Ships to Roermond's industrial ports use the lock north of Roermond, while the Linne lock mainly serves recreational vessels.

Upstream of the Linne weir complex are the Grensmaas and the parallel Juliana Canal. The water level in the Grensmaas is not regulated using weirs and flows naturally. At the northern end of the Juliana Canal the three navigation locks of Maasbracht are located, which dam the water in the canal. Thus, only a relatively small part of the upstream waterway is directly influenced by the Linne weir. However, it is a crucial section, as it allows ships from the Juliana Canal to reach the Lateral Canal Heel-Buggenum and the Canal Wessem-Nederweert.

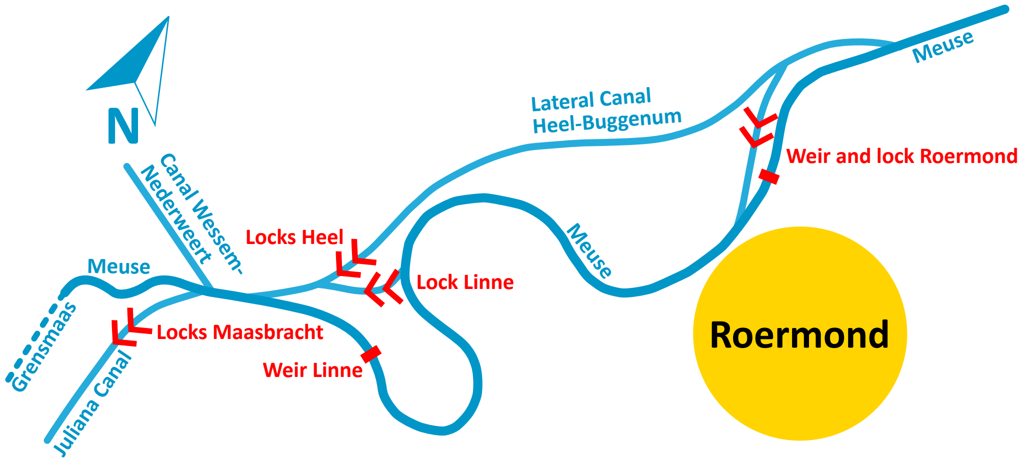


Figure 3.6: Systematic overview of the waterways and structures at Linne and Roermond, adapted from Rijkswaterstaat (2023)

Protected nature areas
It is important to indentify the protected nature areas surrounding the Linne weir complex and the adjacent waterways. These areas, along with their (aquatic) biodiversity, must be preserved. Additionally, maintaining the ecological connectivity between these areas must also be considered during the construction of a new weir.

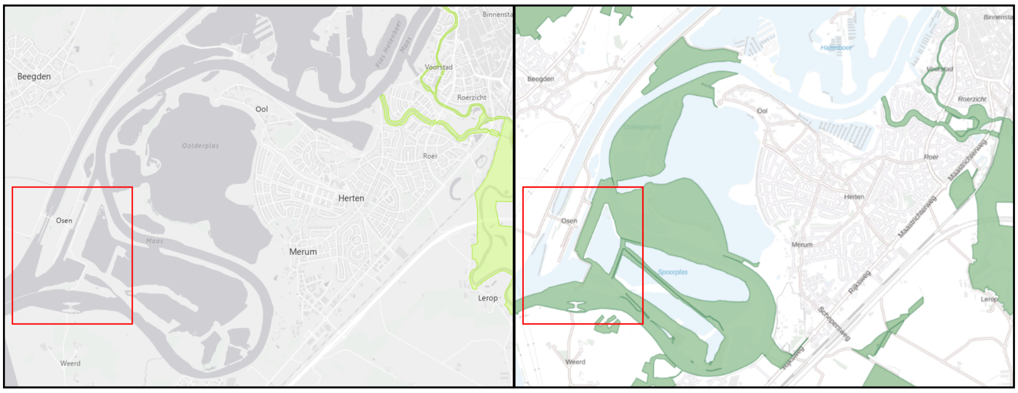


Figure 3.7: Left: Natura 2000 areas (Natura 2000, n.d.) & Right: Natuurnetwerk Nederland (NNN) areas (Atlas Leefomgeving, n.d.). Location of the Linne weir complex is marked.

An overview of the protected nature areas surrounding the Linne and Roermond weir complexes is shown in Figure 3.7. On the left side of the figure, the strictly protected Natura 2000 areas are depicted, with the Roerdal being the only visible Natura 2000 area. The Grensmaas, further upstream of the Meuse, is also a Natura 2000 area. On the right side of the figure, the Natuurwerk Nederland (NNN) areas are depicted. This includes the Natura 2000 areas and extends beyond it, including the land and waterway around the Linne weir. While it is a protected natural area, the level of protection it receives is lower than that of the Natura 2000 areas.

Components of the Linne Weir Complex
The weir is no longer navigable for ships after the construction of a publicly accessible bicycle bridge in 1994, which was made possible due to the construction of the lateral canal. Vessels up to CEMT Class Va can still use the Linne lock or the Roermond weir and lock complex to reach their destination. The bridge shortens the route between Linne and the Osen neighborhood in Heel from 11 km to 4 km, providing residents with a scenic cycling route as an alternative to cycling next to the A2 highway. The location of the bicycle bridge is indicated in Figure 3.8. After passing the Linne weir from the south, both the Linne lock and Heel lock can be passed via bridges to reach Heel.

The Linne weir consists of two distinct sections: a Poirée weir section and a Stoney weir section, placed parallel in the waterway. In Appendix B, technical drawings of both sections are provided and their location is marked in Figure 3.8. One of the requirements of weirs during initial design, was that ships would be able to pass the weir during high river discharges. The Poirée weir consists of a series of foldaway frames, which support rows of removable panels. These panels are used to control the discharge of the Meuse. The structure includes a bridge that allows a crane to travel over the weir, enabling the insertion or removal of panels. During high water, all panels can be removed and the frames can be rotated to lie flat on the riverbed, allowing ships to pass (Delbressine et al., 2023). The Poirée section has significant leakage losses (de Jong, 2014), which can also be seen on the photo in Figure 3.1.

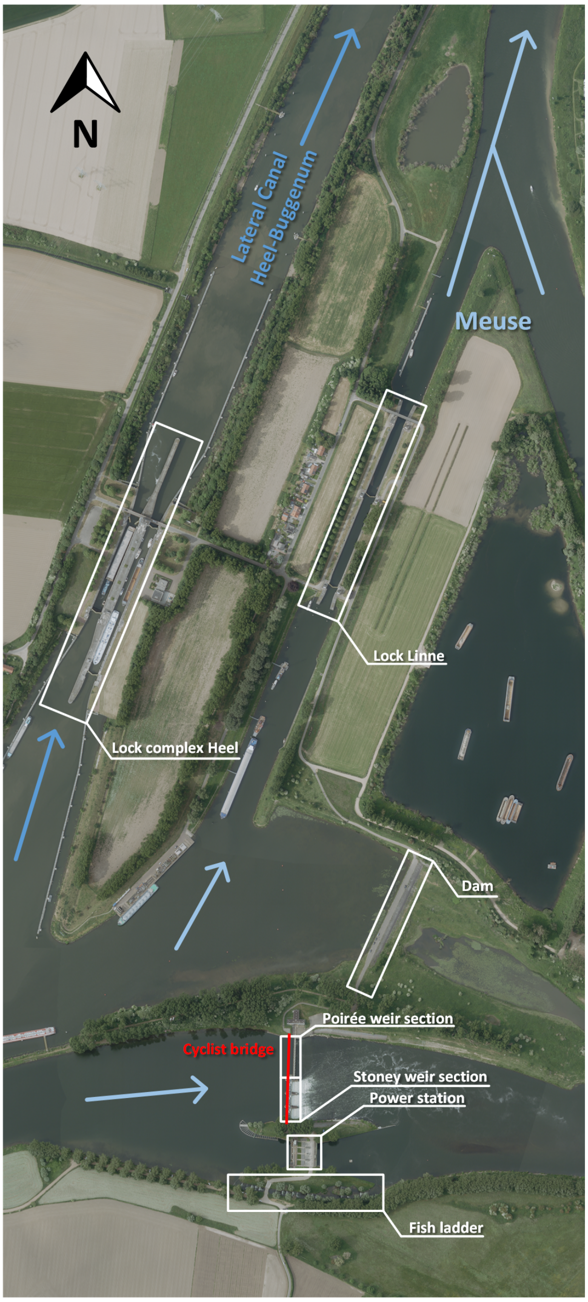


Figure 3.8: Overview of the weir complex at Linne (Beeldmateriaal Nederland, 2023). The flow direction is marked in the overview.

The Stoney weir uses two vertical sliding gates per opening between the piers of the weir. The gates are placed in series and can move independently using rollers. During low discharges, the water flows over the top of both gates. By moving the downstream gate, the retaining height of the weir can be changed and thus the upstream water level can be controlled. If the discharge increases, the upstream gate can be moved up, allowing the water to flow under under the bottom of the gates. When fully opened, the gates are lifted entirely out of the water. The Stoney weir allows for precise water level regulation, complementing the Poirée section of the weir (Delbressine et al., 2023).

3.3. Stakeholder analysis

The stakeholder analysis provides overview of the stakeholders involved in the design and construction of the new Linne weir. It is essential to understand the interests of these stakeholders, as their interests lead to needs, which must be taken into account when designing new weirs. This will be translated to requirements and evaluation criteria when forming the basis of design. Conflicting interests among stakeholders are possible.

It must be noted that this analysis is based on initial assumptions, as no interviews or consultations have been conducted with the stakeholders. Thus, the interests and needs identified might not cover every perspective. To get a clearer and more complete picture, the stakeholders must be engaged.

Public service providers

- Rijkswaterstaat (RWS): RWS, the executive agency of the Ministry of Infrastructure and Waterworks, manages and maintains the seven weirs in the Meuse in the Netherlands. Rijkswaterstaat will issue a tender to select contractors to carry out the renovation of the weirs. Therefore, it is in their best interest the project is successfully carried out within the set time-frame and budget. In addition, the new design must align with their sustainability and circularity goals.
- Provinces: The Linne weir complex is located in the province of Limburg, see Figure 3.2. The province aims to create a safe and appealing living environment. Therefore, their interests lie in high water protection, water quality and ecological development. Moreover, they also want to stimulate recreational use of the Meuse, promote cultural heritage and contribute to the local economy. Each of these processes are affected by the construction of a new weir. The renovation projects for other Meuse weirs will involve similar considerations, since the other weir complexes are also located in and bordering to the provinces of North Brabant and Gelderland.
- Waterschappen (water boards): The primary responsibilities of the water boards include managing the water levels in the region, monitoring the water quality and maintaining dikes and other flood defences. The Meuse weir complexes are part of a larger water system, consisting of the catchment area of the Meuse as can been seen in Figure 1.2. Therefore, the renovation and construction activities of the weirs will affect the work of the water boards. This is especially the case in regions prone to flooding of the Meuse. The Linne weir is located in the water board Limburg, which encompasses the same area as the province of Limburg.
- Municipalities: The hydraulic structures of the Linne weir complex are located within Maasgouw, with some access routes and connecting pathways extending into Roermond. Both municipalities have established an ”omgevingsplan” (environmental plan) that governs spatial development and environmental quality. These plans impact the design and construction of the weir by setting standards for water management, ecological preservation and safety. Obtaining permits from both municipalities is necessary, affecting the project timeline and complexity. Additionally, both Maasgouw and Roermond are responsible for maintaining local infrastructure and river dikes, coordinating with water boards. They are also concerned with impact on the infrastructure integration and the overall well-being of residents in their communities. Collaboration with municipalities is essential for communication with local citizens. The renovation projects for other Meuse weirs will involve similar considerations with their respective municipalities.

Private service providers

- Shipping industry: The shipping industry itself is also a stakeholder, as it relies on the navigability of the Meuse shipping route for its operations. According to Rijkswaterstaat (2024e), the Meuse is one of the most important inland shipping routes in Europe. While the Linne weir itself is not used by the shipping industry, since it uses the more faster Heel-Buggenum lateral canal. Construction at the weir complex could still impact the industry due to the complex's proximity to the Heel lock, which provides access to the lateral canal, see Figure 3.6. It is important for the industry that shipping is hindered as least as possible, assuming that a form of hindrance is unavoidable due to the large scale of the operations. In an ideal scenario, there would be no hindrance at all.
- Engineering firms contractors: One or a consortium of multiple engineering firms and contractors will be responsible for the design and renovation of the Linne weir and the other Meuse weirs. In addition, a contractor might also be carrying out the maintenance work of the structures depending on the type of contract. It is in the consortium's interest to successfully finishing the project for the client, RWS, while incorporating the wishes of the various stakeholders. In addition, depending on the type of contract with the client, the consortium might prioritise a low-priced tender, to create a profit margin.

Core stakeholders

- Local residents: Residents living near the weirs will be directly impacted by construction activities, which may disrupt their daily routines. They will hope for minimal disruptions and clear communication throughout the project. For residents in Linne, there is also a strong interest in preserving the cultural and historical significance of the weir, as it plays a central role in local heritage, evidenced by the 100-year anniversary celebration event they are organising (stichting Stuw Linne 100 Jaar, 2024). Citizens in the wider area around the Meuse will be concerned about the water safety. Additionally, they may be interested in preserving the cultural and historical significance of the weirs. Furthermore, local citizens may also be concerned about effect on recreational activities.

- Environmental NGOs: Environmental NGOs focus on ecological preservation in the river region and sustainable development of renovated structures. They might be concerned with the potential environmental impact of construction and will express this concern.

3.4. Function analysis

The function analysis is used to create an overview of all the functions a weir complex in the Meuse must fulfil, while considering the stakeholders' interests. This analysis specifically applies to the Linne weir and categorises the functions into three types: the principal function, preserving functions and additional functions. This analysis is based on an investigation performed by Rijkswaterstaat (2023).

Principal function

The Linne weir complex has a principal function. This function was the original motivation for constructing all of the Meuse weirs.

- Function.1: Regulating the water level in the Meuse for navigability during low river discharge.

  When the weirs were constructed, they were used to increase the water level in the Meuse to make it navigable for large inland vessels. In the present, this is still the motivation for rennovating or replacing the weirs. However, the Linne weir is now also essential for the water management of the region, especially during droughts (Delbressine et al., 2023).

- Function.2: Buffering water in the upstream weir basin during droughts.

  Water can be stored in the basin upstream of the weir. This stored water can be used during droughts for various purposes, such as drinking water production and irrigation. The volume of this buffer directly depends on the retaining height of the weir.

Preserving functions

The Linne weir complex has several preserving functions. These functions are derived from the need to maintain existing systems. Interference with the natural environment is prevented by integrating the structures using these functions. Additionally, it is essential to preserve other systems, such as the flood defence system.

- Function.3: Preserving the river discharge.

  Constructing a structure in a waterway can obstruct the flow. Although the weir is used to regulate water levels and discharge, it must still have enough capacity to allow all water to pass during high river discharges. If this is not the case, both the flow velocity can increase and the upstream water level can rise further than intended, which can lead to flooding.

- Function.4: Preserving the flood defence system.

  It is essential to preserve the local and regional flood defence systems. This includes ensuring sufficient capacity to allow high discharge waves to pass, as explained in Function 3. It also involves ensuring no impact on the flood defence structures and the dikes surrounding the waterway.

- Function.5: Preserving the sediment transport capacity of the Meuse.

  The natural sediment transport capacity of the Meuse must be preserved to maintain the river's ecological balance. Additionally, excessive sediment build-up must be prevented as it can reduce the river's depth, making it unsuitable for shipping. Lastly, sediment accumulation against the weir from the upstream side can increase the load on the gate, potentially affecting its functioning.

- Function.6: Preserving the water management system in the local area.

  The construction of the weir has impacted the local water management system. Most importantly, its location affects the groundwater table by forming a barrier between two basins and the weir regulates the downstream discharge. Both impacts must be carefully considered during any renovation or replacement of the weir. Maintaining the water management system is important to ensure that other functions, such as drinking water production and irrigation, are not harmed.

- Function.7: Preserving the river-ecosystem and water quality.
- Function.8: Preserving industry, agriculture and residential areas in the surroundings.
- Function.9: Preserving the spatial quality.

Additional functions
The Linne weir complex also has additional functions. These functions extends beyond the system's initial purpose or preservation requirements.

- Function.10: Serving as cultural heritage sites by contributing to the visual landscape of the region.
- Function.11: Facilitating recreational use by allowing visitations of the complex.
- Function.12: Generating power using an hydroelectric power plant.
- Function.13: Allowing traffic to cross the river using a bridge.

4 Basis of design

The basis of design is based on the analyses from Chapter 2 and Chapter 3, specifically the function analysis. The requirements are divided into three categories, each corresponding to one design step: location requirements, functional requirements and structural requirements.

4.1. Requirements

4.1.1. Location requirements

The second step of the approach is to select a location for the new Linne weir. Table 4.1 provides an overview of the requirements for this location, abbreviated as **LR.n**. In Chapter 5 these requirements are used in a sieve analysis to determine the best suitable location for the new Linne weir.

Table 4.1: Overview of location requirements

no.	description
LR.1	**The current weir must be replaced one-to-one in the system** Derived from the principal function, Function.1 Based on the analysis by Antea Group it is assumed the Meuse weirs will be replaced one-to-one (2015). Thus, the current location of the Linne weir within the river system is not to be changed. This entails that the interaction with the other elements in the system, such as the connection to lateral canals or the navigation locks, can not change. This narrows the location of the new weir down to the section of the Meuse, where the current weir is located, see figure 3.8 for an overview of the system.
LR.2	**The weir cannot be constructed within 100 m of existing infrastructure, protected nature or residential and industrial areas.** Derived from Function.7 and Function.8 The new weir should be located in an area where it will have minimal impact on the surrounding environment. Firstly, the weir cannot interfere with other infrastructure in the area, including navigation locks and bridges over the Meuse. Secondly, the weir cannot be constructed near a Natura 2000 area. Lastly, the weir cannot be constructed near residential areas or industrial facilities.
LR.3	**There must be no large deviation in groundwater level in the project area due to the construction of the new weir** Derived from Function.6 Moving the location of the weir will induce a change in groundwater level in the surrounding area. A deviation in groundwater level can have a large impact on foundations in the area, agricultural land use and the ecosystem (Delbressine et al., 2023). Thus, this should be prevented. The exact numerical relation between the weir location and the ground water level is out of scope. It is assumed that a location as close as possible to the current weir is preferred.

LR.4	**The current complex must be operable during the construction of the new weir** Derived from the principal functions, Function.1 and Function.2 As stated in Chapter 1 there are multiple reasons why the Meuse weirs are essential to the Meuse river system. Thus, the construction of the new weir can not impede the operation of the current weir complex.
LR.5	**The new weir must be accessible during construction and maintenance** Derived from Section 2.2.8 The new weir must be accessible during both construction and maintenance, especially if it is to be built in a different section of the waterway than the existing one.

4.1.2. Functional requirements

The functional requirements are directly based on the function analysis in Section 3.4. The concepts generated in Chapter 6 must comply with the requirements. These requirements are needed to develop a design which can be used in practise and can be integrated into the river system. Table 4.2 provides an overview of the requirements, which are abbreviated as **FR.n**.

Table 4.2: Overview of the functional requirements

no.	description
FR.1	**The dammed level of the weir is NAP + 21.35 m** Derived from Function.2 & Section 2.2.3 The current weir can dam water to an upstream water level of NAP + 20.85 m. In the Meuse weirs system analysis RWS advises to increase the retaining height by 50 cm to increased the volume of water dammed. This additional volume can then be used as a water buffer during droughts (Delbressine et al., 2023). This buffer provides water for other functions, such drink water production and irrigation.
FR.2	**There is a maximum leakage loss of 2 m^3/s** Derived from Function.2 & Section 2.2.3 In order to retain enough water during extended periods of low discharge, the leakage losses must be minimised. A maximum leakage loss of 2 m^3/s is accepted (Delbressine et al., 2023).
FR.3	**The weir has a design lifetime of 100 years** Derived from the principal functions, Function.1 and Function.2 The main weir structure must be designed for a lifetime of 100 years. It is assumed the Meuse will still be used for shipping in that time frame. In addition, an extended lifetime will positively contribute to the sustainability of the design. Several subsystems and elements can have a lower design lifetime than the superstructure.
FR.4	**The weir operates up to a discharge of 1400 m^3/s** Derived from Function.1 and Function 3 The current weir operates up to a discharge between 1350 and 1400 m^3/s (Delbressine et al., 2023). The long-term average discharge of the Meuse is expected to remain stable until 2150, see Section 3.2.2. Therefore, it is assumed that the new weir must be able to operate up to a discharge of 1400 m_3/s.
FR.5	**Fish must be able to bypass the weir** Derived from Function.7 & Section 2.2.5 In order to preserve the fish migration routes in the Meuse, fish should be able to bypass the weir in both upstream and downstream directions.
FR.6	**The weir forms a fixed road connection over the Meuse** Derived from Function.13 & Section 2.2.8 The bike bridge that is part of the current weir allows cyclists and pedestrians to cross the Meuse at the Linne weir. This reduces the route between the residential areas on both sides of the Meuse from 10 to 4 km. The new weir must also have a bike bridge.

FR.7	**The weir has sufficient discharge capacity to prevent flooding.** Derived from Function.3 The new weir must have sufficient discharge capacity to no cause flooding during high water levels. This means that the weir must have a large enough cross-section to allow water to pass during high discharge events.
FR.8	**The weir has at least two openings for precise water level regulation** Derived from the principal function, Function.1 The new weir must have at least two openings for precise water level regulation that can be maintained independently. If the weir has only one opening for precise water level control, it cannot be in operation when this single opening is under maintenance. If the weir has two openings, the second opening can be used while the first is under maintenance. However, this reduces the discharge range for which the water level can be regulated, meaning that maintenance can only be done when the expected discharge is low, such as during summer. Thus, having more than two openings can also be beneficial as it increases the available capacity during maintenance.

4.1.3. Structural requirements

Table 4.3 provides an overview of the structural requirements, abbreviated as **SR.n**. As stated in Section 1.3.2, the structural design of the new Linne weir is out of the scope of this project.

Table 4.3: Overview of structural requirements

no.	description
SR.1	**The weir is constructable** Derived from the principal functions It must be physically possible to build the design.
SR.2	**The weir is sufficiently stable** Derived from the principal functions In the Ultimate Limit State (ULS) the weir and subsystems must be stable. Generally, the following stabilities should be checked for each element: • Horizontal stability in longitudinal direction • Horizontal stability in lateral direction • Vertical stability • Rotational stability
SR.3	**The structural elements are sufficiently strong** Derived from the principal functions The elements of the weir should be able to resist to the governing load in ULS, while ensuring a sufficient factor of safety.
SR.4	**The structural elements are sufficiently stiff** Derived from the principal functions In the Serviceability Limit State (SLS) the structural elements must retain their dimensional stability.

4.2. Evaluation criteria

The evaluation criteria will be used to score the weir concepts made in Chapter 6. In Table 4.4 an overview of the evaluation criteria, which are abbreviated as **EC.n**, is given. This first criterion, **EC.1** is based on the sustainable weir design guideline and the other three criteria, **EC.2**, **EC.3** and **EC.4**, are based on the system analysis.

Table 4.4: Overview of evaluation criteria

no.	description
EC.1	**MKI value** Derived from Section 2.2.1, 2.2.2 and 2.2.4 This first criterion is based on the sustainable weir design guideline and incorporates the sustainability themes of circularity and materials, energy and climate mitigation and environmental effects. It can be calculated using software tools such as DuboCalc or estimated using a hand calculation. This criterion considers material usage in the weir, including both primary and secondary materials, CO_2 emissions and other environmental impacts associated with material production, transport and construction. A lower MKI value indicates a more sustainable weir design.
EC.2	**Operational reliability** Derived from the principal functions This criterion evaluates the operational efficiency of the weir, considering factors such as ease of operation, maintenance downtime and accuracy of water control. This is crucial for RWS, the owner of the new weir, as well as for the shipping industry, which relies on the weir to regulate water levels and ensure the navigability of the Meuse. Additionally, it is also in the interest of the firm or consortium contracted to design and/or construct the weir. Lastly, it is important for water boards, as the weir's secondary function is to buffer water during droughts.
EC.3	**Ease of maintenance** Derived from the stakeholder analysis This criterion evaluates the level of effort and resources required to maintain the weir. It is primarily important for RWS and the firm contracted for maintenance. However, maintenance activities could impact the availability of the waterway near Linne, affecting the shipping industry. Additionally, maintenance work may disrupt local residents who use the bridge over the weir, if it is temporarily closed.
EC.4	**Nuisance during construction** Derived from the stakeholder analysis This last criterion assesses the impact of construction activities on the surrounding environment, including noise levels and effects on local traffic and accessibility. While temporary, as the construction period is expected to be much shorter than the weir's lifespan, it will still affect all stakeholders.

4.3. Boundary conditions

The boundary conditions are specific parameters for the Linne weir complex. Below an overview of the natural boundary conditions is given. Additional data for some of the boundary conditions can be found in Appendix B.

Table 4.5: Overview of boundary conditions

no.	description
BC.1	**Water levels along the Meuse** Derived from Section 3.2 Every year Rijkswaterstaat Zuid-Nederland publishes an overview containing the water levels at various measurement locations along the Meuse for given discharges, the relationship lines ('betrekkingslijnen'). The latest report, containing the data for 2023-2024 can be found in Appendix A.1 (Rijkswaterstaat, 2023). These relationship lines are a visual tool to show the relation between the water level at two locations, using the discharge as connecting variable.

BC.2	**Meuse discharge pattern** Derived from Section 3.2 For a final design the entire discharge pattern of the Meuse is needed. For this conceptual design the governing extremes are used. As detailed in Section 3.2.2, a 7 day minimum discharge of 35 m^3/s in 2150 and a maximum discharge of 5000 m^3/s for a return period of 1250 years in 2130 at Linne were determined.
BC.3	**Characteristics of the subsoil at the weir complex** Derived from Section 3.2 There is no comprehensive analysis of the subsoil at the location of the weir complex available. In later phases of the design, this data is needed. For the conceptual design it is assumed that the subsoil at the location of the new weir can be approximated by the data of locations in the vicinity. DINOloket (2024), the public database from the Geological Survey of the Netherlands, provides the data that will be used for the conceptual design. In Appendix A.2 a general overview of physical characteristics of the subsoil near the location of the weir complex is given. The appendix also contains the results from a CPT. This data will be used during the design of the foundation.

5
Location selection

In this chapter the location of the future weir at Linne is determined using a sieve analysis based on the location requirements specified in Chapter 4, which are abbreviated as **LR**. This location will be used during the generation of the concept variants in Chapter 6.

LR.1 The current weir must be replaced one-to-one in the system

The first location requirement states that the weir must be replaced one-to-one in the river system as schematically depicted in Figure 5.1. The current Linne weir is located in the section of the Plassenmaas between the entrance to the Lateral Canal Heel-Buggenum and the downstream side of the lock at Linne.

If the new weir were to be constructed upstream of the entrance to the lateral canal, the water level in the lateral canal would drop and it would no longer be navigable. In addition, both locks would no longer be functional and an additional lock would have to be constructed in order for ships to pass the weir. If the new weir were to be constructed downstream of the lock at Linne, the lock would cease to function. In this case, an additional lock would also have to be constructed in order for ships to pass the weir.

Taking both considerations into account, in Figure 5.2 the available part of waterway is marked as well as the unavailable part, assuming the new weir must be constructed between the entrance to the Lateral Canal Heel-Buggenum and the downstream side of the Linne Lock.

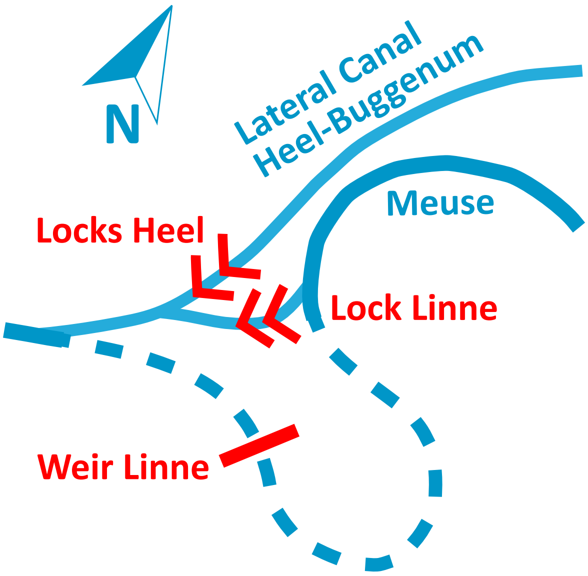


Figure 5.1: Systematic overview of the waterways and structures at the Linne weir complex. The section of the system in which the new weir must be constructed is dashed.

LR.2 The weir cannot be constructed within 100 m of existing infrastructure, protected nature or residential and industrial areas.
The section of the Meuse available to construct the new weir, as marked in Figure 5.1, is used as a basis for a sieve analysis.

- Infrastructure: the locations of all major hydraulic structures are marked in white in Figure 5.2. There are no bridges, tunnels or other fixed connection in the selected area. All of the marked hydraulic structures lie at least at a distance of 100 m from the available waterway. Additionally, there is no other major infrastructure in the direct vicinity of the river section, except for the current Linne weir complex.

- Nature: to create a sustainable new weir, the construction should minimally impact the existing natural environment. To assess this impact, the analysis of the protected nature areas around the weir, as detailed in 3.2.3 (Figure 3.7) is used. Although the land surrounding the weir is not part of the Natura 2000 areas, the entire available section of the waterway and the embankments are part of the Natuurwerk Nederland area.

  The new weir must be constructed within a protected nature reserve, as the section is part of the Natuurwerk Nederland. However, since there are no Natura 2000 areas, the entire section has the same level of protection. Therefore, this criteria does not immediately influence the specific location of the new weir.

- Buildings: in Figure 5.2 the location of all residential and industrial buildings are marked in red. Around these areas a buffer zone with a width of 100 m is drawn. These locations are unsuitable for the new weir to prevent disturbances to residents and businesses. Building the new weir close to existing buildings could lead to noise, vibrations and other disruptions during construction and operation, which should be avoided.

Based on requirement LR.2, the part of the waterway available to construct a new weir is reduced. The section marked red in Figure 5.2 lies too close to the built area and is therefore excluded.

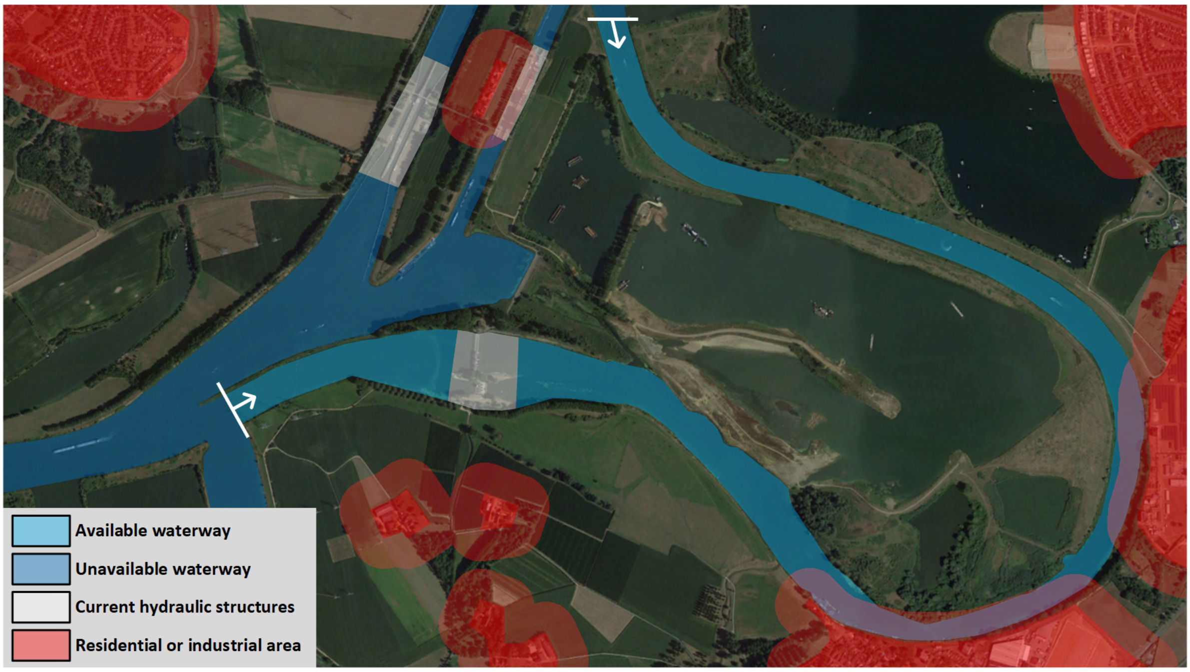


Figure 5.2: Sieve analysis of the possible locations to construct the new weir at Linne (Beeldmateriaal Nederland, 2023)

LR.3 There must be no large deviation in groundwater level in the project area due to the construction of the new weir
Moving the location of the weir will induce a change in groundwater level in the surrounding area. A deviation in ground water level can have a large impact on foundations, agricultural land use and the ecosystem in the area. Therefore, the deviation due to the construction of the new weir must be limited. A location as close as possible to the current weir is preferred. A maximum distance of 250 m from the current weir complex has been set. A full analysis of the impact of moving the weir on the groundwater table is not performed for the conceptual design, as the smallest possible deviation in water level is preferred. Thus, favouring a location close to the current weir. In Figure 5.3 an estimation of the 250 m perimeter, in which the weir must be build, is given. The dam north of the weir is only partly included in this perimeter. However, the dam can provide an opportunity during the concept generation. Therefore it is added to the chosen perimeter.

