Optimizing Longitudinal Wall and Multi-Channel Design at the IJssel River

Master Thesis

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TU Delft

Haskoning
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Optimizing Longitudinal Wall and Multi-Channel Design at the IJssel River

by

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in partial fulfillment of the degree of Master of Science
in Civil Engineering
at the Delft University of Technology

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Faculty:	Civil Engineering and Geosciences, Delft
Project Duration:	Monday 2nd December, 2024 - September, 2025
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Preface

This thesis report marks the final step of my Master's program of Civil Engineering and it is a reflection of years of learning and personal growth. Being able to understand and explain the physics behind the civil world around us has always been the motivation for me to follow the Bachelor's and Master's program of Civil Engineering and doing research in the fields of hydraulic structures and river management was a great way of finalizing my studies. Although the journey was challenging at times, it was also highly rewarding and I am grateful for the opportunities provided by both Haskoning and the TU Delft during this process.

I would like to express my gratitude to my supervisors, both at the TU Delft and Haskoning. Wim Uijttewaal, thank you for your valuable feedback, which helped keep me on track and improved the quality of my work. Bas Hofland, your enthusiasm during this project was contagious and helped me stay motivated and positive. Lisa de Koning, thanks for your time and all the things you did to make the internship at Haskoning possible. Your thinking along was often refreshing and helpful towards a solution. Michel van Heereveld, thanks for making time in your sometimes busy schedule to provide me with new ideas and interesting points of view. Wiebe de Jong, thank you for helping me find an interesting research topic at Haskoning and providing me with constructive feedback. I would also like to thank all the Haskoning colleagues who were always willing to help me with any question or problem I encountered.

Finally, I want to thank my family, friends and girlfriend for supporting me throughout this project. Thanks for giving me the space to relax and think about other things than longitudinal walls and river training.

Lennart Nijsse
Delft, August 2025

Summary

The IJssel, a relatively narrow but important river in the east of the Netherlands, plays a key role in inland navigation and freshwater supply. Traditionally, groynes have been used to guide river flow in the Rhine and Meuse. However, climate change and past flood threats (1993 and 1995) have prompted a shift in river management, leading to initiatives like the Room for the River program. One emerging issue is riverbed erosion, which exposes non-erodible layers and affects flow. While most severe in the Waal, the IJssel is also impacted. Groynes concentrate flow in the center, deepening the riverbed. Alternatives like the longitudinal training wall (LTW) and the multi-channel system aim to guide flow without obstructing it during higher discharges.

LTWs create a main and auxiliary channel, improving navigation, reducing erosion, and enhancing ecology. A pilot in the Waal confirmed these benefits. The multi-channel system, which carves a channel through the floodplain to form a sandy island, offers even greater ecological value and less spatial impact than LTWs.

The aim of this research is to develop alternatives for the design that was used in the pilot project in the Waal and choose the best alternative based on requirements and criteria. This process starts by investigating the area of interest to come up with requirements that all alternatives need to satisfy. Based on the main functions of the river, the following requirements are stated: structural integrity, sufficient discharge capacity and a minimum width of the main channel.

The criteria that are used to evaluate the alternatives are related to the structural aspects *permeability*, *wave reflection* and *flexibility* and spatial aspects *width of structure* and *width of auxiliary channel*. *Constructability*, *management and maintenance*, *sustainability* and *ecology* are the other criteria for the multi-criteria analysis.

A brainstorming session was held to generate alternative concepts and assign weight factors to evaluation criteria, reflecting their relative importance. The final alternatives are:

- A rubble mound LTW, based on the Waal pilot project
- A multi-channel system with one auxiliary channel that cuts into the floodplains
- A gabion-based LTW
- A LTW consisting of concrete Xstream elements

Each alternative was designed according to structural requirements and scored per criterion, quantitatively where possible. A multi-criteria analysis (MCA) was then performed to determine the overall ranking. Comparing the multi-channel system to the other alternatives proved challenging due to its distinct nature and limited available data. Based on the MCA, the Xstream element LTW scores highest and is considered the most promising solution. Although the pilot project design also performs well, its substantial width requires additional excavation, making it too complex and impractical for implementation. The multi-channel system and gabion-based LTW are ranked third and fourth in the MCA. The multi-channel system requires purchasing of land, which is expensive and time-consuming. The slender structure of the gabion wall provides space for a relatively wide auxiliary channel, but this also causes negative effects, such as high wave reflection and low flexibility.

The final selection of the optimal design was based on a cost-benefit analysis. Due to the significantly lower costs associated with the multi-channel system, this alternative achieved the highest score in the cost-benefit analysis. Although it did not perform best in the multi-criteria analysis, the economic advantage of the multi-channel system led to it being identified as the most favorable overall solution in this study. However, further research into the morphological effects of the proposed alternatives will be required to support a well-balanced and informed decision in future design processes.

Contents

List of abbreviations

Abbreviation	Dutch	English
LTW		Longitudinal Training Wall
OLR	Overeengekomen Lage Rivierstand	Agreed-upon Low River Water Level
IRM	Programma Integraal Riviermanagement	Integral River Management
MCA		Multi-Criteria Analysis

1 Introduction

1.1. Research context

In recent decades, river management in the Netherlands has received increasing attention. Various problems have emerged as a consequence of the interventions that have been made in the past centuries in the big rivers that flow through the Netherlands (Rhine and Meuse and their sub-branches). The dominant trend in these interventions was the confinement of rivers between dikes, significantly reducing their natural floodplains. As the land behind the dikes had subsided, the consequences of a possible flood increased both on an economic and social level (*Planologische Kernbeslissing Ruimte voor de Rivier*, 2007).
In the beginning of the 21st century, the project 'Ruimte voor de Rivier', 'Room for the River', was launched. The aim of this project was to come up with a set of measures that would enhance flood safety in the riverine ares of the Netherlands. The urgency for such a program became evident after major flood threats in 1993 and 1995 along the Rhine and Meuse river branches (Wikipedia, 2024). As a precaution, both in 1993 (12,000 people) and 1995 (250,000 people), several areas were evacuated in case the river dikes were breached. These flooding threats were the direct causes for the implementation of the Room for the River project. The program focused on the safety of the river areas by giving more space, 'room', to the river. Key measures included the relocation of river dikes and depoldering of certain areas to accomodate high water levels. The Room for the River program produced measures at 34 positions along subbranches of the Rhine river: the IJssel, Waal, Nederrijn and Lek (Rijkswaterstaat, n.d.-b).
Because the Room for the River project primarily addressed the subbranches of the Rhine, another program was initiated simultaneously: 'Maaswerken'. This program focused on widening the Meuse in various places. Side channels were constructed to accommodate space for the river in the event of floods. 'Maaswerken' was split up into three parts that focused on a different part of the Meuse. While most of the projects were completed in 2017, but some of them are still ongoing and are expected to be finalized by 2027 (Rijkswaterstaat, n.d.-b).

1.1.1. IRM: Programma Integraal Riviermanagement

As most of the projects of Room for the River and Maaswerken have finished, a new program has been launched, 'Programma Integraal Riviermanagement (IRM)', which can be translated as 'Program for integral river management'. As the name already suggests, an integral approach is incorporated in this program as it focuses on both the Rhine and Meuse river systems. Recently, the name of this program was changed towards 'Room for the River 2'. The choice for this integral approach stems from the understanding that a measure in one river system can affect other systems as well. Another aspect of the integral approach is the variety of functions in and along the rivers that can benefit from a comprehensive strategy. Within this approach, all functions and stakeholders are considered. The identified functions are: 'Navigation, agriculture, housing, recreation, entrepreneurialism, nature, freshwater supply, urbanization' (Nationaal Deltaprogramma, n.d.). The ambition of *Room for the River 2* is therefore to create *"a future proof river area that functions well as a river system and is useful in multiple functions"*. (Programma Integraal Riviermanagement, 2024).
The program has two main objectives:

1. To anticipate more frequent and higher high waters, as well as longer-lasting and lower low waters, which are expected as a result of climate change.
2. To address problems caused by past human interventions in the river system.

The human interventions mentioned in the second main task of the IRM program refer to the river management in the past that primarily focused on strengthening dikes and enabling water to flow to the sea as quickly as possible. As the rivers in the Netherlands, which once followed natural courses, have been

canalized over the past centuries, several issues have emerged. One of the most significant problems is riverbed erosion. Several interventions are proposed in the IRM program to mitigate this erosion (Royal HaskoningDHV, 2023). One of the interventions is the use of longitudinal training walls.
Longitudinal training walls (LTWs) -or longitudinal walls- are structures that create a parallel channel within rivers, and in the Netherlands they have been constructed as a pilot project in the Waal river near Tiel. The main objectives for these longitudinal walls are (Czapiga et al., 2022, Le et al., 2020):

- To reduce water levels during floods, due to the increased flow width during floods in comparison with the old system with groynes.
- To increase water levels during low-flow conditions by decreasing flow width during regular conditions.
- To improve ecological development by enhancing habitat conditions.
- To reduce riverbed erosion.

Figure 1.1: Longitudinal training wall in the Waal river (HF Midden Nederland, 2016)

1.2. Research problem

Until today, groynes have been used in various rivers in the Netherlands and abroad to reduce flow velocity along the edges of the summer bed. Although this helps guide the river, a major drawback of groynes is that water is also slowed down during high water events. This increases bed friction, leading to a riverbed incision. To mitigate this negative impact of groynes, one of the possible solutions is the substitution of groynes with longitudinal walls. Although there has been research on the morphological impact of longitudinal walls as a replacement for groynes that were used in the branches of the river Rhine (Czapiga et al., 2022, Le, 2018), less attention has been given to the construction and design of these structures. A pilot project in the Waal river aimed to gain insight into the morphological effects of LTWs. In this pilot project, the LTWs were constructed with simple rubble stone. While this is a straightforward construction method, there are several disadvantages. Firstly, the current longitudinal training walls are positioned deeper into the river than traditional groynes, reducing the width of the main channel through which ships navigate. Secondly, a longitudinal wall constructed with rubble stone is relatively porous, which makes it possible for water to flow from the main channel towards the auxiliary, parallel channel. During low-flow conditions, this is undesirable, as it limits the water depth in the main channel.

Meanwhile, the Waal and IJssel rivers continue to suffer from bed erosion due to the limited space between their dikes. This makes it necessary to implement measures to counteract the bed erosion of these rivers. At the Pannerdense Kop bifurcation of the Rhine, the river is presumably wide enough to place a longitudinal wall. However, in the IJssel River, this appears more challenging due to its relatively narrow profile and its importance for navigation. Any potential LTW design for the IJssel must therefore ensure that navigability is not compromised.

Finally, the 'meergeulenconcept' or 'multi-channel system' is gaining popularity. The main idea of this concept is that instead of a simple rubble stone longitudinal wall and a relatively small secondary channel, a sandy island will be constructed. This island would still require a protection layer at the side of the main navigational channel, but would also have a more natural, ecologically rich secondary channel. This means that the positive effect of mitigating erosion in the river bed remains, but the design is also more nature-based and environmentally friendly (Bureau Stroming, n.d.).

According to Bureau Stroming, n.d., the 'multi-channel system' could address several of the negative effects of the longitudinal walls as constructed in the pilot project. For example, under average discharges, the water depth in the parallel channel next to an LTW is still quite high, and there are few shallow areas. The first measurements of fish populations indicate a higher number of fish behind the LTWs compared to areas around traditional groynes (Collas et al., 2016). However, if the current LTW design is maintained, this positive trend might be reversed in the future due to the high flow velocities in the side channel (van Winden et al., 2022). Therefore, part of this research will explore the potential of integrating this 'multi-channel system' with a sandy island, as this might help reduce flow velocities in the secondary channel and enhance ecological conditions.

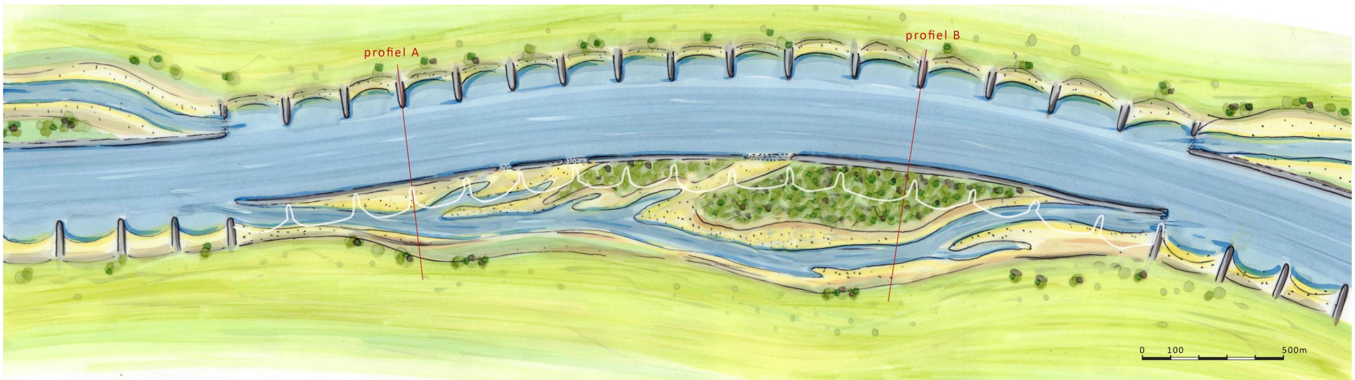


Figure 1.2: A visualization by Bureau Stroming of the multi-channel system in the Waal river (Bureau Stroming, n.d.)

In Figure 1.3, the area of interest is depicted.

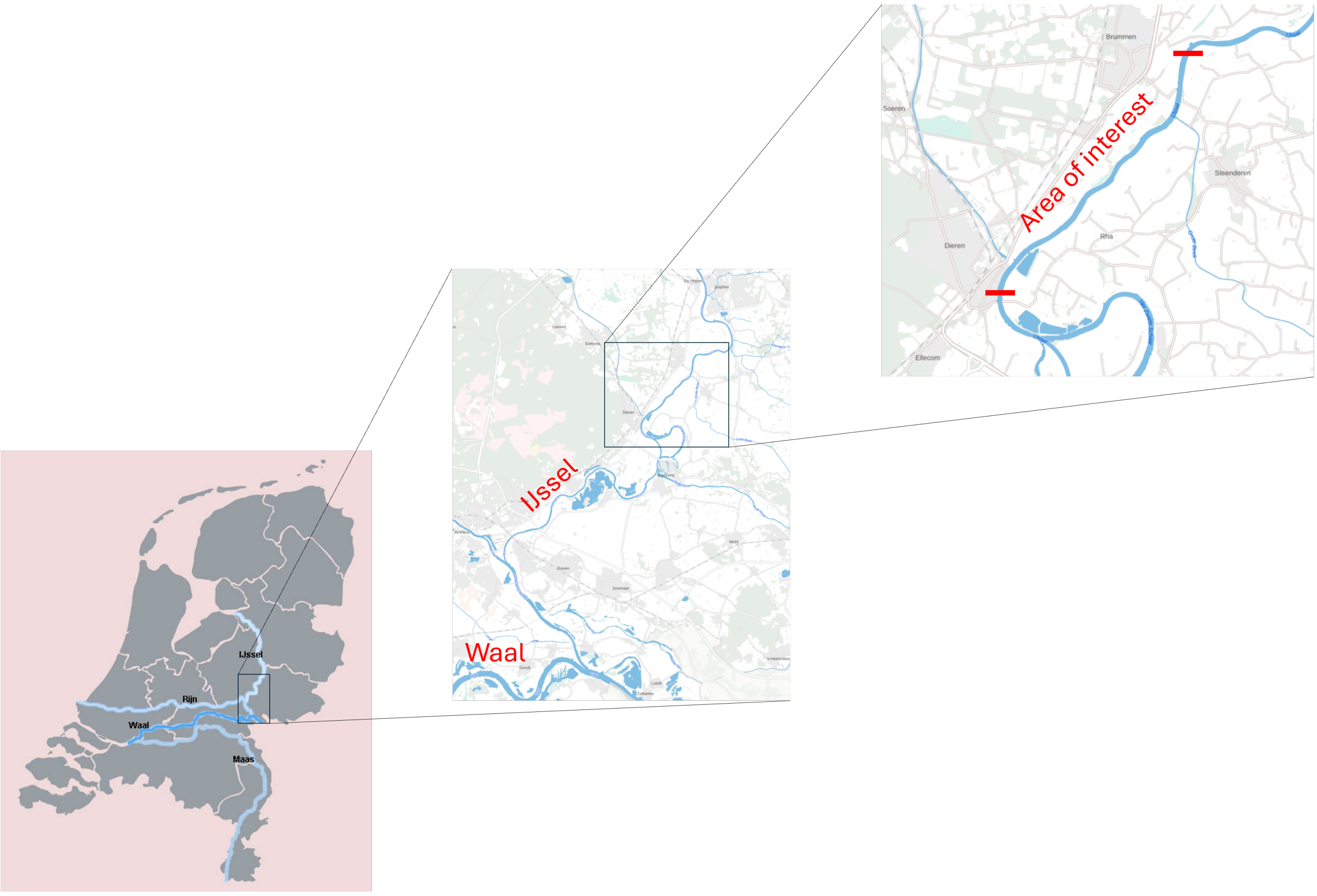


Figure 1.3: Region of interest (Nederland Waterland, n.d.)

1.3. Research questions

The following main question will be answered during the research:

"What is the optimal design for a longitudinal wall in the IJssel river to enhance flood safety, mitigate bed erosion, and maintain navigability"

The following sub-questions will help to answer this main research question:

1. "What are the relevant criteria and boundary conditions for the location, dimensions and materials for the structures in the IJssel river and how can they be quantified?"
2. "What are the advantages and disadvantages of the current design approach for longitudinal walls, as applied in the pilot project near Tiel, when considered in the context of the IJssel River? "
3. "Which alternative construction materials can be used for longitudinal walls, and how do they compare based on the criteria defined in the first sub-question?"

1.4. Research methodology

In order to answer the research questions, the steps of a civil engineering design process will be followed (Roozenburg and Eekels, 1995):

- **Phase 1: Problem analysis.** This step has already been partially covered in the first part of this chapter. It highlights the research problem. In the literature review, this is worked out in more detail.
- **Phase 2: System analysis.** In this phase, the processes, functions and stakeholders of the relevant system are analyzed. A start with this is already made in this chapter. An key component of this phase is the determination of a representative location in the IJssel for the proposed structure.
- **Phase 3: Basis of design.** Based on the system analysis, functional and structural criteria will be established. This phase answers the first sub-question. Criteria will be developed through expert consultation with Rijkswaterstaat and Haskoning, supported with literature study and reference projects..
- **Phase 4: Generation of concepts.** This creative phase involves identifying potential construction materials and design concepts for the longitudinal training wall or multi-channel system. Concepts will be derived from literature and by consulting experts at Haskoning. One of the variants that will be verified in the next phase is the current design of the pilot project at Tiel. This phase will answer the second sub-question.
- **Phase 5: Verification of concepts.** The proposed variants will be evaluated against the criteria. Where possible, aspects will be assessed using design formulas from the *Roch Manual* and other sources. Other criteria that cannot be quantified will be evaluated through expert judgment and literature review. This phase contributes to answering the last sub-question.
- **Phase 6: Evaluation of alternatives.** This phase builds on the previous one by performing a multi-criteria analysis (MCA) cost-benefit analysis of the different design alternatives. The evaluation will be based on the criteria defined in phase 3. With this phase, an answer to sub-question 3 is given.
- **Phase 7: Integration of subsystems.** The best alternative or combination of alternatives from the previous phase will be selected and worked out. This will answer the main research question.

1.5. Research structure and planning

The structure of the thesis follows the phases of the design process, aligning with the sub-questions and the main research question:

1. Problem Analysis
2. Theoretical background
3. System Analysis
4. Basis of design (functional and structural criteria)
5. Generation of concepts

6. Verification of concepts (testing the alternatives)
7. Evaluation of the alternatives (Multi-Criteria Analysis)
8. Final design

1.6. Research scope

This research focuses on the structural design of longitudinal walls and the ’multi-channel system’, within the context of the IJssel river. The morphological impact of the proposed designs lies outside the scope of this study.

2 Theoretical Background

2.1. Aim of Literature Research

The aim of this literature review is to gain insights into the state-of-the-art of river training by longitudinal walls, as well as to explore potential construction materials and structures for these walls. Additionally, this review aims to identify relevant knowledge gaps in the existing literature. At the same time, this literature review serves as a contribution of the problem analysis introduced in Chapter 1.

2.2. Longitudinal Training Walls

The effects of training rivers with longitudinal walls instead of groynes have been extensively studied. Traditionally, transverse groynes have been used in The Netherlands to guide river flow. These groynes maintain sufficient depth in the central part of the river, confine the flow between the surrounding dikes, and prevent the formation of ice jams (Le, 2018).

A key reference for this research is the dissertation by Le Binh, which, although primarily focused on the morphological effects of LTWs, provides valuable insights into their advantages over traditional groynes. Le Binh highlights several drawbacks of groynes that can be mitigated by replacing them with LTWs. One major issue is that groynes reduce the river's conveyance capacity during high flows by obstructing water at the riverbanks. This leads to increased riverbed erosion. In the Waal river, this process of erosion causes non-erodible layers to become obstacles. Other disadvantages of groynes mentioned by Le Binh include the formation of local scour holes at groyne heads and elevated water levels due to flow obstruction.

Longitudinal training walls, by contrast, create a main channel and a secondary channel with an inlet at the upstream end of the LTW. The main channel is used for navigation, whereas the secondary channel can be used during high-discharge events to allow the discharge of more water (Le, 2018). In Figure 2.1, a quick overview is given of the layout of a channel with groynes or LTWs (Czapiga et al., 2022). Longitudinal training walls reduce erosion of the riverbed by diverting water from the primary channel into the secondary channel. An interesting result of Czapiga et al. is that high flows around LTWs trap sediment within the LTW domain. Between flood events, the sediment disperses and scour pits that were formed after a flood at the downstream end of the LTW, are filled again (Czapiga et al., 2022). It should be noted that this study was evaluating the effects on riverbed erosion specifically at the 11 km pilot project in the Waal river. The effects of a different location or a more slender design of the LTW may differ. However, this paper still emphasizes the general benefits of LTWs.

2.3. Pilot project 'Langsdammen in de Waal'

As mentioned earlier, a pilot project has been carried out in the Waal to gain more certainty and insight into the integral effectiveness of a change in river systems by using LTWs. Deltares conducted an evaluation of this project, resulting in a few partial reports that focus on a specific subject, and one main report. The main conclusion of these evaluations is that LTWs have a positive impact on riverbed erosion but also on navigation during low discharge values. Furthermore, the ecological quality is improved and water levels during high discharge events are lower, improving flood safety (Mosselman et al., 2021). However, a downside is that inland navigation skippers expressed skepticism, because they perceive a decrease in navigability due to a seemingly narrower main channel. It is expected that this experience might improve in the case of a more slender structure.

Another notable finding of this evaluation report is that adjusting the inlet openings does not influence erosion during high discharges. However, during low discharges, changes in the inlet configuration can influence erosion and sedimentation of the riverbed in both the main and secondary channels (Mosselman et al., 2021). In Figure 2.1, an overview is given of the main differences between an engineerde channel with groynes or with a longitudinal training wall.

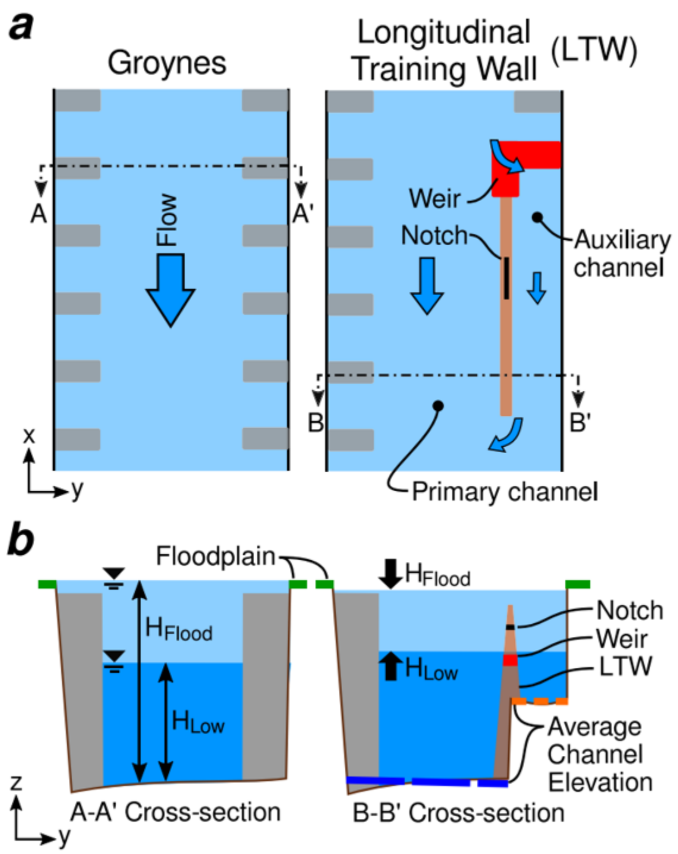


Figure 2.1: Differences between engineered channels with groynes and longitudinal training walls in: (a) plan view and (b) cross-section view. (Czapiga et al., 2022)

2.3.1. Current design

In Table 2.1, the design parameters of the pilot project are presented (Zuijderwijk and de Jong, 2021). The rightmost column provides values with respect to NAP, using an OLR depth of 2.55 m +NAP at Tiel (van Putten and Vrijaldenhoven, 2022). A cross-section in which the parameters are visualized can be found in Figure 2.2.

Table 2.1: Design parameters of the pilot project (Zuijderwijk and de Jong, 2021)

Component	Aspect	Value in Pilot Project	Value w.r.t. NAP (m)
Longitudinal wall	Crest height	OLR + 2.35 m – OLR + 2.78 m	4.90 – 5.33
	Crest width	2 m	–
	Slope	1:2.5	–
	Material	Rubble stone (4-200 kg)	–
Inlet opening	Threshold height	OLR – 1.75 m	0.80
Intermediate opening	Threshold height	OLR + 1.25 m	3.80
	Threshold width	154 – 221 m	–
Secondary channel	Width	Approx. 100 m	–
	Depth	OLR – 4.75 m to OLR + 0 m	–2.20 to +2.55

In this table, OLR is the abbreviation for 'Overeengekomen lage rivierstand' which can be translated as

'Agreed-upon low river level', a measure for the river level at a very low discharge of the Rhine of 1020 m^3/s at Lobith.

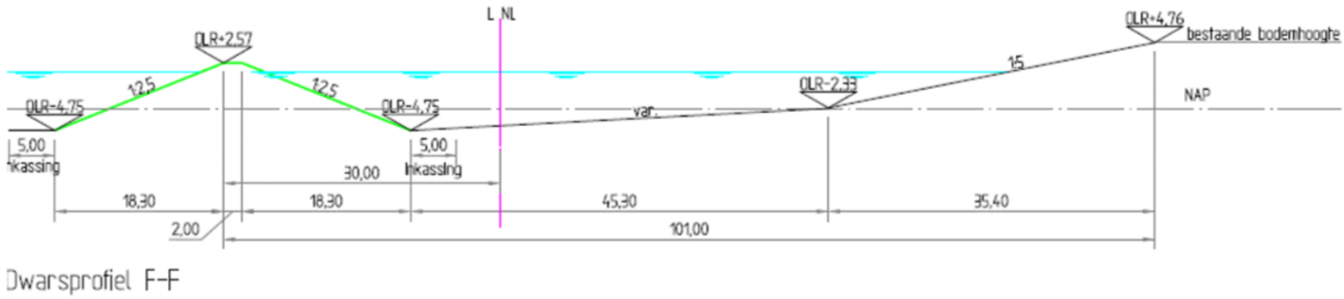


Figure 2.2: Cross-section of LTW design for the pilot project (Zuijderwijk and de Jong, 2021)

The design parameters from the pilot project are used in the verification phase of the design to test the current design method for the different criteria.

2.4. Morphodynamic effects of LTWs

Several studies have investigated the morphodynamic effects of river training with longitudinal training walls (LTWs). Pfeijffer (2023) and Ten Brink (2024) both employed the 2D model *Duurzame Vaardiepte Rijndelta* (DVR) to simulate the long-term morphological effects of river interventions.

Pfeijffer (2023) examined the effects of various LTW designs on erosion mitigation, comparing them with the design that was applied in the Waal river pilot project. Although this study focuses on the Waal river, it found that widening the auxiliary channel leads to the highest reduction in bed degradation. Other design variations included lowering the opening sill and reducing the crest height. However, the differences in morphological outcomes between these designs were small, partly due to the coarse grid resolution of the model. Despite this limitation, maximizing the width of the auxiliary channel has positive effects on sedimentation and should therefore be included in the list of criteria for this research, as was also concluded by Czapiga et al. (2020). Overall, Pfeijffer concluded that LTWs are a promising method to mitigate bed erosion, but emphasized the need for further research into combinations of different river training measures (Pfeijffer, 2023).

Ten Brink (2024) elaborated on this recommendation and quantified 'the effects of implementing different combinations of groyne lowering, longitudinal training dams and side channels with summer dike lowering'. This study also focused on the Waal river. The results showed that lowering groynes to the minimum permissible level in combination with the implementation of longitudinal training walls was the most effective strategy for mitigating bed degradation. The study further recommends refining the design parameters of individual interventions in order to reduce bed degradation. Adaptive designs are needed to be able to fine-tune the combination of interventions (ten Brink, 2024).

Like Pfeijffer (2023), Czapiga et al. (2022) found that lowering the entrance weir negatively affects the erosion-mitigating potential of LTWs. This is due to a larger proportion of the sediment being diverted into the auxiliary channel instead of the primary channel. Other design criteria to mitigate bed erosion proposed by Czapiga et al. (2022) include widening the auxiliary channel, steepening the wall slope, shortening the entrance weir area length and a increasing the overall wall length (Czapiga et al., 2022). Figure 2.3 gives an overview of these design criteria.

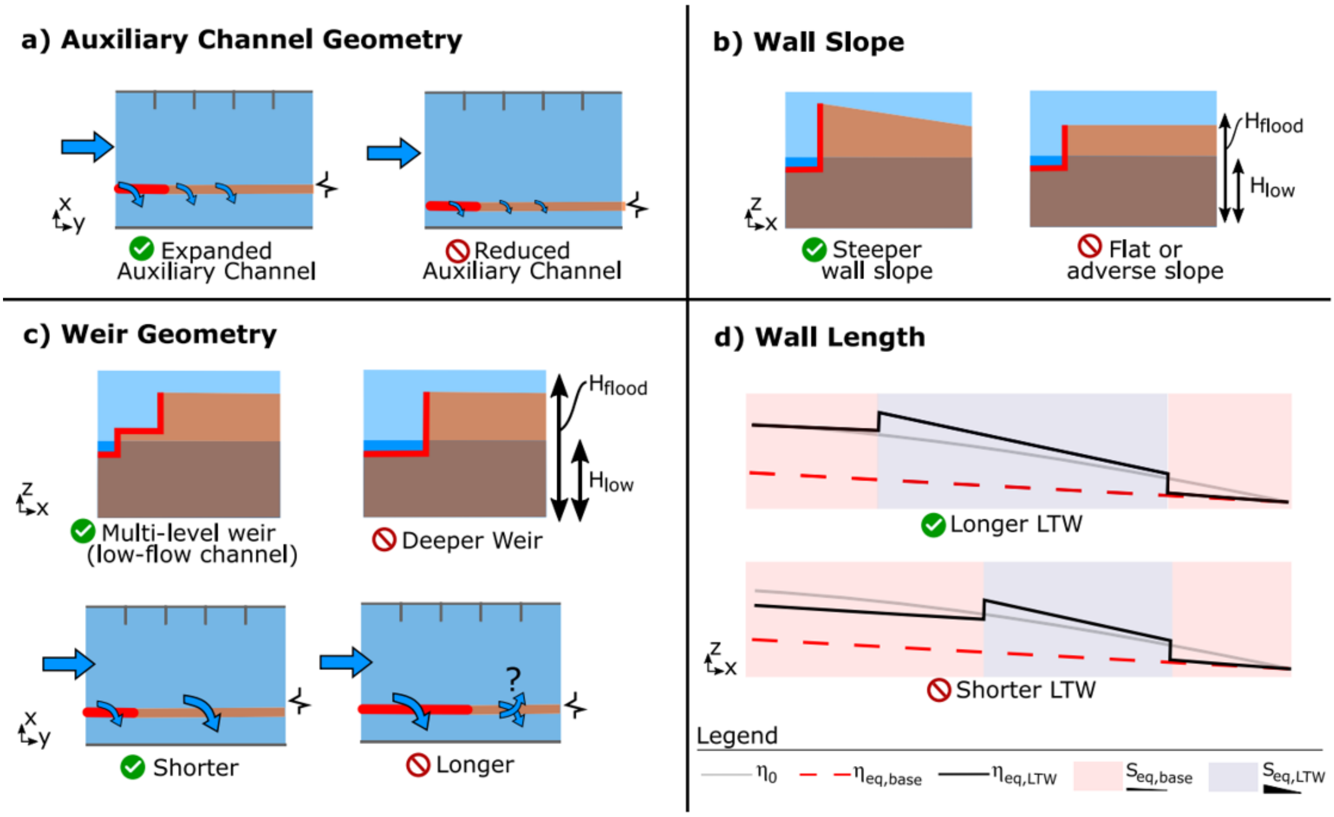


Figure 2.3: Schematic illustrating the design criteria to mitigate erosion with longitudinal training walls. The criteria relate to: (a) auxiliary channel area, (b) wall slope, (c) weir area and geometry and (d) wall length. Figure and caption derived from: (Czapiga et al., 2022)

2.5. River training in an international context

Although longitudinal training walls are primarily a 'Dutch' innovation, river training is practiced worldwide. In Europe (e.g. the Elbe and Loire rivers) and worldwide (e.g. the Mississippi river), groynes are commonly used to guide river vlow. There are also a few examples of river training by longitudinal dams or walls outside the Netherlands.