LR.4 The current complex must be operable during the construction of the new weir
Antea Group advises construction a new weir at a distance of circa 200 m from the current weir, if it is replaced one-to-one in the system in the same waterway (de Jong, 2014). Constructing the new weir too close in the waterway to the existing weir will disrupt its operation. The exact proximity at which the new weir can be built relative to the old weir depends on the design and construction method and therefore cannot yet be determined.

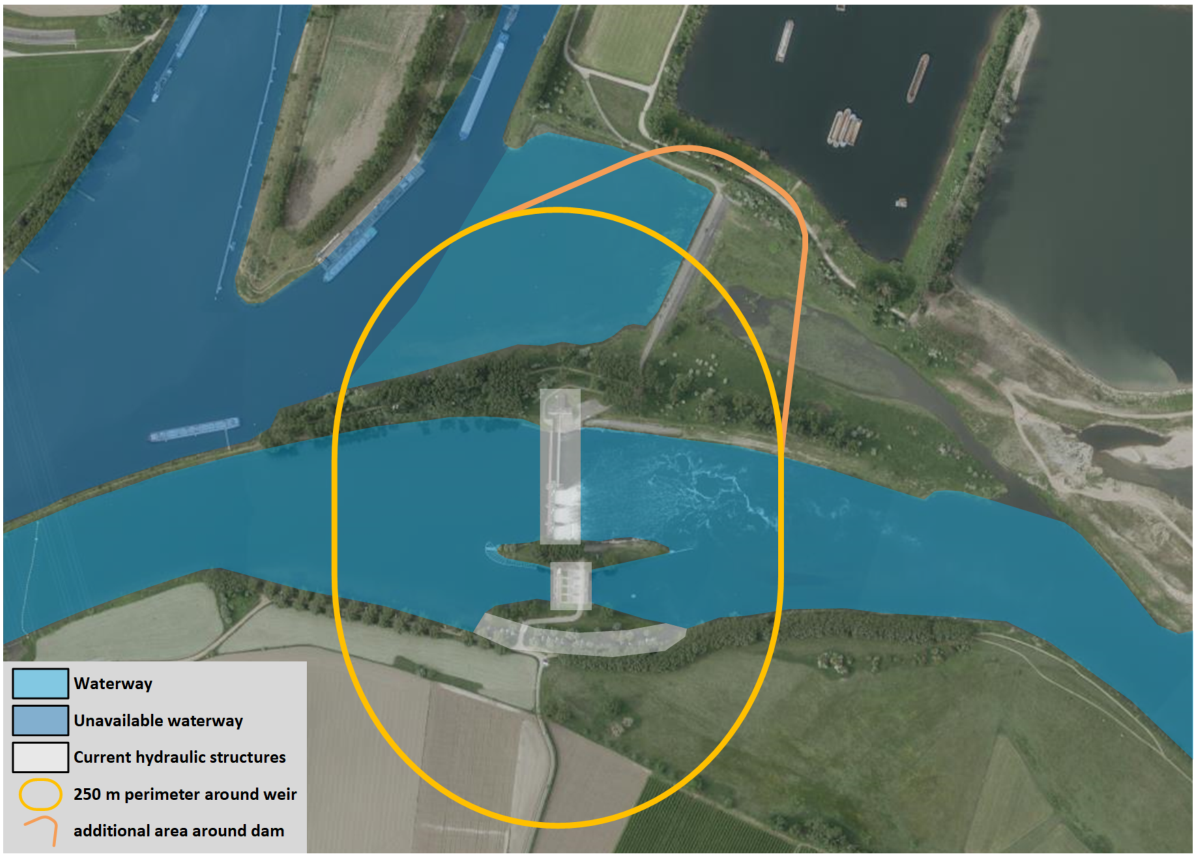


Figure 5.3: Possible area to construct the new weir.

LR.5 The new weir must be accessible during construction and maintenance
The final location requirement states that the weir must be accessible during both initial construction and ongoing maintenance. For each of the available locations within the perimeter, it is assumed that the weir can be accessed either by light vehicles via the northern road, larger vehicles via the southern road or by heavy equipment via the waterway itself. Additionally, it is important that the new weir is not built too close to the existing weir. However, this proximity requirement is stricter for **LR.4**.

Conclusion of the location selection
Figure 5.3 shows the available space for constructing the new weir at Linne, according to the location requirements set in the basis of design. The precise location of the new weir is dependant on the size of the weir openings, which has not yet been elaborated in this stage of the design and will therefore be determined in the functional design in Chapter 6.

6

Functional design

In this chapter, a functional design for the weir at Linne is developed at a conceptual level. In this sixth step of the main approach, four design concepts featuring different weir layouts and gate types are generated. These concepts are presented in Section 6.1. The concepts must be located in the area selected in Chapter 5 and will therefore already meet all location requirements except **LR.4**. In Section 6.2, the concepts are verified against both requirement **LR.4** and the functional requirements. Lastly, the concepts are evaluated in Section 6.3 to determine the most sustainable concept design.

6.1. Generation of design concepts

6.1.1. Inventory of key design variables for a sustainable weir design

As described in the guideline for sustainable weir design, the most sustainability value can be created during this step by focusing on the quantifiable sustainability themes of materials and circularity, energy and climate mitigation and environmental effects. These themes are evaluated using evaluation criterion **EC.1**, the MKI value. In this step of the design process, the following design choices impacting the MKI value must be made:

- Type of gate and material: The current Linne weir has Stoney gates and Poirée gates, both made from steel. Despite being largely recyclable, steel still significantly impacts the environment. Reducing the amount of material used for the gates or using alternative materials with lower impacts than steel can effectively lower the MKI. In Section D.1 an overview of possible gate types suitable for weir design is given.
- Main dimensions of the weir (width, length, height and opening size): The superstructure of the weir will consist mostly of concrete. Reducing the dimensions of the weir and thus the volume of concrete, while maintaining its functionality, will result in a lower MKI. These dimensions also determine the amount of water that can flow through the weir and the type and size of the gates that can be used.
- Final position of the weir within the available space: The position of the weir influences the construction method as well as the suitability of the gate types. Additionally, it also strongly influences the amount of earthworks needed to realise the design.

The stated design choices are highly dependant on each other. For example, the type of gate that is suitable depends on the size of the opening, which in itself depends on the position of the weir. To create the most sustainable design, these choices must be made integrally rather than one at a time. The most important functional requirements for this step are **FR.1** (the dammed level of the weir is NAP + 21.35 m), **FR.4** (the weir operates up to a discharge of 1400 m^3/s) and **FR.7** (the weir has sufficient discharge capacity to prevent flooding), as these requirements directly determine the necessary dimensions of the weir's openings to ensure sufficient flow through the structure.

6.1.2. Determining required wet cross-section

The current weir at Linne is used as the starting point for the concepts, see Section 3.2.3 for details of the weir. Figure 6.1 shows a schematic overview of the weir complex, including the perimeter determined during the location selection in Chapter 5. The new weir sections of the concepts must be located within this perimeter to comply with the location requirements 1 to 3. Additionally, location requirement **LR.4** states that the current complex must be operable during the construction of the new weir. Thus, the construction of the new weir can not obstruct the waterway on either side of the Linne weir.

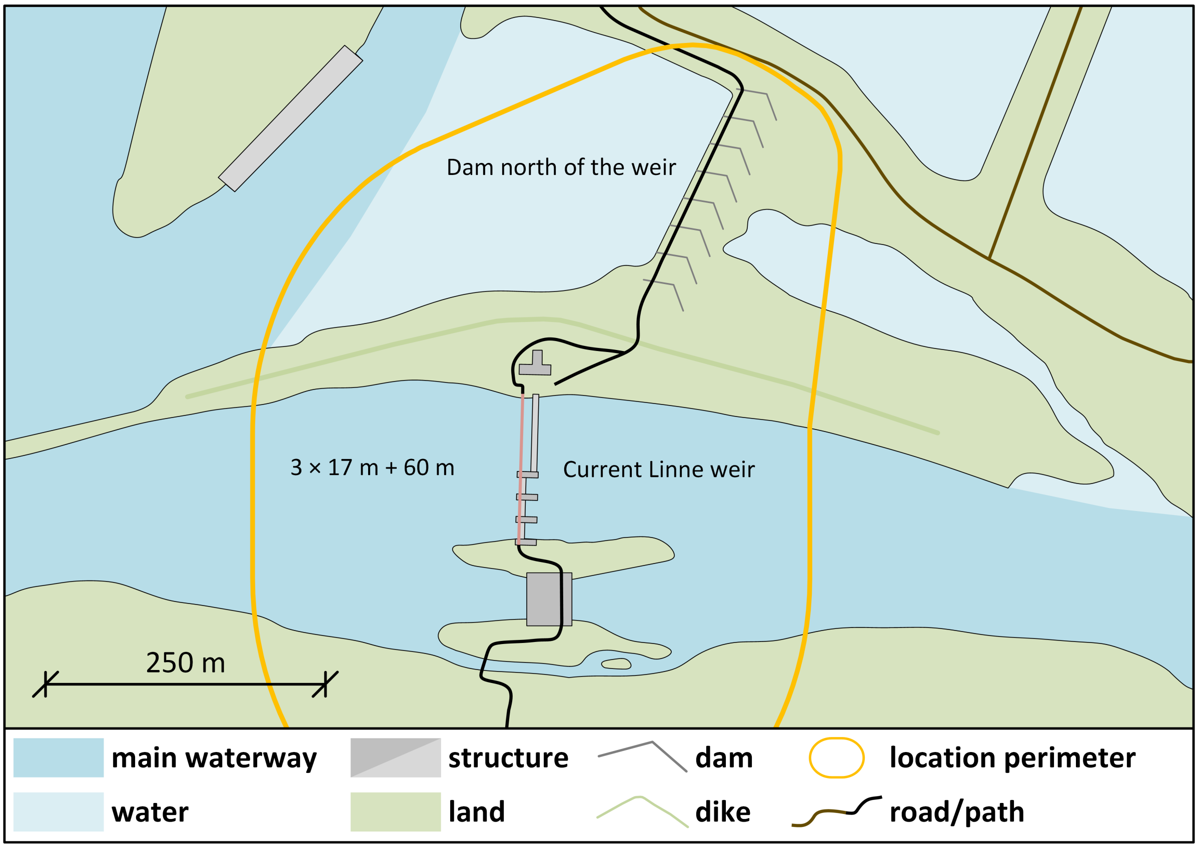


Figure 6.1: Schematisation of the current weir complex at Linne

The Linne weir consists of two distinct sections placed parallel in the waterway. The Stoney section is used for precise water level regulation and the Poirée section is used to create additional discharge capacity. Each proposed concept must fulfill both functions to operate effectively at discharges up to 1400 m^3/s. As a preliminary check, the wet cross-section of the concepts can be compared with that of the current complex at various water levels. The wet cross-section refers to the area of the waterway that is filled with water. When the weir is in operation, this area can be calculated by multiplying the width of the openings by the height of the water level in the openings. When the maximum discharge of the weir is exceeded and the water level rises, the cross-section will also change, eventually including the floodplains. As an initial estimate, each concept should have a cross-section of the same size as that of the existing Linne weir.

Table 6.1 provides an overview of the technical aspects of the weir, which are used to calculate the cross-section. The discharge coefficient of the Stoney weir is estimated using the weir overflow discharge formula found in Appendix C and the information given in the object description of the lock and weir complex at Linne (van Aubel, 2024). In Appendix D.2 an overview of the wet cross-section of flow through the current Linne weir complex is given for several upstream water levels. These upstream water levels correspond to discharges measured at Borgharen, as given by the relationship lines in Section A.1.

If a concept's cross-section is smaller than that of a current weir, the flow velocity will increase or the water upstream will rise more than intended - both are undesirable. A concept is considered sufficiently large if its cross-section is equal to or greater than that of the current weir. However, it shouldn't exceed the current weir's capacity too much, as this would require a larger, less sustainable structure. Therefore, the cross-section of each concept should be the same size as the current cross-section or slightly larger. This determination serves as a starting point for concept development, and the concepts are verified to meet the flow requirements, **FR.4** and **FR.7**, in Section 6.2.

Linne weir	
max Δh	4.0 m
Stoney section	
Width	3×17 m
Sill level	NAP + 16.95 m
Top gate	NAP + 20.90 m
Discharge coefficient	0.96
Poirée section	
Width	60 m
Sill level	NAP + 15.95 m
Top gate	NAP + 20.94 m

Table 6.1: Overview technical aspects current Linne weir

6.1.3. Concept A: reference design

This concept is a reference design based on the current weir at Linne. It serves as a baseline for comparing the other three concepts. The reference design answers the question: "How would the current Linne weir be designed if it were built today?". The design is not a replica of the 1925 weir, as it must meet modern requirements and has gained additional functions. However, the reference design does not have a focus on sustainability, which the other three concepts do have.

The reference design will be constructed in the same waterway as the current weir and will use Stoney gates, similar to the existing structure. The Poirée section of the current weir, which allowed vessels to pass when fully opened, is no longer required in the new design, as specified in Chapter 4. Additionally, the Poirée section has higher leakage losses and requires more maintenance than the Stoney section (de Jong, 2014). Therefore, the new design will exclude the Poirée section while keeping the Stoney sections for both precise water level and discharge regulation.

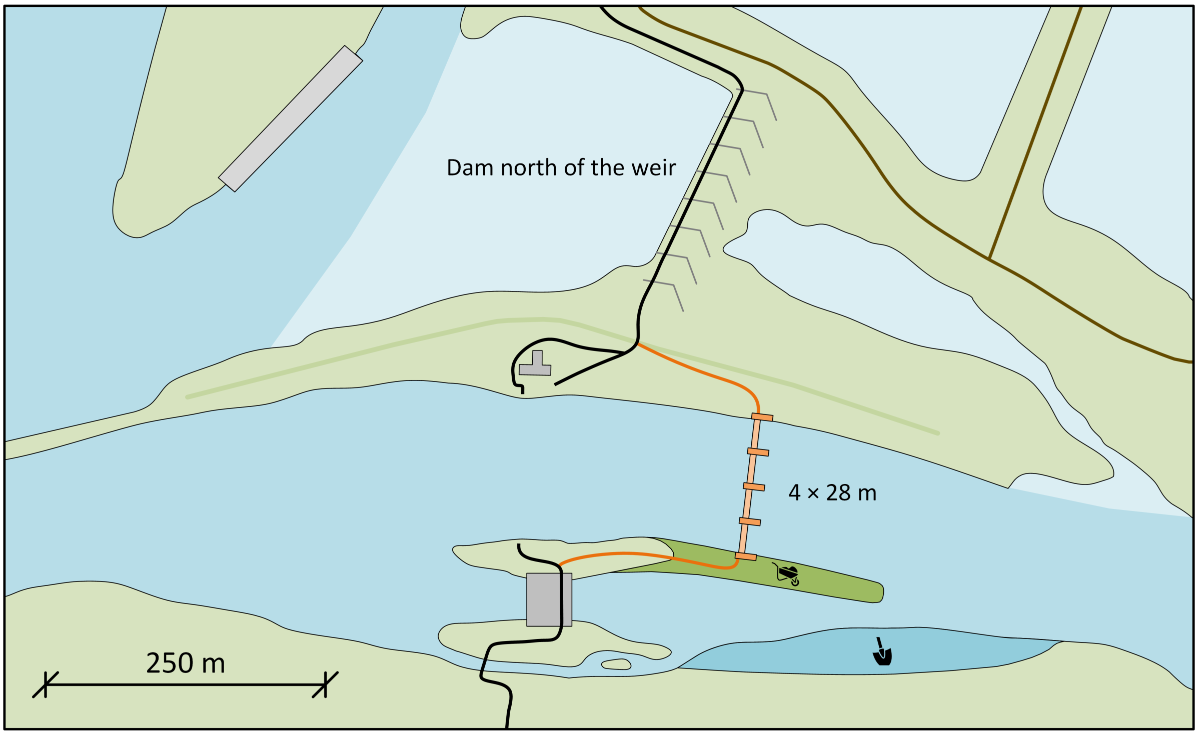


Figure 6.2: Schematisation of concept A

Location and size concept A
The new weir will be located 200 m downstream of the current weir, which must remain operational during construction, see Figure 6.2. Constructing the entire new weir in a single cofferdam is not possible, as it would block the flow. The new weir will make use of Stoney gates and must include at least two openings in order to meet requirement **FR.8**. However, with only two gates, the weir's capacity and the range of water level regulation will be limited if one gate is out of service. The island in the middle of the waterway must also be extended to create a closed waterway and to facilitate parallel flow lines over the weir. Additional land excavation south of the island is required to maintain the hydropower station's functionality, as without it, the opening will be too small.

The new weir's openings can be constructed sequentially in separate cofferdams, allowing water to pass. However, this temporarily reduces the waterway, increasing flow velocity and potentially raising loads on the bed. This can also occur during maintenance. Increasing the number of openings will result in lighter gates with less steel and higher discharge capacity during maintenance. However, this also requires additional piers, narrowing the total available width and increasing concrete use. Based on the analysis in Section D.4.1, it can be concluded that either three or four Stoney openings are optimal considering material usage. However, a weir with four openings is more flexible for both maintenance and water level control as stated in requirement **FR.8**. Therefore, four openings have been chosen for concept A. Each opening is 28 m wide, making the total width 112 m, slightly exceeding the existing Linne weir's width of 111 m. To facilitate sufficient flow through the weir at higher discharges, a sill height of NAP + 16.45 m is needed, which is approximately equal to the current average sill height of the Linne weir, see Table 6.1.

In Section D.2, the calculated wet cross-section for this concept is sufficient. For low discharges, the cross-section is relatively large compared to the current Linne weir. For a discharge of 50 m^3/s at Borgharen and an upstream water level of NAP + 20.85 m, concept A has a 31% increase in wet cross-section. This significant increase is due to the widening of the opening size. Concept A uses the total opening size to regulate the water level for the discharge of 50 m^3/s. The current Linne weir only uses the Stoneys for such low discharges, which have a combined width of 51 m. The effect of this size difference can be calculated using the discharge formula for free overflow, which is derived in Appendix C:

$$Q = \frac{2}{3} \cdot \sqrt{\frac{2}{3} g} \cdot C_D \cdot B \cdot d_1^{\frac{3}{2}} \tag{6.1}$$

The discharge over the weir is dependent on the water depth on the gate, d_1, to the power of $\frac{3}{2}$. If the width of the gate, B, is increased by a factor α, the water depth on the gate must be decreased by a factor $\alpha^{\frac{2}{3}}$ to maintain the same discharge, Q. Thus, increasing the width of the weir will result in a net larger cross-section. This only occurs while the gate is used to regulate the water level. Once the discharge increases and the weir fully opens, the wet cross-section of concept A will be approximately the same as for the current weir.

Gate type concept A
This concept is a reference design, assuming the use of Stoney gates, similar to those at the current Linne weir. The Stoney gates are a type of vertical lifting gate that consist of two leaves that can move independently, allowing for precise water level control. According to the gate type overview in Section D.1, the 28 m opening width is within the acceptable range for this type of gate. For low discharges, the bottom gate rests on the floor at sill height, while the top gate can be adjusted to maintain the correct water level if the discharge fluctuates. If the discharge increases significantly and the top gate cannot be lowered further, additional capacity is required. In such cases, both leaves can be partially lifted out of the water to create an underflow. It is possible for one of the openings to function as an underflow weir, while the other three openings continue to operate as overflow weirs. If the discharge continues to increase, a second gate will also function as an underflow weir, and so on, until the weir reaches its maximum capacity, with all four gates fully lifted out of the water. Each pier and abutment of the weir includes a lifting tower for raising the Stoney gates. As an initial estimate, it is assumed that the lifting towers on the piers between two openings are the same size as those on the abutments at the ends of the weir.

In addition to Stoney gates, there are other gate types that could be used for part of the openings of this concept. For example, two of the four openings could have a visor gate. These visor gates are not suitable for precise water level control, but they would be used to control the discharge, similarly to the Poirée section of the current Linne weir. Additionally, the visor gate has a substantial lower gate mass than a lifting gate for the same span, as highlighted in Appendix D. However, the visor gate does need wider piers and this concept is uses as a reference design. Therefore, it is decided not to incorporate the visor gate into concept A.

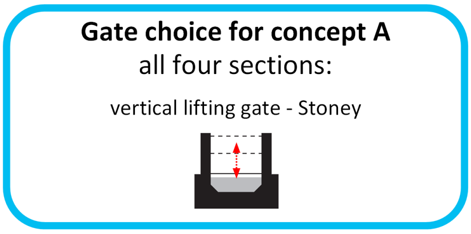


Figure 6.3: Possible gate choice for concept A. Based on (van der Ziel and Dijk, 2010).

Concept A	
New Stoney section	
max Δh	4.5 m
Width openings	4×28 m
Sill level	NAP + 16.45 m
Top gate	NAP + 21.45 m

Table 6.2: Overview technical aspects concept A

6.1.4. Concept B: wide with partly fixed spillway

The goal of concept B is to create a more sustainable design by reducing materials usage. To achieve this, the existing dam north of the current weir is incorporated into the design. The new weir can be constructed in a construction pit around the dam. Two deep weir sections are created in the middle of the dam, see Figure 6.4, to regulate the water level. On both sides of the deep sections, there is a partly fixed spillway that use the dam as a foundation. These spillways are relatively wide sections designed for discharge regulation when it exceeds the capacity of the middle sections. The side sections have a sill at a higher level (NAP + 18.35 m) compared to the deep section (NAP + 17.05 m). As a result, these sections use gates with a lower height and reduced head difference, allowing for different types of gates to be considered, as indicated in the overview in Section D.1.

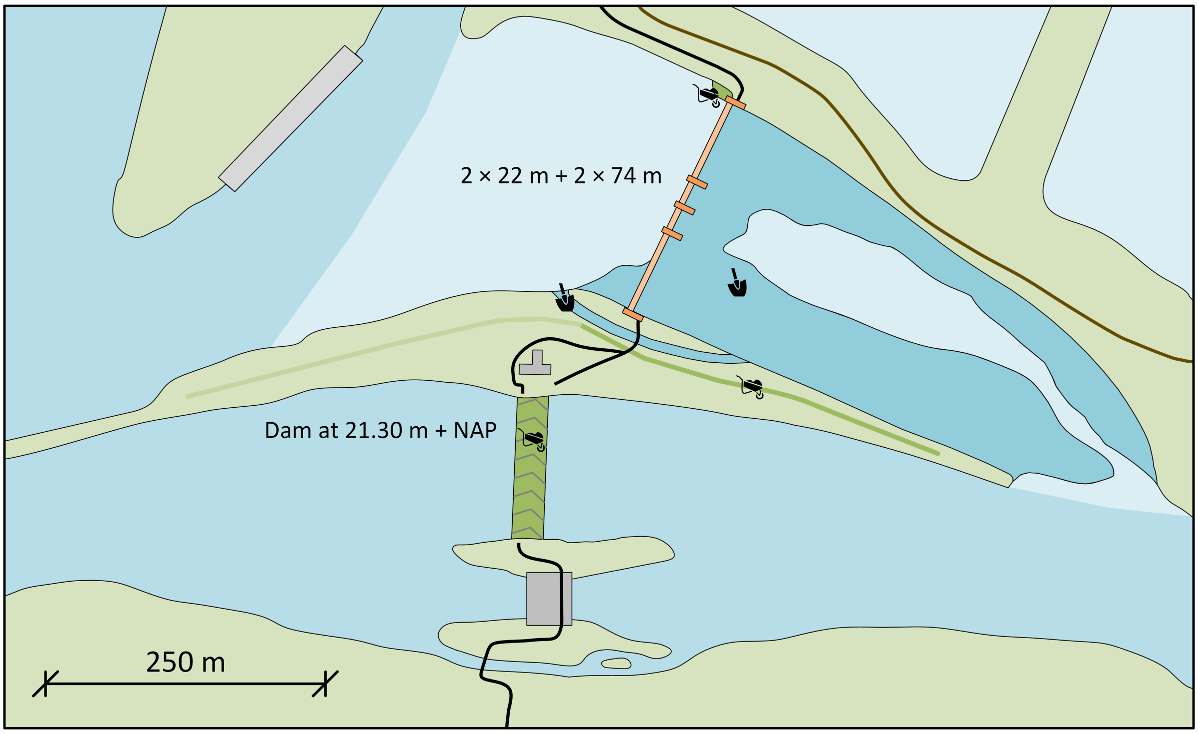


Figure 6.4: Schematisation of concept B

To construct a weir at the dam's location, the waterway must be widened and deepened, requiring considerable soil excavation to ensure sufficient discharge capacity. Part of this soil can be used to build the dam at the site of the old weir once construction is complete. The dam's top will be at NAP + 21.30 m, providing additional discharge capacity if the upstream water level exceeds this height. Additionally, a new fish ladder is needed near the new weir, as the flow through the weir attracts fish, reducing the old fish ladder's effectiveness. Lastly, half of the dike must be moved, see Figure 6.4.

Possible gate types concept B

Figure 6.7 shows potential gate choices for both the deep and wide sections of concept B based on the overview of Section D.1. Concept B is split into two variants: variant B.1 with a visor gate at the wide section and variant B.2 with an inflatable gate at the wide section.

Deep section - water level regulation

The deep section of concept B is used for water level regulation. As discussed in Section 6.1.3, Stoney gates are suitable for concept A, and similarly, they are also a suitable choice for the deep section of concept B. Another gate option is given in the overview in Section D.1: a radial gate with a controllable flap. Unlike Stoney gates, radial gates do not require tall lifting towers, which reduces concrete usage. However, they require strong arms to hold the gate, which increases steel usage. Ultimately, Stoney gates are preferred since they provide a greater range for water level control.

Wide section variant B.1 - discharge regulation

The wide section of concept B is used to create additional discharge capacity if the discharge surpasses the capacity of the deep section. A possible gate type suitable for such a large span is a visor gate as lifting gates are not practical for spans of this size. Visor gates use relatively less material compared to lifting gates or radial gates (van der Ziel and Dijk, 2010). In Section D.4.2 a comparison between Stoney and visor gates supporting this conclusion is made. The span of 74 meters is within the range for which this type of gate can be used (Daniel and Paulus, 2019). In Figure 6.5 a top view of the visor gate is given, with the weir's sill assumed to follow the same semi-circular shape as the visor. The visor gate is loaded in tension and there is a maximum head difference of 2.95 m over the gate. The visor gate can be constructed from steel. Additionally, part of the gate can be constructed using reinforced plastic. This results in both a lower mass of the gate and a lower environmental impact.

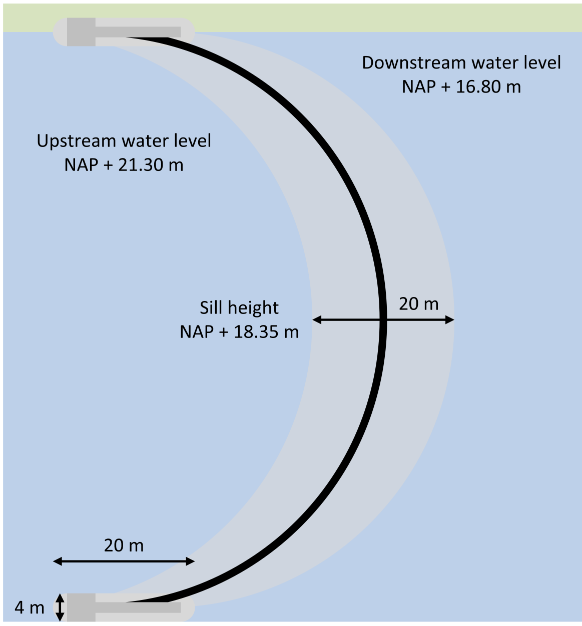


Figure 6.5: Top view of the variant B.1 with a visor gate

Wide section variant B.2 - discharge regulation

Alternatively, a gate supported from its entire bottom can be used, as it has no inherent span limit. An inflatable gate or dam, as shown in Figure 6.6, is a potential alternative to the visor gate. One advantage of this gate type over the visor gate is its lighter weight, since it is made rubber canvas laminated with plastic and rather than steel (U.S. Army Corps of Engineers, 2001). The gate is fully filled with air and has no steel flap on the upstream side. Therefore, it cannot be used to regulate the water level, which is not necessary since the deep section of concept B handles the water level control. The lack of steel flap on the upstream side of the gate, reduces the total weight of the gate. However, a disadvantage is the potential formation of a V-notch when deflating. This can cause the inflatable dam to be locally overflown, which leads to high loads on the downstream bed.

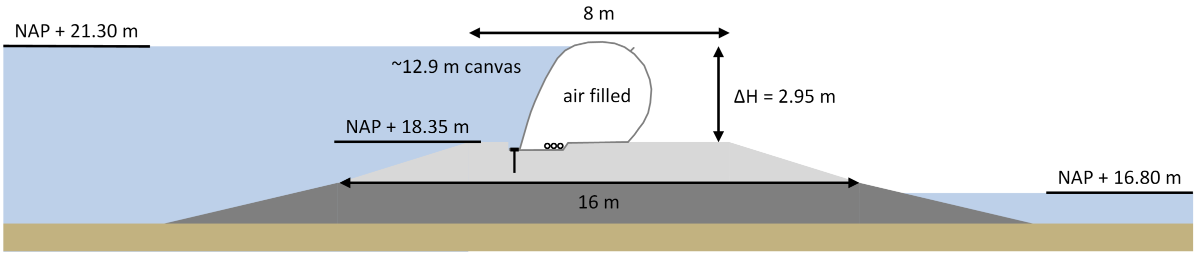


Figure 6.6: Side view of variant B.2 with an inflatable gate

The sizes of the gate, sill and water levels in Figure 6.6 are shown to scale. The figure is used to estimate the required size of the inflatable gate. For a head difference of 2.95 m, the canvas circumference is assumed to be approximately 12.9 m. This circumference is needed to calculate the volume of canvas required, which is then used to determine the gate's total mass in Section D.3.1.

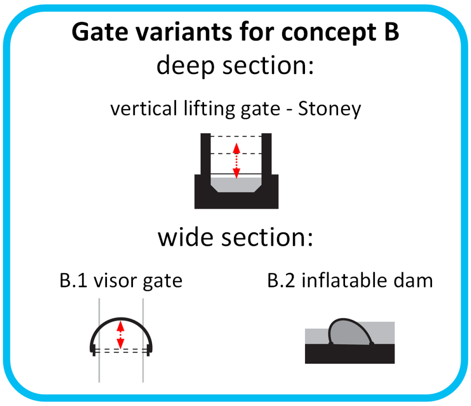


Figure 6.7: Possible gate choices for concept B. Based on (van der Ziel and Dijk, 2010).