In the Grand River, Michigan, wooden longitudinal walls were constructed as early as the 1900s. A study on the morphological impact indicates that the longitudinal walls still influence the river's morphodynamics, even though they are now fully submerged and 'substantially reduced from their original size', as can be expected from the wooden structures constructed more than a century ago (Konsoer et al., 2024). Most of the LTWs in the Grand River were connected to the river banks, indicating that their primary function was to guide the course of the river rather than creating flowing auxiliary channels.

The main difference from the Waal pilot project is that the Grand River LTWs were not designed to create secondary channels for high discharges. Nevertheless, the study concluded that LTWs are an effective measure to guide the course of a river and that the effect of LTWs on channel morphology is substantial, resulting in bed erosion of more than 3 meters at some locations between two longitudinal guiding walls.

2.6. Applicability in other river trajectories

One of the partial reports of Deltares in the final evaluation of the pilot project explores the potential for implementing LTWs at other locations along the Rhine branches, especially the Waal and IJssel rivers (Huppes, 2021). Based on this report and consultations with engineers from askoning, HKV and Bureau Stroming, spatial constraints are particularly significant along the IJssel. As a result, existing groynes are kept short to preserve as much navigable width as possible. These spatial limitations are highly relevant to this thesis, which aims to develop a more slender LTW design that is better suited to such constrained environments.

In addition, this report also provides preliminary concepts for potential LTW cross-section designs (Huppes, 2021). In the pilot project, the longitudinal walls were constructed by simple rubble stones without a geotextile. The report outlines three alternative design concepts:

- **Vertical walls**, constructed using either wooden piles or sheet pile walls. This is especially applicable to the IJssel river where spatial constraints are significant. However, wooden piles have limited structural capacity and would require a double row configuration, which Deltares considers impractical. Sheet pile walls offer a more robust solution but are relatively expensive and should therefore be reserved for locations where space limitations are critical.
- **Gravity construction**, such as the current pilot design using rubble stones ranging from 40 to 200 kg. To limit the spatial footprint, the use of prefabricated concrete elements—such as Xstream blocks—is proposed. These X-stream blocks will be further assessed in the 'Generation of concepts' phase of this study. Another gravity-based option involves constructing an island in the river. This solution saves materials and costs, as the riverbanks can be left intact.
- **Hybrid construction**, combining vertical and gravity-based elements. In this concept, logs are placed at the toe of the structure instead of rubble stones, and a vertical wall is integrated into the center of the LTW to retain water during high discharges. This means that the rest of the construction can be lower than in the original design, as it does not need to retain the water at high discharges. While this concept may offer structural and spatial advantages, its ecological performance remains uncertain due to its reduced porosity compared to rubble stone designs.

2.7. Evaluation of ecological advantage

In addition to their positive impact on erosion mitigation, longitudinal training walls (LTWs) also offer notable ecological benefits. A study on the ecological effects of longitudinal training walls found that the longitudinal training walls in the pilot project provided shelter for various fish species (Collas et al., 2018). Significantly more fish were found in the secondary channel behind LTWs compared to a reference groyne field. Habitat conditions are strongly influenced by waves and water displacements from passing vessels. The LTWs provide a new ecosystem and wave climate compared to the groyne fields. Behind a longitudinal structure, waves and flow conditions are relatively more stable compared to the main navigation channel. Especially during the passage of ships, the difference in flow velocity is significant. The study concluded that LTWs “significantly mitigate wave action and water displacement caused by navigation,” thereby offering a positive sheltering effect for (juvenile) fish (Collas et al., 2018).

Similar conclusions were drawn by Flores et al. (2021). Their research showed that most juvenile and adult fish species were able to pass the LTWs in the pilot project at Tiel without difficulty. In addition, the auxiliary channels behind the LTWs provided more suitable habitats for fish species than both the main channel and groyne fields in the Waal river. However, they recommended increasing the cross-sectional area of the entrance weir to ensure lower flow velocities during high discharge conditions (Flores et al., 2021). To avoid a conflict with the criteria for limiting the length of the entrance weir area as mentioned in Section 2.4, a multi-level weir might be introduced. This idea was also proposed by Czapiga et al. (2022) to make an adaptive design for different discharge conditions.

2.8. Conclusion

In conclusion, while there has been considerable research into the morphological effects of longitudinal training walls as a method for creating multi-channel river systems, structural aspects remain underexplored. This research will focus on the selection of appropriate construction materials and the structural design of LTWs. The aim is to develop a solution that is not only structurally sound and environmentally sustainable, but also easy to maintain and non-obstructive to river navigation.

3 System analysis

This chapter provides a description of the system of interest. First, the geographical area in which the design will be implemented is analyzed. The second section of this chapter contains a stakeholder analysis. Finally, the functions of the system are described.

3.1. Area analysis

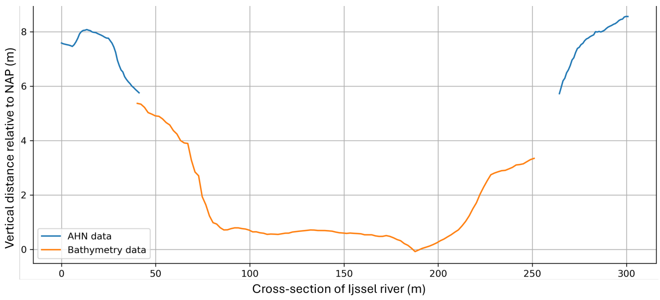
The Boven-IJssel has been selected as the area of interest for this research. TThe primary motivation for this choice is the limited spatial availability for structural interventions in this river. Until now, most of the research on longitudinal training walls and secondary channels has focused on the Waal River (Pfeijffer, 2023, ten Brink, 2024, etc.). This river is significantly wider than the IJssel, leaving more space for structural interventions such as groynes, LTWs and secondary channels.

The IJssel river starts at the IJsselkop near Westervoort, and flows approximately 127 kilometers northward into Lake IJssel. In terms of Rhine kilometers (Rkm), it stretches from Rkm 878 to Rkm 1005. For this project, the upstream section of the IJssel —referred to as the Boven-IJssel— has been selected as the specific area of interest. In this part between Westervoort and Deventer, an average bed erosion is observed of 0.5 cm/year (Huppes, 2021). In contrast, the Beneden-IJssel, downstream of Deventer, shows no significant erosion (0 cm/year on average). Therefore, implementing an LTW to mitigate bed erosion is particularly relevant in the Boven-IJssel.

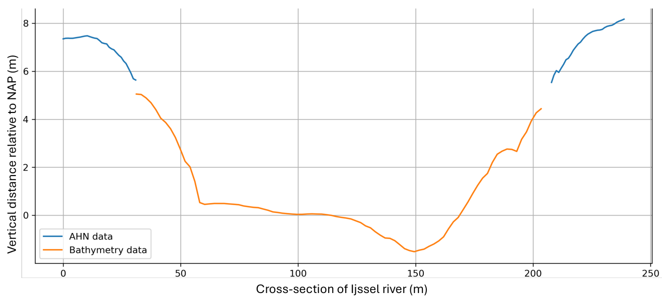
This research focuses on a relatively straight stretch of the IJssel. Sections with one or multiple bends would potentially incorporate flow conditions that are very specific to that location. Since the goal of this study is to develop a design that can be applied to other locations, a straight section is preferred. The area of interest is shown in Figure 1.3 and Figure 3.1.

Figure 3.1: Satellite imagery of area of interest with the IJssel highlighted

Along various locations in the study area, groynes are present. Generally, these groynes are located on both banks of the river or in the outer bends. Compared to groynes in the Waal, the groynes in the IJssel are relatively short. The reason behind this is that enough space must be available for navigation. According to national guidelines, the IJssel should have a navigation channel of at least 40 meters wide with a depth of at least 2.50 m in OLR conditions (Agreed-upon low river level) (Rijkswaterstaat, 2019). To illustrate the spatial implications of these requirements, bathymetric data is presented for two locations within the study area in Figure 3.2. The data used includes AHN elevation data and bathymetric measurements of the IJssel. Although there are some gaps due to imperfect data overlap, the figures still provide a clear representation of the summer bed of the river.



(a) Bathymetry at blue dot

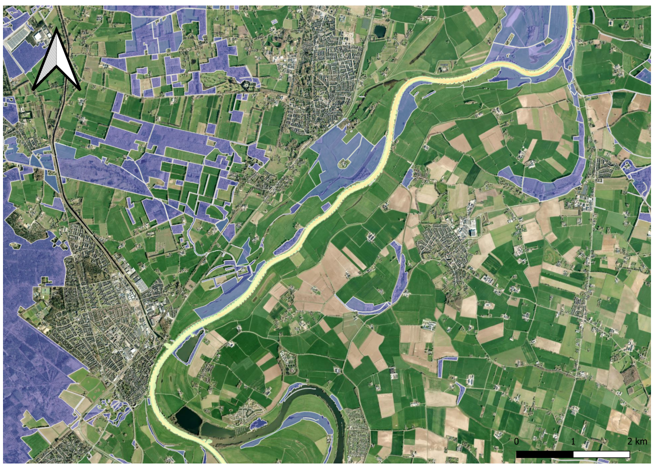


(b) Bathymetry at red dot

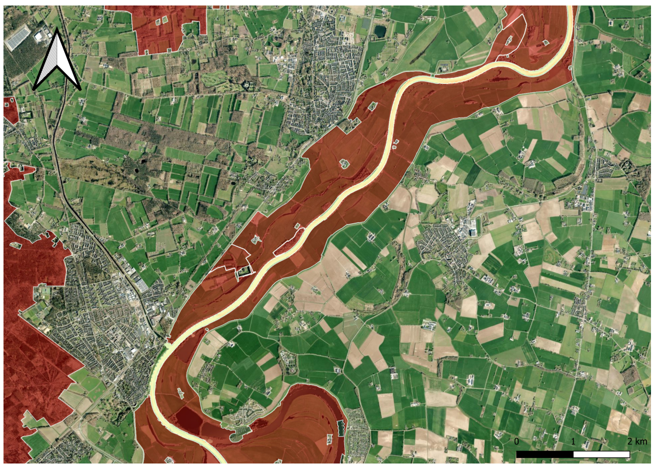
(c) Locations where the data is extracted

Figure 3.2: Bathymetry of area of interest at two locations (Actueel Hoogtebestand Nederland, 2023). Horizontal and vertical distances in the two graphs are in meters.

The study area is surrounded by several protected zones that are part of the Nature Network Netherlands and designated Natura 2000 areas. TAs a result, specific regulations apply, generally requiring that any spatial interventions contribute positively to the local ecosystem. For this research, this implies that ecological considerations must be carefully integrated into the design process.



(a) Nature Network Netherlands (NNN) areas in blue



(b) Designated Natura2000 areas in red

Figure 3.3: Study area with NNN and Natura2000 areas (PDOK, n.d.).

There are no clear obstacles for a structure in the area of interest. The floodplains are relatively open, with only a few farmhouses and a historical estate featuring a tower. Notably, several auxiliary channels already exist within the floodplains, suggesting potential for the development of a multi-channel system that utilizes parts of the floodplain.

3.1.1. Ship waves

In the IJssel, the maximum allowed class of vessels is CEMT class Va, corresponding to a length of 110 m and a width of 12 m. The resulting ship waves can be divided into primary and secondary waves. The design ship waves for structures in the river are calculated in Appendix A. The results can be found in Table 3.1.

Table 3.1: Design ship waves

	Primary Ship Waves	**Secondary Ship Waves**
Maximum wave height (water depth = 9.5 m)	0.64 m	0.34 m

3.2. Stakeholder analysis

This section identifies the key stakeholders involved in the system and outlines their respective interests.

Rijkswaterstaat and government
Rijkswaterstaat, the executive agency of the Ministry of Infrastructure and Water Management, is responsible for the maintenance, management, and development of the main road and waterway networks in the Netherlands. This includes the Rhine distributaries, such as the IJssel. As the primary authority overseeing river infrastructure, Rijkswaterstaat plays a central role in the approval, design, and implementation of interventions like longitudinal training walls.

World Wildlife Fund
It is the aim of the World Wildlife Fund to realize a more natural environment in which humans can 'live in harmony with nature' (WWF - Find your local WWF office). The multi-channel concept has been developed by WWF in collaboration with Bureau Stroming and ARK Rewilding. WWF advocates for nature-based solutions that enhance biodiversity while addressing hydraulic challenges such as bed erosion.

Contractors and research organizations
Many companies will play a (supporting) role in the development of plans for longitudinal training walls or the multi-channel. In this thesis, it is Haskoning who have initiated the research into potential new designs for the LTWs. HKV and Deltares have conducted extensive research into the morphodynamic effects of LTWs. Bureau Stroming and ARK Rewilding developed basic layouts for the multi-channel system in the Rhine branches Boven-Rijn, Boven-Waal, Boven-IJssel and Pannerdensch Kanaal. In cooperation with WWF, they aim to come up with a nature-based solution that mitigates the problem of bed erosion.

Local stakeholders
This group includes residents, farmers, and fishermen in the area. Their primary concerns typically relate to minimizing disruptions to daily life and preserving the existing landscape. Significant changes in the river layout may face resistance unless clear benefits are demonstrated and local interests are respected.

Shipping industry
The shipping sector is a critical stakeholder, particularly given the narrow profile of the IJssel. Ensuring sufficient navigable space is essential. While this imposes constraints on the design, it also presents an opportunity to develop a slender, efficient structure that may even enhance navigability compared to the current situation.

3.3. Function analysis

Longitudinal training walls are intended to replace groynes as river training structures. As such, they must positively influence key river functions (Zuijderwijk and de Jong, 2021):

1. **Water Safety**

During high discharge events, rivers trained with LTWs exhibit lower water levels compared to those trained with groynes. This is due to the higher flow conveyance capacity of LTW-trained rivers Le et al., 2020.

2. **Navigation**
During low discharge periods, water levels in the auxiliary channel drop below the entrance weirs and inter-wall notches, reducing the effective flow area and increasing water levels in the main channel. Longitudinal training walls provide the same level of navigability as series of groynes (Le, 2018).In addition to commercial shipping, recreational boating also occurs on the IJssel. Both contribute to the design wave loads that the structure must withstand (CUR-publicatie 197, 2000).

3. **Nature**
In the auxiliary channel behind longitudinal training walls or in the multi-channel system, there are less waves and currents induced by passing vessels. These protected areas provide shelter to vegetation and fish species (Zuijderwijk and de Jong, 2021).

3.4. Subsystems

A river with a longitudinal training wall consists of various subsystems. In this section, they are briefly discussed.

- **Main channel**
The main channel serves the dual functions of water conveyance and navigation. The implementation of an LTW or multi-channel system indirectly affects this channel, and sufficient space must be preserved to ensure safe and efficient navigation.
- **Auxiliary channel**
The current channel will be divided into a main channel and an auxiliary channel. The LTW dampens wave energy, resulting in a more stable wave climate in the auxiliary channel. During high discharge conditions, water will not only be discharged through the main channel, but also through the auxiliary channel.
- **Basic wall geometry**
The first step during the generation of alternatives will be to determine the basic geometry of the wall. This consists of a choice of material and corresponding dimensions. The wall needs to be stable against (ship) waves.
- **Entrance weir, inter-wall notches and exit weir**
The entrance weir, inter-wall notches and exit weir control the discharge through the auxiliary channel. The dimensions of these weirs and notches should be designed in a way that is in accordance with hydrodynamical and ecological criteria. However, the exact design of these components is strongly influenced by the local morphodynamics, which is outside the scope of this research.