Concept B	
Deep weir section	
max Δh	4.3 m
Width openings	2×22 m
Sill level	NAP + 17.05 m
Top gate	NAP + 21.45 m
Wide weir section	
max Δh	2.95 m
Width openings	2×74 m
Sill level	NAP + 18.35 m
Top gate	NAP + 21.45 m

Table 6.3: Overview technical aspects concept B

6.1.5. Concept C: reusing the old foundation

This concept involves reusing the old Linne weir. Reusing part of the old structure contributes to circularity and a lower environmental impact. As stated in Section 1.2.2, the Linne and the other Meuse weirs are reaching the end of their technical lifetime between 2028 and 2035. It is assumed that only the foundation and sill of the current weir could potentially be reused for a new structure, while the piers, lifting towers, gates and all mechanical and electrical parts must be replaced. If the foundation is reused, the new load must not exceed its capacity. Thus, it is assumed that the new weir piers can only be constructed at the locations of the old piers and not elsewhere on the foundation.

Additionally, the current Linne weir must stay operational during the construction of the new weir elements. Therefore, the old sections must be replaced individually within cofferdams placed around each section. This means that when the piers of the Stoney section are being replaced, only one gate can remain operational while the pier between the other two gates is replaced. This approach also makes altering the size of the openings very challenging and more importantly very costly.

At the location of the old Stoney openings, which were three 17 m wide openings, three new openings of the same size will be created. These will continue to be used for precise water level regulation. The Poirée section will also be replaced by an opening of the same size. This new opening will take over the role of the Poirée and be used to create additional discharge capacity. The dam north of the weir will not be changed.

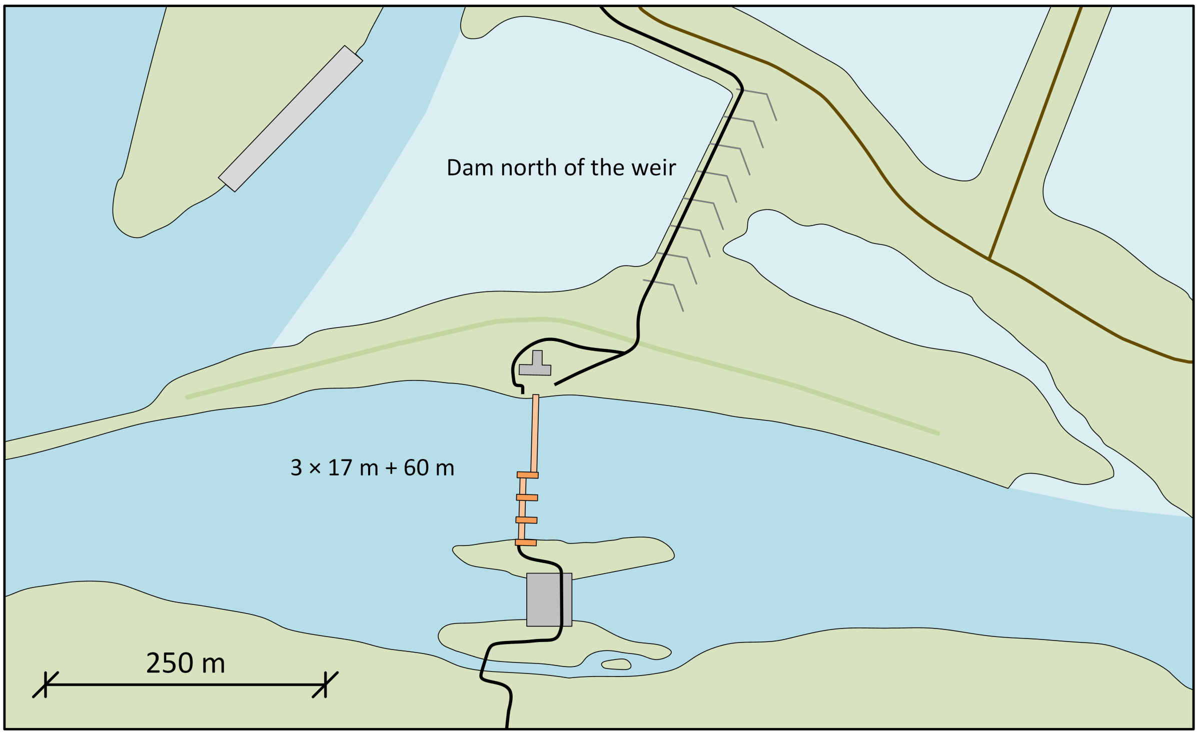


Figure 6.8: Schematisation of concept C

Possible gate types concept C
Similarly to concept B, concept C has two distinct sections: a new section at the old Stoney location, which will be used to regulate the water level, and a new section at the old Poirée location, which will be used to regulate the discharge.

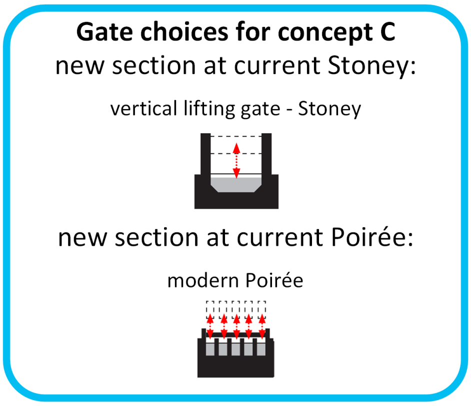


Figure 6.9: Possible gate choices for concept C. Based on (van der Ziel and Dijk, 2010).

Concept C	
New section at old Stoney	
Width	34 m
max Δh	4.4 m
Sill level	NAP + 16.95 m
Top gate	NAP + 21.45 m
New section at old Poirée	
max Δh	4.5 m
Width	60 m
Sill level	NAP + 15.95 m
Top gate	NAP + 21.45 m

Table 6.4: Overview technical aspects concept C

New section at current Stoney - water level regulation
From the possible gate overview in Section D.1, two options are suitable: a vertical lifting gate, such as a Stoney, or a radial gate with an adjustable flap. Similar to the previous concepts, Stoney gates are preferred for their precise water level regulation. The new gates will have the same width as the current Stoney gates but will be taller, as they must dam an additional 50 cm of water.

New section at current Poirée - discharge regulation

The new section at the old Poirée location is 60 meters wide. However, the total head over this weir section is greater than that over the wide section of concept B, making an inflatable gate or flap gate unsuitable. A visor gate is also impractical due to the limited space on the old foundation. Visor gates require relatively more space, because the span is much larger than the opening width and it needs larger piers, both for which there is no room. Additionally, the weight of such a visor gate would be very larger and concentrated on two points when opened. The foundation of the current Linne weir is not designed to handle this load.

Lastly, a modern version of the Poirée could be constructed, allowing for the reuse of the existing rail system and crane. This Poirée section must have significantly lower leakage losses than the current Poirée sections; otherwise, it cannot fulfil requirement **FR.2**: there is a maximum leakage loss of 2 m^3/s. To achieve this, the panels of the Poirée design must be adapted to address the leakage occurring between the panels.

Stability of the new weir on the reused floor

In Appendix E the stability of the new piers and lifting towers on the reused weir floor is checked. This includes potential uplift during construction, as well as the horizontal, rotational and vertical stability of the new piers. The calculations indicate that, given the specified dimensions and boundary conditions, the concept design is stable. However, uplift during construction will be a major challenge.

6.1.6. Concept D: combination fixed spillway and reusing the old foundation

Concept D combines elements from both Concept B and Concept C. It uses the dam north of the current Linne weir as a partly fixed spillway, while reusing the foundation and sill of the weir to construct a new weir section for precise water level control. On top of the foundation of the old Stoney section, three new openings of each 17 m wide will be constructed, similar to concept C. Additionally, a dam will be built on top of the old Poirée section. Between the dam and the new Stoney section, an island is created to ensure parallel streamlines over the weir. For discharge regulation, Concept D includes two wide sections on the old dam. These sections have an increased opening size compared to Concept B, expanding from 74 to 100 meters. However, the sill of these wide sections is 70 cm higher than in Concept B, resulting in shorter piers and gates.

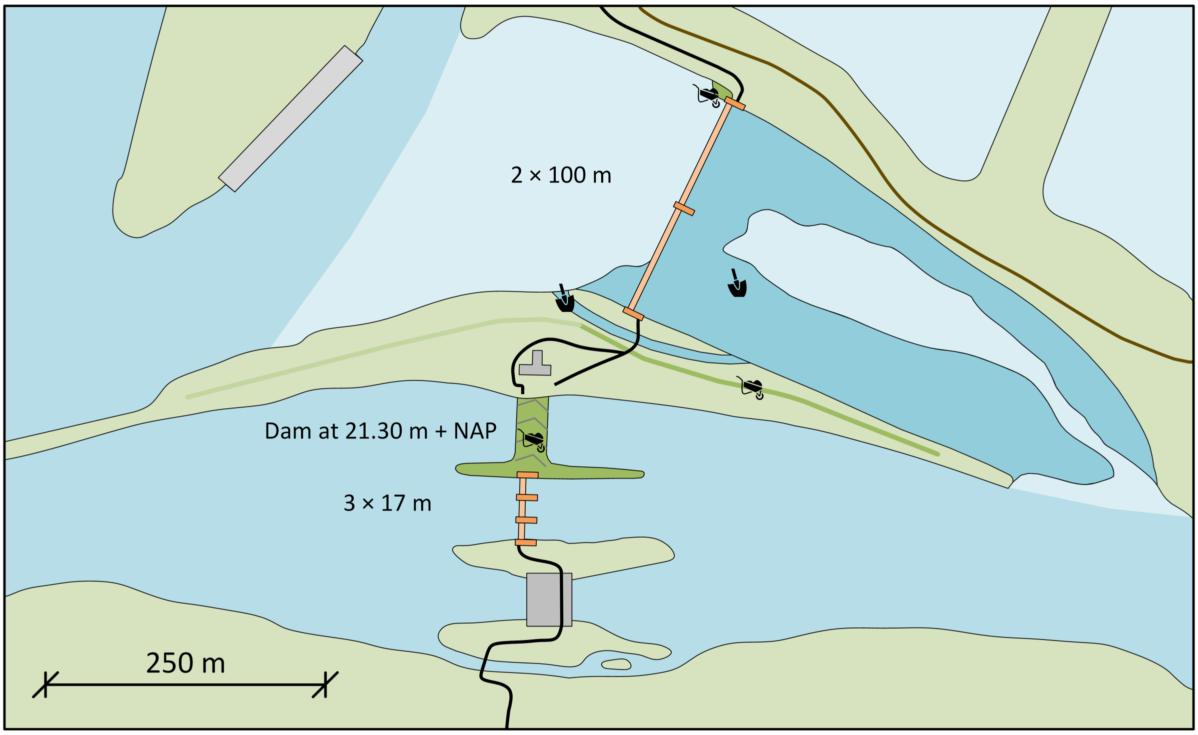


Figure 6.10: Schematisation of concept D

Similar to concept B, this concept also requires the waterway to be widened and deepened. A considerable amount of soil must be excavated to ensure sufficient capacity to regulate the discharge. Some of this excavated soil can be used to create the island and dam at the site of the old weir. The top of this land will be at NAP + 21.30 m. Additionally, a new fish ladder must be constructed near the new weir and half of the dike must be moved, as shown in Figure 6.10.

Possible gate types concept D
Figure 6.7 shows potential gate choices for both the deep and wide sections of concept D based on the overview of Section D.1. Like concept B, concept D is also split into two variants: variant D.1 with a visor gate at the wide section and variant D.2 with an inflatable gate at the wide section.

New section at current Stoney - water level regulation
This section can make use of the same potential gates as the water level regulation section of concept C. The old Stoneys are to be replaced by new piers and new Stoney gates, as these allow for precise water level control. The new gates will have the same width as the current Stoney gates but will be taller, as they must dam an additional 50 cm of water.

Wide section variant D.1 - discharge regulation
Similar to the wide section of concept B, a visor gate is a suitable option for the large span of the wide section in concept D. The 100 m span is at the upper limit of the range for which this type of gate is typically used (Daniel and Paulus, 2019). In Figure 6.5, a top view of the visor gate for concept B is shown. The visor gate for concept D will have the same semi-circular shape and will also be loaded in tension. The sill is positioned at a higher level, with a maximum head difference of 2.30 m over the gate.

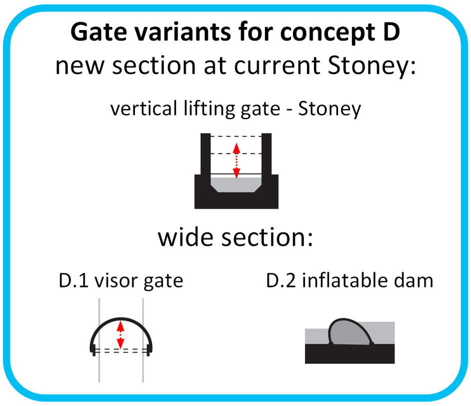


Figure 6.11: Possible gate choices for concept D. Based on (van der Ziel and Dijk, 2010).

Concept D	
New section at old Stoney	
max Δh	4.5 m
Width	3×17 m
Sill level	NAP + 16.95 m
Top gate	NAP + 21.45 m
Wide weir section	
max Δh	2.30 m
Width	2×100 m
Sill level	NAP + 19.05 m
Top gate	NAP + 21.45 m

Table 6.5: Overview technical aspects concept D

Wide section variant D.2 - discharge regulation
Instead, an inflatable gate could be used. Similar to the inflatable gate of concept B, this gate is fully filled with air and has no steel flap on the upstream side. The sizes of the gate, sill and water levels in Figure 6.12 are shown to scale. The figure is used to estimate the required size of the inflatable gate. For a head difference of 2.30 m, the canvas circumference is assumed to be approximately 10.0 m.

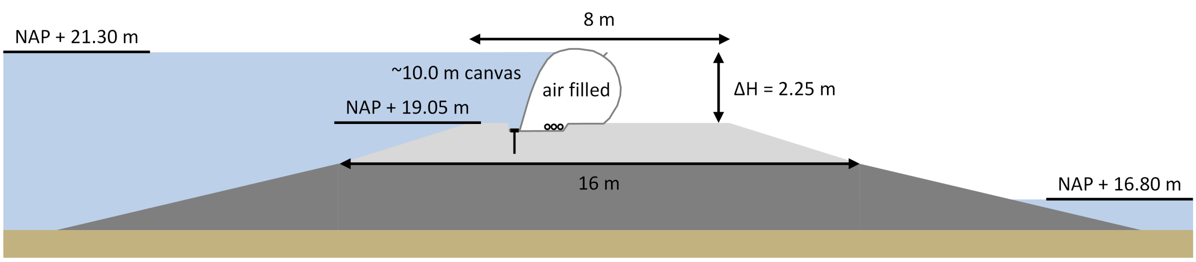


Figure 6.12: Side view of variant D.2 with an inflatable gate

6.2. Verification of concepts

It must be verified that each of the four concepts meets all requirements stated in the basis of design. As specified in Chapter 5, the concepts already meet location requirements **LR.1**, **LR.2**, **LR.3** and **LR.5**. It must still be checked for **LR.4** and all functional requirements. An overview of the verification is given in Figure 6.13.

Location requirement

LR.4: The last location requirement states that the current weir complex must be operable during the construction of the new weir.

- Concept A: This weir is constructed 200 m downstream in the same waterway as the current weir. It is assumed that this distance is sufficient to avoid disrupting the operation of the existing weir. The openings of the concept are constructed in sequentially in separate cofferdams to prevent blocking the entire flow. Therefore, it meets this requirement.
- Concept B: This concept is entirely constructed on top of the dam in construction pit. It is assumed that transport to the dam has no influence on the functioning of the current weir. This concept also meets the requirement.
- Concept C: The entirety of this concept must be constructed on the foundation of the current weir, which must remain in use. This is a very difficult challenge as each opening must be replaced one at a time. Replacing a pier between two Stoney openings means that only one of the three Stoney openings can be operational at a time. For now, it is assumed that the current weir can function with just one Stoney gate and the Poirée section for a limited period. However, the feasibility of this should be analysed in a further study.
- Concept D: The wide section of this concept is also constructed on top of the dam in a construction pit. However, the new gates at the old Stoney section face the same challenges as the new weir in concept C. These gates must be replaced before the Poirée section. It is assumed that regulating the water level with one old Stoney gate and the new visor or inflatable gate is not feasible. Thus, the Poirée section must remain operational until the entire new weir is constructed. As with Concept C, it is currently assumed that this requirement can be met.

	Concepts			
Requirements	A	B	C	D
LR.4: The current complex must be able to operate during the construction of the new weir	✓	✓	✓	✓
FR.1: The dammed level of the weir is at NAP + 21.35 m	✓	✓	✓	✓
FR.2: There is a maximum leakage loss of 2 m^3/s	✓	✓	~	✓
FR.3: The weir has a design lifetime of 100 years	✓	✓	✓	✓
FR.4: The weir operates up to a discharge of 1400 m^3/s	✓	✓	✓	✓
FR.5: Fish must be able to bypass the weir	✓	✓	✓	✓
FR.6: The weir forms a fixed road connection over the Meuse	✓	~	✓	~
FR.7: The weir has sufficient discharge capacity to prevent flooding	✓	✓	✓	✓
FR.8: The weir has at least two openings for precise water level regulation	✓	✓	✓	✓

Figure 6.13: Verification of the design concepts based on the LR.4 and the functional requirements. The concepts meet most of the requirements. However, there are three points of concern, indicated by a ' '.

Functional requirements

FR.1: The first functional requirement states that the dammed level of the weir is at NAP + 21.35 m. This is essential to storing enough water in the upstream basin to use during droughts. However, this also increases the head difference over the weir, limiting the suitable gate types.

- Concept A, B, C & D: For each concept the dammed level of NAP + 21.35 m is achieved. The head over each gate is within the possible margins. In both the wide section of Concept B and Concept D, part of this head difference is redirected via the sill to the foundation and the dam on which it is built.

FR.2: This requirement states that the weir must have a maximum leakage loss of 2 m^3/s, which is also crucial for maintaining the water stored in the upstream basin. Based on the conceptual design it can not be fully verified whether all concepts meet this requirement, as the leakage loss partially depends on design choices that will be made in later steps of the design process, which are not part of case study. Therefore, assumptions will be made on the available information.

- Concept A, B & D: Both the Stoney and visor gates must have effective seals on all sides to prevent leakage, but with a single contact point between the bottom of the gate and the sill, it is assumed that this requirement can be met. The inflatable gate is expected to be watertight when fully inflated. However, there is a risk of a V-notch forming when deflating. Leakage must not occur during periods of low discharge, but the gate will remain inflated during these periods.
- Concept C: As mentioned in Section 3.2.3, the Poirée section of the current Linne weir has significant leakage losses. Concept C aims to reuse the current weir's foundation to construct an modern version of the Poirée. This concept can only meet the requirement if the new Poirée has been adapted to reduce the leakage losses. A possible adaptation is to add rubber seals around the individual gate panels. A further analysis is needed to determine whether this solution could be implemented effectively.

FR.3: The weir must have a design lifetime of 100 years. During the generation of design concepts this design lifetime is used. However, it can be fully verified during the structural design, which is not part of this case study.

FR.4: This requirement states that the weir operates up to a discharge of 1400 m^3/s. This has been verified by comparing the wet cross-section of the design concepts to the wet cross-section of the current Linne weir in Section D.2. All cross-sections are deemed sufficient. Thus, the concepts meet this requirement.

FR.5: To meet this requirement fish must be able to bypass the weir.

- Concept A & C: In both concepts the original fish ladder will keep its functionality, allowing fish to bypass the weir.
- Concept B & D: For these concepts, an additional fish ladder will be constructed, also allowing fish to bypass the weir.

FR.6: To requirement states that the weir must form a fixed road connection over the Meuse. Non of the design concepts feature a bridge, since this functionality must be incorporated into the design in the next step of process.

- Concept A & C: It is assumed that a bridge for pedestrians and cyclists can be constructed on the piers of these weir concepts. For Concept C, this would resemble the current situation. For Concept A, the bridge supports would be spaced further apart, but it is assumed that the 28 m span is manageable.
- Concept B & D: These concepts have openings of 22 m and 17 m, respectively, which could potentially be spanned by a bridge. However, they also include wider openings of 74 m and 100 m. While these larger spans could technically also be spanned by a bridge without additional supports, by using an arch or suspension design. This would need a lot of extra materials, which goes against the goal of combining the functions of the weir and bridge.

FR.7: To meet this requirement the weir must have sufficient discharge capacity to not induce flooding during events of high river discharge. This has also been checked during the comparison of wet cross-sections. Therefore, all concepts meet this requirement.

FR.8: The last functional requirement states that the weir must have at least two openings for precise water level regulation. All concepts meet this requirement.

Conclusion of the verification
From the verification, it can be concluded that concept A meets all the location and functional requirements. Both concept B and D also meet all the requirements. However, it should be noted that the addition of a fixed road connection in these designs could result in a lower sustainability value, as these concepts feature very wide weir openings. Lastly, concept C can meet all requirements if the modern version of the Poirée is adapted to minimise leakage loss.

6.3. Evaluation of concepts

In this section, all concepts will be evaluated based on the four evaluation criteria, as derived in Section 4.2, using a multi-criteria analysis (MCA). A distinction is made between each concept variant, resulting in a total of six variants being evaluated. Both the sustainability and non-sustainability criteria are assessed together to produce an integral score for each variant. Since not all criteria are equally important, they are weighted accordingly, with the most important criteria receiving higher weights. Applying these weights results in a weighted score that reflects the relative importance of the different aspects.

6.3.1. Weights of evaluation criteria

The weights of the evaluation criteria (both sustainability and non-sustainability) are determined using basic pairwise comparison. The criteria are arranged in a square matrix, see Figure 6.14. In this matrix, each pair of criteria is compared to assess their relative importance for the weir design. This is a subjective process.

In the pairwise comparison, the more important criterion in each pair is given a score of '1'. For instance, if Criterion A is deemed more important than Criterion B, A receives a score of '1' over B. Conversely, B receives a score of '0' for being less important than A. The scores for each criterion are then summed across rows to rank them. To determine the weights, the scores are doubled. The least important criterion, which scores the lowest, is assigned a weight of 1. Finally, the weights are normalised so that their total equals 1. Using the weighted evaluation criteria, the created concepts can be evaluated.

Criteria \ Criteria	EC.1	EC.2	EC.3	EC.4	Total	Weight	Weighting factors
EC.1 MKI value		1	1	1	3	6	6/13 ≈ 0.461
EC.2 Operational reliability	0		1	1	2	4	4/13 ≈ 0.308
EC.3 Ease of maintenance	0	0		1	1	2	2/13 ≈ 0.154
EC.4 Nuisance during construction	0	0	0		0	1	1/13 ≈ 0.077
						Σ = 13	Σ = 1

Figure 6.14: Weighting factors for the four evaluation criteria

- **MKI value (6/13):** The goal of the sustainability guideline is to support the most sustainable decision-making. In this case study, the guideline is applied to create the most sustainable weir design. Therefore, the MKI value, as the quantifiable criterion to assess the sustainability of the concepts, is given the highest weight.
- **Operational reliability (4/13):** The second highest weight is assigned to the criterion of operational reliability, as it is crucial throughout the weir's entire lifetime for all stakeholders who depend on the weirs functionality, such as RWS, the water boards and the shipping industry.
- **Ease of maintenance (2/13):** Ease of maintenance is primarily important for RWS and the contractor responsible for the work. However, since maintenance will recur throughout the weir's lifetime, users may also be negatively affected by disruptions during these periods.

- **Nuisance during construction (1/13):** This criterion is assigned the lowest weight, as construction represents only a small portion of the weir's entire lifetime. Therefore, any nuisance caused during construction is temporary.

For each criterion, the variants are assigned a relative score on a scale from 1 to 5, where 1 is the worst score, 2 indicates a poor score, 3 is considered average, 4 signifies a good score and 5 is the best possible score. These scores are used together with the weights to form a single score for each variant, displaying the total value of that variant.

6.3.2. MKI value (EC.1)

Overview of the MKI per concept

In Appendix D the total MKI value of the design is calculated for each concept and its variants. In Figure 6.15 and Table 6.6 an overview of the MKI in €1,000 euro is given. The final MKI value for each variant is a rough estimate and does not accurately reflect the MKI if the variant were to be built. It is only used for comparing the variants against each other.

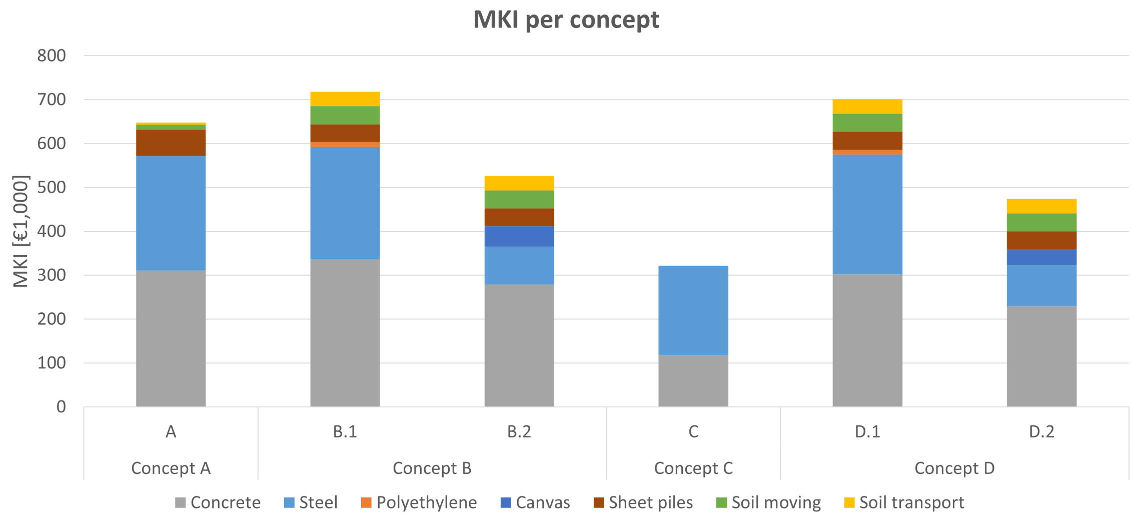


Figure 6.15: Overview of the MKI per concept as calculated in Appendix D

For all variants except concept C, concrete usage is the largest contributor to the total MKI score. Unsurprisingly, concept C has the lowest MKI, as it uses the least concrete by reusing the foundation of the existing Linne weir. Steel usage is the second largest contributor to the total MKI score across all the concepts. Both variant B_2 and D_2 have a noticeably lower MKI score than their counterparts, as these variants incorporate an inflatable gate. Lastly, the contributions from sheet piles and earthworks form a significant portion of the total MKI, creating a noticeable difference between concept A and variants B_1 and D_1.

MKI [€1,000]	**Concept A**	**Concept B**		**Concept C**	**Concept D**	
	A	B_1	B_2	C	D_1	D_2
Concrete	310.7	337.3	278.8	119.1	302.1	228.7
Steel	260.8	255.7	86.7	202.5	273.2	94.9
Polyethylene	0	10.4	0	0	10.9	0
Canvas	0	0	46.3	0	0	35.9
Sheet piles	59.9	40.8	40.8	0	40.8	40.8
Soil moving	12.1	41.1	41.1	0	40.8	40.8
Soil transport	4.6	32.7	32.7	0	33.1	33.1
Total MKI	648	718	526	322	701	474
Given MCA score	3	2	4	5	2	4

Table 6.6: Overview of the MKI per concept as calculated in Appendix D

Material impact on MKI

Some conclusions can be drawn about the impact on the MKI of three main design choices, as outlined in the guideline for the exploratory phase.

- Reuse is effective: Reusing the floor of Linne reduces the MKI of concept C by approximately 50% compared to concept A, the reference design.
- Gates have a significant impact: Steel gates, like those used in the current Meuse weirs, contribute 30% to 40% of the total MKI over the weir's lifetime. Since gate designs can be modified or improved in various ways, they offer a great opportunity for increasing sustainability. The assumed design lifetime of the weir is 100 years, while steel gates last only 50 years. This means that renovating the gates once would account for 15% to 20% of the total MKI of a new design. Therefore, if the concrete superstructure remains in good condition, renovation is a highly sustainable option.
- Inflatable gate as an alternative: Designs incorporating an inflatable gate have an MKI roughly 20% lower than concept A. While this reduction is smaller than that achieved through reuse, it is still significant.

From MKI to MCA score

Each variant's MKI value is converted into an MCA score between 1 and 5. This conversion inevitably results in some loss of nuance between variants. For instance, variants B_2 and D_2 both receive the same MCA score despite having an 11% difference in their MKI values. However, given the many estimations and assumptions involved in calculating the MKI, these scores should already be considered an approximation.

- Concept A: This concept is a reference concept. It serves as a baseline for comparing the sustainability of the other concepts. Therefore, this design is given a score of 3 for the MKI value and it is used to give the other designs a relative score.
- Variant B_1: This variant of concept B has the highest MKI value of all designs. However, the difference between this variant and concept A is smaller than the difference between concept A and C. Therefore, it is given a score of 2.
- Variant B_2: This variant of concept B has a below average MKI value that lies close to the average of concept A and C. Thus, it is given a score of 4.
- Concept C: This concept has by far the lowest MKI value, less than half the score of concept A, which has an average score. Since it scores the best by far, it is given a score of 5.
- Variant D_1: This variant of concept D has an MKI value that is very close to the value of variant B_1. Therefore, it is also given a score of 2.
- Variant D_2: This variant of concept D has an MKI, which is a bit lower than variant B_2. However, it does not nearly score as good as concept C. Therefore, it is also given a score of 4.

6.3.3. Operational reliability (EC.2)

The operational reliability of the variants is scored based on the type and amount of gates it has. For an indication of the reliability of a gate type both the analysis of gate types for weir design by Daniel and Paulus (2019) and the analysis of gate types by Van der Ziel and Dijk (2010) are used.

- Concept A: This concept only has Stoney gates, a type of vertical lifting gate. These gates are considered to have good reliability. Thus, this concept scores a 4.
- Variant B_1: This variant features Stoney gates and visor gates. Both gate types are considered to have good reliability. Thus, this variant scores a 4.
- Variant B_2: This variant features Stoney gates and an inflatable gate. In contrast to both the Stoney and visor gates, inflatable gates are considered to have average reliability. Therefore, this concept scores a 3.
- Concept C: This variant features Stoney gates and a Poirée gate. The Poirée gate is also considered to have good reliability. Therefore, this concept scores a 4.

- Variant D_1: This concept features the same gate types as variant B_1 and almost has the same number of gates. Therefore, it also scores a 4.
- Variant D_2: This concept features the same gate types as variant B_2 and almost has the same number of gates. Therefore, it also scores a 3.

6.3.4. Ease of maintenance (EC.3)

The ease of maintenance depends on the gate types feature in the variant. Again, the scores are based on the two analyses.

- Concept A: This concept only has Stoney gates, a type of vertical lifting gate. These gates are considered to require an average amount of maintenance. Therefore, this concept scores a 3.
- Variant B_1: This variant features Stoney gates and visor gates. Both gate types are considered to require an average amount of maintenance. Thus, this variant also scores a 3.
- Variant B_2: This variant features Stoney gates and an inflatable gate. In contrast to both the Stoney and visor gates, inflatable gates require less maintenance. Therefore, this concept scores a 4.
- Concept C: This variant features Stoney gates and a Poirée gate. The Poirée gate is considered require a lot of maintenance. Therefore, this concept scores a 2.
- Variant D_1: This concept features the same gate types as variant B_1 and almost has the same number of gates. Therefore, it also scores a 3.
- Variant D_2: This concept features the same gate types as variant B_2 and almost has the same number of gates. Therefore, it also scores a 4.

6.3.5. Nuisance during construction (EC.4)

The nuisance during construction depends on the location of the weir concept and the construction method used. It is assumed that both variants of concept B score the same and both variants of concept D also score the same.