4 Basis of Design

To assess the different design alternatives later in this research, a set of requirements and criteria is defined in this chapter. The **requirements** represent the minimum conditions that each alternative must meet. The **criteria** are used to evaluate and compare the performance of the alternatives.

Together, these form the Basis of Design. During the evaluation, the LTW design from the pilot project in the Waal River will be used as a reference.

4.1. Requirements

In the design of a longitudinal training wall or multi-channel system, three key requirements must be met: a minimum width of the navigation channel, structural stability, and sufficient discharge capacity. These requirements define the design space within which viable solutions can be developed.

4.1.1. Width of navigation channel

For the branches of the Rhine in the Netherlands, the minimal dimensions of the navigation channel are legally defined by the government (Rijkswaterstaat, 2019). In the area of interest, this means that the navigation channel should at least be **40 meters wide**, in order to provide enough space for vessels to pass each other. In addition, the **OLR water depth is 2.50 m** in this area. The OLR depth is the agreed-upon water depth at a low discharge value of 1020 m^3/s of the Rhine at Lobith. In Figure 4.1, the minimal width and depth of the navigation channel are provided.

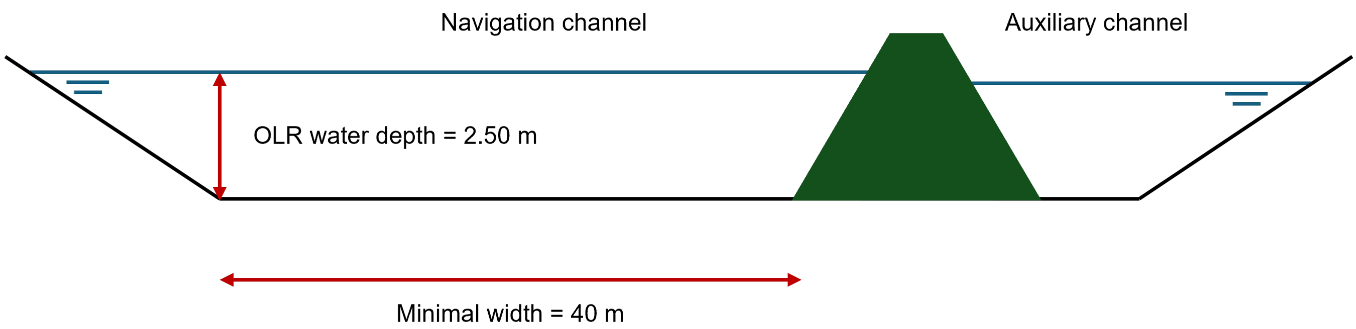


Figure 4.1: Sketch of water depth under OLR conditions and minimum width of navigation channel at the IJssel River (not to scale). Under low discharge conditions, the water level in the river may be slightly elevated within the navigation channel if it remains below the height of the inlet openings to the auxiliary channels.

4.1.2. Stability

Since a longitudinal training wall is constructed inside a river, various loads will be exerted on the structure. Therefore, the second requirement for this structure is that it should remain stable under all conditions. Given the broad interpretation of the term ”stability,” the following definition will be used in this research: stability is ”the ability of a structure to maintain its equilibrium and resist any external forces or loads without experiencing excessive deformation or failure” (Haseeb Jamal, 2017). In practical terms, this means that the LTW must continue to function as a guiding structure under all relevant load scenarios during its design life. This requirement will form the basis for the dimensions of the different alternatives. For each alternative, the stability will be checked first, which will result in dimensions for the body and/or protection units of an LTW. Based on these dimensions, the LTWs can be tested for the different criteria.

4.1.3. Discharge capacity

As described in Chapter 1 and Chapter 3, longitudinal training walls offer benefits during both high and low discharge conditions. During low discharge, the water level in the main channel increases because no flow enters the auxiliary channel. In contrast, during high discharge events, the pilot project on the Waal demonstrated that a system with LTWs offers a higher discharge capacity than traditional groyne fields, as LTWs obstruct the flow to a lesser extent.

For this project, the third requirement is that the discharge capacity must not be significantly lower than in the current situation with groynes. To verify this, water levels in the main and navigation channels will be modeled and compared. This requirement is satisfied if no significant (less than 2 percent difference) increase in water level is observed in the LTW scenario compared to the existing situation.

4.2. Criteria

The criteria presented in this section are grouped into thematic categories. In the next section, the evaluation process will be described. To define the criteria, a reference project was studied that explored alternatives for groyne lowering in the Pannerdensch Kanaal. This project provided a set of criteria with associated weighting factors de Jong et al., 2017. Several of these criteria have been adopted in this research, supplemented with new criteria specifically relevant to the current study.

4.2.1. Structural

In addition to the stability requirement discussed in the previous section, the following structural criteria are considered:

- **Permeability of body**
  One of the key functions of the LTW will be to separate the auxiliary channel from the main channel. During low discharge conditions, no flow should enter the auxiliary channel, allowing the water level in the main channel to rise and improve navigability. This requires the structure to have low permeability. To assess this, the seepage flow velocity through the longitudinal training wall will be calculated and used as an indicator for this criterion.
- **Wave Reflection**
  Wave reflection is important for two reasons: (1) High wave reflection results in high waves on the river which is unfavorable for inland vessels. (2) High wave absorption, the opposite of reflection, leads to unfavorable loading situations for a protection layer (Schiereck and Verhagen, 2012). Despite this trade-off, minimizing wave reflection is preferred, as navigability is a key function of the river. A design that reduces wave heights in the navigation channel contributes to safer and more comfortable passage for vessels.
  There are different methods to determine the wave reflection as a function of the breaker parameter ξ , but in this research the approach of Seelig and Ahrens (1981) as described in the *Rock Manual* is used (CIRIA, CUR, CETMEF, 2007):

  $$C_r = H_r/H_i \tag{4.1}$$

  $$C_r = c\xi^2/(d+\xi^2) \tag{4.2}$$

  In which C_r is the reflection coefficient, H_r and H_i the reflected and incoming wave heights and ξ the breaker parameter or Irribarren number:

  $$\xi = \frac{tan(\alpha)}{\sqrt{H/L_0}} \tag{4.3}$$

  In which α is the slope of the protection layer and L_0 the wavelength. In Equation 4.2, c and d are coefficients that are specific for different types of protection. For (almost) vertical walls, and thus high values for ξ, Equation 4.2 is no longer applicable, as the waves are fully reflected and $C_r \approx 1$. The calculations for the wave parameters and loads can be found in Appendix A.
- **Flexibility of structure**
  As local conditions and boundary parameters may change over time —due to factors such as climate change or revised government regulations— the LTW or multi-channel system should be able to adapt

accordingly. A structure composed of modular elements that can be easily rearranged, extended, or removed will score higher on this criterion than a rigid structure that requires significant effort to modify. Since it is difficult to assign a precise numerical value to adaptability, expert judgment will be used to qualitatively assess and score the alternatives on this criterion.

4.2.2. Spatial impact

The implementation of a longitudinal training wall or multi-channel system will inevitably affect the spatial configuration of the IJssel. According to Deltares, space along the IJssel is so limited that excavation in the winter bed is required to accommodate an auxiliary channel (Huppes, 2021). This emphasizes the need for a solution that requires as little space as possible. In addition to the navigation channel width requirement discussed in Section 4.1.1, the following criteria are also considered:

- **Width of Structure**
  The first criterion is the width of the structure that separates the auxiliary channel from the main channel. A structure that is more slender in comparison with the pilot project design scores high on this criterion. However, this criterion only applies to structures consisting of non-local material. Alternatives that can use local materials efficiently should not score negatively on this criterion.
- **Width of Auxiliary Channel**
  According to (Czapiga et al., 2022), a wider auxiliary channel is favorable, as it limits erosion in the main channel during high discharge conditions. In these conditions, more water can be diverted to the auxiliary channel in case of increased auxiliary channel area.

4.2.3. Constructability

This criterion tests alternatives for their relative constructability. The alternatives are evaluated by looking at the technical difficulty during construction and the speed of the realization of the different alternatives. Information on material properties and construction methods will be used, supplemented by expert judgment from professionals at Haskoning.

4.2.4. Management and Maintenance

Maintenance of the structure is important to ensure that the intended design lifetime is reached. The criterion can be quantified by making an estimate of the maintenance costs. Deltares has presented some key figures for the design of longitudinal training walls in the pilot project in the Waal river (Eerden, 2021). In cases where no reliable cost data is available, the criterion will be assessed qualitatively, based on expert judgment and comparison with similar reference projects.

4.2.5. Sustainability

Sustainability is assessed using the Environmental Cost Indicator (MKI – Milieukostenindicator), which expresses environmental impact in euros per year DuboCalc, n.d. The MKI is based on a Life Cycle Assessment (LCA) that includes all environmental effects during construction, operation, and end-of-life phases. Information from the National Environmental Database will be used for this criterion.

4.2.6. Ecology

As described in Chapter 2, longitudinal training walls have the potential to enhance the ecological value of the river system, compared to systems with groynes. Different designs for the LTW or multi-channel system might have a different effect on ecology. This criterion distinguishes between the ecological potential of the structure itself and that of the auxiliary channel. The structure may support colonization by aquatic organisms, while the auxiliary channel can provide shelter from waves and currents. Together, they form a potential ecosystem.

As in other evaluation projects ((Royal HaskoningDHV, 2023), (de Jong et al., 2017)), the effects on ecology are evaluated qualitatively and not quantitatively. However, to do this in a structured manner, the following questions are asked for this criterion:

1. To what extent can organisms grow on the structure?
2. Do the structure and corresponding auxiliary channel create an ecosystem with differences in hydrodynamics such that the conditions for different species improve?

3. To what extent does the structure create shelter in the auxiliary channel against the wave conditions in the main channel?

These questions are based on the research conducted by Collas et al. (2016) and findings by Rijkswaterstaat ((Rijkswaterstaat, n.d.-c, (Rijkswaterstaat, n.d.-a)).

4.3. Weight of criteria

In Chapter 5, several alternatives for the design of a LTW or multi-channel system will be developed. These alternatives will be evaluated in Chapter 6 and Chapter 7. Each criterion from the previous section is assigned a weighting factor based on its relative importance. This results in a total score for each alternative, referred to as its value. The costs of each alternative are then estimated, allowing for the calculation of a value-to-cost ratio. Costs are not treated as a separate criterion, as they represent the resources required to realize an alternative, whereas the criteria reflect the value delivered by the system (Voorendt, 2015). The alternative with the highest value/cost ratio will then be selected, as long as the ratios are sufficiently distinctive. If the ratios are too close to draw a clear conclusion, expert judgment will be used to determine the most suitable alternative for this specific case.

Weighing the criteria is done by creating a table in which the criteria are set against each other. A value of 1 will be assigned to the more important criterion and a value of 0 to the other.

		Permeability	Wave reflection	Flexibility	Width of structure	Width of auxiliary channel	Management and Maintenance	Sustainability	Ecology	sum	weighting factor
1	Permeability		1	1	0	0	1	1	1	5	6
2	Wave reflection	0		0	0	0	1	1	1	3	4
3	Flexibility	0	1		0	0	1	0	1	3	4
4	Width of structure	1	1	1		0	1	0	0	4	5
5	Width of auxiliary channel	1	1	1	1		1	1	1	7	8
6	Management and Maintenance	0	0	0	0	0		0	1	1	2
7	Sustainability	0	0	1	1	0	1		1	4	5
8	Ecology	0	0	0	1	0	0	0		1	2

Figure 4.2: Weighing table of criteria

During a brainstorming session with experts from Haskoning, all participants filled in the table independently. More information can be found in Appendix B.

Although the resulting weighting factors (Table 4.1) are mostly based on the judgment of experienced professionals in the field of flood protection and river management, the results will remain subjective and therefore not fully reliable. To reduce the influence of small, potentially arbitrary differences, the average scores (ranging from 3 to 8) were normalized to a scale from 1 to 3:

- Averages of 3–4 $\rightarrow$ weighting factor **1**
- Averages of 5–6 $\rightarrow$ weighting factor **2**
- Averages of 7–8 $\rightarrow$ weighting factor **3**

Table 4.1: Resulting weighting factors from experts at Haskoning and author

Criterion	Expert 1	Expert 2	Expert 3	Author	Average	Final weighting factor
Permeability	3	4	2	7	4	1
Wave reflection	7	3	1	8	5	2
Flexibility	7	4	7	3	5	2
Width of structure	3	6	3	4	4	1
Width of auxiliary channel	9	6	5	9	7	3
Management and Maintenance	7	9	8	6	8	3
Sustainability	1	1	7	2	3	1
Ecology	3	4	5	1	3	1
Constructability	4	8	7	5	6	2

5
Generation of concepts

This chapter presents the alternative designs that will be evaluated in the subsequent chapters. To develop these alternatives, a brainstorming session was organized, allowing the preferences and expertise of various professionals to serve as input for three distinct design concepts.

5.1. Lateral Thinking and Brainstorming

Lateral thinking is used as a method to structure the process of generating alternatives. The term 'Lateral Thinking' was first introduced by Edward de Bono. Lateral thinking can be seen as the opposite of vertical thinking. Using vertical thinking, one aims to come up with the best solution to a specific problem. However, in lateral thinking, the problem solver tries to come up with as many alternative solutions as possible (de Bono, 1970). It is important that the alternatives are not evaluated during the 'creative phase' during which alternatives are derived, as this could limit the creativity of the participants.

According to De Bono, brainstorming is 'a formal setting for the use of lateral thinking' (de Bono, 1970). It is important that during brainstorming, judgment is suspended, and evaluation of ideas is not done during the brainstorming session. Furthermore, strict time management by the session chairman and the creation of a formal session are crucial for productive brainstorming. A formal setting encourages participants to be informal in their ideas. Proper time management ensures that the session does not take too long, forcing the last ideas out of people (de Bono, 1970). These ideas formulated by Edward de Bono are incorporated into a brainstorming session with experts from Haskoning to develop concepts for a longitudinal training wall or multi-channel system in the IJssel river.

5.2. Brainstorming session

To generate concepts as potential solutions for a LTW or multi-channel system, a brainstorming session was organized in which several experts from Haskoning were present. They all have a technical background and together they have many years of experience in river management and the design of hydraulic structures. To structure the session, the author of this report was the chairman of the session. A strict time limit was applied to each of the activities. These activities are presented below:

1. First, an introduction of the project, area of interest, and research question were given.
2. The design requirements were presented and explained to the participants:
    - The width of the navigation channel should have a minimum width of 40 meters at OLR depth (waterdepth of 2.50 m).
    - The construction needs to be stable and have enough strength.
    - The discharge capacity of the system must be at least equivalent to the current situation with groynes in the river.
3. The participants got 3 minutes to <u>individually</u> write down everything they could think of that mights be a potential solution for this case study.
4. Based on the ideas that were presented in the previous step, each participant <u>individually</u> sketched 2 or 3 variants on a graph with the bottom profile of the IJssel at the area of interest.
5. During a 15-minute discussion, the ideas of each participant were discussed <u>plenary</u>.
6. As described in the previous section, the experts <u>individually</u> filled in a table to come up with a relative weighing of each criterion.

5.2.1. Results

All participants contributed one or more design concepts. These designs are described in the following sections, and a sketch is provided where applicable.

- Multi-channel system with 1 or more auxiliary channels in the winterbed. To prevent erosion of the river banks, some form of protection can be applied, such as geobags, rubble mound or sheet piles.

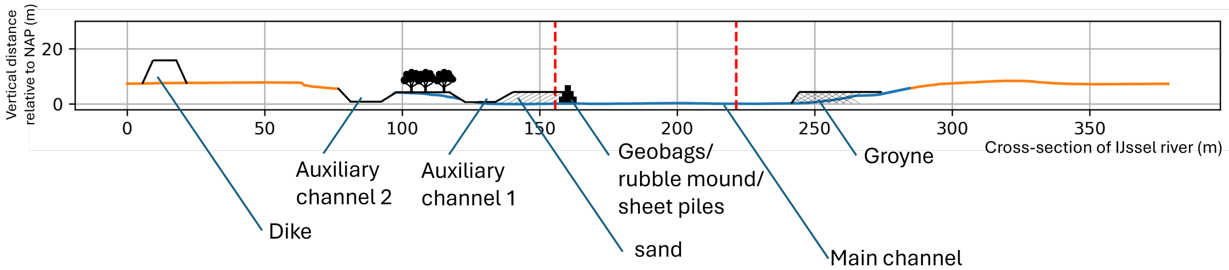


Figure 5.1: Multi-channel system with two auxiliary channels. The current cross-section is indicated with a yellow line at the two sides and a blue line in the middle. The dashed red line indicates the current navigation channel.

- Multi-channel system with 1 or more auxiliary channels and a nature-friendly bank. If needed, extra armor protection is added at the banks of the river in the form of rubble mound or wooden piles around fascines.

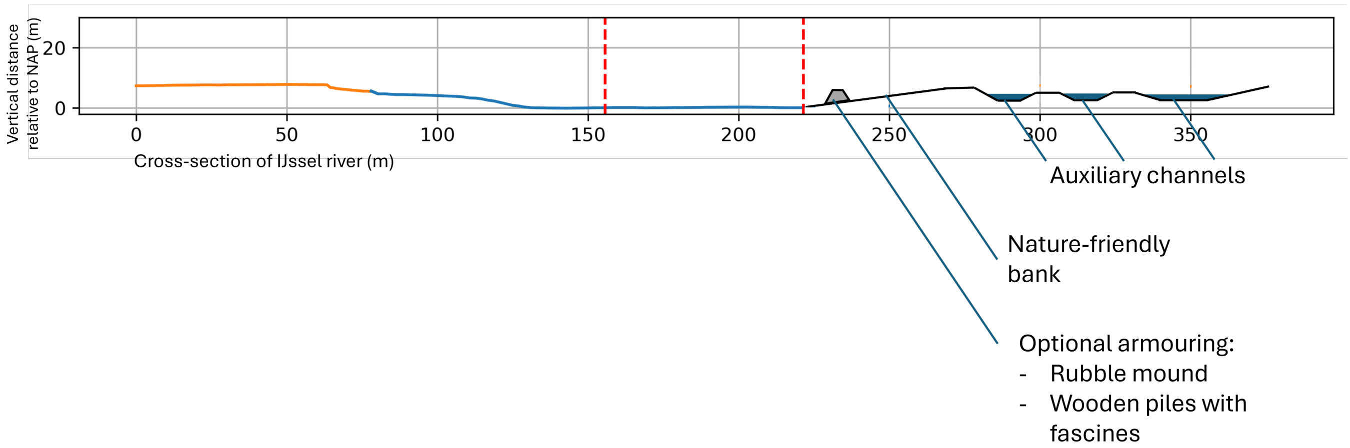


Figure 5.2: Multi-channel system with nature-friendly riverbanks. The current cross-section is indicated with a yellow line at the two sides and a blue line in the middle. The dashed red line indicates the current navigation channel.

- Groynes with an opening and extended nose, creating sheltered groyne fields. This design has a smaller spatial impact because the current groynes can partially remain intact.

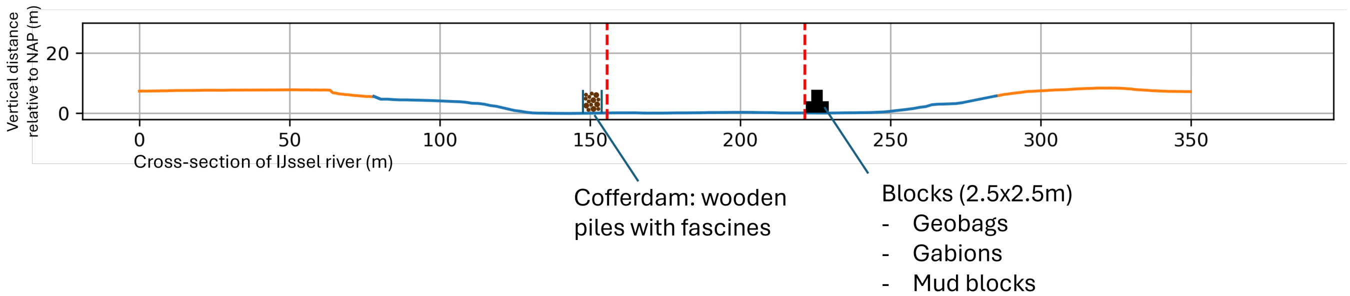


Figure 5.3: Groyne with opening and extended nose

- Longitudinal training wall, consisting of either a cofferdam of wooden piles with fascines, or constructed with blocks (geobags, gabions or mud blocks). In the Figure 5.4, the two options are shown in the same cross-section.

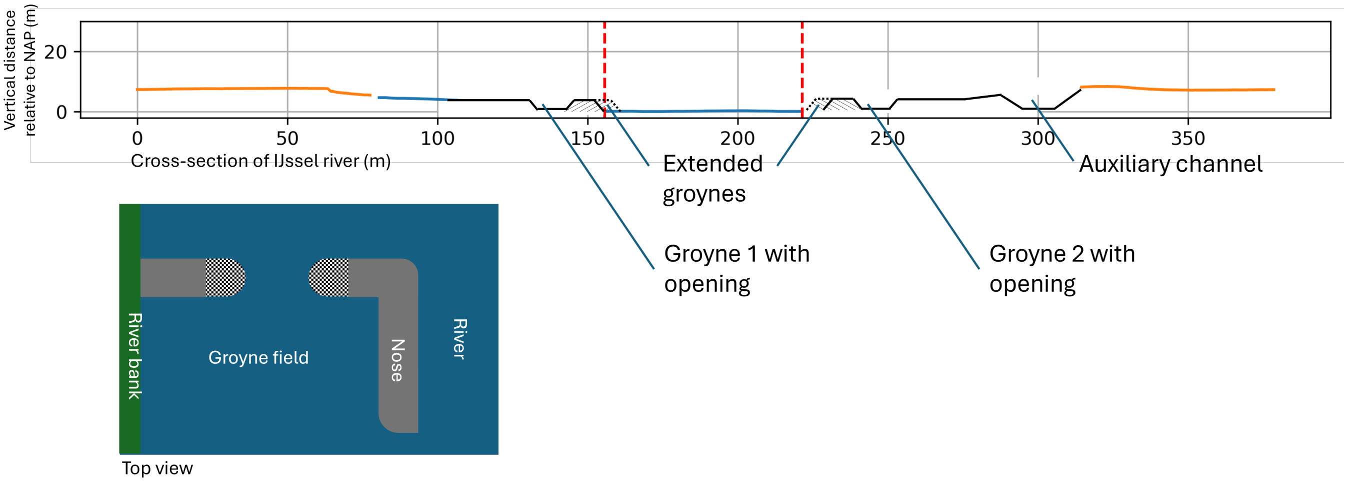


Figure 5.4: LTW consisting of cofferdam and/or blocks. The current cross-section is indicated with a yellow line at the two sides and a blue line in the middle. The dashed red line indicates the current navigation channel.

5.3. Final alternatives

noindent During the brainstorming session, experts were encouraged to think creatively and propose innovative, out-of-the-box alternatives. These ideas formed the foundation for the final design concepts evaluated in this research. In addition, insights from relevant literature and previous studies were incorporated to refine and strengthen the proposed solutions. As a result, three final alternatives were developed.

5.3.1. 'Sandy' Multi-channel System

The first alternative is a sandy multi-channel system, a concept previously proposed by Bureau Stroming (Bureau Stroming, n.d.) and a visualization has been provided in Figure 1.2. The idea of this system is that instead of using a hard structure like a rubble mound longitudinal training wall, the solution is a soft and sandy structure. The auxiliary channel in this system can deviate more from the main channel, using the existing floodplain as a natural barrier. In the area of interest, various waterways can be identified in the floodplains along the IJssel river. These may potentially be repurposed as auxiliary channels, reducing the need for extensive excavation. In Figure 5.5 and Figure 5.6, a top view and a cross-section are added to visualize the multi-channel system in the area of interest.

Figure 5.5: Area of interest with orange line representing the auxiliary channels. The red line indicates the location of the cross-section in Figure 5.6.

Dimensions

For the dimensions of the auxiliary channel, the starting point is to limit the degradation or aggradation. Excessive degradation could lead to an increasing share of discharge being diverted from the main channel, while aggradation may eventually block the channel, rendering it ineffective in mitigating bed erosion (van Denderen, 2019).

Van Denderen suggests basic parameters corresponding to the primary type of sediment transport of auxiliary channels: bed load supplied side channels, suspended bed-material load supplied side channels or wash load supplied channels. The case study of Van Denderen focuses on side channels in the river Waal. These channels can be categorized as suspended bed-material load supplied channels. Suspended bed-material load supplied channels have bed-material that consists primarily of sand and the sediment in the main channel is generally coarser than the sediment in the side channel. Although the IJssel and Waal rivers are different branches of the river Rhine with their own hydrodynamics, morphology and dimensions, a general rule can be applied that is presented by van Denderen, 2019 which states that a side channel with a 'small width/depth ratio is beneficial'. Such a ratio reduces the influence of bed roughness, increases flow velocity, and enhances sediment transport capacity—thereby reducing the risk of aggradation. Additionally, constructing the auxiliary channel with a relatively high bed level helps prevent bed load from entering, which could otherwise lead to bar formation and reduced discharge capacity.

The time before a equilibrium state is reached between aggradation and degradation in a side channel depends on the primary type of sediment transport, the width/depth ratio and the relative length of the side channel (van Denderen, 2019). For this thesis, a width/depth ratio will be chosen that leads to a fast conversion to an equilibrium state, since this will limit the effect on the main channel. The auxiliary channel at the right bank in Figure 5.5 is roughly as long as the section of the river it bypasses: the auxiliary channel is 1490 m long, the section of the IJssel river is 1450 m long. The corresponding design width/depth ratio for a suspended bed-material load-type side channel according to Van Denderen is approximately equal to 3. For the bed level at the (upstream) beginning of the auxiliary channel, the same level will be applied as was used for the inlet opening of the longitudinal training wall design that was used in the pilot project in the river Waal. The inlet opening is designed at a height of OLR - 1.75 meters. The OLR level at the location of Figure 5.5 (Rkm 915) is 3.79 m above NAP (van Putten and Vrijaldenhoven, 2022), which means that the level of the auxiliary channel bed is at 2.04 m + NAP. To determine the width/depth ratio, the most frequent water level at the start of the auxiliary channel from Figure 5.5 is selected, based on the last 10 years (2016-2025), which is approximately 5.50 meters + NAP ("Waterstandsduurlijnen Rijn 2022", 2022).

This corresponds to a water depth of around 5.50 - 2.04 = 3.46 meters and thus a width of 3 * 3.46 = 10.38 meters. In Figure 5.6, the river IJssel is visualized with the auxiliary channel of 10 meters wide in the floodplain.

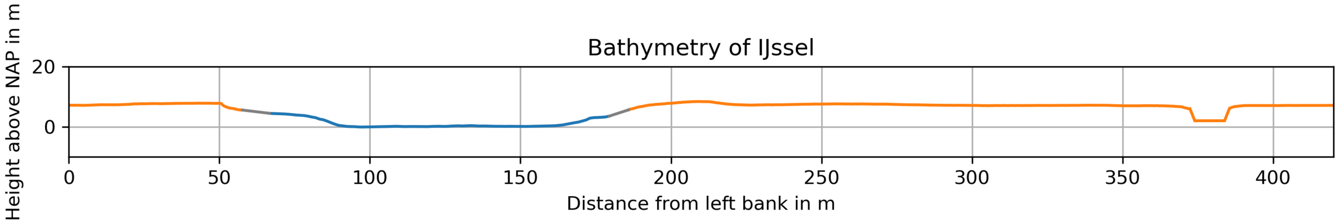


Figure 5.6: Cross-section of the multi-channel system with a auxiliary channel at the right hand side. The cross section is composed by combining AHN data (yellow line) and bathymetry of the IJssel River (blue line).

5.3.2. Gabion wall

The second alternative is a Longitudinal Training Wall constructed from gabions. Gabions are defined as 'stones wrapped in wire fence meshes for added stability and strength' (Bureau of Agriculture and Fisheries Standards, 2017). A typical building unit for gabion walls is shown in Figure 5.7. These modular units are filled with stone, making the structure inherently permeable. To ensure stability, the box gabions are tied together with (steel) wire.

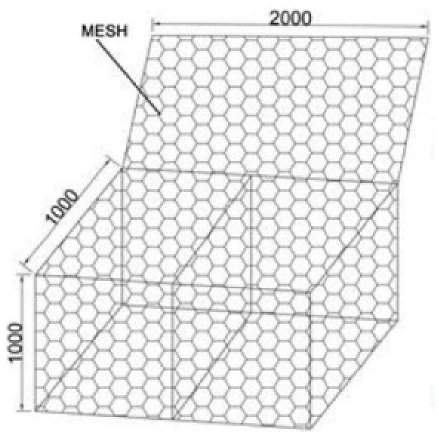


Figure 5.7: Typical building unit for a gabion wall (Alsubih et al., 2023)

Figure 5.8: A gabion wall placed parallel to the stream channel, preventing bank erosion (Apriyono et al., 2019).

Dimensions

For the basic dimensions of the gabion wall, the same relative height has been adopted as used for the rubble mound LTW in the pilot project along the River Waal. This height is approximately 2.50 m (ranging from 2.35 to 2.78 m) above OLR, resulting in a total wall height of around 5.7 meters. The detailed calculation of this height is provided in Section 6.1.1.

Gabions can be placed in different configurations, either vertically or in a triangular form. The Philippine National Standard for designing check dams gives an example shown in Figure 5.9 of a gabion wall with a vertical face at the side with the highest water pressure.

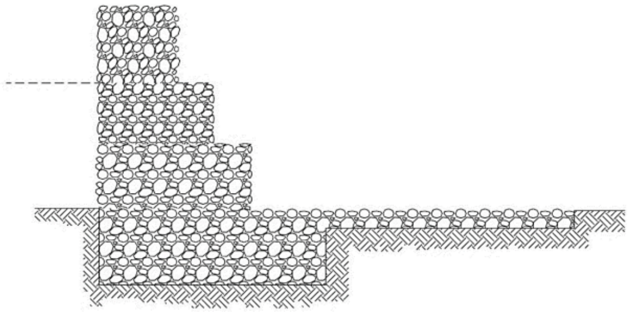


Figure 5.9: Example of Gabion Check Dam (Bureau of Agriculture and Fisheries Standards, 2017) and (Geyik, 1986)

The Food and Agriculture Organization of the United States (FAO) gives design guidelines for gabion check dams. For gabion check dams with a total height (effective height + foundation depth) of 3 to 5 meters, the following formulas are given (Geyik, 1986):

$$k = 0.4H \tag{5.1}$$

$$d = 0.6H \tag{5.2}$$

$k =$ thickness of the dam's crest at spillway level (OLR - 1.75 m)
$d =$ thickness of the dam's base
$H =$ total height of the dam including foundation

However, the total height H of the structure will be significantly greater than 5 meters, as the height of the wall above the foundation is 5.7 meters. The foundation depth is assumed to be approximately half of the effective height of the dam, which equals 2.85 meters. This results in a total structural height of 8.55 m. In Chapter 6, a stability calculation will be performed to assess both overturning stability and bearing capacity. For this step, Equation 5.1 and Equation 5.2 are used, leading to the following dimensions:

$k = 0.4 * 8.55 = 3.42\ m$
$d = 0.6 * 8.55 = 5.13\ m$

To simplify the construction process, the dimensions are simplified as follows:

$$H_{effective} = 6\ m$$
$$H_{foundation} = 3\ m$$
$$H_{inlet} = 2\ m$$
$$d = 4\ m$$
$$k = 6\ m$$

The gabion wall is designed to consist of gabions that are 2 meters high and 1 meter deep. Visualizations are shown in Figure 5.10 (cross section of the river) and Figure 5.11 (detail of the structure).

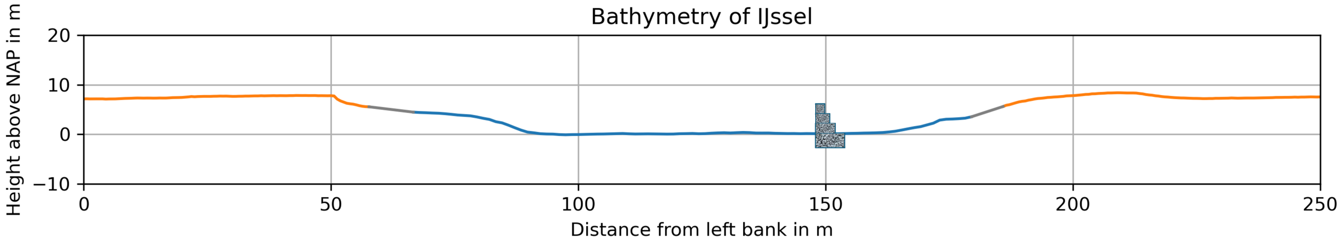


Figure 5.10: Cross-section of the river with a longitudinal training wall consisting of a gabion dam. The cross section is composed by combining AHN data (yellow line) and bathymetry of the IJssel River (blue line).