- Concept A: This concept is construction in separate cofferdams downstream of the current weir. This will partly block the flow of the waterway, but compared to both concept C and D, this concept scores above average, a 4.
- Concept B: This concept can entirely be constructed in a construction pit in a separate waterway. Therefore, this concept scores a 5.
- Concept C: This concept must be constructed within cofferdams around the current weir. One of the challenges is that when the piers of the Stoney section are replaced, only one gate can remain operational while the pier between the other two gates is replaced. As a result, this concept scores a 1.
- Concept D: This concept can partially be constructed in a construction pit in a separate waterway. However, the other part must be constructed within cofferdams around the current weir. This concept scores a 3.

6.3.6. Final MCA scores

Table 6.7 provides an overview of the scores for each variant across all criteria. These scores are weighted using the respective fractional weighting factors to calculate a final MCA score. A score of 1 represents the worst result across all criteria, where as a score of 5 represents the best. A score of 3 indicates an average results compared to the other variants. This provides a clear overview of where the final MCA scores fall on the scale.

Concept C scores the highest on the MCA, mainly due to its lowest MKI value combined with good reliability. Concept B follows closely in second place, as it also has a low MKI value. Variant D_1 scores the lowest, as it fails to achieve a low MKI and also scores poorly on **EC.4** due to being constructed very close to the current weir.

		Concept A	Concept B		Concept C	Concept D	
		A	B_1	B_2	C	D_1	D_2
EC.1	MKI value ($\frac{6}{13}$)	3	2	4	5	2	4
EC.2	Operational reliability ($\frac{4}{13}$)	4	4	3	4	4	3
EC.3	Ease of maintenance ($\frac{2}{13}$)	3	3	4	2	3	4
EC.4	Nuisance during construction ($\frac{1}{13}$)	4	5	5	1	3	3
	Weighted score	3.38	3.00	3.77	3.92	2.85	3.62

Table 6.7: Overview of weighted MCA scores

Value-cost ratio variants

The last step after the evaluation is determining the relative cost of the concept value by plotting the weighted MCA scores against the construction costs in a value-cost graph. The construction costs of the designs can be viewed as a condition that must be met in order to create the corresponding value. The costs depend on several factors, of which a few are discussed below.

- Main dimensions: These are the most important factors in determining construction costs. The main dimensions considered are the width and height of the weir, as well as the head difference over the weir. These values are known for each variant, and based on them, a rough estimation of the construction costs can be made using the following equation (Jonkeren et al., 2010):

$$\text{Total construction costs} = W \cdot H \cdot \Delta h \cdot 30,000 \quad [\text{euro}] \tag{6.2}$$

  Where:
  W [m] : The total width of the weir
  H [m] : The height of the weir
  Δh [m] : The head difference over the weir

- Gate mechanism and material: The choice of gate type (e.g., Stoney gates, visor gates, inflatable gates) affects the cost, as it influences the type and amount of material needed. However, this is not taken into account by Equation 6.2. No adjustments to the equation will be made to incorporate the gate type, as there is insufficient reference data to accurately do so.
- Construction method: The exact effect of the methods used to construct the weir designs in the variants cannot be fully estimated with only the conceptual design given in Section 6.1. However, it is assumed that the designs incorporating elements from the current weir will be more difficult to construct, leading to higher construction costs. For concept C, an increase of 10% is assumed, as the entire weir is constructed on the old foundation. For both variants of concept D, an increase of 5% is assumed, as only part of the weir is built on the old foundation.
- Location of the project site: The location of the weir affects transportation and logistics costs. Additionally, it influences the cost of creating temporary facilities at the project site. However, for this case study, the project site location is the same for all variants, so this factor does not need to be considered when comparing construction costs.

Equation 6.2 is used to estimate the construction costs of the weir variants. Concept B, C and D all consist of two separate weir sections with different dimensions. For these variants, the costs of both sections are calculated separately and then summed. Additionally, a 10% increase is applied to concept C and a 5% increase is applied to both variants of concept D. In Table 6.8 an overview of the construction costs for each variant is given, alongside their relative scores. The relative score is calculated using the following equation:

$$\text{Relative score} = \frac{\text{Weighted MCA score}}{\text{Construction costs [mln euro]}} \cdot 100 \quad [10,000 \text{ euro}^{-1}] \tag{6.3}$$

		Concept A	Concept B		Concept C	Concept D	
		A	B_1	B_2	C	D_1	D_2
Weighted MCA score	[-]	3.38	3.00	3.77	3.92	2.85	3.62
Construction costs	[mln €]	89.1	77.5	77.5	92.7	79.4	79.4
Value-cost ratio	[10,000 $€^{-1}$]	3.79	3.87	4.87	4.23	3.59	4.56

Table 6.8: Overview of weighted MCA scores

In Figure 6.16, the weighted MCA scores of the variants are plotted against the estimated construction costs. For both concepts C and D, the graph also shows the assumed increase in costs due to the chosen construction methods.

Conclusions concept evaluation
Using the concept evaluation, it has been determined that concept C is the most sustainable design variant, as it has the lowest MKI while meeting all requirements. Additionally, concept C scores the highest absolute MCA score, indicating that, when all evaluation criteria are considered integrally, it is the best option for a new weir at Linne. However, when the estimated construction costs are taken into account, both variants B_2 and D_2 score higher relative MCA scores than concept C. The difference between B_2 and D_2 is negligible given the accuracy of the calculations. Either of these variants is considered to be the best alternative to concept C.

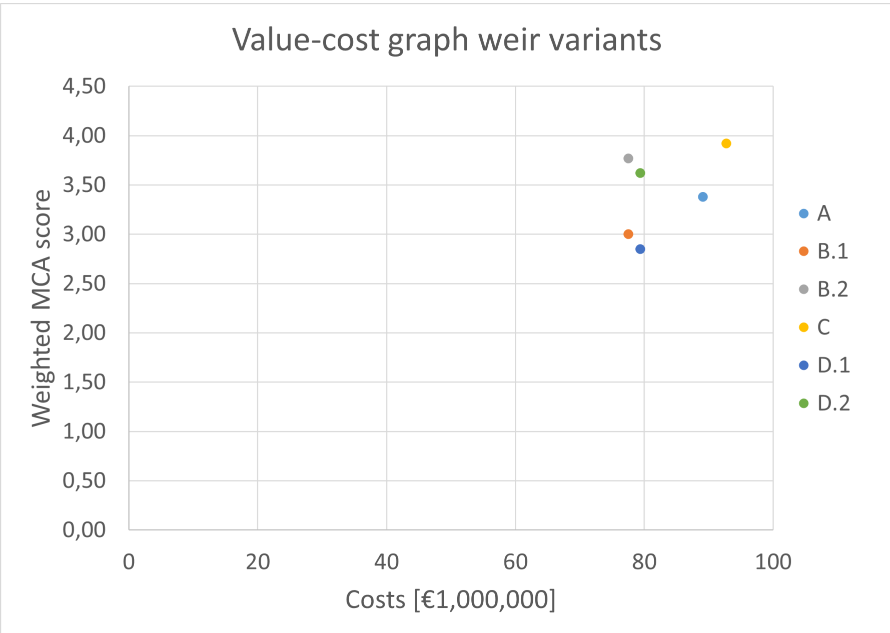


Figure 6.16: Value-cost graph for the weir variants

For concept C and both variant B_2 and variant D_2, there is an additional point of concern, considering the requirements, see Figure 6.13. For concept C it is assumed the maximum leakage loss of 2 m^3/s (**FR.2**) is achievable with an adapted Poirée weir. However, this will most likely be a challenging goal. In contrast, variant B_2 and D_2 could both include a fixed road connection over the Meuse (**FR.6**). However, this would require a bridge with a span of 74 m and 100 m respectively, or additional supports in the waterway. This will likely result in higher material usage compared to the material usage of the bridge using the weir in concept C. An alternative approach would be to reconsider requirement **FR.6** and decide that a bridge should only be included if its MKI is acceptable. However, this would need to be investigated in further analysis.

Taking these considerations into account, it is believed that variants B_2 and D_2 have the greatest potential to be used as a sustainable weir design for Linne.

7 Guideline generalisation and validation

7.1. Generalisation

In Chapter 3 through 6 the sustainable weir guideline has been applied to a case study for the Linne weir. The Linne weir is part of a system of seven weirs, which regulate the water level of the Meuse. This case study provided several insights into the practical application of the guideline, which allows for making a generalisation. In this section, three expanded uses are considered: applying the guideline to weirs outside the Meuse, designing new weirs instead of replacements and adapting it for other types of hydraulic structures such as navigation locks, sluices or barriers.

7.1.1. Weir locations outside of the Meuse

The motivation for developing the guideline was the system of Meuse weirs reaching the end of their functional and technical lifespan. This poses a significant risk to the river ecosystem, water management and navigation along the river. The first consideration in the generalisation is the use of the guideline for weir locations other than the Meuse weir system.

The guideline has been shaped by the motivation described in Section 1.1, but it has no reliance on principles or decisions directly tied to the Meuse itself. Therefore, it the use can be extended to other weir locations. The core sustainability considerations related to material usage and circularity, environmental impact, reusability of the old weir, ecological effects and spatial quality are generally applicable to other river systems.

7.1.2. Newly build weirs instead of replacements

While the guideline has been developed for the replacement of existing weirs, it can be extended to the design of newly constructed weirs. However, there are some limitations. An overview of these limitations for each phase of the guideline is provided below:

- Pre-exploratory phase: The focus of this phase is on determining the necessity of a new structure. The presence of an existing weir is therefore assumed. The most sustainability value is gained by maintaining or renovating the existing structure, preserving its value. Constructing a new structure is considered less sustainable. These considerations do not apply when there is no existing weir to replace. Thus, most of this part of the guideline is irrelevant for newly built weirs.
- Exploratory phase: This phase assumes that a weir will be replaced, focusing on identifying the most sustainable design decisions with the lowest environmental impact. For a newly built weir, much of this phase remains the same, except for the reuse of old weir parts, which is a major sustainability measure in replacement projects.
- Plan development phase: The plan development phase remains largely unchanged. The main difference is the consideration of what to do with the old weir, which is not relevant in the case of a new construction.
- Tendering and execution phase: No significant changes are needed in this phase.

7.1.3. Other types of hydraulic structures

The guideline has been developed specifically for weirs. However, with specific adaptations it could be applied to other hydraulic structures, such as navigations locks, dams, sluices or barriers, as these structures share many similar elements and design choices. Additionally, the main sustainability and circularity principles remain the same across these structures. Below is an overview of the required adaptations for each phase of the guideline:

- Pre-exploratory phase: No significant changes are needed in this phase.
- Exploratory phase: The three design choices central to this phase may differ for other structures. Additionally, the potential value gained by incorporating other functions will vary for different types of structures, as these functions are specifically formulated for weirs. Lastly, while the quantifiable sustainability themes used in the evaluation are expected to stay the same, the specific qualitative themes relevant to structures other than weirs will differ. As an example, during the design of a lock more emphasis might be placed on energy consumption and flow efficiency, while during the design of a dam more focus is placed on long-term ecological impacts.
- Plan development phase: The additional considerations made during this phase regarding the qualitative sustainability themes will also differ between various structures.
- Tendering and execution phase: No significant changes are needed in this phase.

7.2. Validation

The final step in developing the guideline for sustainable weir design is its validation. By validating the guideline, its relevance and applicability to weir design projects can be confirmed. It is checked whether it is a valuable tool for creating more sustainable weir designs. The guideline was validated through reviews by three specialists: a sustainability expert and a hydraulic engineer from Royal Haskoning DHV and a technical advisor from Rijkswaterstaat. In the overview below a summary of the validation is given. The final version of the guideline can be found at the very end of this document.

7.2.1. Feedback on the guideline

General feedback on the guideline

- The guideline provides a helpful overview of how to incorporate sustainability throughout the entire design process from a technical viewpoint. Additionally, it can serve as a useful tool to explain this process to stakeholders. However, for this purpose, it would be beneficial if the guideline included more practical examples of measures and design decisions, as well as reference projects, in which these measures have been taken.
- At the start of each of the four phases a main question is posed. However, during the guideline it is not specified what type of answer is to be expected and where exactly in the guideline this answer is obtained. Therefore, the guideline should be adapted to include the expected outcomes of each phase.

Pre-exploratory phase

- The steps of this phase of the guideline align with the RWS ”Vervanging en Renovatie” (VenR) [Replacement and Renovation] project. However, it must be noted that maintenance and renovation themselves should also be evaluated. For instance, it may be the case that renovation is not yet necessary and maintenance is sufficient, but choosing renovation could be more sustainable if maintenance involves materials with a high environmental impact.
- After the decision to replace the weir is made, the guideline specifies the need to determine both the functions and boundary conditions to be used during the exploratory phase of the design. However, the requirements and evaluation criteria, especially those for assessing sustainability, should also be specified before the concept designs are made. This is not explicitly mentioned. If the evaluation criteria are specified at a later stage, they may be influenced by design choices made during the generation of the concepts. This prevents a fair comparison of the alternatives and makes it difficult to identify the most sustainable option.

- Lastly, it is mentioned in the guideline that combining the functions of multiple objects when they are replaced can be a sustainable practise. However, a distinction can be made between combining functions of different types of objects and combining functions of multiple weirs in a system, which could reduce the total amount of weirs needed. Both decisions should be made after the scope of the replacement project is determined.

Exploratory phase

- The guideline suggests choosing a single concept after evaluation. However, the potential of the concepts to gain additional sustainability value during the plan development phase, should be considered. It is possible for certain alternatives to score a lower estimated value based on the evaluation during the exploratory phase, but have a bigger potential and surpass the other concepts in value during the plan development phase. Therefore, in order to find the most sustainable design, the potential of the concepts must already be considered during the exploratory phase. It is assumed that determining the exact potential of the concepts is not feasible, as this would require a detailed design for each concept. Therefore, expert judgment is needed to estimate it.

Plan development phase

- During the plan development phase the design is refined and detailed. Therefore, the guideline includes an additional evaluation at the end of this phase. This evaluation must include at least the same quantifiable and qualitative criteria as used during the exploratory phase.
- A general optimisation of materials is carried out during this phase. However, this optimisation should be linked to the exploration of alternative materials that can be used, as some materials may have a higher environmental impact per unit but enable design optimisations that reduce overall material use, resulting in a more sustainable design. This link was absent in the guideline.

Tendering and execution phase

- In order to effectively include sustainability during tendering and execution as an incentive, construction and maintenance must both already be considered during the plan development phase.

7.2.2. Validated and updated guideline

The feedback from the three experts consulted during the validation has been used to improve the guideline. Some feedback fell outside the initial scope set for the guideline. This feedback was not incorporated into the guideline itself but was considered in the discussion and recommendations in Chapter 8. Other insights helped to refine the guideline's structure, which is directly visible in the updated version presented at the end of this document. Finally, their feedback helped increase the guideline's applicability by adding several additional steps and considerations.

8

Discussion, conclusions and recommendations

8.1. Discussion on results

Technical and political viewpoints
The guideline for sustainable weir design has been developed from a technical viewpoint, assuming that decisions are based primarily on technical design aspects. In the first phase of the guideline, this is visible in the systematic approach used to determine whether replacing the existing weir is necessary. However, in practice, these decisions are often influenced by political factors. If a structure no longer meets its functional requirements and has reached the end of its functional lifetime, it is also possible to change the functional requirements. If the required performance standards are lowered, the structure may still be considered acceptable and its remaining technical lifetime could be used.

Accuracy of the MKI calculation
The MKI is the main quantifiable indicator that is used to determine the sustainability value of a design. It is used to compare the sustainability of the design alternatives. However, every MKI calculation depends on multiple assumptions, which affect the accuracy of the calculation. For a conceptual design the following considerations are crucial to estimate the MKI and the ability to compare alternatives:

- The gate weight contributes a significant part of the total MKI of the design variant. Therefore, the estimation of the gate weight, which depends on the weight of reference gates, has a large influence on the MKI value. Consequently, an error in the values used for the weight of these gates, could lead to quite big differences in the final MKI score of each concept.
- The MKI data used in the calculation is category 3 data. This is brand-independent information compiled by experts based on international databases. However, these 'default' values are considered conservative estimates. For example, a fixed distance is assumed for the transportation of the elements. When a more refined calculation is performed, it is possible that the MKI turns out to be higher or lower.

MKI 'costs' versus construction costs
The weir construction costs are plotted on a value-cost graph, see Figure 6.16. The environmental impacts of the designs, measured in MKI, are included as values in the multi-criteria analysis (MCA). However, the MKI is also expressed as a monetary value. It takes into account the environmental impact of numerous different impacts, such as CO_2 and nitrogen. In order to compare these impacts to each other, a monetary 'weighting factor' is used. During the evaluation of the case study the monetary value of the MKI is not used as indication of costs involved during the construction. Therefore, it is justified to used both values in the value-cost graph.

Reliability and availability of the weir gates
During the concept generation of the case study several sources have been used to determine the suitability of possible gate types for the weir. The gate type has a significant influence on the reliability and availability of the weir for both main functions: regulating water levels and buffering water upstream. For each gate type featured in the case study an initial assumption is made in order to compare the

types in a MCA. Increasing the amount of reference data used would improve the accuracy of these assumptions. However, since the assumptions are based on average statistics — also from gates not specifically used in weirs — more detailed reliability studies are necessary to refine the comparison.

Quantitative and qualitative criteria
The sustainability aspects of weir design have been categorised using 10 themes, which are used to assess the sustainability of the design. A distinction is made between evaluation criteria and requirements, both of which can be either quantitative or qualitative. In the case study, the themes materials and circularity, energy and climate mitigation and environmental effects were combined into a single quantifiable criterion, the MKI, to numerically express the sustainability of the design concepts. Other themes were used to set functional requirements. These include climate adaptation, ecology and accessibility.

Additionally, some themes could be used to formulate qualitative evaluation criteria, such as social relevance, spatial quality, well-being and health and utilisation of space. However, using qualitative evaluation criteria requires input from stakeholders. Since it was not possible to consult stakeholders for the case study, these themes were not included in the evaluation and only the quantitative evaluation criteria were used.

8.2. Thesis conclusions

8.2.1. Conclusions on the development and validation of the guideline

The goal of this thesis was to develop a sustainable weir design guideline. This guideline has been applied in a case study to design a new sustainable weir for Linne. Several conclusions can be drawn from the development and validation of the sustainable weir design guideline:

- **Start with sustainability:** The most sustainability value can be gained at the beginning of the project when decisions have the most impact on the design. As the project progresses and design choices are made, the ability to influence sustainability outcomes diminishes. Below is an estimate of the order of magnitude of emissions that can be prevented in each phase, based on the results of the case study.
  - Pre-exploratory phase: During this phase the necessity of replacing the weir is determined. Maintaining or renovating an existing weir can reduce emissions by approximately 80% to 95%, as primarily steel elements and electronics are replaced, and no new concrete superstructure is needed.
    - The case study shows that steel gates contribute 30% to 40% of the total MKI of a design for its entire lifetime. Therefore, renovating steel gates once could extend the weir's lifetime for 15% to 20% of the total MKI of a new design, see Section 6.3.2.
  - Exploratory phase: In this phase, the greatest sustainability value can be achieved by exploring design alternatives that minimise material use. This can be further improved by integrating the surrounding land into the design. If a new weir is required, the potential for emission reduction is lower but still significant. Emissions can be reduced by approximately 40% to 50% in this phase.
    - From the case study it can be concluded that reusing the floor the Linne weir can reduce the total MKI of the design by 50%, see Section 6.3.2.
  - Plan development phase: In this phase, the design is optimised and various material types are considered to reduce the caused emissions. However, as the most impactful design decisions have already been made, the potential for further emission reductions is limited. It is estimated that only a 10% to 15% reduction in emissions can be achieved at this stage.
    - The case study suggests that replacing parts of the retaining elements of a gate with plastic can help reduce emissions. In the case of the visor gate, the MKI of the gate itself could be reduced by 26%, see Table D.4. Additionally, although not applied in the case study, the concrete superstructure could also be optimised. Therefore, an estimated 10% to 15% reduction of the total MKI should be achievable in this phase.

- Tendering and execution phase: In this phase, the design is finalised, and material selection is confirmed. The ability to influence emissions reduction is limited during this phase, but optimising construction processes can still yield some sustainability improvements. A reduction of approximately < 5% in emissions can be achieved during this phase, mainly through sustainable construction practices.
  - This phase was not part of the case study. However, the main opportunity for emission reduction in this phase lies in the use of emission-free construction equipment. It is assumed that this will contribute only a small portion of the total reduction. The case study shows that emissions from earthworks and soil transport account for only about 2.5% of the total MKI. Of course, emission-free construction equipment can also reduce the MKI of other activities involved in constructing the weir itself.

- **Consider concept potential:** To maximise sustainability, a concept's potential to gain additional value during the plan development phase must already be considered in the exploratory phase. As making a detailed design for every concept is unfeasible, expert judgment should be used to estimate this potential. Concepts with high sustainability potential should be developed further in the exploratory phase.
- **Guideline for other hydraulic structures:** The motivation for developing the guideline is the ageing of the Meuse weirs. However, it has no reliance on decisions directly tied to the Meuse itself. Therefore, the use can be extended to other weir locations. Additionally, the guideline can be adapted for use with other hydraulic structures, such as navigation locks, dams, sluices or barriers, as these structures share many similar elements and design choices. The main sustainability and circularity principles remain consistent across these structures, although specific measures and evaluation criteria must be adapted to apply the weir design guideline to them.
- **Helpful overview and tool:** Based on the validation conducted with three experts in Chapter 7, it can be concluded that the guideline provides a helpful overview of how to incorporate sustainability throughout the entire design process from a technical viewpoint. Additionally, it can serve as a useful tool to explain this process to stakeholders.

8.2.2. Additional conclusions from the case study

Several additional insights were gained from the Linne case study:

- **Reuse old weir floor:** Reusing the weir floor of Linne results in the lowest MKI score. However, building on top of the floor while the old weir remains operational will lead to extra construction difficulties. Therefore, it can not immediately be said that this is the best option, if sustainability is integrally taken into account, especially considering the temporary structures required for the construction. Additionally, the feasibility of this design concept entirely depends on the reusability of the floor. While the case study assessed the floor's stability, it did not evaluate the structural strength of the concrete to be reused. This is necessary in order to determine whether the floor can be reused. When reusing the Linne weir floor, ensuring the stability during the removal of the old pier is crucial, as for the assumed schematisation, there is a risk of uplift.
- **Inflatable gate as alternative:** An inflatable gate is a sustainable alternative to steel gates when used for discharge control, as its significantly lower weight results in a reduced total MKI for the design. Additionally, leakage losses are minimal since the gate is fully watertight. However, it is not suitable for precise water level control and cannot be used for the entire weir. Therefore, it is best combined with a vertical lifting gate. In the Linne case study, the area north of the weir offers space for constructing the new weir. The increased width of this area allows for a higher weir floor, reducing the head difference over the gate and making it a suitable location for an inflatable gate.

8.3. Recommendations

- **Apply the guideline:** Apply the sustainable weir design guideline in renovation and replacement projects. The guideline should be used from the start of the project as a tool to keep an overview of the most important sustainability considerations.

- **Reuse concrete elements when replacing:** From the case study it was concluded that reusing concrete elements from the old structure can lead to a major reduction in MKI, making it a very interesting method for creating a sustainable weir. This does depend on the reusability of these elements, which differs case by case. Therefore, it is recommended to investigate the reusability of concrete elements of weirs that are to be replaced. Additionally, the impact of the temporary structures required for the construction must be investigated, as they can offset the sustainability benefits of reuse.
- **Expand pre-exploratory phase of guideline:** Based on the validation of the guideline it is recommended to expand the pre-exploratory phase of the guideline. In the final version of the guideline presented at the end of this document, both maintenance and renovation are considered as distinct options for extending the technical or functional lifetime of a weir. However, evaluating these options simultaneously could lead to a more sustainable outcome. This ensures that maintenance is not automatically chosen when renovation—though not yet necessary—would be the more sustainable choice in the long term.
- **Consult stakeholders to incorporate qualitative sustainability themes:** As previously discussed, several sustainability themes relevant to weir design require input from stakeholders to effectively be taken into account. Therefore, potential stakeholders should be identified during the pre-exploratory phase, with some being consulted in the exploratory phase. Delaying stakeholder consultation to a later stage could result in overlooking some sustainability aspects or needing to make design adaptations that are difficult or costly to implement.
- **Consider reliability and availability during design:** A final recommendation is to consider reliability and availability during the design phase, as these aspects are not included in the guideline itself.

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A. Data boundary conditions

A.1. Relationship lines

Table A.1: The water level directly up- and downstream of the weir at Linne given the measured discharge at St. Pieter and the discharge at Borgharen (Rijkswaterstaat, 2023).

St. Pieter	Borgharen	Linne u	Linne d
Q	Q	h	h
m^3/s	m^3/s	m + NAP	m + NAP
80	50	20.85	16.86
155	125	20.85	16.91
280	250	20.84	17.16
530	500	20.81	17.83
1030	1000	20.67	18.96
1280	1250	20.52	19.36
1500	1470	20.40	19.54
1722	1700	20.69	19.83
2113	2100	21.32	20.47
2512	2500	21.82	21.18
2813	2800	22.15	21.63
3211	3200	22.55	22.10
3608	3600	22.86	22.50
4101	4100	23.18	22.86
4511	4500	23.37	23.09

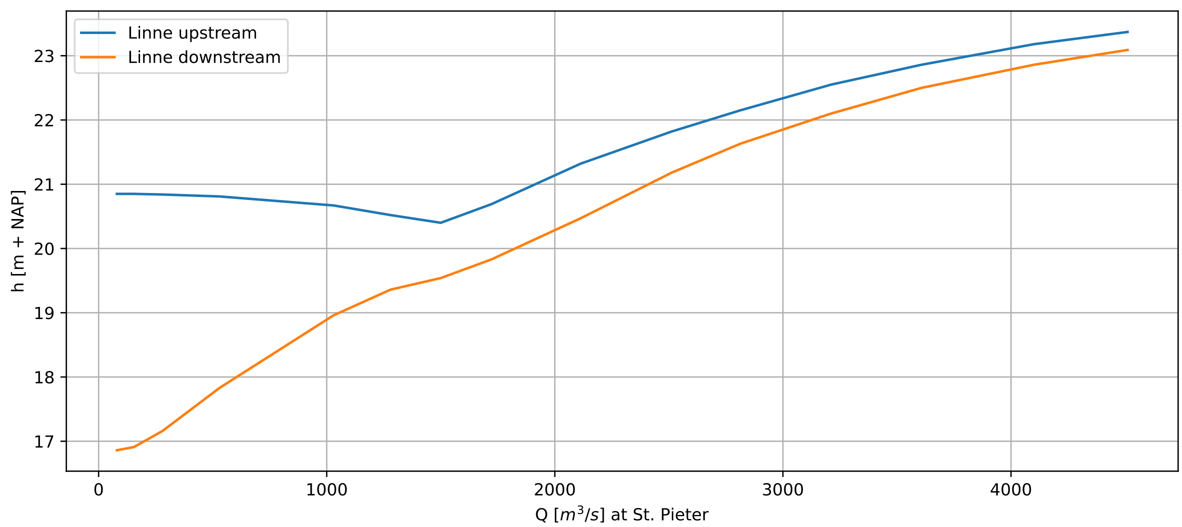


Figure A.1: Relationship lines indicating the water level directly up- and downstream of the weir at Linne given the measured discharge at St. Pieter.

A.2. Subsurface data

This data was gathered at a distance of 1000 meters from the weir complex and 100 meters from the Meuse bed.

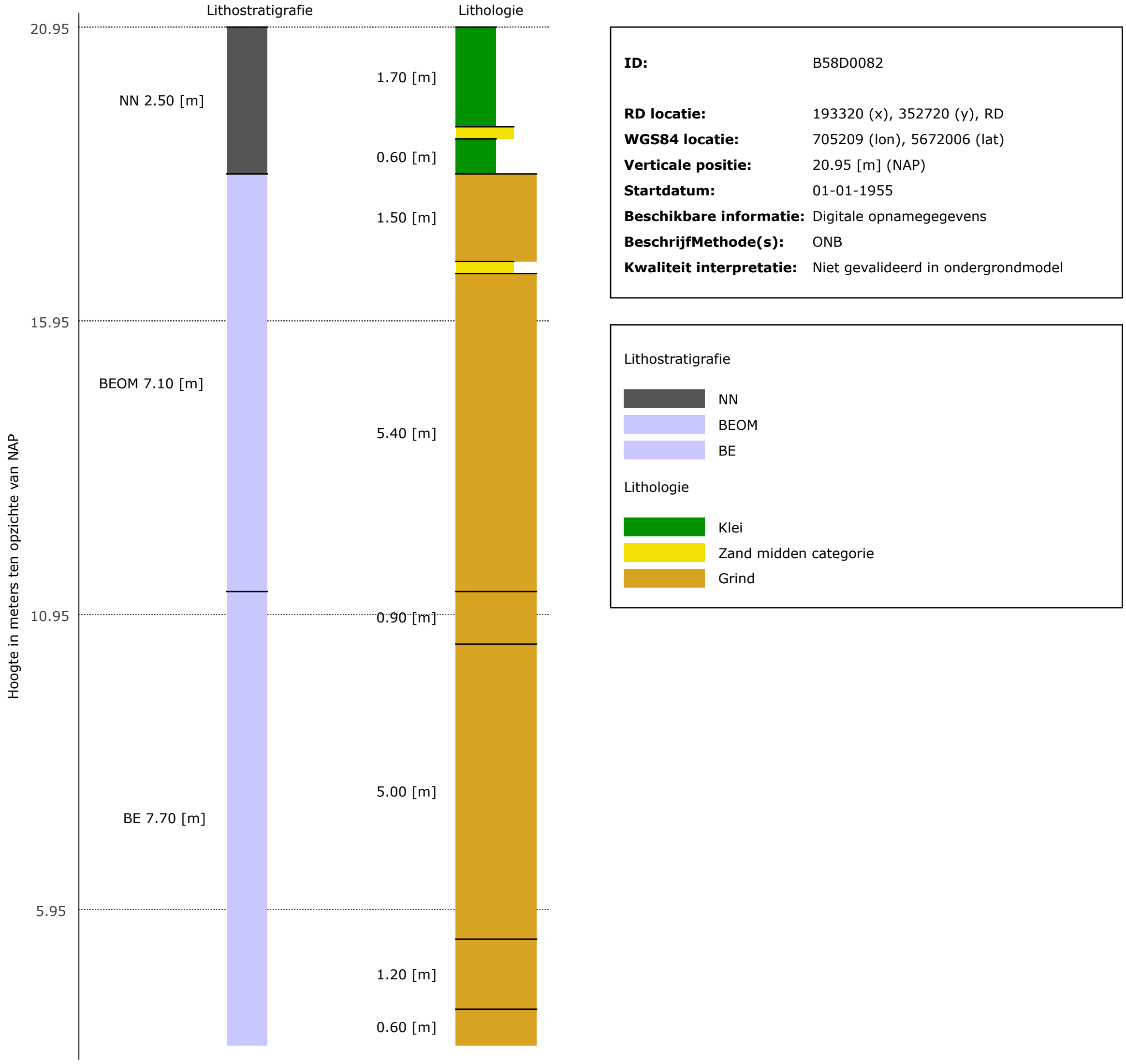


Figure A.2: Lithology near the Linne weir (DINOloket, 2024)

This data was gathered at a distance of 500 meters from the weir complex and 250 meters from the Meuse bed.

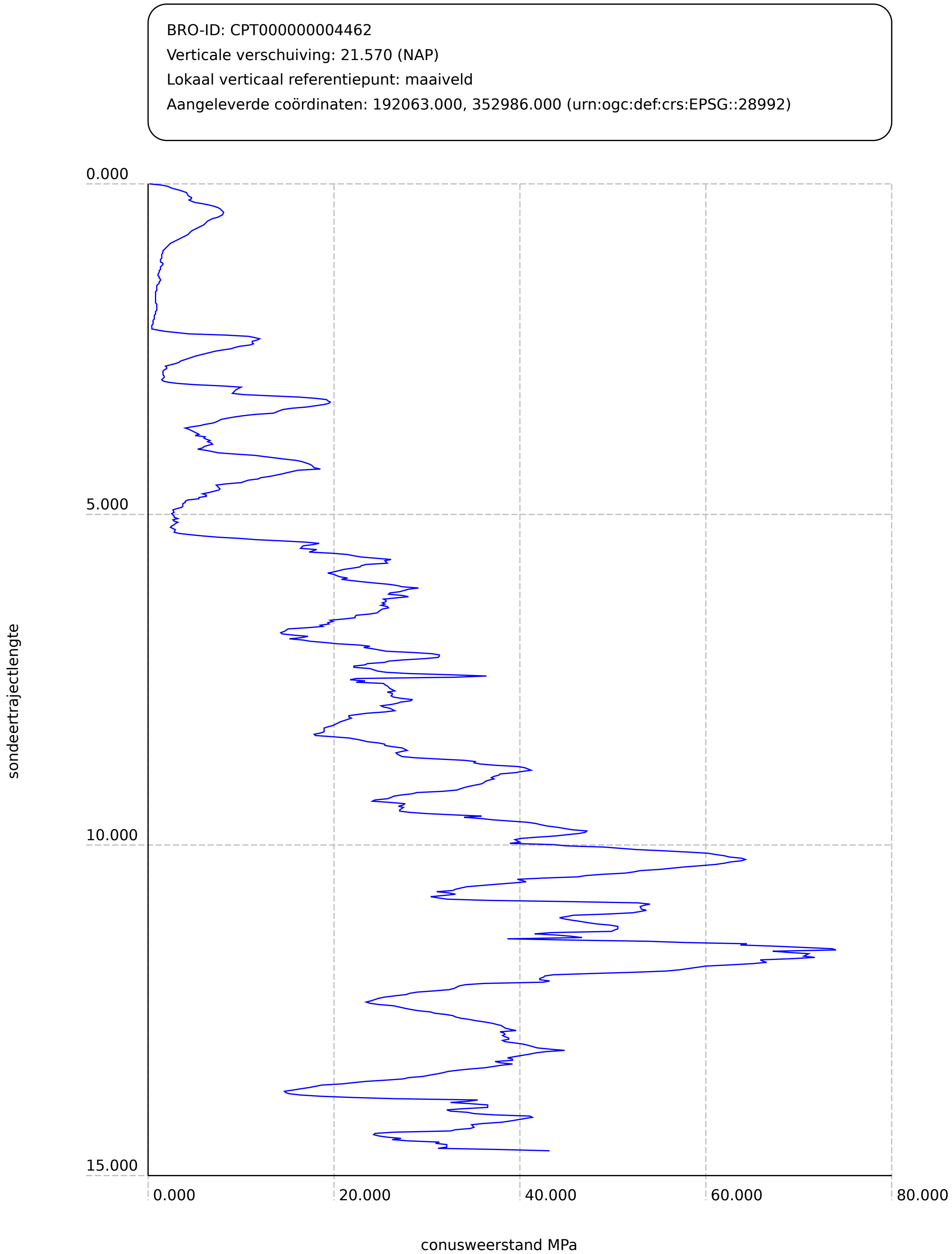


Figure A.3: Results of the CPT near the Linne weir (DINOloket, 2024)

B. Technical drawings of the current Linne weir

This appendix includes several technical drawings of the current Linne weir. Figure B.1 shows the Stoney gates of the weir at various discharge levels, as well as the Poirée gate when fully upright.

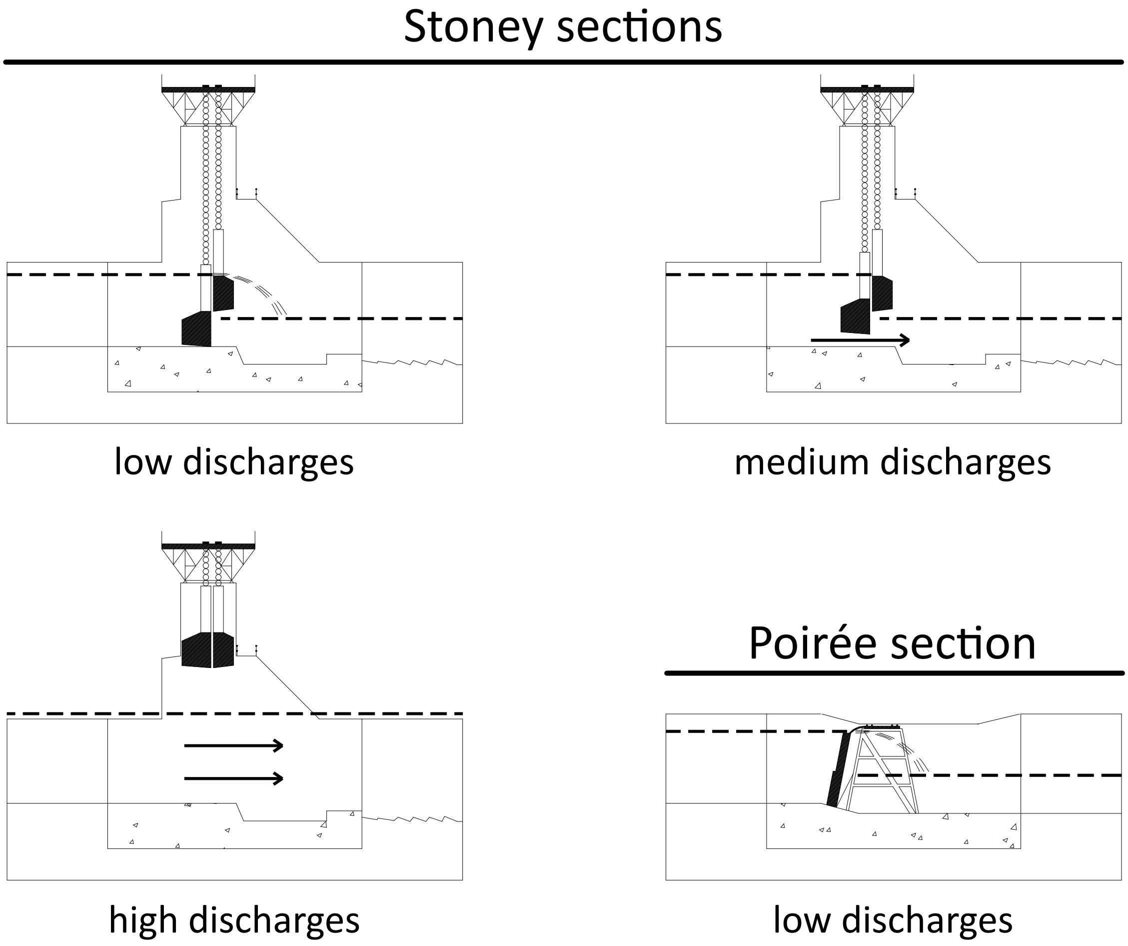


Figure B.1: Technical drawing of the Linne weir, flow through the sections of the Linne weir for different discharges, adapted from (Janssen, 1998)

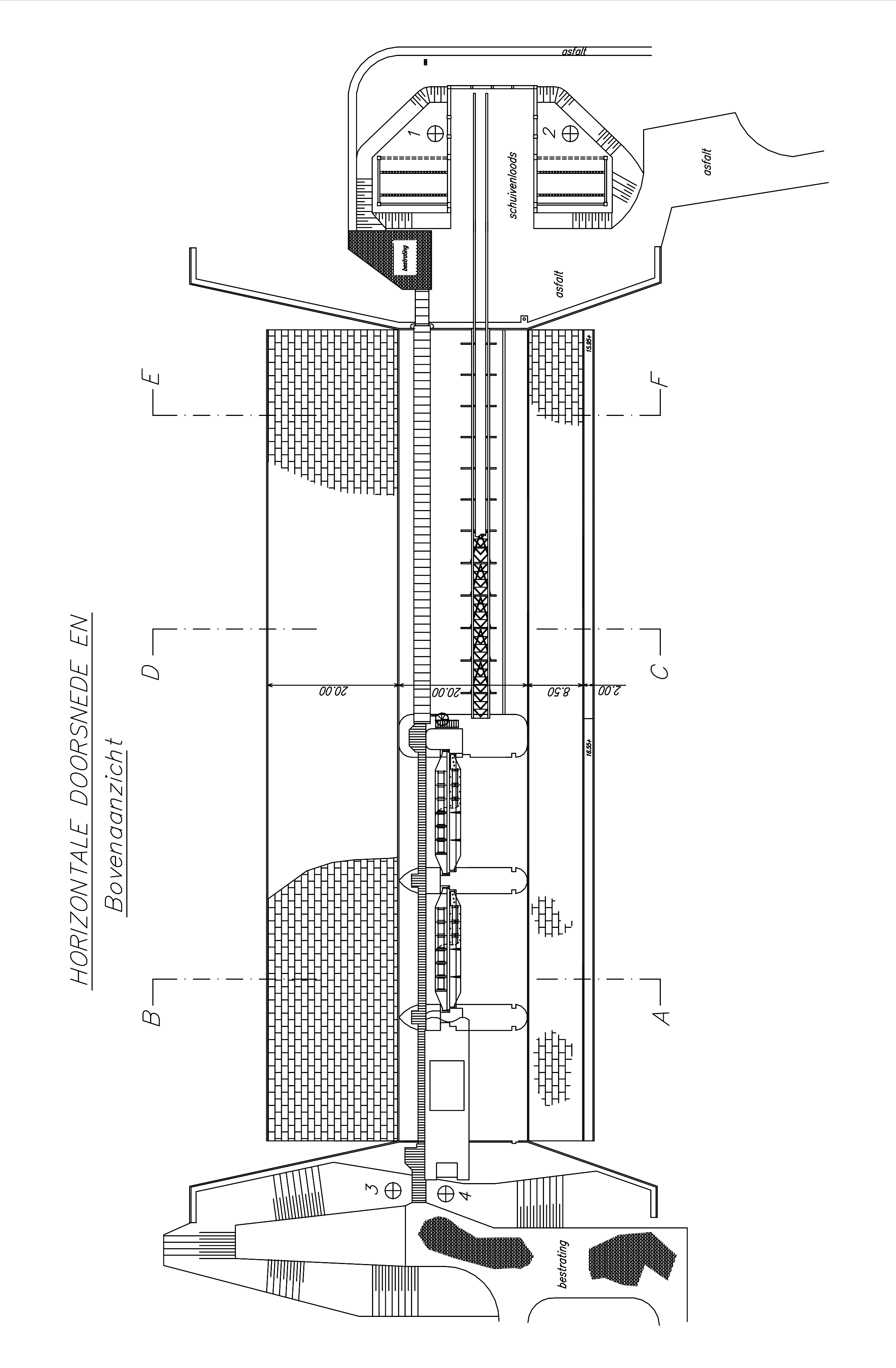


Figure B.2: Technical drawing of the Linne weir, top view, adapted from (Janssen, 1997)

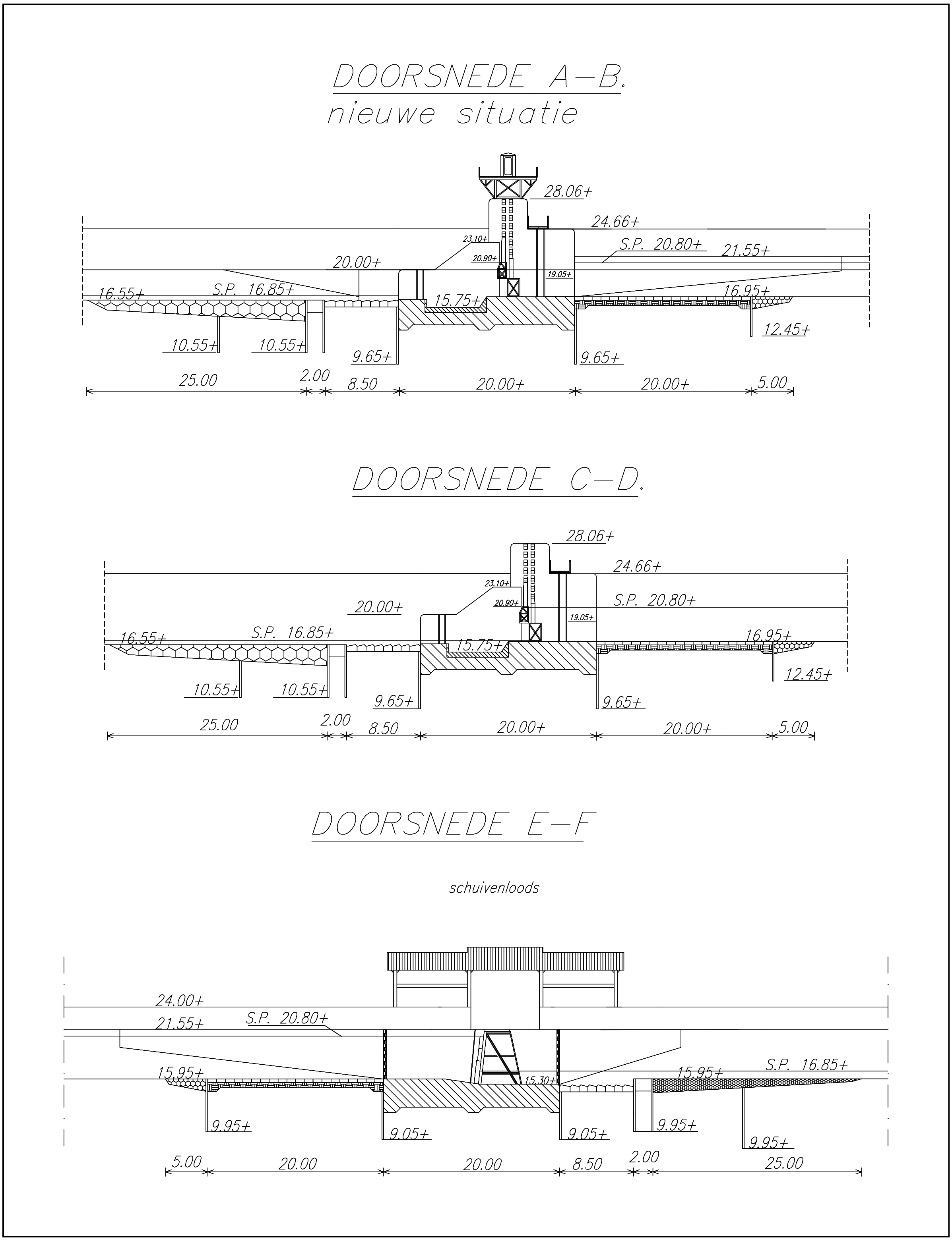


Figure B.3: Technical drawing of the Linne weir, cross-section of the locations marked in Figure B.2, adapted from (Janssen, 1997)

C. Weir flow

The gates of a weir regulate both water level and discharge. Two types of flow are distinguished: overflow and underflow. Overflow weirs are ideal for controlling the upstream water level, whereas underflow weirs are best for managing the discharge through the weir. Both types are depicted in Figure C.1.

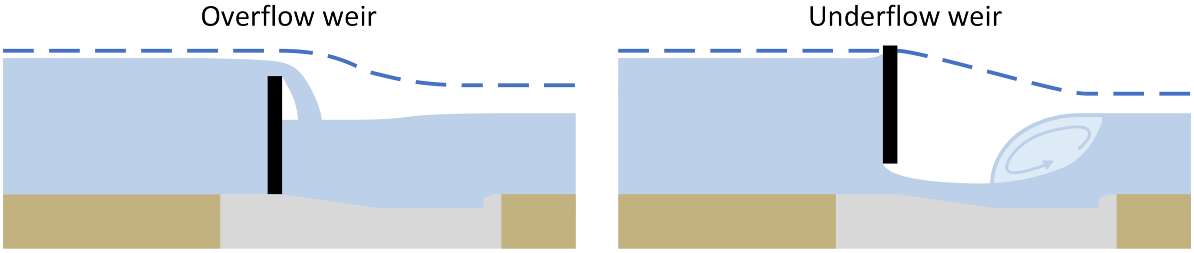


Figure C.1: Left: free overflow weir & Right: free underflow weir.

The weir concepts generated in Chapter 6 are movable overflow weirs. The crest level of the weir can be lowered or raised to control the upstream water level. The goal of this calculation is to determine the variable crest level of the weir during operation. The crest level of the weir affects the relation between the up- and downstream water levels and the discharge over the weir. This relation can be expressed using the discharge formulas for overflow weirs.

C.1. Derivation of the discharge formula for overflow weirs

C.1.1. Submerged overflow

In Figure C.2 an overflow weir for submerged conditions is shown. For this flow condition, both the upstream water level h_1 and the downstream water level h_3 influence the discharge over the weir.

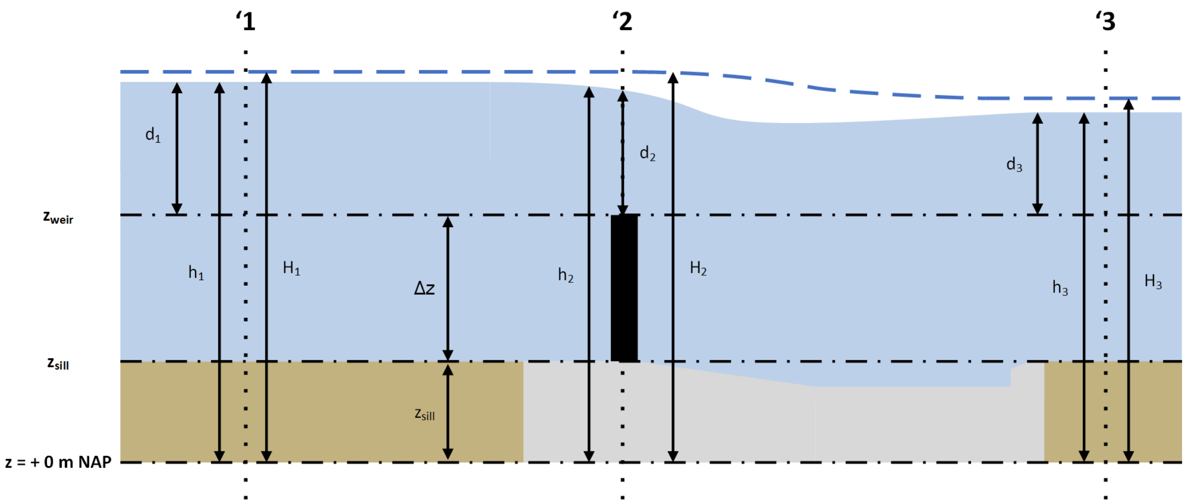


Figure C.2: Submerged overflow weir, sharp crest

Conservation of energy is applied to the section ’1-’2 by using Bernoulli’s equation, assuming there is no loss of energy between both points:

$$H_1 = (z_{sill} + \Delta z) + d_1 + \frac{u_1^2}{2g} = H_2 = (z_{sill} + \Delta z) + d_2 + \frac{u_2^2}{2g} \tag{C.1}$$

The resulting Equation C.1 can be rewritten to find the flow velocity on the crest of the weir. The weir crest itself has a variable height, indicated by the parameter Δz.

$$u_2 = \sqrt{2g \cdot (H_1 - (z_{sill} + \Delta z) - d_2)} \tag{C.2}$$

Using this velocity, along with the water depth on the crest d_2 and the width of the weir B, the discharge over the weir can be calculated:

$$Q = B \cdot d_2 \cdot u_2 = B \cdot d_2 \cdot \sqrt{2g \cdot (H_1 - (z_{sill} + \Delta z) - d_2)} \tag{C.3}$$

However, both the upstream energy head H_1 and the water depth d_2 are unknown. Therefore, the upstream water level h_1 is used instead of the energy head H_1:

$$H_1 \approx h_1 = (z_{sill} + \Delta z) + d_1 \tag{C.4}$$

Additionally, he downstream water depth d_3 is used instead of the water depth d_2. These parameters will slightly differ. Therefore, to correct the resulting outcome, a discharge coefficient C_D is introduced:

$$Q = C_D \cdot B \cdot d_3 \cdot \sqrt{2g \cdot (d_1 - d_3)} \tag{C.5}$$

The coefficient C_D also accounts for the difference in energy levels between points '1 and '3. This coefficient depends on the type of weir gate and can be found in the literature. The crest level of the weir can be found by rewriting Equation C.5:

$$\Delta z = h_3 - z_{sill} - d_3 = h_3 - z_{sill} - \frac{Q}{C_D \cdot B \cdot \sqrt{2g \cdot (d_1 - d_3)}} \tag{C.6}$$

C.1.2. Free overflow

If the downstream water level drops sufficiently, free flow conditions will occur. Then the discharge over the weir will no longer be dependent on the downstream water level. This occurs when the downstream water levels becomes smaller than two thirds of the upstream energy head (Voorendt, 2024):

$$h_3 < \frac{2}{3} H_1 \tag{C.7}$$

When the downstream water level drops even further, the water will plunge over the gate as depicted in Figure C.3. It is assumed that critical flow occurs above the weir (Voorendt, 2024). Thus, the Froude number is equal to 1:

$$Fr = \frac{u_2}{\sqrt{g d_2}} = 1.0 \tag{C.8}$$

Combining equation C.1 and equation C.8 results in the discharge formula for free overflow weirs:

$$Q = \frac{2}{3} \cdot \sqrt{\frac{2}{3} g} \cdot C_D \cdot B \cdot d_1^{\frac{3}{2}} \tag{C.9}$$

The biggest difference between submerged and free overflow is that in free overflow, only the upstream water level has an effect, while the downstream level does not. When river discharge is low, water level control is typically managed by free overflow. A movable gate can be used for precise water level regulation. Using the discharge formula for free overflow, the crest level of the gate can be found:

$$\Delta z = h_1 - z_{sill} - d_1 = h_1 - z_{sill} - \frac{3}{2} \cdot \frac{\sqrt[3]{Q^2}}{\sqrt[3]{g \cdot C_D^2 \cdot B^2}} \tag{C.10}$$

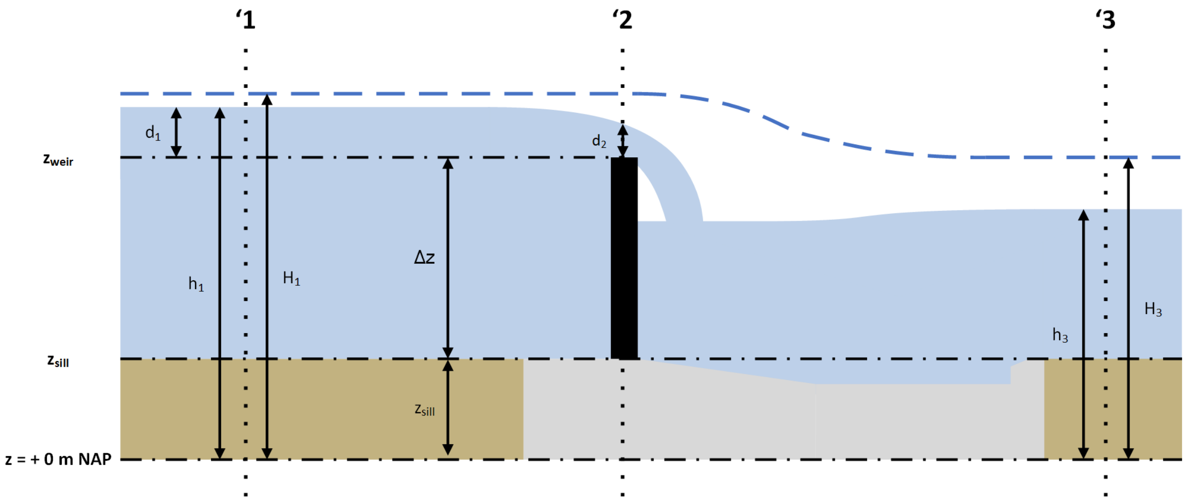


Figure C.3: Free overflow weir, sharp crest

C.2. Python code for weir flow calculations

The Python code in this section was used to perform the weir flow calculations.

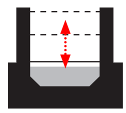
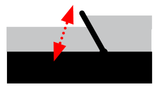
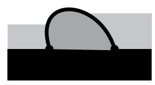
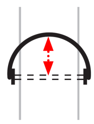
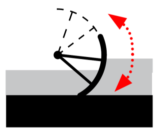
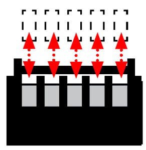
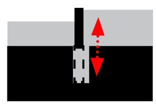
```
import numpy as np

def calc_Q_free_overflow(C, B, h_1, g=9.81):
    Q = (2/3) * np.sqrt(2/3 * g) * C * B * h_1**(3/2)

    return Q

def calc_Q_submerged_overflow(C, B, h_1, h_3, g=9.81):
    Q = C * B * h_3 * np.sqrt(2 * g * (h_1 - h_3))

    return Q

def calc_dz_free_overflow(Q, C, B, H_1, g=9.81):
    h_1 = (3 / 2) * (Q**2)**(1/3) / (g * C**2 * B**2)**(1/3)
    dz = H_1 - h_1

    return dz

def calc_dz_submerged_overflow(Q, C, B, H_1, H_3, g=9.81):
    h_3 = Q / (C * B * np.sqrt(2 * g * (H_1 - H_3)))
    dz = H_3 - h_3

    return dz
```

D. Weir concepts

This appendix provides the information and calculations used in the generation, verification and evaluation of the weir design concepts presented in Chapter 6. Section D.1 provides an overview of the possible gate types considered. Section D.2 covers the discharge capacity calculations for each weir concept and in Section D.3 the total MKI for each concept is calculated. Lastly, in Section D.4 multiple layouts of the weir concept A are compared.

D.1. Overview of possible gate types

Below an overview is given of several gate types considered for the weir concepts of Chapter 6.

gate type	maximum width [m]	maximum Δh [m]	notes	figure[1]
Lifting gate	60[2]	4[1]	- Gates with two leaves, like Stoneys, excel at water level control - Can be used for overflow and underflow - Requires lifting towers	
Flap gate	80[2]	2[1]	- Is supported via the bottom, can have even greater width - Insufficient maximum head difference	
Inflatable gate	80[2]	4.6[3]	- Is supported via the bottom, can have even greater width - Vulnerable to piercing loads - Risk of V-notch forming	
Visor gate	60[2]	3[1]	- Has on average a lower material usage than lifting gates - Span is larger than the opening size	
Sector gate	50[2]	6[1]	- Controllable flap can be added - Can be used for overflow and underflow - Needs relatively large arms to hold	
Poirée gate	6[2]	4[1]	- The maximum width is equal to distance between foldaway frames - Can have high leakage losses	
Submerged gate	20[1]	2[1]	- Insufficient maximum head difference - Needs a large floor and foundation to house the gate when opened	

[1]Source: (van der Ziel and Dijk, 2010)
[2]Source: (Daniel and Paulus, 2019)
[3]Source: (U.S. Army Corps of Engineers, 2001)

D.2. Weir discharge capacity calculation

The goal of this calculation is to determine whether the weir concepts generated in Section 6.1 have sufficient capacity and comply with requirement **FR.4**, wich states that the weir must operate up to a discharge of 1400 m^3/s, and requirement **FR.7**, which ensures the weir has enough discharge capacity to prevent flooding during high water levels. This is achieved by comparing the wet cross-sectional area of the current weir complex with that of each of the four concepts. For both concept B and D, it is assumed that the choice of gate for the wide section, leading to variants B.1, B.2, D.1, and D.2, does not affect the opening size of the weir and thus has no effect on the size of the cross-section.

The comparison evaluates whether the weir openings in the concepts are sufficiently large. If a concept allows at least the same volume of water to pass as the current weir at any given upstream water level, it is deemed sufficient to regulate water flow during high discharge events and avoid any negative impacts on waterway management. However, the capacity should not exceed the current weir's by too much. An excessively large capacity would require a larger structure, which would result in increased material use and a less sustainable design.

Figure D.1 shows a schematisation of the current weir complex at Linne. The wet cross-section refers to the area of the waterway that is filled with water. At low water levels, this includes only the water through the weir, fish ladder and possible hydropower plant. If the upstream water level rises above NAP + 21.30 m, the dam to the north of the weir will overflow, increasing the wet cross-section. Additionally, the land south of the complex contribute to the total cross-section. Areas that remain unchanged across all concepts are considered to add a constant value to the wet cross-section. For example, the contribution to the wet cross-section from the hydropower plant is the same in each concept as in the original situation. Therefore, it is excluded from the comparison.

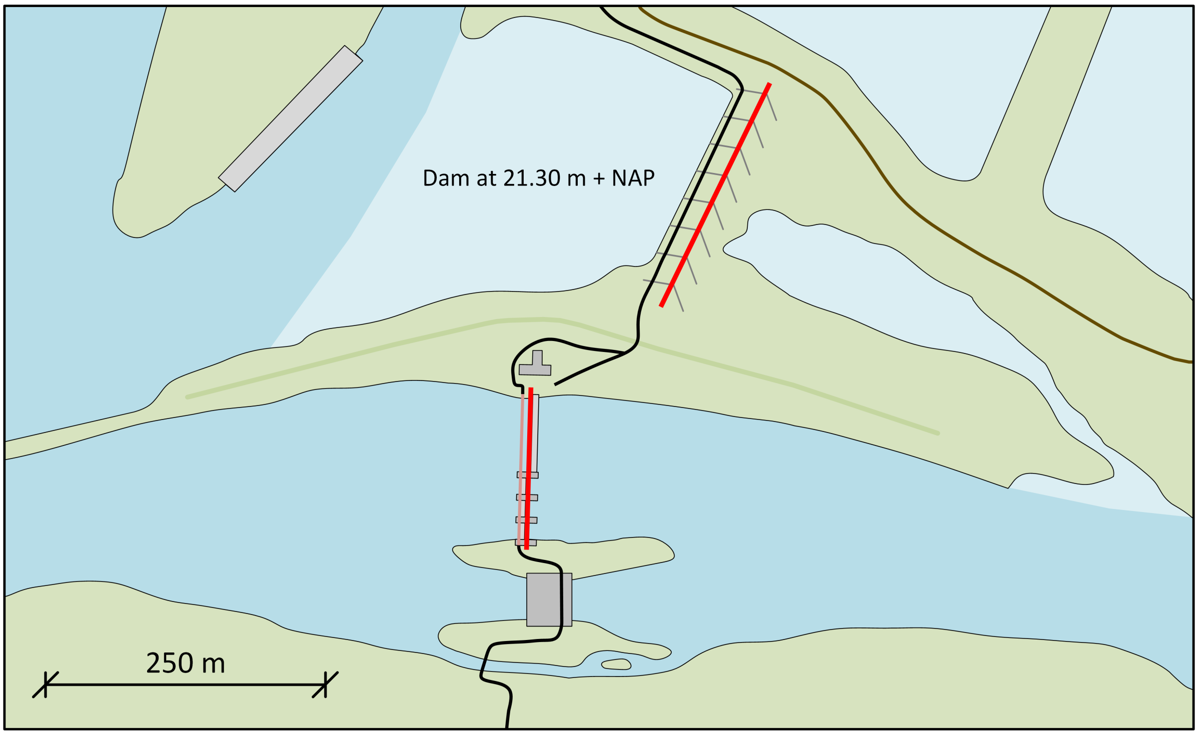


Figure D.1: Schematisation of the current weir complex at Linne, highlighting two locations for cross-section calculation.

Figure D.2 gives an example of a simplified weir cross-section. The wet cross-section consists of multiple contributing sections of different sizes. Each section has a fixed width, b_1, and a height, h_1, which depends on the upstream water level and can also vary with gate position. The total wet cross-section for a given upstream water height is calculated as the sum of individual contributions:

$$A_{total} = \sum_i b_i \cdot h_i \quad \text{(D.1)}$$

For overflow weirs, at low discharge levels - and therefore low upstream water heights - the cross-sectional area is calculated by multiplying the water height above the gates by the opening widths, see Figure D.2. As the discharge increases, the gates lower, raising the height of the water above them. When the discharge exceeds the weir's operating capacity, the gates fully open and the cross-section is then determined by the sill height and the opening widths. For extremely high discharges, additional capacity is gained when the land adjacent to the weir is overflown, see area A_3 in the figure.