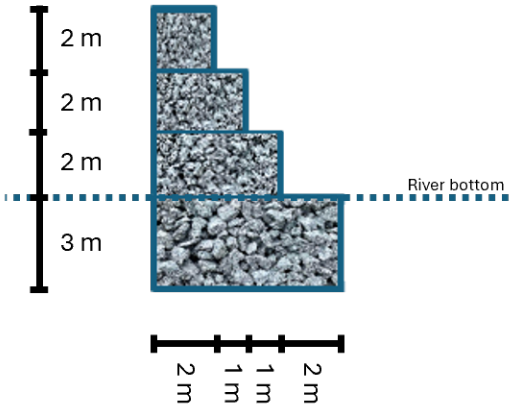


Figure 5.11: Detail of gabion wall with dimensions

For this alternative, scour protection will be required to protect the riverbed. If this alternative proves to be promising, detailed calculations must be made to calculate the necessary scour protection.

5.3.3. Xstream wall

The final alternative closely resembles the design used in the pilot project but occupies less space within the riverbed. Instead of a rubble mound, this concept utilizes Xstream blocks as the primary material for the longitudinal training wall (LTW). The key advantage of this approach is that a steeper slope—approximately 1:1—can be achieved, due to the interlocking nature of the Xstream blocks, which provides greater structural stability compared to loose rock. Xstream elements have already been applied in another pilot project in the Netherlands, where they were used to construct so-called ”flexible” groynes.

The evaluation by Deltares of that project concluded that flexible groynes made from Xstream elements offer a sustainable alternative to traditional rubble mound groynes. One of the main advantages highlighted in the evaluation is the significant reduction in material usage, made possible by the steeper slope (Buschman et al., 2024). Additionally, flexible groynes consist solely of concrete Xstream blocks, eliminating the need for a filter layer or different core materials. This makes the construction process considerably easier.

Although flexible groynes are still in the pilot phase, the evaluation results are promising enough to consider the application of Xstream blocks in LTWs as well. The following section outlines the basic properties of Xstream blocks.

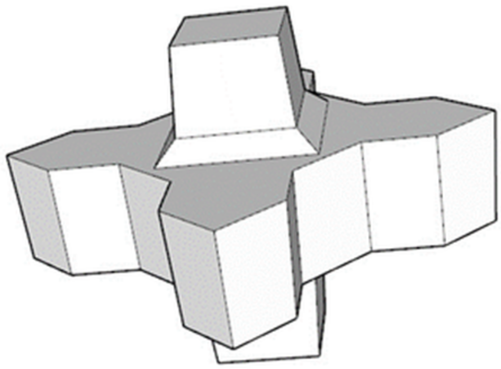


Figure 5.12: Xstream block (Xbloc, n.d.)

Properties

Xstream blocks, a smaller variant of the Xbloc armor unit, have a height of 33 cm and a weight of 27 kg (DMC marine consultants and BAM, n.d.). They exhibit a porosity of approximately 60 %, which is significantly higher than that of loose rock, typically ranging between 30 % and 40 % (Ruwiel et al., 2016). In groyne applications, the use of Xstream blocks can reduce the required material volume by up to 50 %. Moreover, these blocks can be produced locally in the Netherlands and allow for rapid construction, as they can be transported and installed in bulk. As previously mentioned, their interlocking design enables the realization of a 1:1 slope. Altogether, Deltares claims that these factors contribute to a reduction in CO_2 emissions of more than 50 % compared to traditional rubble mound groynes (Ruwiel et al., 2016).

Dimensions

For the design of a longitudinal training wall with Xstream blocks, the main parameters that were used in the pilot project in the river Waal will be used (Table 2.1). The biggest difference will be the slope of the sides, which will be designed to be 1:1 instead of 1:2.5. The difference is visualized in Figure 5.13. The difference in volume for an LTW with a crest width of 2 meters and a crest height of 5.7 meters and a slope of 1:1 compared to 1:2.5 is:

$$\text{Volume for a slope of 1:2.5} = 43.9 \text{ m}^3$$
$$\text{Volume for a slope of 1:1} = 92.6 \text{ m}^3$$
$$\text{Difference} = 48.7 \text{ m}^3$$
$$\text{Relative difference} = -53\%$$

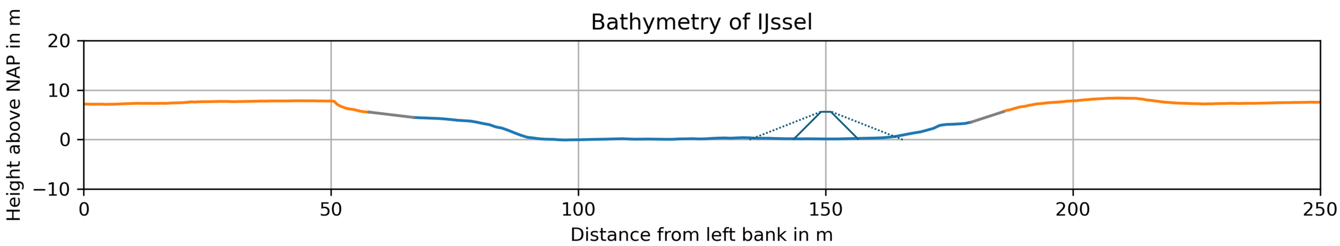


Figure 5.13: Cross section of the river with a longitudinal training wall consisting of Xstream blocks. For reference, a LTW with a slope of 1:2.5 (as used in the pilot project) is added with dotted lines. The cross section is composed by combining AHN data (yellow line) and bathymetry of the IJssel River (blue line).

5.4. Conclusion

To explore potential alternatives to the current groyne system in the River IJssel, a brainstorming session was conducted. This session generated several ideas, elements of which were incorporated into the final design alternatives: (1) a multi-channel system, (2) a longitudinal training wall (LTW) constructed with

gabions, and (3) a LTW constructed with Xstream blocks. These conceptual designs were developed using basic engineering judgement and simplified design principles.
In the following chapter, stability analyses will be carried out to evaluate these designs and adjust them where necessary. Additionally, both the pilot project design from the River Waal and the three proposed alternatives will be assessed against the design criteria outlined in Chapter 4.

6
Verification of concepts

To determine a preferred alternative, the concepts developed in Chapter 5 are evaluated against the criteria defined in Chapter 4. As a first step, the design used for the longitudinal training walls (LTWs) in the pilot project along the Waal River is assessed.

6.1. Pilot project design

The design parameters for the design of the pilot project in the Waal river are presented in Table 2.1. A cross-sectional view is provided in Figure 2.2. For this design, a score is given to each criterion as defined in Chapter 4 in combination with a (quantitative) explanation. First of all, the design is tested for the requirements:

6.1.1. Requirements

Width of navigation channel

The width of the longitudinal training wall (LTW) is determined based on its height and side slopes. Assuming a slope of 1:2.5 on both sides and a crest width of 2 meters, the total width can be derived accordingly. For the crest height, a representative value of 2.5 meters above OLR is used. At the location of interest (Rkm 916), the water level at OLR is approximately 3.72 meters above NAP, and the riverbed lies around 0.5 meters above NAP (van Putten and Vrijaldenhoven, 2022). Based on these parameters, the crest height and total width of the LTW are established for further analysis.

$$\text{Crest height} = 5.7 \text{ m}$$
$$\text{Width} = 30.6 \text{ m}$$

A visualization of the LTW in a cross section of the IJssel river is provided in Figure 6.1.

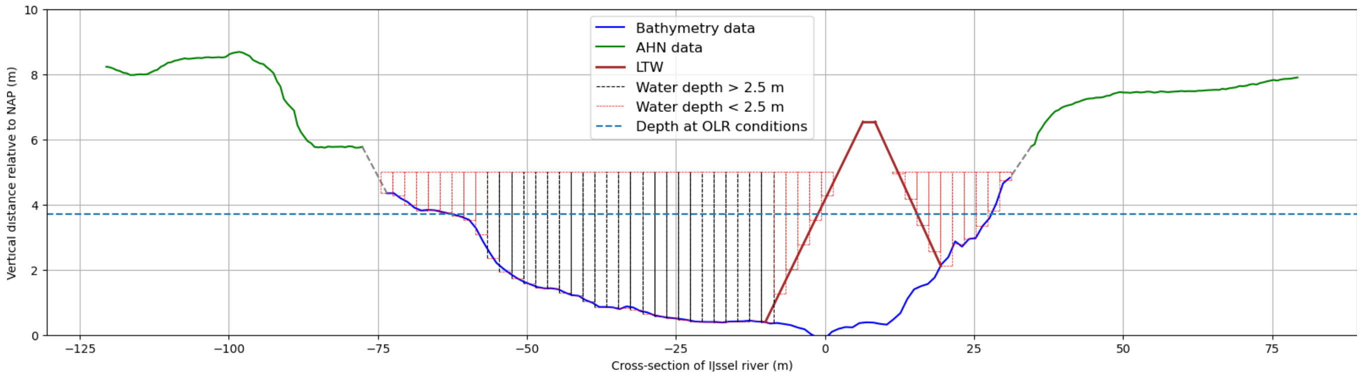


Figure 6.1: Visualization of the LTW in a cross section of the river IJssel. Black dashed lines indicate a sufficient water depth of 2.5 m for navigation. The unit of the vertical axis is m above NAP.

In the area of interest, groynes are typically positioned along the inner bends of the river. Even in relatively straight sections, the river exhibits minor meanders, and groynes are still placed on the inner side. The longitudinal training walls (LTWs) are aligned on the same side of the river as these existing groynes. The minimum required width of the navigation channel is 40 meters at an OLR depth of 2.50 m (Rijkswaterstaat, 2019). The available width for the auxiliary channel behind the LTW is determined by subtracting the width of the LTW (30.6 m) and the navigation channel (40 m) from the total river width. In the area of interest, the distance between the groynes on the outer bend and the inner riverbank typically ranges from 95 to 110 meters. This results in an estimated auxiliary channel width of approximately 25 meters:

$$\text{Width auxiliary channel} \approx 25 \text{ m}$$

It should be noted that this is an idealized estimate, assuming that the OLR depth can also be achieved near the riverbank. Figure 6.1 illustrates a configuration where the LTW is positioned to maintain a 40-meter-wide main channel under OLR conditions. In this setup, the auxiliary channel remains shallow, and dredging would likely be required to improve flow conditions.

Stability

Although the pilot project design is assumed to be stable, a preliminary check is performed to verify this. A design water depth of 5.5 meters is used, as this corresponds to wave conditions where wave crests reach the top of the LTW, exerting the highest forces on the structure.

The stability calculations are detailed in Appendix A. If applied in the IJssel, the rubble mound should have a grading of at least 5–40 kg. In the Waal pilot project, a grading of 40–200 kg was used, which is appropriate given the larger scale of the Waal compared to the IJssel.

Discharge Capacity

The discharge capacity of the system must be at least equivalent to the current situation with groynes. To assess this, a model was developed to calculate the water level difference between two river sections—upstream and downstream of a longitudinal training wall. The modeling process is illustrated in Figure 6.2.

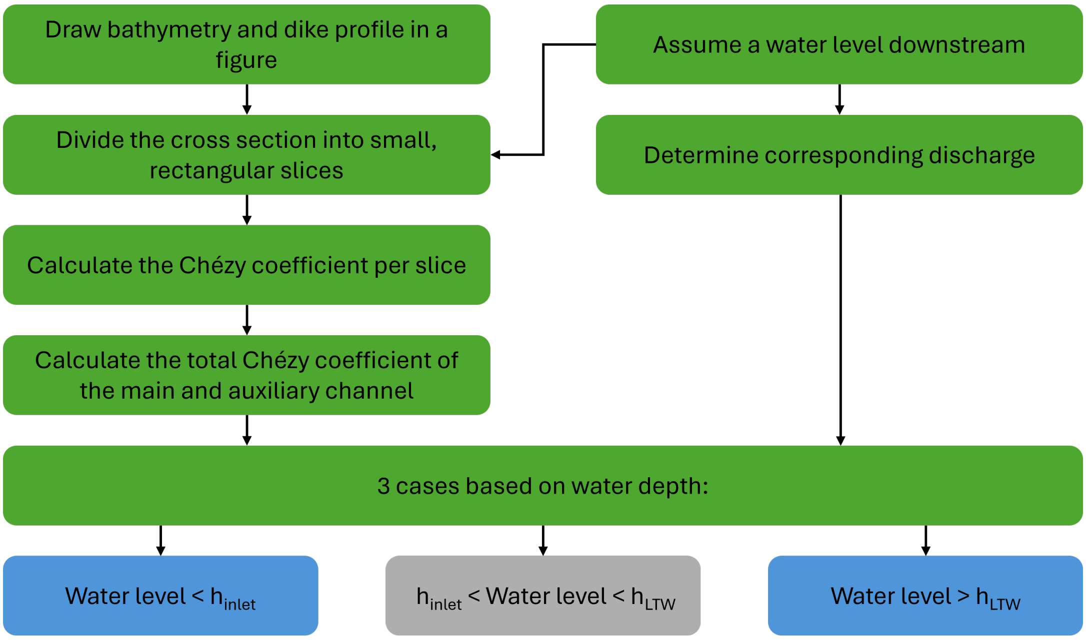


Figure 6.2: Schematized version of the model

The three cases described in Figure 6.2 are worked out in the following figures. The first and third case are very similar, as there is only one channel through which the water flows. The second case is different, as the water flows through both the main and auxiliary channels, without much water flowing from one to the other.

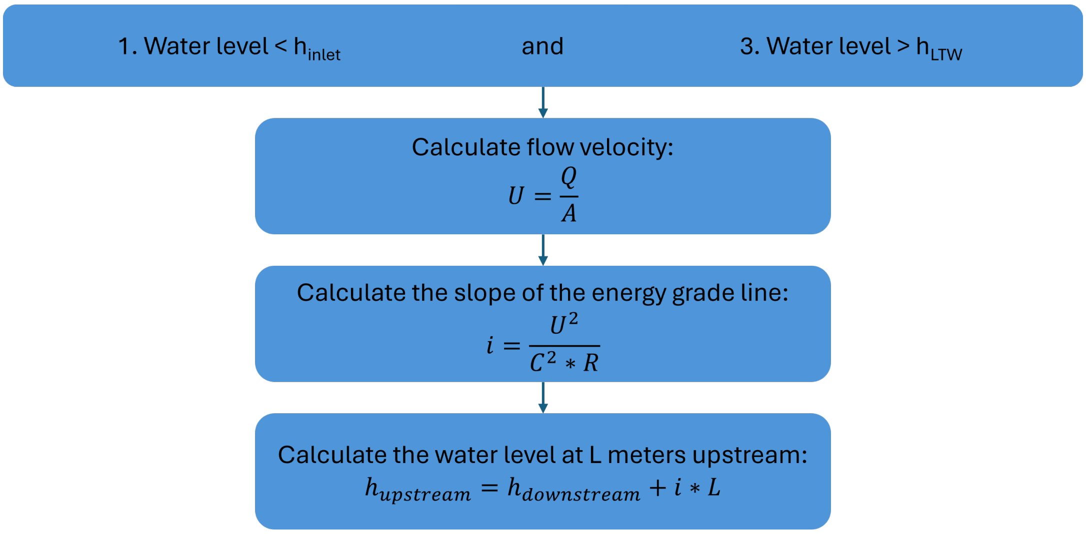


Figure 6.3: Calculation of the downstream water depth for cases 1 (water level < height of inlet opening) and 3 (water level > crest level of LTW)