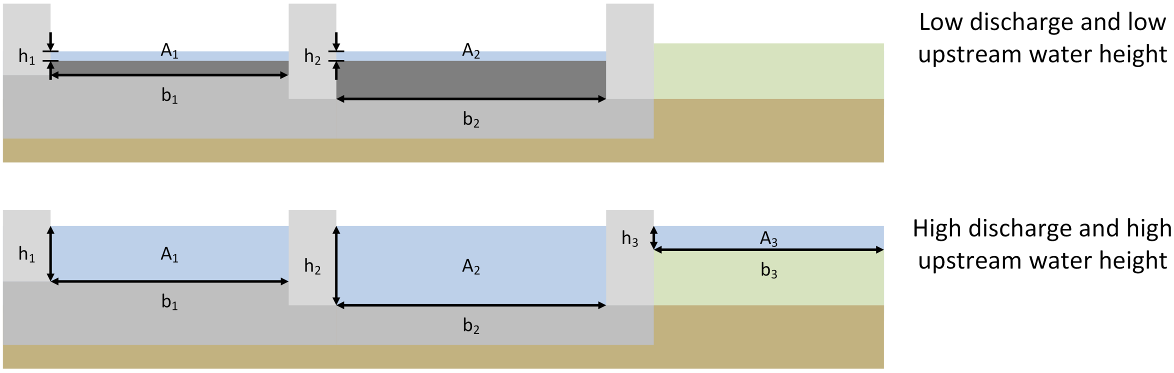


Figure D.2: Contributions to the wet cross-section of the weir depending on the upstream water level

During concept generation in Section 6.1, the opening sizes and sill heights of the weir concepts are determined. For low discharges, while the weir is in operation, the position of the gate is calculated using the weir flow equations given in Appendix C.

D.2.1. Wet cross-section of the current Linne weir

In Figure D.1, the two main locations impacting the difference in wet cross-section size between the concepts are marked. These are the weir itself, which in the current complex consists of the Stoney section and the Poirée section, and the dam on the north side of the complex. In Table D.1 the size of the wet cross-section A in m^2 is given for several upstream water levels. This cross-section is a sum of the contribution of the Stoney section, the Poirée section and the dam:

- For low discharges, the upstream water level remains constant. First, only the Stoney section of the weir is in use. The wet cross-section is equal to the width of the Stoney openings times the water height above the gate. The three Stoney sections each have an opening width of 17 m.
- For a discharge above 210 m^3/s, the Poirée is needed and the wet cross-section is determined using the sum of both sections (van Aubel, 2024). The Poirée section has an opening width of 60 m.
- Once the maximum of the weir is exceeded, it is fully opened. There is no longer a changing interaction between both sections.
- When the upstream water level exceeds NAP + 21.30 m the dam overflows and the wet cross-section will increase quite significantly. It is estimated that the dam contributes an effective width of 230 m to the cross-section.

Table D.1: cross-section of the flow through the weir for given discharges

Discharge Borgharen	Upstream water level	cross-section	Notes
Q [m^3/s]	h [NAP + m]	A [m^2]	-
50	20.85	36.26	low discharge, only Stoney
250	20.85	131.3	combination Stoney and Poirée
1470	20.40	443.0	maximum weir exceeded
2100	21.32	549.7	dam overflows (NAP + 21.30 m)
2500	21.82	720.2	lock overflows (NAP + 21.80 m)
3200	22.55	969.1	-
4500	23.37	1249	-

D.2.2. Wet cross-sections of the design concepts

The design concepts alter the wet cross-section of the waterway. As stated above, it is assumed that the weir itself and the dam north of the weir are the two main locations where the cross-section is altered. In the over below the changes per concept are discussed and in Table D.2 the size of the cross-sections and the respective change are given.

- Concept A: The new weir is build downstream of the current Linne weir and has three Stoney openings. These openings govern the wet-cross section up to a water level of NAP + 21.30 m. It is assumed the gates have a discharge coefficient of 0.96, the same as the current Stoney gates. Using the formula for overflow presented in Appendix C, the position of the top of the gates is determined as well as the size of the wet cross-section. The dam remains unchanged.
- Concept B: The dam north of the current Linne weir is used to build new weir. Thus, this concept does not have the additional capacity the dam provides. For low discharges, the wet cross-section is dependent on the two deep middle sections of the concept. If the discharge increases above 200 m^3/s, the two wide sections are used to regulate the discharge. At the location of the old weir, a dam is built with a height of NAP + 21.30 m, which will overflow, providing an additional capacity.
- Concept C: This concept used the old foundation. It is assumed the sill height and opening width will remain same, resulting in no changes in the wet cross-section.
- Concept D: The dimensions of the Stoney openings remain the same as for the current Linne weir. However, the dam is used to create two wide weir openings, which replace the Poirée section. At the location of the Poirée a dam is build with a height of NAP + 21.30 m.

Table D.2: cross-section of the flow through the weir for given discharges and respective water levels

Q [m^3/s]	h [NAP + m]	A_0 [m^2]	A_A [m^2]		A_B [m^2]		A_C [m^2]	A_D [m^2]	
50	20.85	36.3	47.1	+30 %	35.6	-1.8 %	n/a	n/a	
250	20.85	131	138	+4.9 %	165	+25 %	n/a	180	+37 %
1470	20.40	443	450	+1.7 %	451	+1.8 %	n/a	446	+0.7 %
2100	21.32	550	560	+1.8 %	632	+15 %	n/a	678	+23 %
2500	21.82	720	732	+1.6 %	843	+17 %	n/a	834	+16 %
3200	22.55	969	983	+1.4 %	1151	+19 %	n/a	1061	+9.4 %
4500	23.37	1249	1265	+1.3 %	1497	+20 %	n/a	1316	+5.4 %

D.3. MKI calculation

The goal of this calculation is to determine the total MKI for each concept and compare the concepts using this quantifiable criterion. To calculate the MKI for each concept, the dimensions of all main elements are estimated in Section D.3.1. Then, the MKI of each elements is calculated using an MKI value per unit material. With this information, the total MKI for each concept can be estimated. This calculation provides insight into which elements and materials contribute the most to the environmental impact, which can be used to find possibilities to reduce this impact.

The MKI per unit material is based on reports from the "Nationale Milieudatabase" [National Environmental Database] (2024). This can be either a single unit of an element, a unit of mass or a unit of volume. In Section D.3.2 an overview of the MKI values per material is given for each of the elements.

D.3.1. Estimation of main dimensions

Weir gates

The weir gates account for a significant portion of the total material usage in the weir design. Additionally, the mass of each gate type considered in the concept generation in Section 6.1 differs significantly. Therefore, the total mass of each gate type used in the concepts must be estimated. These estimates are parametrised to be applicable to the dimensions of all the concepts.

- Stoney gates: Stoney gates are a type of vertical lifting gate consisting of two leaves that can move independently. All four concepts feature this type of gate. It is assumed these gates are primarily constructed using steel.

  The weight of the Stoney gates of each concept can be estimated using an analysis performed by Erbisti. Erbisti analysed the weight of 266 hydraulic gates of various types and fitted a general equation to each gate type. The following equation can be used to approximate the weight of a double-leaf gate (Erbisti, 2004):

  $$W_{double-leaf} = 0.913 \cdot (B^2 \cdot H \cdot \Delta h)^{0.669} \quad [\text{kN}] \tag{D.2}$$

  Where:
  $W_{double-leaf}$ [kN] : Weight of the double-leaf gate
  B [m] : Span of the double-leaf gate, which is not equal to the width of the opening!
  H [m] : Height of the double-leaf gate
  Δh [m] : Head difference over the double-leaf gate

  From the equation, it is clear that the span is the most important parameter for reducing the weight of the gate. This is because adjusting the span is easier than altering the gate height or the head difference over the gate. Additionally, the span has a quadratic contribution compared to the other two parameters.

  To verify the use of this equation, it used to approximate the weight of the current Stoney gates. The openings of the current Stoney gates have a width of 17 m and the gates have an average span of 18.2 m (Ministerie van Waterstaat, 1921). This additional width is needed to support the gate at the piers and corresponds to 7% of the opening width. It is assumed that the span of the modern Stoney gates of the concepts is only 5% bigger than the width. The current gates have a total height of 3.95 m and a maximum head difference of 3.95 m (van Aubel, 2024). Filling in these value in Equation D.2 results in a weight of 278 kN or a mass of 28.4 tonne. The actual combined mass of the two leaves of a single Stoney gate is 51 tonne (Ministerie van Waterstaat, 1921). To adjust for this difference, a linear factor of 1.80 is applied to the equation of Erbisti. Additionally, the weight is converted from kN to a mass in tonne:

  $$M_{Stoney} = 0.913 \cdot (B^2 \cdot H \cdot \Delta h)^{0.669} \cdot \frac{1.97}{9.81} \quad [\text{tonne}] \tag{D.3}$$

- Visor gate: Both concepts B and D include a version with a visor gate. Erbisti does not provide an estimation for the mass of visor gates. However, an estimate can be derived from the mass of the visor gate weirs on the Nederrijn and Lek rivers and the previously used Equation D.2. Each of these weirs has two 48 m openings. The visor gates in these openings span 54 m, have a height of 9 m and a maximum head difference of 3 m (Rijkswaterstaat, 2024f). Therefore, the span of these visor gates is 12.5% bigger than the width. It is assumed that the span of the visor gates in the concepts is only 10% bigger than the width. Based on the dimensions of these visor gates, the calculated gate mass is 175.5 tonne. However, the actual mass of a visor gate is 270 tonne (SealteQ, 2019). To adjust for this difference, a linear factor of 1.54 is applied to the equation of Erbisti:

$$M_{visor} = 0.913 \cdot (B^2 \cdot H \cdot \Delta h)^{0.669} \cdot \frac{1.54}{9.81} \quad [\text{tonne}] \tag{D.4}$$

  Assuming that the mass of both a Stoney gate and a visor gate can be estimated using Equation D.2, it can be concluded that the estimated mass for the visor gate is approximately 22% lighter than that of a Stoney gate with the same span. However, the span of each gate is not equal to the opening size and it is the opening size that determines whether the weir has sufficient capacity.

- Inflatable gate: Both concepts B and D also include a version with an inflatable gate instead of the visor gate. The mass of the inflatable gates is not estimated using Erbisti's equation, as these equations are developed for steel gates. The inflatable gate is a tube primarily made from rubber canvas laminated with plastic (U.S. Army Corps of Engineers, 2001). The mass of the gate is assumed to be equal to the volume of canvas multiplied by the density of the canvas:

$$M_{inflatable} = V \cdot \rho = L \cdot A \cdot t \cdot \rho \quad [\text{tonne}] \tag{D.5}$$

  Where:
  $M_{inflatable}$ [tonne] : Mass of the inflatable gate
  V [m^3] : Volume of canvas
  ρ [tonne/m^3] : Density of canvas
  L [m] : Length of the inflatable gate
  A [m] : Circumference of the inflatable gate
  t [m] : Thickness of the canvas

  The gate is simplified as a tube with a length L, circumference A and thickness t. In reality, the gate is not a tube with a consistent circumference, as adjustments are needed at both ends to secure it to the abutment and pier. In this schematisation, the gate is assumed to have a consistent circumference along its entire length, with the length of the gate equal to the width of the opening. The circumference of each gate is estimated in the corresponding paragraph for each concept in Section 6.1. Lastly, the density and thickness of the canvas are estimated based on the inflatable storm surge barrier at Ramspol, which has a canvas thickness of 16 mm and a surface density of 19.3 kg/m^2, equivalent to a volume density of 1206 kg/m^3. For the inflatable weir gates of both concept B and D, a thickness of 15 mm and the same density are assumed.

- Poirée gate: Concept C includes a modern version of the current Poirée. The gate is simplified as a plate with a constant thickness over its span and height:

$$M_{Poire} = (B \cdot H \cdot t) \cdot \rho \quad [\text{tonne}] \tag{D.6}$$

  Where:
  M_{Poire} [tonne] : Mass of the Poirée gate
  B [m] : Span of the Poirée gate
  H [m] : Height of the Poirée gate
  t [m] : Average thickness of the Poirée gate, assumed to be 8 cm or 0.08 m
  ρ [tonne/m^3] : Density of construction steel, 7.85 tonne/m^3

Piers and abutments

Each concept includes a number of piers and abutments. The abutments are located at the end of the weir and do not stand in the waterway. The piers are located between the abutments and stand in the waterway. For simplicity, it is assumed that the abutments are of the same shape and size as the piers.

- Width: The piers of the original Linne weir have a width of 4 m each (RWS, 1921). For the piers adjacent to a Stoney gate in all four concepts and the piers adjacent to the Poirée of concept C, a width of 4 m is also assumed. However, for the visor gate and inflatable gate of concepts B and D, a larger pier width is probably needed to house the gate if it is adjacent to another gate. For all piers adjacent to at least one visor gate or inflatable gate and another gate, an extra 4 m width is assumed. This schematised in the calculation in Section D.3.3 as an additional pier.
- Length: The piers of the original Linne weir have a length of 20 m each to create parallel streamlines over the weir (Ministerie van Waterstaat, 1921). For all concepts, it is assumed that the piers have this same length.
- Shape factor α : The piers do not have a rectangular shape, since a rectangular round-nosed pier induces scour. Additionally, the piers might need notches to fit the gate. The current piers cover about 87.5% of a rectangle (de Jong, 2014). This is also assumed for the piers of the concepts. Therefore, the area of the piers is multiplied with the shape factor $\alpha = 0.875$.
- Height: In Figure D.3 three different cases concerning the height of the piers are identified. In the first case, the piers are constructed on an underwater concrete (UWC) floor within a cofferdam. For these piers it is assumed that the bottom of the pier is located on the UWC floor, which also acts as a sill between the piers. In the second case, the piers are constructed on top of the old dam in a construction pit. For these piers it is assumed that the bottom of the pier rests on the dam at the same level as the bottom of the sill (which, in this case, is not made of UWC). In the third and last case, the piers are constructed on the soil deeper under the dam, where an additional floor is constructed.

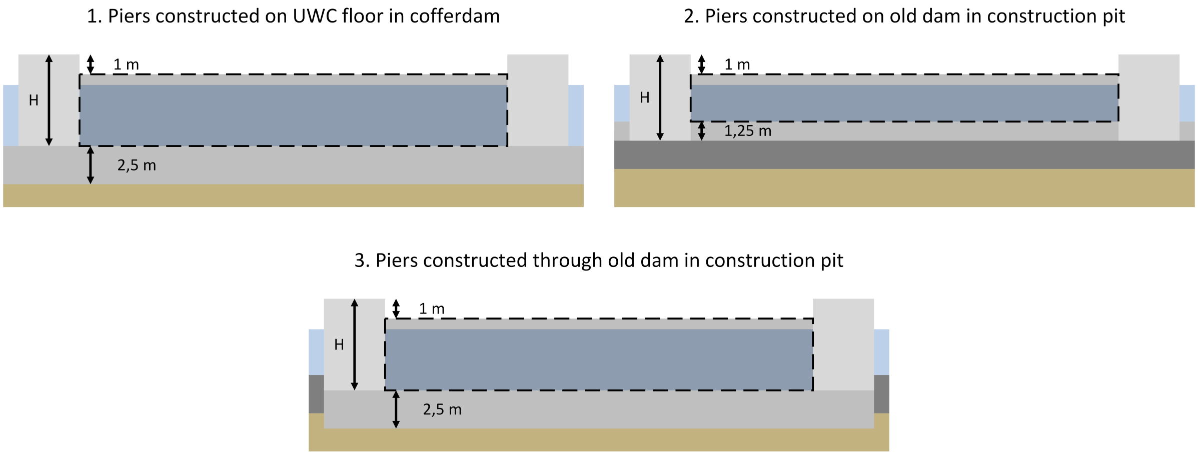


Figure D.3: The cross-section of three cases, indicating the height of the pier with respect to the sill between the piers.

All piers extend to 1 m above the top of the gate in closed position. The height of the pier is assumed to be constant over the entire length.

- Volume: Using these dimensions the parametrised volume of a single pier can be calculated:

$$V = \alpha \cdot (B \cdot L) \cdot H \quad [\mathrm{m}^3] \tag{D.7}$$

Floor, sill and foundation

In this section the size of the floor and sill of each of the concepts is determined. The subsoil beneath the waterway mainly consists of gravel and sand, see Appendix A.2. Therefore, it is assumed that the piers are constructed on a shallow foundation, which is constructed as part of the pier.

- Concept A: The piers of concept A are constructed in cofferdams in the waterway. This is case 1 as depicted in Figure D.3. It is assumed that an UWC floor with a thickness of 2.5 m is needed to prevent uplift and create a watertight cofferdam. Additionally, it is assumed that the sill between the piers has the same thickness as this floor. Therefore, it is schematised as one continuous floor slab. The width of the slab is equal to the length of the piers, which is 20 m, and the length of the slab is equal to the sum of the widths of the openings and piers.
- Wide sections concept B & D: Both concept B and concept D have two variants of the wide sections: the visor gate variant and the inflatable dam variant. For both variants of both concepts, the piers are constructed in a construction pit around the dam north of the current weir. For the wide sections, a sill with a thickness of 1.25 m between each of the piers is assumed, see case 2 in Figure D.3. The sill has a length equal to the opening size. The sill under the visor gate is crescent-shaped and has a width of 20 m, while the sill under the inflatable gate has a width of 12 m, see Section 6.1.

  It is possible that the piers of either variant are loaded in tension. Thus, a shallow foundation will not suffice. Therefore, these piers must be supported by tension piles. To get a first indication of the materials needed for the pile foundation, the following assumptions are made:

  - The piles are square concrete prefab piles.
  - The piles measure 400 mm by 400 mm.
  - The piles have a length of 15 m.
  - The piles are placed with a centre-to-centre distance of 2 m.

  Based on these assumptions, 48 m^3 of concrete is needed for the piles of a single pier. This amount is negligible compared to the volume of concrete needed to construct the pier itself and the sill. Therefore, no further calculations regarding the actual size of the piles are made.
- Deep sections concept B: The deep sections of concept B are schematised as case 3 of Figure D.3. It is assumed that the piers are placed on a floor with a thickness of 2.5 m. Additionally, it is assumed that the sill between the piers has the same thickness as this floor. Therefore, it is schematised as one continuous floor slab. The width of the slab is equal to the length of the piers, which is 20 m, and the length of the slab is equal to the sum of the width of the opening and piers.
- Concept C & deep section concept D: For both concept C and the deep section of concept D it is assumed that the sill and foundation of the current weir can be reused. Therefore, no additional elements are constructed.
- Volume: Using the given dimensions per concept, the parametrised volume of the floor slab(s) can be calculated:

$$V = B \cdot L \cdot t \quad [\mathrm{m}^3] \tag{D.8}$$

Lifting towers

Only openings with Stoney gates or visor gates have lifting towers. These towers are simplified as square tubes with a floor at the bottom, one intermediate floor and a roof, each with the same thickness. In reality, the towers also house stairs and possibly additional intermediate floors. This will be neglected.

- Width and length: It is assumed that the lifting towers are hollow and have a square base, with each side equal to the width of a single pier, which is 4 m. Between two Stoney gates, there is only one pier and thus one lifting tower. A visor gate has its own pier and its own lifting tower on either side. Thus, between the visor gate and Stoney gate in concept B, there are two lifting towers, and between the two visor gates in concept D, there are also two lifting towers.
- Height: The towers are placed on the piers. The height of the towers is equal to the distance from the pier to the maximum height of the top of the gate in opened position, plus an additional 2 m on top of that for the lifting mechanism.
- Wall thickness: As an initial assumption, the towers have a wall and floor thickness 0.6 m. This is uses to calculate the total volume of concrete in the towers.

- Volume: The volume of the tower can be calculated using the width, length, height and wall thickness of the tower:

$$V = B \cdot L \cdot H - (B - 2t) \cdot (L - 2t) \cdot (H - 3t) \quad [\mathrm{m}^3] \tag{D.9}$$

Earthworks and sheet pile walls

Concepts A, B, and D involve two types of earthworks: soil deposition and soil excavation. Concept C does not include any earthworks. Figure D.4 provides an estimate of the soil volumes, with deposition shown in dark green and excavation in blue. It is assumed that the additional land created in the water must be heightened by 10 m relative to the bottom. In concepts B and D, the dike north of the current weir must be relocated. The new dike is schematized as a single surface area that needs to be heightened by 8 m. However, in reality, it encompasses a larger surface area with sloped sides.

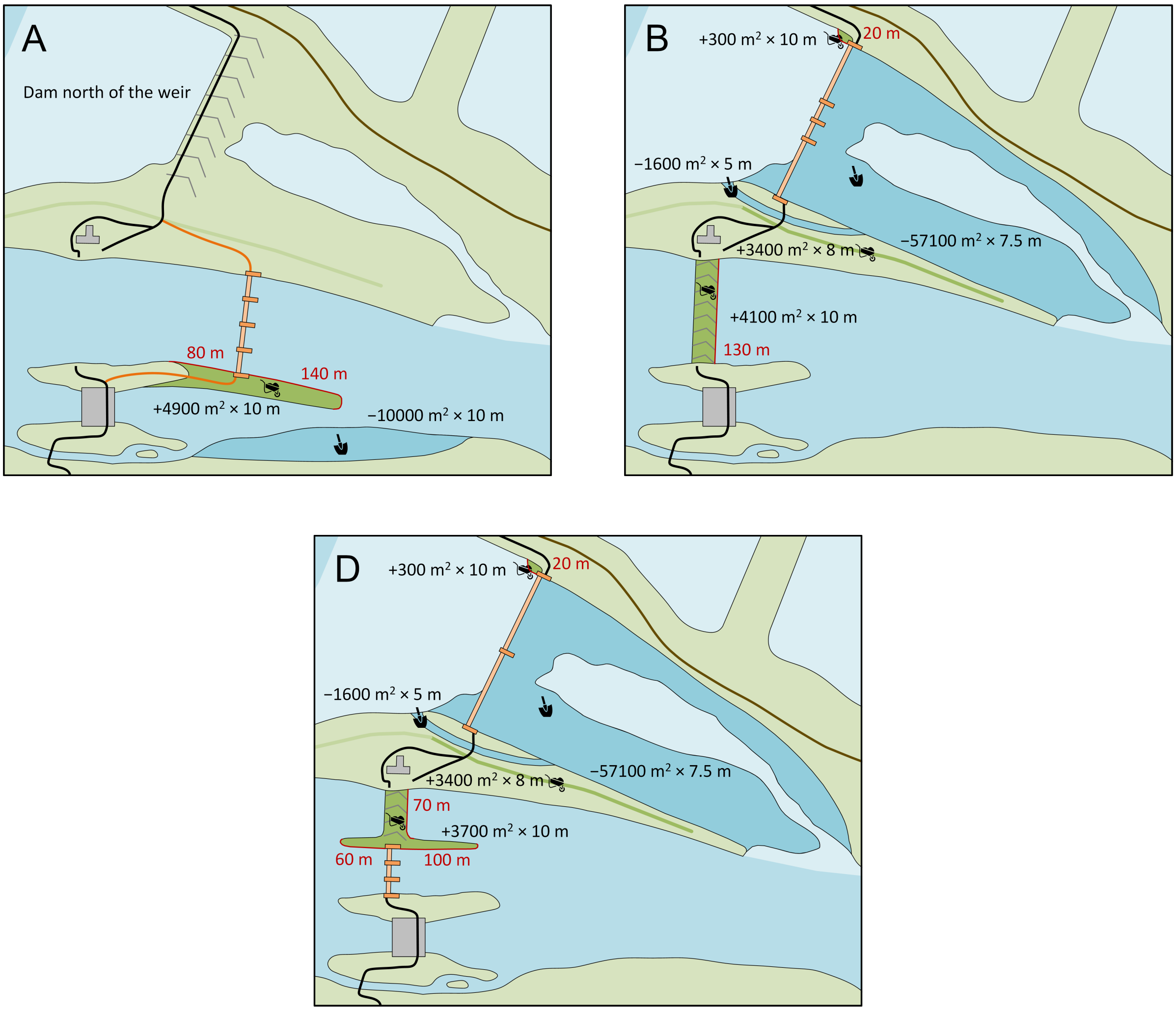


Figure D.4: Estimation of volumes of soil excavated and deposited for concept A, B and D. Additionally, the needed length of sheet pile wall is marked.

In concept A, the land south of the new weir must be lowered by an average of 10 m. The excavation in both concepts B and D involves a much larger surface area. However, the average height of this land is lower, so it only needs to be excavated by 7.5 m. The soil excavated in each concept can be used to create the depositions mentioned above, resulting in the soil being moved twice. The total volume of soil moved can be calculated as follows:

$$V_{moving} = V_{excavation} + V_{deposition} \quad [\mathrm{m}^3] \tag{D.10}$$

The remaining soil must be transported to a depot. This volume is equal to:

$$V_{transport} = V_{excavation} - V_{deposition} \quad [\mathrm{m}^3] \tag{D.11}$$

Additionally, at some locations, sheet pile walls are needed to contain the soil depositions when there is no space to create a slope. The length of the sheet pile walls needed is estimated and marked in Figure D.4. The sheet pile walls must reach a height of 21.30 m + NAP, and the average bottom of the waterway is estimated to be at 15.00 m + NAP. It is assumed that $\frac{2}{3}$ of the sheet pile wall is placed above the bottom of the waterway and about $\frac{1}{3}$ is in the ground. Using these assumptions, an estimation for the height of the sheet piles can be made:

$$H = 1.5 \cdot (21.30 - 15.00) = 9.5 \quad [\mathrm{m}] \tag{D.12}$$

Energy usage

An estimation of the energy used during the entire technical lifetime of the weir concepts has been made. This estimation is based on an analysis of the energy consumption in national and regional water management in the Netherlands by Deltares. The report states that two of the ten weirs managed by Rijkswaterstaat were included in the research. It does not specify which two, but the ten weirs are the seven Meuse weirs and the three visor weirs in the Nederrijn and Lek. It is assumed that the two analysed weirs are representative of the Meuse weirs. The report states that the two weirs use an average yearly maximum of 0.3 MWh per year (Dahm and Bruggers, 2009). Even tough this value is an average yearly maximum, it is assumed that an average Meuse weir uses 150 kWh per year.

To estimate the energy consumption for the weir concepts, it is assumed that the energy consumption of the weir is linearly related to the mass of the gates. This is a significant simplification, but it can provide a first indication. The following equation is used:

$$E_{concept\ yr} = \frac{M_{gates\ concept}}{M_{gates\ Linne}} \cdot E_{Meuse\ weir\ yr} \quad [\mathrm{kWh/year}] \tag{D.13}$$

D.3.2. MKI per unit material and design lifetime

The MKI of each element is calculated based on an MKI value per unit of weight or volume, derived from reports in the "Nationale Milieudatabase" [National Environmental Database] (2024). An overview of the materials is provided for each element of the weir, specifying the MKI values and technical lifetimes. While the superstructure of the weir has a technical lifetime of 100 years, certain elements may have shorter lifetimes, which must be factored into the calculations.

In the National Environmental Database (NMD), environmental declarations are classified into three categories. In addition to the verified category 1 and 2 declarations, category 3 data consists of brand-independent information compiled by experts based on international databases (Nationale Milieudatabase, 2024). The category 3 data consists of 'default' values, which are considered conservative estimates. Due to the unverified nature of this data, a 30% adjustment is applied to account for potential uncertainties. All data used in this calculation falls under category 3. As such, it does not provide an exact estimate of the total MKI of the weir concepts, since several important factors — such as the origin and transport distance of the materials — have been roughly estimated. However, the purpose of this calculation is to compare the concepts relative to each other, making the uncertainty of category 3 data less significant, as all concepts are subject to the same level of uncertainty.

Weir gates

The various weir gate types used in the concepts are constructed from different materials. Therefore, for each gate type, the used materials are specified.

- Stoney gates: The Stoney gates are primarily made from construction steel. It is assumed that their mass composition is similar to that of a steel rolling gate, for which the MKI data is available in the National Environmental Database. The database distinguishes two types of rolling gates: one with a head difference of 3 meters and one with 6 meters. For both gates, the MKI is provided in the database per set of two doors. The head over the Stoney gates in the weir concepts ranges between 4.0 and 4.5 meters. Therefore, the average of the two rolling gates in the database is taken and it is converted to a value per tonne, see Table D.3. The used MKI is 263 €/tonne, with a technical lifetime of 50 years (Nationale Milieudatabase, 2024). Therefore, over the entire lifespan of the weirs, these gates will need to be replaced once, effectively doubling the MKI impact. This is taken into account during the final MKI calculation using a lifetime factor of 2.

Table D.3: Determining the MKI per tonne steel gate (Nationale Milieudatabase, 2024)

Rolling gate	Mass [kg]	MKI [€]	MKI per unit [€/tonne]
3 m ΔH	34848	9233	265
6 m ΔH	50992	13312	261
		average:	263

- Visor gates: Visor gates, as used at the weirs in the Nederrijn and Lek, are typically constructed from steel. Therefore, the same assumption as for the Stoney gates can be applied: the mass composition of the visor gate is similar to that of a steel rolling gate, so the same MKI value can be used. Additionally, part of the gate can be replaced by reinforced plastic to reduce both the total weight and MKI. It is assumed this applies to the gate's skin plates, with up to 30% of the total steel volume being replaceable with fibre-reinforced polyethylene. However, this plastic has lower strength than structural steel, so 3 times the volume of steel replaced is needed in plastic. This leads to the following volume of plastic per visor gate:

$$V_{gate,plastic} = 3 \cdot 0.30 \cdot V_{gate,steel} = 0.9 \cdot \frac{M_{gate,est}}{\rho_{steel}} \tag{D.14}$$

With the mass of the visor gate estimated in Section D.3.1, the mass of plastic in the gate can be determined. This mass is needed to calculate the MKI of the visor:

$$M_{gate,plastic} = \rho_{plastic} \cdot V_{gate,plastic} = \rho_{plastic} \cdot 0.9 \cdot \frac{M_{gate,est}}{\rho_{steel}} \tag{D.15}$$

The plastic is assumed to have a density of 950 kg/m^3 and the steel a density of 7850 kg/m^3. Using these values, the mass of the plastic in the gate can be expressed as a proportion of the gate's mass, previously calculated under the assumption that the entire gate was made of steel.

$$M_{gate,plastic} = 0.9 \cdot \frac{\rho_{plastic}}{\rho_{steel}} \cdot M_{gate,est} = 0.9 \cdot \frac{950}{7850} \cdot M_{gate,est} \approx 0.109 \cdot M_{gate,est} \tag{D.16}$$

$$M_{gate,steel} = 0.70 \cdot M_{gate,est} \tag{D.17}$$

For the steel part of the visor gate, the previously determined MKI of €263/tonne and technical lifetime of 50 years for the Stoney gate is used. Since plastic skin plates for a visor gate are not listed in the National Environmental Database, the MKI for polyethylene sheet piles (€69.1/tonne) is used as a proxy (Nationale Milieudatabase, 2024), assuming the material composition of the plastic skin plates is similar to that of these sheet piles. The skin plates are assumed to have a technical lifetime of 33 years. Thus, over the lifespan of the weirs, these plates will require two replacements, effectively tripling their MKI impact. This is accounted for in the final MKI calculation by applying a lifetime factor of 3.

  - By combining the weight composition of the gate with the MKI per unit of material, the total MKI difference between a fully steel visor gate and a partially plastic visor gate can be calculated. The table below shows that using plastics reduces the MKI by 25.7%.

$$1 - \frac{388}{522} = 25.7\% \tag{D.18}$$

Table D.4: Difference in MKI between a fully steel visor gate and a partially plastic visor gate

	Material	Mass proportion	MKI per unit	Lifetime factor	Total MKI
Fully steel	Steel	1.000	€261	2	€522
Partially plastic	Steel	0.700	€261	2	€365.40
	Plastic	0.109	€69.10	3	€22.60
	Gate				€388.00

- Inflatable gates: As described in Section 6.1.4, the inflatable gate is made from a rubber canvas laminated with plastic, with an assumed composition of 75% rubber and 25% plastic by mass. Since this type of canvas is not available in the database, separate proxies are used for the rubber and plastic components. For the plastic part, the previously determined MKI of €69.1/tonne is used. For the rubber part, the MKI of a rubber fender — a large rubber cylinder used to protect vessels and berthing structures during docking — is applied, at €531/tonne rubber (Nationale Milieudatabase, 2024). The resulting MKI per tonne of canvas can be calculated:

$$\text{MKI} = 0.75 \cdot 521 + 0.25 \cdot 69.1 = 408 \quad [\text{euro/tonne}] \tag{D.19}$$

  The MKI of the inflatable gate is €408/tonne, with an assumed technical lifetime of 25 years. Thus, the canvas will need to be replaced three times over the lifespan of the weirs, effectively quadrupling its MKI impact. This is taken into account in the final MKI calculation by applying a lifetime factor of 4.
- Poirée gates: It is assumed that the Poirée gates are made entirely of structural steel. For the steel, the same MKI of €263/tonne and technical lifetime of 50 years, as used for the Stoney gates, is applied.