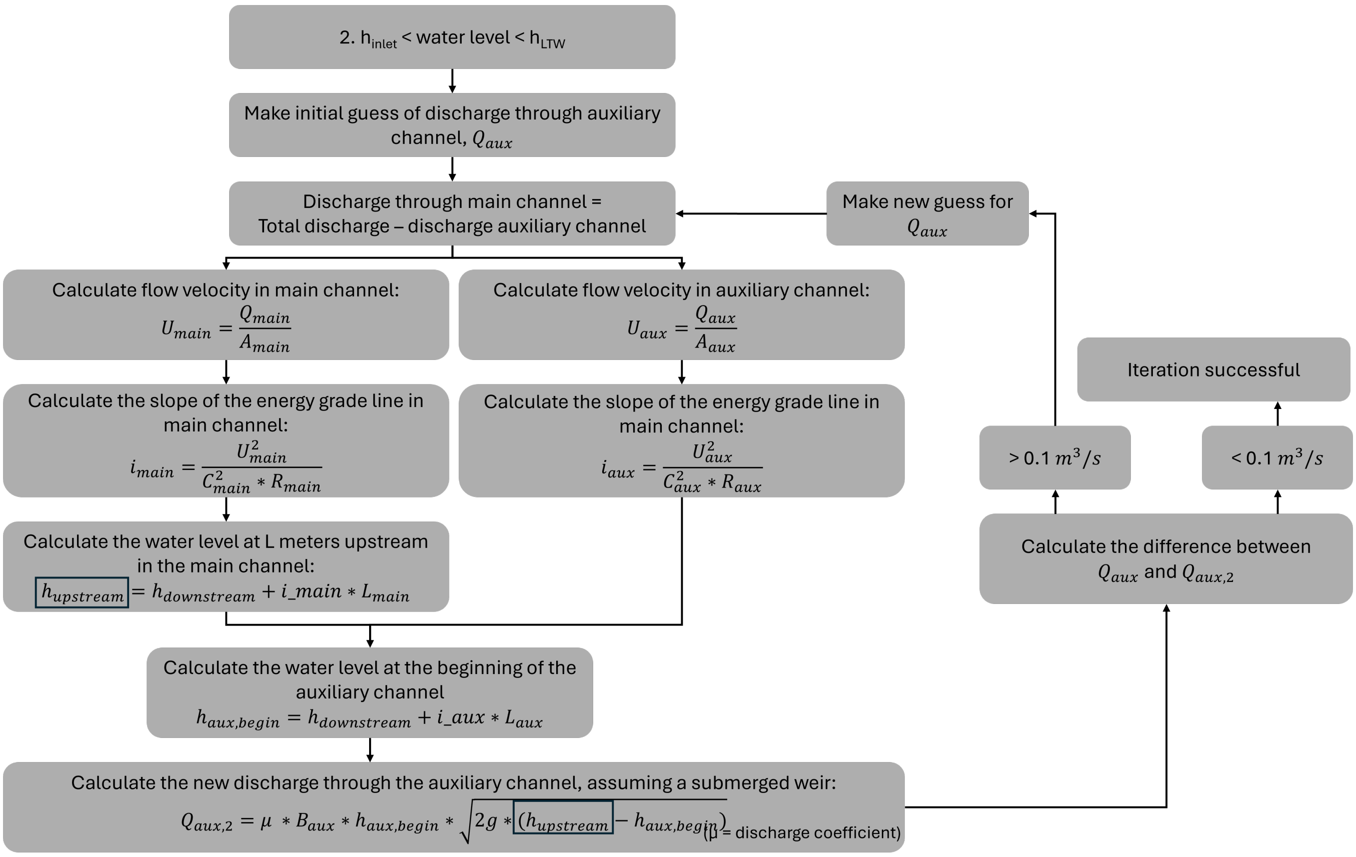


Figure 6.4: Calculation of the downstream water depth for case 2

A visualization is provided in for case 2 (the water level is between the inlet opening and the crest level of the LTW).

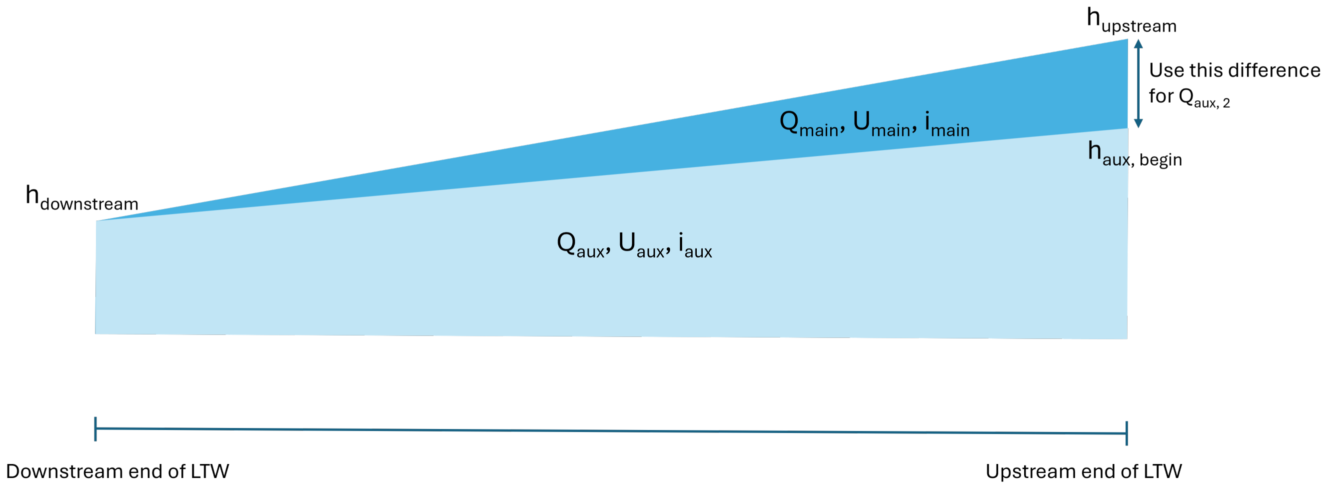


Figure 6.5: A visualization of Case 2 (the water level is between the inlet opening and the crest level of the LTW). The water depth in the main channel is visualizaed in darker blue than the water depth in the auxiliary channel. The difference between $h_{upstream}$ and $h_{aux,begin}$ is used to calculate $Q_{aux,2}$ with a weir formula. Note: the water depth difference is exaggerated.

To determine the effects of a longitudinal training wall, the downstream water levels of situations with and without a longitudinal training wall are calculated and can be found in Table 6.1. Note: for these calculations, the area of the auxiliary channel was assumed to be 50 % bigger than it could be if no additional dredging would be performed. However, this area would be unreasonably small, which led to the decision to incorporate extra excavation to enlarge the area of the auxiliary channel.

Table 6.1: Comparison of upstream water levels (1000 m upstream) for different downstream water levels, with and without LTW. Verification data from ("Waterstandsduurlijnen Rijn 2022", 2022) is included to check the model. The last column provides the percentage difference between a situation with and without an LTW.

Downstream WL [m]	Verification (no LTW) [m]	Model (no LTW) [m]	Model (with LTW) [m]	% Difference (with vs. no LTW)
3.98	4.08	4.05	4.22	4.20
4.41	4.51	4.48	4.64	3.57
4.88	4.98	4.94	5.05	2.23
5.42	5.51	5.47	5.57	1.83
5.93	6.02	6.01	6.15	2.33
6.44	6.53	6.52	6.63	1.69
6.94	7.04	7.01	7.16	2.14
7.38	7.47	7.46	7.59	1.74
7.89	7.99	7.97	8.11	1.76
8.39	8.50	8.50	8.62	1.41

The results indicate that the presence of a longitudinal training wall (LTW) significantly affects the flow conditions, particularly under low discharge scenarios. The LTW introduces an obstruction that alters the velocity profile and increases upstream water levels. The discrepancy between the model results (without an LTW) and the verification data from "Waterstandsduurlijnen Rijn 2022", 2022 is likely due to the model's simplification: it uses only a single cross-section and does not account for groynes or other flow-restricting structures. These elements reduce the effective cross-sectional area of the river, meaning the model underestimates upstream water levels in the absence of such obstructions.

Unless extra material is excavated, the discharge capacity of this system is not within acceptable limits.

This means that this solution is probably not viable for the IJssel river. However, to compare this design with the alternatives, scores are given for the criteria for this design as well.

6.1.2. Criteria

Permeability of the body

For the permeability of the LTW, the seepage flow velocity is calculated with the following formula (Martins and Escarameia, 1989):

$$U_v = KC_U^{-0.26}\sqrt{2geD_{50}i} \tag{6.1}$$

Where:

$$\begin{aligned}
K &= \text{coefficient that depends on stone shape (-);} K = 0.56 \text{ for crushed stone;}\\
C_U &= \text{coefficient of uniformity defined as } D_{60}/D_{10} \text{ (-)}\\
e &= \text{voids ratio defined as the ratio of volume of the voids and total rockfill volume;}\\
e &= \frac{1}{90}(e_0)\,\text{arctan}(0.645 \cdot n_{RRD}) \text{ (Tsirel, 1997)}\\
N_{RRD} &= \text{ uniformity coefficient; } 5.22 \text{ for a 5-40 kg grading}\\
i &= \frac{h_{main\ channel} - h_{auxiliary\ channel}}{L}; \text{ hydraulic gradient (-)}\\
n_v &= \frac{e}{1+e}; \text{ armourstone porosity of the medium}
\end{aligned}$$

The values for D_{10} and D_{60} were determined using EN 13383-1:2002 in which values are specified for the mass distribution of standard light gradings. This leads to $D_{10} = 0.16$, $D_{60} = 0.26$ and thus $C_U = 0.26/0.16 = 1.61$. The intermediate steps can be found in Section C.2.

The calculations for the seepage flow velocity can be found in Section C.3. The final result is an average flow velocity of 0.077 m/s through the wall.

Wave Reflection

The wave reflection for the pilot project design can be calculated with the following formulas

$$C_r = H_r/H_i \tag{6.2}$$

$$C_r = c\xi^2/(d+\xi^2) \tag{6.3}$$

$$\xi = \frac{tan(\alpha)}{\sqrt{H/L_0}} \tag{6.4}$$

c and d are coefficients that depend on the type of armour, in this case, it is a one-layer armourstone. The corresponding coefficients are $c = 0.64$ and $d = 7.22$ (Allsop and Hettiarachchi, 1989). As detailed in Appendix A, ship-induced waves were analyzed to determine the required rock size for ensuring armour stability. Among the different wave types, secondary ship waves result in the highest combination of incoming wave energy and breaker parameter, and are therefore used as the critical case for the wave reflection analysis. For a representative water depth of 4.5 meters, the secondary wave height is 0.09 meters and the corresponding wavelength is 3.62 meters. Given a slope of 1:2.5, these parameters yield the following value for the breaker parameter ξ:

$$\xi = \frac{(1/2.5)}{\sqrt{0.09/3.62}} = 2.54\ (-) \tag{6.5}$$

$$C_r = \frac{0.64 \cdot 2.54^2}{7.22 + 2.54^2} = 0.302\ (-) \tag{6.6}$$

This means that the wave height of the reflected waves is approximately 30 % of the height of the incoming waves.

Flexibility of Structure
The design from the pilot project scores high on flexibility. It is relatively easy to change the geometry of the longitudinal training walls. To give an example, the geometry of the inlet openings of the LTWs in the Waal have been changed several times during the pilot project. This indicates adaptability to local flow conditions and possibly also to future climate change.

The original goal of Rijkswaterstaat for the longitudinal training walls was to develop a structure that could easily be adapted to local conditions and climate change (Mosselman et al., 2021). This goal is achieved with flexible inlet openings and consequently, this structure scores high on flexibility.

Width of Structure and auxiliary channel
In Figure 6.1, the LTW is shown in a cross-section of the IJssel River. Although the axes are not equally scaled, it is evident that the available space is limited. The right side of the LTW intersects the riverbed approximately halfway along the right bank. Shifting the LTW further toward the center of the river is not feasible, as that would mean that the navigation channel would become too shallow under OLR conditions. Under OLR conditions, the navigation channel should be at least 40 meters wide.
In the current configuration, the structure spans approximately 30 meters. The average width of the auxiliary channel varies with the water level, but its maximum width—corresponding to a water level just below the crest of the longitudinal wall—is around 28.5 meters. From Figure 6.1 it can be concluded that the auxiliary channel is not wide enough to function effectively. Therefore, additional excavation will be necessary to establish an active side channel.

Constructability
Although longitudinal training walls are a relatively new concept, the design of the LTWs in the pilot project is not complex and shows similarities to other hydraulic structures such as groynes and breakwaters. The structure consists of granular material (5-40 kg natural rock) and this specific design has no geotextile between the soil and the structure (Chavarrias et al., 2021). There is only one main step in the construction process:

1. Rock placement: this is done by unloading a bulk vessel with a crane on a floating pontoon.

While site preparation, signage installation, and other finishing activities are also necessary, these are not listed here as they are common to all alternatives and therefore do not influence the decision-making process.

Management and Maintenance
Deltares has investigated the differences between management and maintenance for a situation with longitudinal training wall and one with traditional groynes. The overall conclusion is that the main difference lies in the repair costs after a collision. For the design in the pilot project, these costs are relatively high: the repair costs for two incidents in 2016 and 2019 were both well above €100,000. This is a multiple of the costs for the repair of regular groynes (Mosselman et al., 2021). The reason behind this is likely the absence of a geotextile between the armour layer and filter layers, causing the smaller granular material in the filter layers to be washed away. According to experts, this problem roots in the form of contract with the contractor and the experts assume that maintenance costs during the lifetime could have been significantly lower with a different form of contract (Mosselman et al., 2021).

According to the same final evaluation of Deltares, there is no clear difference in dredging maintenance between the LTW and regular groynes. However, *Rijkswaterstaat* mentions the difficulty in the removal of vegetation of the LTW's. In the Waal, this was dangerous due to the coarse grading of the rubble mound, which was 40-200 kg. Vegetation can also be removed from a vessel, but this is a costly option (Chavarrias et al., 2021). In the case of the river IJssel, smaller armour stones are enough to make a stable structure. This means that maintaining the LTWs from the crests of the dams is less dangerous, and consequently vegetation can be removed more easily.

Sustainability
To quantify the sustainability criterion, the environmental costs of the dam are calculated. To do this, the individual costs of the building materials are multiplied by their volume in the longitudinal training wall. The design from the pilot project consists of rubble mound with a cross-sectional area of roughly 93 m^2. The Dutch Environmental Database provides environmental costs for natural rock as armour in hydraulic structures. The costs amount to €6.77 per m^3. This leads to a total environmental cost of $118 \cdot 6.77 =$ € 629.61 per meter length (Nationale Milieudatabase, 2025a).

Ecology
In this paragraph, the answers are given to the questions that were described in Chapter 4:

1. To what extent can organisms grow on the structure?
   Vegetation on longitudinal training walls in the Waal river is on average less dense than on groynes in the same river sections. In addition, during high discharges, most of the vegetation is washed away by the river (Mosselman et al., 2021). Still, organisms can grow on the structure, comparable to groynes.
2. Do the structure and corresponding auxiliary channel create an ecosystem with differences in hydrodynamics such that the conditions for different species improve?
   In a research on fish diversity in auxiliary channels behind LTWs compared to groyne fields, the number of fish of most investigated species were significantly higher in the auxiliary channels. This indicates that the flow regime is not only favourable for specific fish species, but it provides good habitat for various species.
3. To what extent does the structure create shelter in the auxiliary channel against the wave conditions in the main channel?
   Yes, the hydrodynamics in the auxiliary channel are positive for (juvenile) fish. The energy of the waves in the main channel is much lower in the auxiliary channel, which also prevents the fish from washing out. It is assumed that the results of this research, conducted along the LTWs in the Waal river, are generalizable and therefor also applicable to the IJssel river (Collas et al., 2018).

6.1.3. Costs

Although it is not part of the Multi Criteria Analysis, the costs of a design are taken into account in cost-benefit analysis and are thus a deciding factor in the choice for a design. The costs of the design from the pilot project in the Waal are roughly €43 million, excluding VAT and at 2015 price levels (Eerden, 2021). In the evaluation of the pilot project, key figures are given for the construction and management maintenance of LTWs in the Waal (all costs excluding VAT): k€/km 4,104 for construction, €/km/yr 31,143 for maintenance and €/km/yr 9,524 for periodically changing the inlet openings to the current situation (Eerden, 2021). For a design life of 50 years, this leads to a total price per kilometer of:

$$\text{Total costs} = €43,087,643 + 50 \cdot (€31,143 + €4,104) = €44.8 \text{ million}$$

However, the costs of the other alternatives are estimated using cost data provided by Haskoning. To ensure a consistent and fair comparison between all design options, the same cost estimation approach will also be applied to this design:

The costs for the construction of a LTW with a design as used in the pilot project can be divided into the following direct costs:

- Grading of riverbed (€1.00 / m^2)
- Transport of rock material per ship (€30.00 / ton)
- Unloading of rock material (€3.00 / ton)
- Placement of rock material (€2.50 / ton)

Since only a preliminary design is provided in this research, 20% is added to the direct costs. In addition, an extra 40% is added to account for indirect costs, such as project management costs and temporary facilities. These total construction costs are now multiplied by the amount of material. The base area of the LTW is 30.5 m^2 per meter length and the cross-sectional area is 93 m^3 per meter length. The density of natural rock is estimated to be 2650 kg/m^3. This leads to the following total costs:

Table 6.2: Cost breakdown per meter for the pilot project design (Source: Haskoning)

Activity	**Unit Cost**	**Cost per meter (€)**
Grading of riverbed	€ 1.00 / m^2	€ 51
Transport of rock material per ship	€ 30.00 / ton	€ 12.421
Unloading of rock material	€ 3.00 / ton	€ 1242
Placement of rock material	€ 2.50 / ton	€ 1035
Total		**€ 14,750**

6.1.4. Summary

A brief summary of the scores per criterion is given in Table 6.3.