Piers and abutments
The pier and abutments are constructed using reinforced concrete of class C35/45, with an MKI of €45.04/m^3 and a technical lifetime of 100 years (Nationale Milieudatabase, 2024). This matches the lifespan of the weir, meaning that the concrete should not have to be replaced during the weir's technical lifetime.

Floor, sill and foundation
The concrete used for the floor and sill in the cofferdam is underwater concrete of class C30/37, with an MKI of €30.84/m^3 and a technical lifetime of 100 years (Nationale Milieudatabase, 2024). This also matches the lifespan of the weir, so this concrete should not have to be replaced during the weir's technical lifetime. The MKI of this material is lower per unit volume than that of the concrete used for the piers and abutments, as it has no reinforcements.

Lifting towers
It is assumed that the lifting towers are constructed from the same class C35/45 reinforced concrete as the piers and abutments, with an MKI of €45.04/m^3 and a technical lifetime of 100 years (Nationale Milieudatabase, 2024).

Earthworks and sheet pile walls
The earthworks consist of two main activities: on-site soil movement, including both excavation and deposition, and transporting soil to a depot. First, the MKI per unit of moved soil is calculated. Soil is excavated and deposited using construction machinery, assumed to be a 130 kW diesel excavator, as larger machinery is required to handle the significant volume of soil within the set time frame for the construction and have enough reach to dig to the required depth. Small electric excavators are also available, but larger machines are needed here. This diesel excavator has an MKI of €0.45/l diesel (Nationale Milieudatabase, 2024). The excavator is assumed to consume 12 l of diesel per hour and move an estimated 100 m^3 of soil per hour. Additionally, the soil will likely be transported short distances on-site by a dumper. To account for this and uncertainties in the assumptions, a factor of 1.5 is applied, leading to the following MKI of €0.081/m^3 or €81/1000 m^3:

$$\text{MKI} = \frac{\text{euro per l diesel} \cdot \text{l diesel per hour}}{\text{m}^3 \text{ per hour}} \cdot \gamma = \frac{0.45 \cdot 12}{100} \cdot 1.5 = 0.081 \quad [\text{euro/m}^3] \tag{D.20}$$

Soil that is excavated and not redeposited on-site is transported to a depot or storage location. It is assumed this soil is shipped via an inland vessel along the Meuse to the port of Roermond, located 10 km away. The vessel has an MKI of €0.0056 per tonne of material transported per km (Nationale Milieudatabase, 2024). The transported soil is assumed to have a density of 1600 kg/m^3.

Lastly, the MKI of the permanent sheet pile walls must be determined. The database includes two types of category 3 steel sheet piles: new sheet piles and sheet piles that will be reused. According to the database, both have a technical lifetime of 100 years and are suitable for depths up to 12 m. All sheet pile heights calculated in Section D.3.3 fall into this range. For a full analysis, it would be necessary to calculate whether these sheet pile walls can withstand the loads placed on them, but this is considered outside the scope of this initial estimate. The primary sheet pile has an MKI of €39.93/m^2, while the reused sheet pile has an MKI of €17.34/m^2 (Nationale Milieudatabase, 2024). Reusing an old sheet pile would be the most sustainable option. However, it is uncertain whether there is a sufficient supply of reusable sheet piles and whether the sheet pile will always be suitable for the new location. Therefore, an average MKI of €28.64/m^2 is assumed.

$$\text{MKI} = \frac{17.34 + 39.93}{2} = 28.64 \quad [\text{euro/m}^2] \tag{D.21}$$

Energy usage

The MKI for energy consumption is expressed in €/kWh. This value can vary significantly depending on factors such as the method of energy use, location and, most importantly, the type of energy consumed. For the purposes of this calculation, the MKI for the energy usage of the weirs is based on the MKI for energy delivered to consumers, as provided in the database. This ranges from €0.01/kWh for green energy to €0.03/kWh for grey energy, which is produced from fossil fuels. RWS aims to exclusively use renewable energy, see Section 1.2.2, so it is assumed that the new weir will operate on green energy. However, as the database rounds the MKI to the nearest cent, the actual value ranges from €0.005/kWh to €0.015/kWh.

Using Equation D.13, the yearly energy consumption of the weir concepts can be determined. Concept D, with gate variant 1 (the visor gates), has the largest total gate mass at 643 tonnes, see Section D.3.3. In comparison, the total gate mass of the Linne weir is 341 tonnes. As a result, the energy usage for Concept D.1 is estimated at 283 kWh/year:

$$E_{D.1\ yr} = \frac{M_{gates\ D.1}}{M_{gates\ Linne}} \cdot E_{Meuse\ weir\ yr} = \frac{643}{341} \cdot 150 = 283 \quad [\text{kWh/year}] \tag{D.22}$$

The yearly energy consumption can be multiplied by the technical lifetime of 100 years and the maximum MKI of €0.015/kWh to calculate the total MKI for energy usage. For Concept D.1, this amounts to €4,240:

$$\text{MKI} = 283 \cdot 100 \cdot 0.015 = 4240 \quad [\text{euro}] \tag{D.23}$$

When compared to the total MKI of Concept D.1, which is €708,000, this value is insignificantly low. Therefore, the total energy usage of the weir is not considered in the final MKI calculation.

D.3.3. Overview MKI calculation for the concepts

Using the equations to determine the main weir dimensions from Section D.3.1 and the MKI per-unit values from Section D.3.2, the total MKI for each weir concept is calculated. Below is an overview of the calculation for each individual concept. Each calculation includes the respective design parameters from Section 6.1. For each element of the weir, the main dimensions are calculated using the design parameters, followed by the MKI calculation for that element. Finally, the total MKI for each concept is determined. For both concept B and D a distinction is made between variant 1 with the visor gate and variant 2 with the inflatable gate.

The calculations are colour-coded as follows: Yellow cells are input cells, containing boundary conditions or parameters that have been chosen or assumed. Blue cells are calculation cells, which contain values derived using equations from Section D.3.1. Green cells have the actual MKI value and may also include a lifetime factor. Lastly, the orange cells contain the final MKI for the concept. The results of the calculations are discussed in Section 6.3.

MKI calculation concept A					
Design parameters concept A					
Design water level	[m + NAP]	23,40	Head difference	[m]	4,5
Sill height	[m + NAP]	16,45			
Top gate	[m + NAP]	21,45			
n opening	[-]	4			
Width	[m]	28			
Height total gate	[m]	5,00			
Height Stoney leaf	[m]	2,70			
Max level door	[m + NAP]	26,60			
Piers and abutments			**Floor and sill**		
H	[m]	6	B	[m]	20
B	[m]	4	L	[m]	132
L	[m]	20	t	[m]	2,5
factor	[-]	0,85	V_total	[m^3]	6600
V_one_pier	[m^3]	408	MKI per unit	[€/m^3] 100 y	30,84
n	[-]	5	Lifetime factor	[-]	1
V_total	[m^3]	2040	MKI value	[€1,000]	203,5
MKI per unit	[€/m^3] 100 y	45,04	Onderwaterbeton, C30/37, 0% betongranulaat		
Lifetime factor	[-]	1			
MKI value	[€1,000]	91,88	**Lifting towers Stoney**		
Doorgaand Gewapend Beton C35/45 CEM III			H	[m]	6,15
			B	[m]	4
Stoney gates			L	[m]	4
H	[m]	5,00	t	[m]	0,6
Opening width	[m]	28	V_filled	[m^3]	98,40
Span	[m]	29,4	V_air	[m^3]	30,49
M_one_gate	[tonne]	124,0	V_one_tower	[m^3]	67,91
n	[-]	4	n	[-]	5
M_total	[tonne]	495,9	V_total	[m^3]	340
MKI per unit	[€/tonne] 50 y	263,0	MKI per unit	[€/m^3] 100 y	45,04
Lifetime factor	[-]	2	Lifetime factor	[-]	1
MKI value	[€1,000]	260,8	MKI value	[€1,000]	15,29
Puntsluisdeur set staal (3m en 6m verval)			Doorgaand Gewapend Beton C35/45 CEM III		
Soil			**Sheet piles**		
V_excavate	[1000 m^3]	100	L_wall	[m]	220
V_deposit	[1000 m^3]	49	H_wall	[m]	9,5
Density	[kg/m^3]	1600	A_wall	[m^2]	2090
Transport distance	[km]	10	MKI per unit	[€/m^2] 100 y	28,64
V_moving	[1000 m^3]	149	Lifetime factor	[-]	1
V_transport	[1000 m^3]	51	MKI value	[€1,000]	59,86
M_S_transport	[M kg km]	816	Hergebruikte stalen damwand, AZ24-700		
MKI unit moving	[€/1000 m^3]	81,00			
MKI value moving	[€1,000]	12,07	**Total MKI concept A**		
MKI unit transport	[€/M kg km]	5,60	MKI value A	[€1,000]	648
MKI value transport	[€1,000]	4,57			
MKI total value	[€1,000]	16,64			

MKI calculation concept B					
Design parameters concept B					
Design water level	[m + NAP]	23,40	Head difference	[m]	4,5
Sill height deep	[m + NAP]	17,05	Sill height wide	[m]	18,35
Top gate deep	[m + NAP]	21,45	Top gate wide	[m]	21,45
n opening deep	[-]	2	n opening wide	[-]	2
Width deep	[m]	22	Width wide	[m]	74
Height total gate	[m]	4,40	Height total gate	[m]	3,10
Height Stoney leaf	[m]	2,40	Max level door	[m + NAP]	27,00
Max level door	[m + NAP]	26,30			
Piers deep section			**Floor and sill deep section**		
H	[m]	5,4	B	[m]	20
B	[m]	4	L	[m]	56
L	[m]	20	t	[m]	2,5
factor	[-]	0,85	V_total	[m^3]	2800
V_one_pier	[m^3]	367,2	MKI per unit	[€/m^3] 100 y	30,84
n	[-]	3	Lifetime factor	[-]	1
V_total	[m^3]	1101,6	MKI value	[€1,000]	86,35
MKI per unit	[€/m^3] 100 y	45,04	Onderwaterbeton, C30/37, 0% betongranulaat		
Lifetime factor	[-]	1			
MKI value	[€1,000]	49,62	**Lifting towers Stoney deep section**		
Doorgaand Gewapend Beton C35/45 CEM III			H	[m]	5,85
			B	[m]	4
Stoney gates deep section			L	[m]	4
H	[m]	4,40	t	[m]	0,6
Opening width	[m]	22	V_filled	[m^3]	93,60
Span	[m]	23,1	V_air	[m^3]	28,64
M_one_gate	[tonne]	82,4	V_one_tower	[m^3]	64,96
n	[-]	2	n	[-]	3
M_total	[tonne]	164,8	V_total	[m^3]	195
MKI per unit	[€/tonne] 50 y	263,0	MKI per unit	[€/m^3] 100 y	45,04
Lifetime factor	[-]	2	Lifetime factor	[-]	1
MKI value	[€1,000]	86,71	MKI value	[€1,000]	8,777
Puntsluisdeur set staal (3m en 6m verval)			Doorgaand Gewapend Beton C35/45 CEM III		
Piers and abutments wide section			**1. Sill visor gates**		
H	[m]	5,35	B	[m]	20
B	[m]	4	L	[m]	148
L	[m]	20	t	[m]	1,25
factor	[-]	0,85	V_total	[m^3]	3700
V_one_pier	[m^3]	363,8	MKI per unit	[€/m^3] 100 y	30,84
n	[-]	4	Lifetime factor	[-]	1
V_total	[m^3]	1455,2	MKI value	[€1,000]	114,1
MKI per unit	[€/m^3] 100 y	45,04	Onderwaterbeton, C30/37, 0% betongranulaat		
Lifetime factor	[-]	1			
MKI value	[€1,000]	65,54			
Doorgaand Gewapend Beton C35/45 CEM III					

1. Vistor gates wide section		
H	[m]	3,10
Span	[m]	81,4
M_fully_steel_gate	[tonne]	229,4
n	[-]	2
M_total	[tonne]	458,9
M_steel	[tonne]	321,2
M_plastic	[tonne]	50,0
MKI unit steel	[€/tonne] 50 y	263,0
Lifetime factor	[-]	2
MKI value steel	[€1,000]	168,96
MKI unit plastic	[€/tonne] 33 y	69,1
Lifetime factor	[-]	3
MKI value plastic	[€1,000]	10,35
MKI total value	[€1,000]	179,31
Puntsluisdeur set staal (3m en 6m verval)		
2. Inflatable gates wide section		
H	[m]	3,10
Span	[m]	74
M	[tonne]	18,9
n	[-]	2
M_total	[tonne]	37,8
MKI per unit	[€/tonne] 25 y	408,1
Lifetime factor	[-]	3
MKI value	[€1,000]	46,29
Deelproduct: Cilindrische fender, rubber		
Sheet piles		
L_wall	[m]	150
H_wall	[m]	9,5
A_wall	[m^2]	1425
MKI per unit	[€/m^2] 100 y	28,64
Lifetime factor	[-]	1
MKI value	[€1,000]	40,81
Hergebruikte stalen damwand, AZ24-700		
Total MKI concept B		
MKI value B.1	[€1,000]	718
MKI value B.2	[€1,000]	526

1. Lifting towers Visor wide section		
H	[m]	6,55
B	[m]	4
L	[m]	4
t	[m]	0,6
V_filled	[m^3]	104,8
V_air	[m^3]	32,96
V_one_tower	[m^3]	71,84
n	[-]	4
V_total	[m^3]	287
MKI per unit	[€/m^3] 100 y	45,04
Lifetime factor	[-]	1
MKI value	[€1,000]	12,94
Doorgaand Gewapend Beton C35/45 CEM III		
2. Sill inflatable gates		
B	[m]	12
L	[m]	148
t	[m]	1,25
V_total	[m^3]	2220
MKI per unit	[€/m^3] 100 y	30,84
Lifetime factor	[-]	1
MKI value	[€1,000]	68,46
Onderwaterbeton, C30/37, 0% betongranulaat		
Soil		
V_excavate	[1000 m^3]	436
V_deposit	[1000 m^3]	71
Density	[kg/m^3]	1600
Transport distance	[km]	10
V_moving	[1000 m^3]	507
V_transport	[1000 m^3]	365
M_S_transport	[M kg km]	5841
MKI unit moving	[€/1000 m^3]	81,00
MKI value moving	[€1,000]	41,10
MKI unit transport	[€/M kg km]	5,60
MKI value transport	[€1,000]	32,71
MKI total value	[€1,000]	73,81

MKI calculation concept C					
Design parameters concept C					
Design water level	[m + NAP]	23,40	Head difference	[m]	4,5
Sill height Stoney	[m + NAP]	16,95	Sill height Poirée	[m]	15,95
Top gate Stoney	[m + NAP]	21,45	Top gate Poirée	[m]	21,45
n opening Stoney	[-]	3	n opening Poirée	[-]	1
Width Stoney	[m]	17	Width Poirée	[m]	60
Height total gate	[m]	4,50	Height total gate	[m]	5,50
Height Stoney leaf	[m]	2,50			
Max level door	[m + NAP]	26,40			
Piers Stoney			**Lifting Towers Stoney**		
H	[m]	5,5	H	[m]	5,95
B	[m]	4	B	[m]	4
L	[m]	20	L	[m]	4
factor	[-]	0,85	t	[m]	0,6
V_one_pier	[m^3]	374	V_filled	[m^3]	95,20
n	[-]	4	V_air	[m^3]	29,26
V_total	[m^3]	1496	V_one_tower	[m^3]	65,94
MKI per unit	[€/m^3] 100 y	45,04	n	[-]	4
Lifetime factor	[-]	1	V_total	[m^3]	264
MKI value	[€1,000]	67,38	MKI per unit	[€/m^3] 100 y	45,04
Doorgaand Gewapend Beton C35/45 CEM III			Lifetime factor	[-]	1
			MKI value	[€1,000]	11,88
Stoney gates			Doorgaand Gewapend Beton C35/45 CEM III		
H	[m]	4,50			
Opening width	[m]	17	**Poirée gates**		
Span	[m]	17,85	H	[m]	5,50
M_one_gate	[tonne]	59,3	Span	[m]	60,00
n	[-]	3	t	[mm]	80
M_total	[tonne]	177,8	rho	[tonne/m^3]	7,85
MKI per unit	[€/tonne] 50 y	263,0	M	[tonne]	207,2
Lifetime factor	[-]	2	MKI per unit	[€/tonne] 50 y	263,0
MKI value	[€1,000]	93,51	Lifetime factor	[-]	2
Puntsluisdeur set staal (3m en 6m verval)			MKI value	[€1,000]	109,0
			Puntsluisdeur set staal (3m en 6m verval)		
Piers Poirée					
H	[m]	6,50	**Total MKI concept C**		
B	[m]	4	MKI value C	[€1,000]	322
L	[m]	20			
factor	[-]	0,85			
V_one_pier	[m^3]	442			
n	[-]	2			
V_total	[m^3]	884			
MKI per unit	[€/m^3] 100 y	45,04			
Lifetime factor	[-]	1			
MKI value	[€1,000]	39,82			
Doorgaand Gewapend Beton C35/45 CEM III					

MKI calculation concept D

Design parameters concept D					
Design water level	[m + NAP]	23,40	Head difference	[m]	4,5
Sill height deep	[m + NAP]	16,95	Sill height wide	[m]	19,05
Top gate deep	[m + NAP]	21,45	Top gate wide	[m]	21,45
n opening deep	[-]	3	n opening wide	[-]	2
Width deep	[m]	17	Width wide	[m]	100
Height total gate	[m]	4,50	Height total gate	[m]	2,40
Height Stoney leaf	[m]	2,50	Max level door	[m + NAP]	26,30
Max level door	[m + NAP]	26,40			
Piers Stoney					
H	[m]	5,5			
B	[m]	4			
L	[m]	20			
factor	[-]	0,85			
V_one_pier	[m^3]	374			
n	[-]	4			
V_total	[m^3]	1496			
MKI per unit	[€/m^3] 100 y	45,04			
Lifetime factor	[-]	1			
MKI value	[€1.000]	67,38	**Lifting towers Stoney deep section**		
Doorgaand Gewapend Beton C35/45 CEM III			H	[m]	5,95
			B	[m]	4
Stoney gates			L	[m]	4
H	[m]	4,50	t	[m]	0,6
Opening width	[m]	17	V_filled	[m^3]	95,20
Span	[m]	18,05	V_air	[m^3]	29,26
M_one_gate	[tonne]	60,2	V_one_tower	[m^3]	65,94
n	[-]	3	n	[-]	4
M_total	[tonne]	180,5	V_total	[m^3]	264
MKI per unit	[€/tonne] 50 y	263,0	MKI per unit	[€/m^3] 100 y	45,04
Lifetime factor	[-]	2	Lifetime factor	[-]	1
MKI value	[€1,000]	94,92	MKI value	[€1,000]	11,88
Puntsluisdeur set staal (3m en 6m verval)			Doorgaand Gewapend Beton C35/45 CEM III		
Piers and abutments wide section			**1. Sill visor gates**		
H	[m]	4,65	B	[m]	20
B	[m]	4	L	[m]	200
L	[m]	20	t	[m]	1,25
factor	[-]	0,85	V_total	[m^3]	5000
V_one_pier	[m^3]	316,2	MKI per unit	[€/m^3] 100 y	30,84
n	[-]	4	Lifetime factor	[-]	1
V_total	[m^3]	1264,8	MKI value	[€1.000]	154,2
MKI per unit	[€/m^3] 100 y	45,04	Onderwaterbeton, C30/37, 0% betongranulaat		
Lifetime factor	[-]	1			
MKI value	[€1.000]	56,97			
Doorgaand Gewapend Beton C35/45 CEM III					

1. Vistor gates wide section		
H	[m]	2,40
Span	[m]	110
M_fully_steel_gate	[tonne]	242,1
n	[-]	2
M_total	[tonne]	484,3
M_steel	[tonne]	339,0
M_plastic	[tonne]	52,7
MKI unit steel	[€/tonne] 50 y	263,0
Lifetime factor	[-]	2
MKI value steel	[€1,000]	178,3
MKI unit plastic	[€/tonne] 33 y	69,1
Lifetime factor	[-]	3
MKI value plastic	[€1,000]	10,93
MKI total value	[€1,000]	189,2
Puntsluisdeur set staal (3m en 6m verval)		

2. Inflatable gates wide section		
H	[m]	2,40
Span	[m]	100
M	[tonne]	14,7
n	[-]	2
M_total	[tonne]	29,3
MKI per unit	[€/tonne] 25 y	408,1
Lifetime factor	[-]	3
MKI value	[€1,000]	35,88
Deelproduct: Cilindrische fender, rubber		

Sheet piles		
L_wall	[m]	150
H_wall	[m]	9,5
A_wall	[m^2]	1425
MKI per unit	[€/m^2] 100 y	28,64
Lifetime factor	[-]	1
MKI value	[€1,000]	40,81
Hergebruikte stalen damwand, AZ24-700		

Total MKI concept B		
MKI value B.1	[€1,000]	701
MKI value B.2	[€1,000]	474

1. Lifting towers Visor wide section		
H	[m]	5,85
B	[m]	4
L	[m]	4
t	[m]	0,6
V_filled	[m^3]	93,6
V_air	[m^3]	28,64
V_one_tower	[m^3]	64,96
n	[-]	4
V_total	[m^3]	260
MKI per unit	[€/m^3] 100 y	45,04
Lifetime factor	[-]	1
MKI value	[€1,000]	11,70
Doorgaand Gewapend Beton C35/45 CEM III		

2. Sill inflatable gates		
B	[m]	12
L	[m]	200
t	[m]	1,25
V_total	[m^3]	3000
MKI per unit	[€/m^3] 100 y	30,84
Lifetime factor	[-]	1
MKI value	[€1,000]	92,52
Onderwaterbeton, C30/37, 0% betongranulaat		

Soil		
V_excavate	[1000 m^3]	436
V_deposit	[1000 m^3]	67
Density	[kg/m^3]	1600
Transport distance	[km]	10
V_moving	[1000 m^3]	503
V_transport	[1000 m^3]	369
M_S_transport	[M kg km]	5905
MKI unit moving	[€/1000 m^3]	81,00
MKI value moving	[€1,000]	40,78
MKI unit transport	[€/M kg km]	5,60
MKI value transport	[€1,000]	33,07
MKI total value	[€1,000]	73,85

D.4. MKI comparison of different variants for concept A

D.4.1. Varying numbers of openings and corresponding widths

For concept A, a comparison between the MKI of multiple layouts has been made. The goal of this comparison is to determine the optimal amount of openings and gates for this concept. This is done by recalculating the MKI of concept A with different input values. Both the number of openings (n opening [-]) and the opening width (width [m]) of the calculation have been adjusted. The following combinations were used:

- A weir with 2 Stoney openings, each 56 m wide, abbreviated as **2xS56**.
- A weir with 3 Stoney openings, each 37.35 m wide, abbreviated as **3xS37.35**.
- A weir with 4 Stoney openings, each 28 m wide, abbreviated as **4xS28**. This is the original concept A, as presented in Section 6.1.3.
- A weir with 5 Stoney openings, each 22.40 m wide, abbreviated as **5xS22.40**.
- A weir with 6 Stoney openings, each 18.70 m wide, abbreviated as **6xS18.70**.

It should be noted that the total opening width remains approximately the same across all tested combinations. However, the total width of the weir increases as the number of openings grows, as more piers are required. For this comparison, it is assumed there is sufficient space in the waterway to allow for this additional width. Widening the weir will also mean moving the island of concept A further south, which will require some extra excavation on the southern bank. This will lead to a higher MKI because of the additional earthworks, but this contribution is not included in the comparison. Additionally, it is assumed that the wet cross-section of each layout is sufficient, as neither the total openings width nor the original sill height is changed in any of the layouts.

Table D.5 provides an overview of the results of the MKI calculation for the five layouts. The MKI values for the sheet piles, soil moving and soil transported are not shown in the comparison, as it assumed these values are the same for each of the five layouts. Layout **3xS37.35** has the lowest MKI, but the difference with **4xS28** is so small (0.1 %) that it is negligible.

Table D.5: MKI calculation for five layouts of concept A

MKI [€1,000]	**2xS56**	**3xS37.35**	**4xS28**	**5xS22.40**	**6xS18.70**
Floor and sill	191.2	197.5	203.5	209.7	216.2
Piers	55.1	73.5	91.9	110.3	128.6
Lifting towers	9.2	12.2	15.3	18.4	21.4
Stoney gates	329.7	287.7	260.8	241.9	228.0
Total	585.2	570.8	571.6	580.2	594.2

The MKI values are also plotted in the graph of Figure D.5, which clearly shows that the MKI of the concrete elements increases linearly as the number of openings increases, while the MKI of the steel gates decreases according to an inverse power function. Both of these relations can be attributed to the equation used to calculate the main dimensions of these elements.

For Concept A, layout **4xS28** is preferred over **3xS37.35**. The difference in MKI value is negligible, while **4xS28** provides more flexibility in discharge regulation due to having more openings. Additionally, more openings are beneficial during construction and maintenance, as a smaller section of the waterway is blocked by the cofferdam. This results in lower loads on the bed compared to a layout with fewer openings.

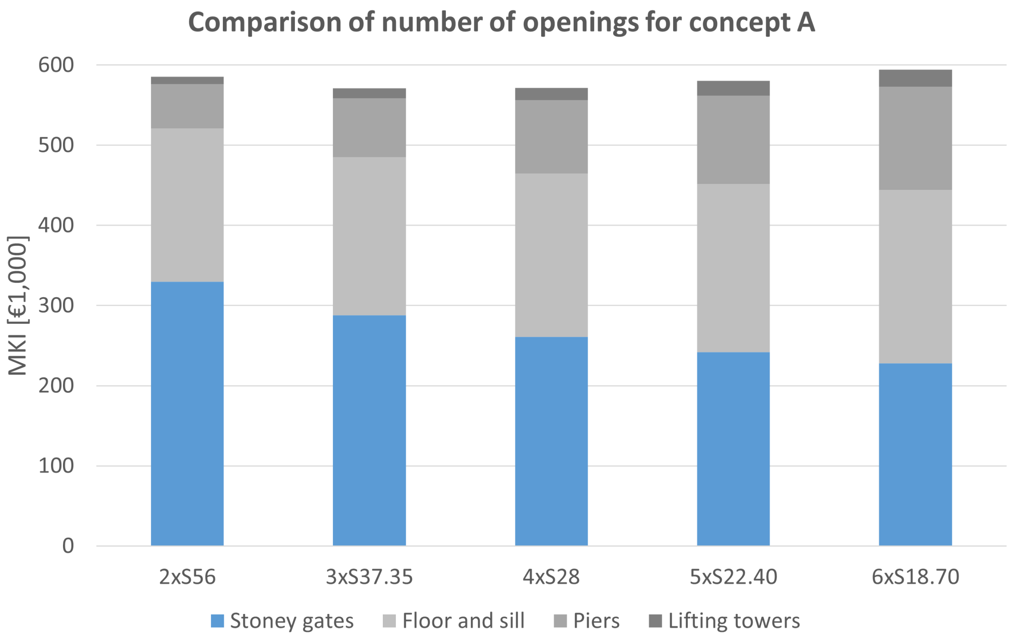


Figure D.5: MKI calculation for five layouts of concept A

D.4.2. Comparison of Stoney and visor gates

In addition to the comparison between different layouts for concept A, a comparison between Stoney and visor gates is made using concept A as the basis. The goal of this calculation is to determine whether incorporating visor gates is an effective method to reduce the MKI of the design. This is done by recalculating the MKI of concept A with different input values. The following variants are compared:

- A weir with 4 Stoney openings, each 28 m wide, abbreviated as **4xS28**. This is the original concept A, as presented in Section 6.1.3.
- A weir with 2 Stoney openings and 2 visor openings, all 28 m wide, abbreviated as **2xS28 2xV28**. In this variant, half of the Stoney gates are replaced by visor gates with the same width, resulting in a larger span, as explained in Section D.3.1. The two remaining Stoney gates are needed for precise water level control, a function that the visor gates can not perform.
- A weir with 2 Stoney openings each 17 m wide, and 2 visor openings, each 39 m wide, abbreviated as **2xS28 2xV28**. A visor gate is lighter and has a lower MKI compared to a Stoney gate of the same span. Therefore, it should be evaluated whether reducing the size of the Stoney gates and increasing the size of the visor gates can help reduce the total MKI.

It should be noted that the total opening width remains approximately the same across all three variants. However, the total width of the weir increases for the variants with visor gates, as in Section D.3.1 it is assumed that visor gates need a larger pier than Stoney gates. Therefore, for this comparison, the same assumptions regarding available space and required earthworks as in the previous comparison are made.

Table D.6 provides an overview of the MKI calculation results for the three variants. The MKI values for the sheet piles, soil moving and soil transported are not shown in the comparison, as it assumed these values are the same for each of the five layouts. Variant **4xS28** has the lowest MKI, even though the total MKI attributed to the combination of Stoney and visor gate in the other variants is lower than the total MKI of the Stoney gates in this variant. The visor gates of variant **2xS28 2xV28** have a MKI of 28% lower than it's Stoney gates with the same opening size.

Table D.6: MKI calculation for Stoney and visor gates for concept A

MKI [€1,000]	**4xS28**	**2xS28 2xV28**	**2xS17 2xV39**
Floor and sill	203.5	215.9	215.9
Piers	91.9	128.6	128.6
Lifting towers	15.3	21.41	21.41
Stoney gates	260.8	130.4	66.89
Visor gates	0	93.39	145.5
Total	571.6	589.7	578.3

In Figure D.6 it can be seen that the increase in MKI attributed to the piers is the main reason why both variants with visor gates score lower than the original variant with only Stoney gates. This is due to the assumption in Section D.3.1 that the piers of the visor gates are twice as wide. It is assumed that the piers of both gate types are solid and made of reinforced concrete, in order to provide enough weight to remain stable in the waterway when loaded. However, if the amount of concrete in their pier can be reduced, visor gates would form a more sustainable alternative to Stoney gates. It should be noted that visor gates cannot be used for precise water level regulation and the weir design requires a section with this function.

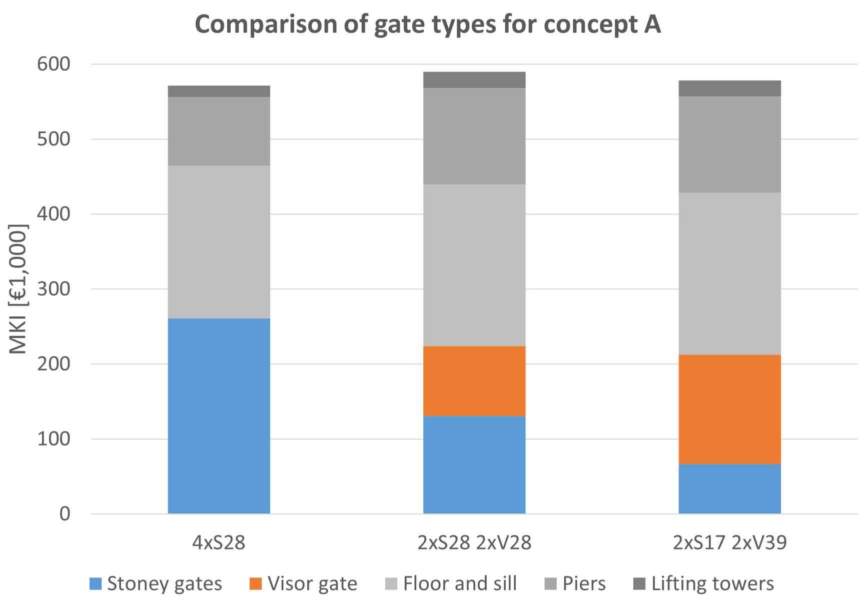


Figure D.6: MKI calculation for Stoney and visor gates for concept A

E. Stability analysis Linne weir floor

The goal of this appendix is to assess the stability of the floor of weir concept C, see Section 6.1.5. This floor is reused from the current Linne weir and a new pier with lifting towers is build on top. In Section E.1, it is checked whether uplift can occur during construction of the new piers in the cofferdam. Section E.2 evaluates the potential for sliding of the pier and floor, while Section E.3 assesses the possibility of rotation. Lastly, Section E.4 checks the bearing capacity of the subsoil.

E.1. Vertical stability: uplift floor

During the construction of the new piers, the old piers of the current Linne weir must be removed from the weir floor. To achieve this, the cofferdam must first be sealed watertight to create dry working conditions. The soil on both sides of the floor is excavated and then underwater concrete is cast, forming a connection between the floor and the sheet piles of the cofferdam. Once the cofferdam is drained, the old pier can be demolished.

The reinforcing bars of the old floor and pier are part of a single mesh. The portion of the bars extending above the floor must be preserved and integrated into the reinforcement mesh of the new pier. When the old pier on top of the floor is removed, there is a risk of uplift, which would lead to failure of the floor and cofferdam. To prevent uplift, the downward weight of the foundation, G, must exceed the upward buoyant force caused by water pressure on the bottom of the foundation, F_{uplift}:

$$G > F_{uplift} \tag{E.1}$$

The piers are removed during the summer, when the average discharge of the Meuse is low. A complete analysis of Meuse discharge during the summer, based on the KNMI'23 climate scenarios, is not available. Therefore, for this initial calculation, it is assumed that the discharge measured at Borgharen does not exceed 1700 m^3/s during construction.

Given these boundary conditions, the governing situation is assumed to be a discharge of 250 m^3/s, with a downstream water level of NAP + 17.15 m and an upstream water level equal to NAP + 20.85 m, see the relationship lines in Section A.1. This results in the highest local upward pressure on the floor. This situation is depicted in Figure E.1. A strutted cofferdam has been placed around the pier. At both ends of the floor, the soil has been excavated and filled with underwater concrete to create a watertight floor. Afterwards, the cofferdam is drained and the pier is removed.

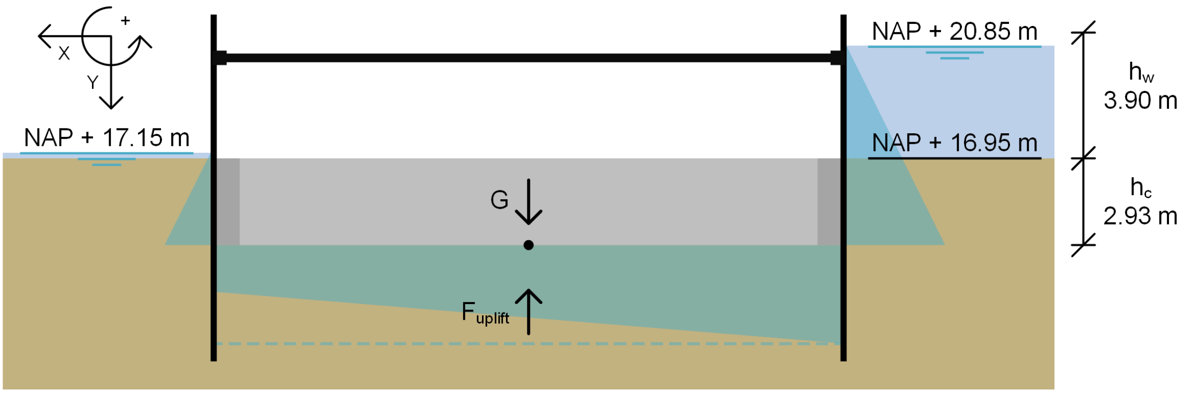


Figure E.1: Cofferdam around the old Linne weir floor after the pier has been removed

Based on the technical drawings in Appendix B, the weir floor is schematised as a slab with a uniform height of 2.93 m across its entire width of 20 m. The water pressure on the floor is not uniform over the width, as the downstream water level differs from the upstream water level. As indicated in Appendix B, there are several seepage screens under the floor, affecting the flow of water. For this calculation it is assumed that the maximum water pressure, located at the upstream end of the floor, is governing. Therefore, the floor must be thick enough to overcome the uplifting pressure:

$$G = h_c \cdot \rho_c \cdot g > F_{uplift} = (h_w + h_c) \cdot \rho_w \cdot g \tag{E.2}$$

The original floor consists of reinforced concrete, of which the exact density is unknown. On both sides of the floor, there is an additional stretch of underwater concrete. Therefore, it is assumed that the entire slab has a density of 2400 kg/m^3. Using a weight of 10 kN/m^3 for the water, it can be checked whether uplift occurs:

$$\begin{aligned} G = 2.93 \cdot 2400 \cdot 9.81 &> F_{uplift} = (3.90 + 2.93) \cdot 10 \\ 69.0 \quad [\text{kN/m}^2] &> \quad 68.3 \quad [\text{kN/m}^2] \end{aligned} \tag{E.3}$$

Based on this calculation it can be concluded that the weight of the underwater concrete floor is barely sufficient to prevent uplift for the given schematisation. However, if the discharge rises above 1700 m^3/s, the upstream water level will exceed NAP + 20.85 m. Additionally, no factor of safety is considered during the calculation. Therefore, additional weight will be required to ensure no uplift occurs during construction. While uplift is not expected to affect the overall feasibility of this concept, it will present a significant challenge during construction.

E.2. Horizontal stability: sliding pier on floor

The goal of this calculation is to determine whether there is a risk of sliding for the new pier. It is assumed that the connection between the new pier, the lifting tower and the reused floor is rigid. Thus, these elements cannot move independently. Therefore, it must be checked whether the weight of the structure is sufficient to prevent sliding when subjected to maximum horizontal loading. Sliding will not occur if the sum of the vertical loads, ΣV, multiplied by a dimensionless friction coefficient, f, is greater than the sum of the horizontal loads, ΣH:

$$\Sigma V \cdot f > \Sigma H \tag{E.4}$$

A single pier in the middle of the Stoney section of concept C is considered, see Figure E.2. It is assumed that the load on half of the floor between the two piers on either side is transferred to this section. The governing situation is shown in Figure E.3. There is a drought and the Meuse discharge does not exceed 50 m^3/s. The upstream basin is used to buffer water up to a height of NAP + 21.35 m. This situation results in the largest net horizontal force due to water pressure.

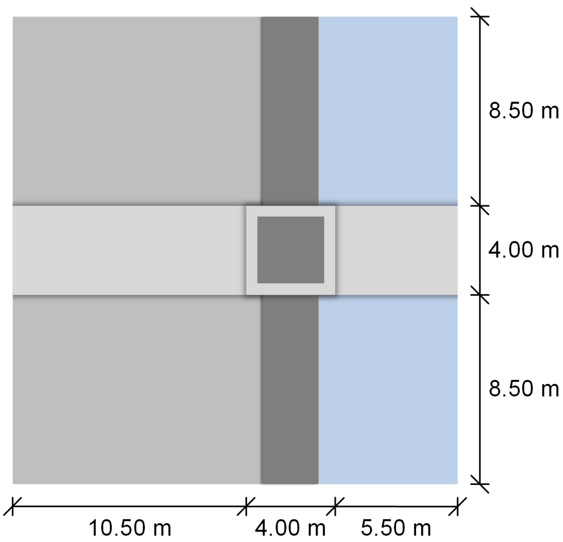


Figure E.2: Top view of a pier with half a floor section on either side

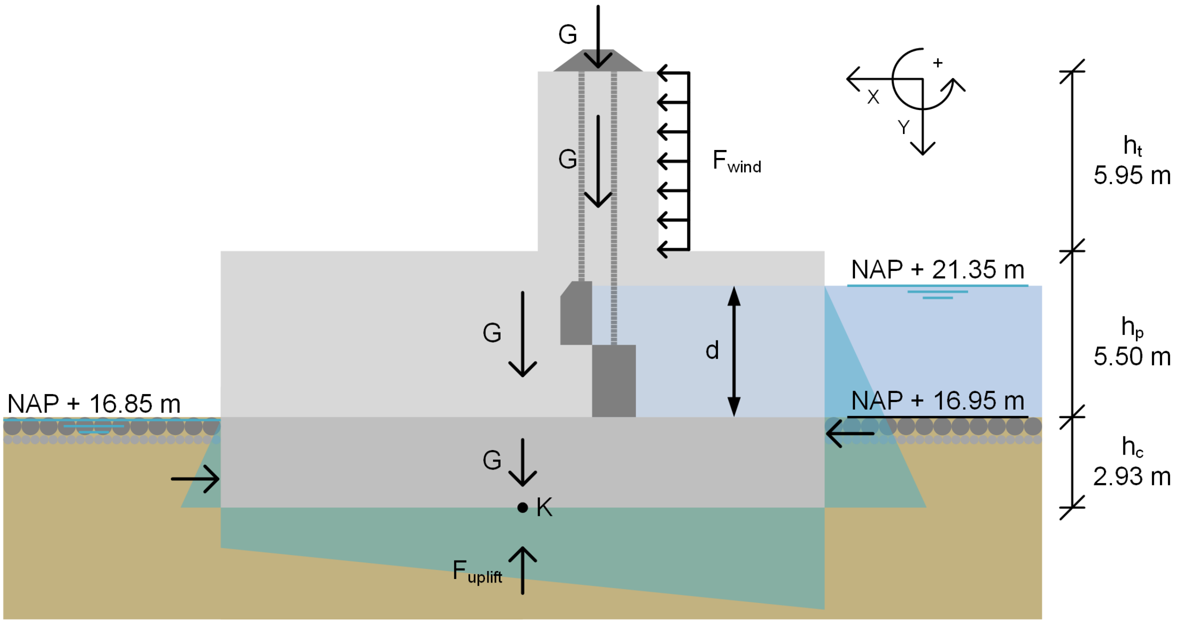


Figure E.3: New pier with Stoney gate on the old Linne floor during a drought

Horizontal loads: stationary water pressure
There is a stationary water pressure on both side of the weir. The upstream water level is at NAP + 21.35 m, the maximum buffered height, and the downstream water level is at NAP + 16.85 m, the minimum water level required for navigation. This results in the largest net horizontal load on the weir.

- Upstream: The horizontal water pressure acting on the upstream side of the structure has three components: the water pressure acting on the gate, the water pressure acting on the pier and floor beneath and the water pressure acting on the floor beneath the gate. In the given situation, the gate is closed and rest above the floor. No water flows over the weir. Therefore, all three components can be schematised as a single triangular distribution acting along the entire width of the section, with a maximum pressure calculated as:

$$p_{water,upstream} = (d + h_c) \cdot \rho \cdot g = (4.4 + 2.93) \cdot 1000 \cdot 9.81 = 71.9 \quad [\text{kPa}] \leftarrow \tag{E.5}$$

  The corresponding force is:

$$F_{water,upstream} = \frac{1}{2} \cdot (d + h_c) \cdot L \cdot p_{w,up} = \frac{1}{2} \cdot (4.4 + 2.93) \cdot 21 \cdot 71.9 = 5530 \quad [\text{kN}] \leftarrow \tag{E.6}$$

- Downstream: The horizontal water pressure acting on the downstream side of the structure acts only on the floor. It has a triangular distribution, with a maximum pressure calculated as:

$$p_{water,downstream} = (h_c - 0.10) \cdot \rho \cdot g = (2.93 - 0.10) \cdot 1000 \cdot 9.81 = 27.8 \quad [\text{kPa}] \rightarrow \tag{E.7}$$

  The corresponding force is:

$$F_{water,downstream} = \frac{1}{2} \cdot (h_c - 0.10) \cdot L \cdot p_{w,down} = \frac{1}{2} \cdot (2.93 - 0.10) \cdot 21 \cdot 27.8 = 830 \quad [\text{kN}] \rightarrow \tag{E.8}$$

Horizontal load: wind load
It is assumed that the wind load acts only on the lifting towers. The wind load on the top part of the gate extending above the waterline, as well as the pier height above the waterline, are both neglected. A first indication of the wind load is made using an approach based on Eurocode 1. The wind force is calculated using the following equation (Voorendt, 2024):

$$F_{wind,external} = c_s c_d \cdot c_f \cdot \sum_{surfaces} (w_e \cdot A_{ref}) \quad \text{(E.9)}$$

Where:
$c_s c_d$ [-] : Structural factor, may be taken as 1 for buildings with h < 15 (Voorendt, 2024)
c_f [-] : Force coefficient, depends on the shape of the element, conservatively taken as 1
w_e [kN/m^2] : Wind pressure acting on external surfaces
A_{ref} [m^2] : Reference area of the surface

The external wind pressure acting on the lifting tower is be determined using the peak velocity pressure, $q_p(z_e)$, multiplied by a pressure coefficient, c_{pe}:

$$w_e = q_p(z_e) \cdot c_{pe} \quad \text{(E.10)}$$

Since the height of the lifting tower is greater than its width but less than twice its width, two distinct reference areas, with each there own peak velocity pressure, must be considered:

- Area 1, from $z = 0$ to $z = b$, with a height of b and a width of b. $A_1 = 16.0$ m^2.
- Area 2, from $z = b$ to $z = h$, with a height of $h - b$ and a width of b. $A_2 = 11.8$ m^2.

The top of the tower lies at a height of 6.95 m above the waterline, see Section D.3.3. The weir is located in an open area in Linne, which lies in wind zone III. Therefore, the peak velocity pressure for the area 1, $w_{e,1}$, is equal to 0.49 kN/m^2 and for the area 2, $w_{e,2}$, is equal to 0.64 kN/m^2 (Voorendt, 2024).

It is assumed that the wind direction is parallel to the waterway, which results in a pressure coefficient of 0.8 (Voorendt, 2024). The wind pressure acting on the reference areas can now be calculated:

$$w_{e,1} = q_p(4) \cdot c_{pe} = 0.49 \cdot 0.8 = 0.392 \quad [\text{kN/m}^2] \leftarrow \quad \text{(E.11)}$$

$$w_{e,2} = q_p(\ 7) \cdot c_{pe} = 0.64 \cdot 0.8 = 0.504 \quad [\text{kN/m}^2] \leftarrow \quad \text{(E.12)}$$

The total wind load on the lifting tower is 12.2 kN. This is negligible compared to the water pressure and is therefore excluded from the remaining sliding calculation in order to simplify the check.

$$F_{wind,external,1} = c_s c_d \cdot c_f \cdot (w_{e,1} \cdot A_{ref,1}) = 1 \cdot 1 \cdot (0.392 \cdot 16.0) = 6.3 \quad [\text{kN}] \leftarrow \quad \text{(E.13)}$$

$$F_{wind,external,2} = c_s c_d \cdot c_f \cdot (w_{e,2} \cdot A_{ref,2}) = 1 \cdot 1 \cdot (0.504 \cdot 11.8) = 5.9 \quad [\text{kN}] \leftarrow \quad \text{(E.14)}$$

Horizontal load: wave load
In addition to the stationary water pressure acting on the weir, a wave load may act on the upstream side of the gate. It is assumed that non-breaking waves hit the gate and reflect back to the waterway. As a preliminary estimate, a simple rule of thumb is applied. It is assumed that the wave increases the water level, thereby increasing the stationary water pressure, see figure E.4. This provides an estimation of the upper boundary value of the wave load (Voorendt, 2024). The wave load can be calculated using the following equation:

$$F_{wave,max} = \frac{1}{2} \cdot \rho \cdot g \cdot H_i^2 + d \cdot \rho \cdot g \cdot H_i \quad [\text{kN/m}] \quad \text{(E.15)}$$

Where:
H_i [-] : The wave height of an incoming wave

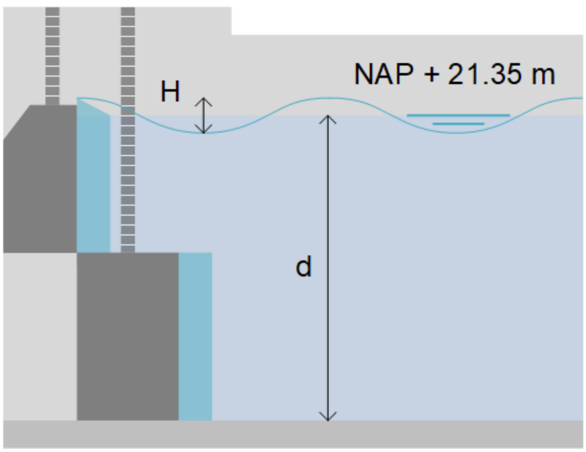


Figure E.4: Wave load on the Stoney gates using simple rule of thumb

The incoming wave height H_i is equal to half the total wave height, H. As a first indication, it is assumed that the waves on the upstream basin can reach a maximum wave height of 0.40 m. Therefore, the incoming wave height is equal to 0.20 m. Using the upstream basin depth of 4.4 m, the wave load can be calculated:

$$\begin{aligned} F_{wave,max} &= \frac{1}{2} \cdot \rho \cdot g \cdot H_i^2 + d \cdot \rho \cdot g \cdot H_i \\ &= \frac{1}{2} \cdot 1000 \cdot 9.81 \cdot 0.20^2 + 4.4 \cdot 1000 \cdot 9.81 \cdot 0.20 \\ &= 8.83 \quad [\text{kN/m}] \leftarrow \end{aligned} \tag{E.16}$$

The wave load shown in Figure E.4 acts on the gate. Additionally, wave loads also act on the piers standing in the waterway. To calculate the total wave load acting on the weir section depicted in Figure E.2, the wave load is multiplied by the width of the entire section:

$$F_{wave} = 8.83 \cdot 17 = 150 \quad [\text{kN}] \leftarrow \tag{E.17}$$

Vertical loads: self-weight of concrete and steel
The self-weight of the concrete and steel elements contribute to sum of vertical loads:

- <u>Floor:</u> The considered floor element has a width of 20 m, a thickness of 2.93 m and a length of 21 m. Assuming a density of 2400 kg/m^3, the self-weight can be determined:

$$G = V \cdot \rho \cdot g = (20 \cdot 2.93 \cdot 21) \cdot 2400 \cdot 9.81 = 29700 \quad [\text{kN}] \downarrow \tag{E.18}$$

- <u>Pier:</u> The pier has a volume of 374 m^3, as calculated in Section D.3.3. Assuming a density of 2500 kg/m^3, the self-weight can be determined:

$$G = V \cdot \rho \cdot g = 374 \cdot 2500 \cdot 9.81 = 9170 \quad [\text{kN}] \downarrow \tag{E.19}$$

- <u>Lifting tower:</u> The lifting tower has a volume of 66 m^3, as calculated in Section D.3.3. Assuming a density of 2500 kg/m^3, the self-weight can be determined:

$$G = V \cdot \rho \cdot g = 66 \cdot 2500 \cdot 9.81 = 1620 \quad [\text{kN}] \downarrow \tag{E.20}$$

- <u>Stoney gate:</u> The mass of the Stoney gate is estimated to be 59.3 tonnes in Section D.3.3, corresponding to a self-weight of 582 kN $\downarrow$.
- <u>Gate mechanism:</u> It is assumed that the mass of the gate mechanism is approximately equal to the mass of the gate, resulting in a load of 582 kN $\downarrow$.

Vertical load: buoyant force
The buoyant force on the bottom of the floor is equal to the average water pressure multiplied by the area of the floor:

$$F_{uplift} = p_{avg} \cdot A = \left(\frac{27.8 + 71.9}{2} \right) \cdot (20 \cdot 21) = 20900 \quad [\text{kN}] \uparrow \tag{E.21}$$

Friction coefficient
Friction between the floor and the subsoil must be high enough to overcome the sum of horizontal forces. It is assumed that the soil beneath the weir floor consists of gravel, see the subsurface data in Section A.2. For an interface between cast concrete and gravel, gravel-sand mixtures or coarse sand, the value of the friction coefficient lies between 0.55 to 0.60 (Voorendt, 2024). Since the characteristics of the subsoil at exactly the floor's location are unknown, the lowest friction coefficient value of 0.55 is used as a conservative assumption.

Final calculation sliding
In Table E.1 an overview of all the calculated forces is given.

Table E.1: Overview significant load stability pier

Load	Force [kN]	Arm [m]	Moment [MNm]
Horizontal loads			
Upstream stationary water	5530	2.44	13.49
Downstream stationary water	-830	0.94	-0.78
Wave load	150	5.13	0.77
Total	$\Sigma H = 4850$		$\Sigma M_H = 13.48$
Vertical loads			
Self-weight floor	29700	0	0
Self-weight pier	9170	0	0
Self-weight lifting tower	1620	-2.50	-4.05
Self-weight gate	582	-2.50	-1.46
Self-weight mechanism	582	-2.50	-1.46
Upward water pressure	-20900	-1.47	30.72
Total	$\Sigma V = 20754$		$\Sigma M_V = 23.75$

As stated at the beginning of this calculation, in order to prevent sliding the sum of vertical loads multiplied by the friction coefficient, must be larger than the sum of horizontal loads:

$$\begin{gathered} \Sigma V \cdot f > \Sigma H \\ 20754 \cdot 0.55 = 11415 \quad [\text{kN}] \quad > \quad 4850 \quad [\text{kN}] \end{gathered} \tag{E.22}$$

The section of pier and floor is not at risk of sliding.

E.3. Rotational stability: rotation pier on floor

In addition to sliding, the pier could fail due to rotation. The pier and floor beneath are rotationally stable if the resultant force due to the loads acting on the structure falls within its core (Voorendt, 2024). The core is defined as the area extending $\frac{1}{6}$ of the structure's width on either side of its midpoint (point K in Figure E.3). This can be expressed by the following equation:

$$e_R = \frac{\Sigma M}{\Sigma V} \leq \frac{1}{6} b \tag{E.23}$$

It is assumed that the situation described in Section E.2 is also governing for the rotation stability of the pier. Thus, the previously calculated loads presented in Table E.1 can be used:

$$\begin{gathered} \frac{13480 + 23750}{20754} < \frac{1}{6} \cdot 20 \\ 1.79 \quad [\text{m}] \quad < \quad 3.33 \quad [\text{m}] \end{gathered} \tag{E.24}$$

The section of pier and floor is not at risk of rotating.

E.4. Vertical stability: bearing capacity subsoil

Lastly, the pier's vertical stability must be checked. Thus includes the soil's bearing capacity and potential settlements. However, the settlement of the gravel subsoil is considered out of the scope of this conceptual design phase.

Maximum load
The maximum load acting on the subsoil may not exceed the bearing capacity of the soil (Voorendt, 2024):

$$\sigma_{k,max} < p'_{max} \tag{E.25}$$

Using the sum of the acting vertical forces and the sum of acting moments, the maximum load on the subsoil can be calculated:

$$\sigma_{k,max} = \frac{\Sigma V}{b \cdot l} + \frac{\Sigma M}{\frac{1}{6} \cdot l \cdot b^2} \tag{E.26}$$

It is assumed that the situation described in Section E.2 is also governing for the vertical stability of the pier. Thus, the previously calculated loads presented in Table E.1 can be used:

$$\sigma_{k,max} = \frac{20754}{20 \cdot 21} + \frac{13480 + 23750}{\frac{1}{6} \cdot 21 \cdot 20^2} = 76.0 \quad [\text{kN/m}^2] \tag{E.27}$$

The bearing capacity of gravel can range between 200 to 600 kN/m^2. Therefore, it is assumed as a first indication that the bearing capacity of the subsoil is not exceeded.

Minimum load
The subsoil can not handle tensile forces. Thus the minimum load acting on the subsoil must be positive (Voorendt, 2024):

$$\sigma_{k,min} > 0 \tag{E.28}$$

The minimum load on the subsoil can be calculated similarly:

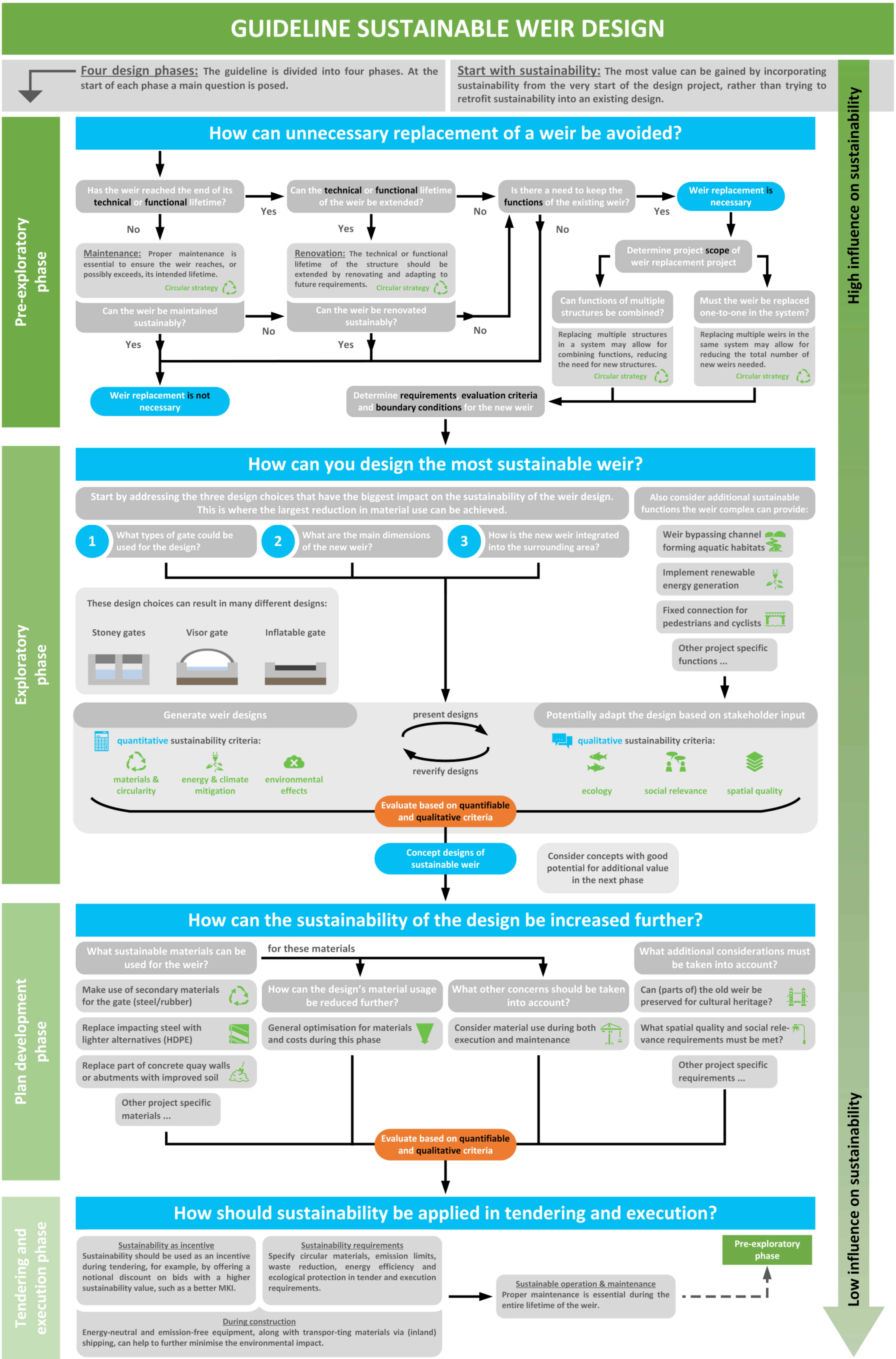
$$\sigma_{k,min} = \frac{\Sigma V}{b \cdot l} - \frac{\Sigma M}{\frac{1}{6} \cdot l \cdot b^2} \tag{E.29}$$

$$\sigma_{k,min} = \frac{20754}{20 \cdot 21} - \frac{13480 + 23750}{\frac{1}{6} \cdot 21 \cdot 20^2} = 22.8 \quad [\text{kN/m}^2] \tag{E.30}$$

As the minimum load on the subsoil is greater than zero, it will not fail due to tension.

Guideline sustainable weir design

In Chapter 2 the guideline for sustainable weir design has been developed. This guideline has been used for the case study of the Linne weir. In Chapter 7 the guideline has been validated through reviews by three specialists: a sustainability expert and a hydraulic engineer from Royal Haskoning DHV and a technical advisor from RWS. The feedback from this validation has been used to improve and expand the guideline. In this appendix the final version is presented.


GUIDELINE SUSTAINABLE WEIR DESIGN
Four design phases: The guideline is divided into four phases. At the start of each phase a main question is posed.
Start with sustainability: The most value can be gained by incorporating sustainability from the very start of the design project, rather than trying to retrofit sustainability into an existing design.
High influence on sustainability
Low influence on sustainability
Pre-exploratory phase
How can unnecessary replacement of a weir be avoided?
Has the weir reached the end of its technical or functional lifetime?
Yes
No
Maintenance: Proper maintenance is essential to ensure the weir reaches, or possibly exceeds, its intended lifetime.
Circular strategy
Can the weir be maintained sustainably?
No
Yes
Can the technical or functional lifetime of the weir be extended?
Yes
No
Renovation: The technical or functional lifetime of the structure should be extended by renovating and adapting to future requirements.
Circular strategy
Can the weir be renovated sustainably?
No
Yes
Is there a need to keep the functions of the existing weir?
Yes
No
Weir replacement is necessary
Determine project scope of weir replacement project
Can functions of multiple structures be combined?
Replacing multiple structures in a system may allow for combining functions, reducing the need for new structures.
Circular strategy
Must the weir be replaced one-to-one in the system?
Replacing multiple weirs in the same system may allow for reducing the total number of new weirs needed.
Circular strategy
Weir replacement is not necessary
Determine requirements, evaluation criteria and boundary conditions for the new weir
Exploratory phase
How can you design the most sustainable weir?
Start by addressing the three design choices that have the biggest impact on the sustainability of the weir design. This is where the largest reduction in material use can be achieved.
Also consider additional sustainable functions the weir complex can provide:
1 What types of gate could be used for the design?
2 What are the main dimensions of the new weir?
3 How is the new weir integrated into the surrounding area?
Weir bypassing channel forming aquatic habitats
Implement renewable energy generation
Fixed connection for pedestrians and cyclists
Other project specific functions ...
These design choices can result in many different designs:
Stoney gates
Visor gate
Inflatable gate
Generate weir designs
quantitative sustainability criteria:
materials & circularity
energy & climate mitigation
environmental effects
present designs
reverify designs
Potentially adapt the design based on stakeholder input
qualitative sustainability criteria:
ecology
social relevance
spatial quality
Evaluate based on quantifiable and qualitative criteria
Concept designs of sustainable weir
Consider concepts with good potential for additional value in the next phase
Plan development phase
How can the sustainability of the design be increased further?
What sustainable materials can be used for the weir?
for these materials
Make use of secondary materials for the gate (steel/rubber)
Replace impacting steel with lighter alternatives (HDPE)
Replace part of concrete quay walls or abutments with improved soil
Other project specific materials ...
How can the design's material usage be reduced further?
General optimisation for materials and costs during this phase
What other concerns should be taken into account?
Consider material use during both execution and maintenance
What additional considerations must be taken into account?
Can (parts of) the old weir be preserved for cultural heritage?
What spatial quality and social relevance requirements must be met?
Other project specific requirements ...
Evaluate based on quantifiable and qualitative criteria
Tendering and execution phase
How should sustainability be applied in tendering and execution?
Sustainability as incentive
Sustainability should be used as an incentive during tendering, for example, by offering a notional discount on bids with a higher sustainability value, such as a better MKI.
Sustainability requirements
Specify circular materials, emission limits, waste reduction, energy efficiency and ecological protection in tender and execution requirements.
During construction
Energy-neutral and emission-free equipment, along with transpor-ting materials via (inland) shipping, can help to further minimise the environmental impact.
Sustainable operation & maintenance
Proper maintenance is essential during the entire lifetime of the weir.
Pre-exploratory phase