Table 6.3: Brief summary of all criteria for the design used in the pilot project in the river Waal

Criterion	**Summary**	**Qualitative Result**
Permeability	The pores are relatively small, resulting in a low flow velocity.	Seepage flow velocity = 0.077 m/s
Wave reflection	A slope of 1:2.5 can dissipate a significant portion of the wave energy.	C_r = 0.3
Flexibility	Modifying the geometry of the LTW is straightforward due to the use of natural rock (5–40 kg).	Not applicable
Width of structure	The 1:2.5 slope results in a wide structure that obstructs a significant part of the main channel.	Width at bottom level ≈ 35 m
Width of the auxiliary channel	The auxiliary channel is narrow and shallow; additional excavation is needed.	Maximum width ≈ 28.5 m
Constructability	The concept is new, but the construction process is familiar and straightforward.	Main construction steps = 1
Management and Maintenance	Maintenance costs are relatively high; dredging frequency is comparable to groyne fields.	Not applicable
Sustainability	Environmental costs are calculated for natural rock.	Environmental cost per meter = €629.61
Ecology	The LTW and auxiliary channel support a thriving ecosystem.	Not applicable
Costs per meter length		€14,750

6.2. Alternative design 1: ’Sandy’ Multi-channel system

The first alternative design fundamentally differs from the other two, as it does not involve the construction of a hard structure—except potentially at the inlet opening. Consequently, several evaluation criteria cannot be directly compared. Nevertheless, a reasonable assessment of the multi-channel system is provided, highlighting its advantages and disadvantages in relation to the criteria defined in Chapter 4.

6.2.1. Requirements

Width of navigation channel

The width of the navigation channel remains unchanged, as no new structure is introduced into the river. This implies that the existing groynes, which currently guide the river flow, will remain in place. However, in the long term, the addition of a separate channel may influence sediment dynamics, potentially altering the dimensions of the navigation channel.

Stability

In terms of structural stability, this requirement is automatically met, as there is no structure involved. However, bank protection will likely be required at the location of the inlet and outlet openings, because cross currents and turbulence can be expected there. If this alternative were selected, further research is necessary to calculate the exact currents and necessary protection. Chapter 8 of the Rock Manual can be used as a guideline for designing a revetment.

Discharge Capacity

Some changes were made to the model that was described in Section 6.1.1. Instead of determining the area of the auxiliary channel by placing a structure in the river cross section, the average width of 10.38 meters (Section 5.3.1) is multiplied by the water depth in the channel. With a bottom level of 2.04 m + NAP, the water depth can be calculated by the water level (+ NAP) minus 2.04 m.
The reference data that was used to verify the calculations in Table 6.1 provides data every kilometer, whereas the auxiliary channel has a length of 1490 meters. However, to check whether the discharge capacity is sufficient, a length of 1000 meters is assumed in the model. The results are depicted in Table 6.4.

Table 6.4: Comparison of upstream water levels (1000 m upstream) for different downstream water levels, with and without auxiliary channel. Model results without an auxiliary channel are used as reference.

Downstream WL [m]	Model (no LTW) [m]	Model (with auxiliary channel) [m]	% Difference
3.98	4.05	4.04	-0.25
4.41	4.48	4.47	-0.22
4.88	4.94	4.93	-0.20
5.42	5.47	5.46	-0.18
5.93	6.01	6.00	-0.17
6.44	6.52	6.51	-0.15
6.94	7.01	7.00	-0.14
7.38	7.46	7.45	-0.13
7.89	7.97	7.96	-0.13
8.39	8.50	8.48	-0.24

Although the differences are relatively small, it can be concluded from the data that a multi-channel system improves the discharge capacity, based on the upstream water levels that are lower for a situation with an auxiliary channel than the current situation.

6.2.2. Criteria

Permeability of body

The auxiliary channel differs from the other alternatives in that it extends deep into the floodplains. In contrast to a longitudinal training wall, the flow exchange between the main and auxiliary channels is expected to be limited. However, during a consultation with experts from Haskoning, concerns were raised regarding potential changes to the groundwater table and flow patterns if an auxiliary channel is excavated in the floodplains. This risk arises if a sand layer (aquifer) beneath a clay layer is exposed during excavation. In the floodplains of the IJssel River, this is a plausible scenario, as the clay layer is approximately 3 meters deep (TNO - Geological Survey of the Netherlands, 2025), while the auxiliary channel is designed to be around 5 meters deep.

Part of this issue is mitigated by aligning the auxiliary channel with existing ditches and creeks, which already provide a connection to the aquifer. As a result, the impact on the groundwater table is expected to be limited.

Wave reflection

Since no structure is introduced in or near the main channel, wave reflection will remain unchanged compared to the current situation. However, this criterion is based on the principle of minimizing the impact on the shipping industry. Auxiliary channels can generate cross-currents at their outlet openings, which —if not properly mitigated— may pose a hazard to vessels navigating the IJssel River.

Flexibility of structure

Auxiliary channels in a multi-channel system are not flexible in a sense that they could be easily repositioned. In case of changing boundary conditions, the width and depth of the channel might need change, which can be done by performing additional dredging, which is costly and labor intensive. Furthermore, implementing changes in the floodplains requires extensive consultation with stakeholders.

In terms of morphology, the system is more flexible as the shape of the auxiliary channels will mainly be formed by erosion and/or sedimentation (Bureau Stroming, n.d.). However, since the main focus of this criterion was on structural flexibility, this alternative receives a low score.

Width of structure and auxiliary channel

For the width of the structure, the same reasoning applies as in earlier criteria: there is no structure that obstructs part of the flow in the main channel. Furthermore, only changes will be made to the river dikes and in the floodplains, not to the river itself. This minimizes the spatial impact on the river.

The width of the auxiliary channel is on average 10.38 meters, which is relatively small compared to other alternatives. However, this width has been computed by finding an optimal width/depth ratio as defined by van Denderen, 2019.

Constructability

The constructability of a multi-channel system was discussed with 2 experts from Haskoning.

First of all, constructing the multi-channel is not complicated in technical terms. It comprises the following steps:

1. Excavation of a connection between the river and existing streams in the floodplains (Figure 6.6).
2. Constructing bank protections near the inlet and outlet openings of the auxiliary channel.

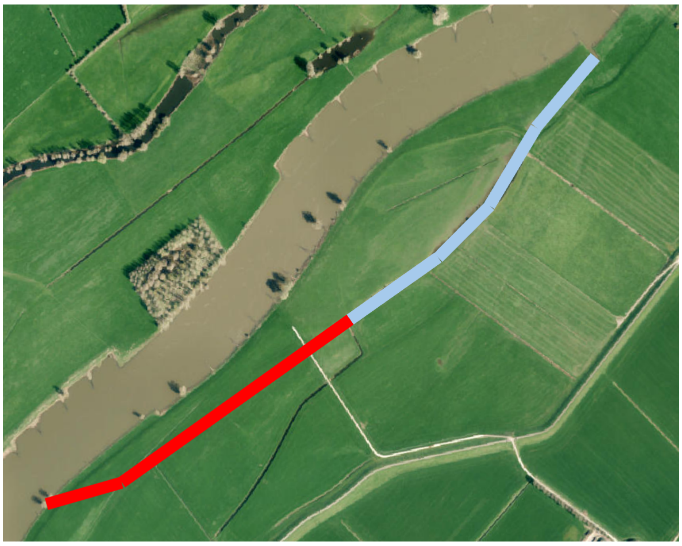


Figure 6.6: Auxiliary channel: the parts that need excavation are indicated with a red line. The existing creeks are indicated with a blue line.

The more complex aspect of this alternative lies in obtaining the necessary permits. The area designated for the auxiliary channels currently holds a zoning classification of 'agricultural floodplains' (Atlas Leefomgeving, 2025). Furthermore, the proposed excavation would take place on farmland owned by private landowners, who would need to be compensated or bought out.
In conclusion, the complexity of this alternative does not stem from technical feasibility, but rather from legal and administrative challenges related to excavation permits and land ownership.

Management and Maintenance
Several studies emphasize the importance of regular maintenance for auxiliary channels, as these channels tend to be morphologically unstable (Riquier et al., 2017; van Denderen et al., 2019; van Denderen, 2019). Although the dimensions of the auxiliary channel in this study were selected based on the recommendations of van Denderen, 2019—which aim to minimize morphological instability—site-specific research is still required to verify their effectiveness under local conditions. Van Denderen concludes: "... we hypothesize that in general side channels in lowland rivers always close." This suggests that regular dredging will be necessary to maintain the functionality of the side channels. Additionally, both the overall dimensions of the channel and the design of the inlet opening will significantly influence its morphodynamic behavior.
In conclusion, continuous monitoring is essential to track changes in sedimentation or erosion within both the auxiliary and main channels, as these may affect the long-term discharge capacity.

Sustainability
To quantify the sustainable impact of the construction process for a multi-channel system, the environmental costs are calculated. The primary contributor to these costs is the excavation process. Since the environmental impact depends on the type of excavator and local site conditions, a rough estimation has been made.
In the Dutch Environmental Database, information is given for different types of excavators, based on their fuel-type usage. The newest category of excavators (category V) has environmental costs ranging from €3.00 (Hydrotreated Vegetable Oil fuel) to €5.49 (Gas-To-Liquids fuel) per hour. An excavator powered by diesel fuel has environmental costs of €4.47 per hour, which is roughly in the middle between the two aforementioned and it will be used for this case (Nationale Milieudatabase, 2025b). The surface level of the floodplains in the area of interest are at roughly 7.5 meters +NAP (Actueel Hoogtebestand Nederland, 2023). With a bottom level of 2.04 m +NAP and a width of on average 10.38 (see Section 5.3.1) the cross-sectional area that needs to be excavated is $56.7\ m^2$. Assuming a productivity of 40 m^3/hour (Planning Engineer, 2013), the environmental costs per meter length are then:

$$Environmental\ costs = \frac{€4.47 \cdot 56.7\ m^3}{40\ m^3} = €6.34$$

In practice, the excavated material must be transported to a designated disposal site, which significantly increases the environmental costs. According to the Dutch Environmental Database, the environmental cost for a diesel-powered truck is approximately €0.011 per ton-kilometer (Nationale Milieudatabase, 2025c). Publicly available data indicate that the nearest soil storage facility is located approximately 35 kilometers from the project area (Grondbalans, n.d.), and the average truck capacity is 25 tons (CIRIA, CUR, CETMEF, 2007). Given that 56.7 m^3 of material is excavated per meter length of the auxiliary channel, and assuming a density close to 1 ton/m^3, approximately 2.27 truckloads are required per meter.

Therefore, the total environmental cost for both excavation and transport amounts to approximately €28.17 per meter length of the auxiliary channel.

Ecology
In this paragraph, the answers are given to the questions that were described in Chapter 4:

1. To what extent can organisms grow on the structure?
   There is no real 'structure' on which organisms can grow, but this is compensated by the ecological potential of the auxiliary channel.
2. Do the structure and corresponding auxiliary channel create an ecosystem with differences in hydrodynamics such that the conditions for different species improve?
   According to Bureau Stroming, the multi-channel system creates a 'fish-friendly' environment. The flow velocities are generally lower in the auxiliary channels than in the main channel. Research has shown that the density of species is much higher in auxiliary channels (ca. 6000 species/m^2) than in the main channel (ca. 700 species/m^2) for an auxiliary channel that is located in the northern part of the river IJssel (de Rooij et al., 2009).
3. To what extent does the structure create shelter in the auxiliary channel against the wave conditions in the main channel?
   Except near the inlet and outlet openings, the flow regime in the auxiliary channel differs significantly from that of the main channel. The channel can adapt to local conditions and provides essential habitat for a wide range of species, both within the channel and along its banks (Bureau Stroming, n.d.).

6.2.3. Costs

The costs of this alternative are calculated in the same way as in Section 6.1.3. The results can be found in Table 6.5.

Table 6.5: Cost breakdown per meter for the multi channel system (Source: Haskoning)

Activity	Unit Cost	Cost per meter
Excavation of sand	€ 2.00 / m^3	€ 191
Loading and transport with dump trucks to barges	€ 3.00 / m^3	€ 286
Transport over water by hopper barge, including shipping and unloading costs	€ 15.00 / m^3	€ 1429
Temporary works for transshipment site	€ 100,000 for whole project	€ 113
Total		**€ 2018**

In the estimation of the costs, a volume of 56.7 m^3 was used per meter length. The last cost, *temporary works for transshipment site* is divided by the total length of the auxiliary channel, 1490 m for this particular case.

6.2.4. Summary

A brief summary of the scores per criterion is given in Table 6.6.

Table 6.6: Brief summary of all criteria for the design of the alternative auxiliary channel concept

Criterion	Summary	Qualitative Result
Permeability	There is no structure separating the main and auxiliary channel. It is recommended to use existing creeks as parts of the auxiliary channel to limit the effects on the groundwater table.	Seepage flow velocity ≈ 0 m/s
Wave reflection	Due to the absence of a structure, wave reflection does not occur. However, cross-currents at bifurcation points may affect navigation.	Not applicable
Flexibility	The auxiliary channel cannot be easily relocated, and modifications to its geometry are labor-intensive and costly.	Not applicable
Width of structure	No structure is present that obstructs the river flow.	Width at bottom level = 0 m
Width of the auxiliary channel	The dimensions follow the guidelines of Van Denderen (2019) and are expected to result in a morphologically stable system.	Maximum width = 10.38 m
Constructability	Technically straightforward, but legal and administrative challenges are expected in obtaining permits.	Main construction steps = 2
Management and Maintenance	Monitoring is required to track sedimentation and erosion that may affect discharge capacity.	Not applicable
Sustainability	Environmental costs are calculated for excavation and transport of material. Armour protection is not included.	Environmental cost per meter = €28.17
Ecology	The auxiliary channel creates a connected ecosystem with favorable hydrodynamic conditions for various species.	Not applicable
Costs per meter length		€ 2,018

6.3. Alternative design 2: Gabion wall

6.3.1. Requirements

Width of navigation channel

A visualization of the gabion wall design is presented in Figure 6.7. Based on discussions with experts from Haskoning, the initial design—introduced in Chapter 5—was slightly modified by centering the gabion blocks. This adjustment results in a symmetrical slope on both sides of the longitudinal training wall (LTW), replacing the original configuration that featured a vertical wall on the main channel side and a slope on the auxiliary channel side. The crest height of this structures is slightly lower compared to the other structures in this chapter, since standard sizes for gabion boxes were used (height of 2 meters).
The horizontal positioning of the wall is determined such that a minimum navigation channel width of 40 meters is maintained under OLR conditions. An updated visualization of the gabion wall is also provided in Figure 6.8. The maximum width of the gabion wall is 4 meters.

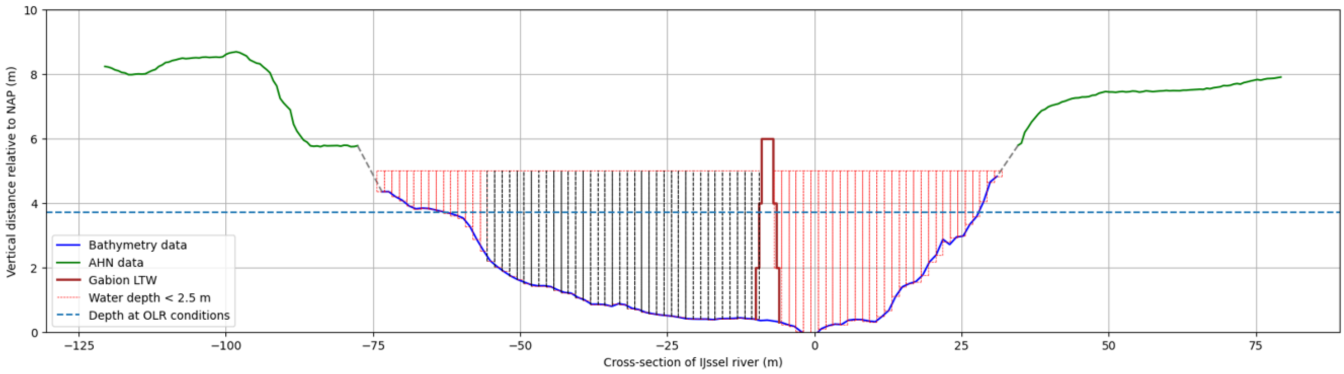


Figure 6.7: Visualization of the gabion LTW in a cross section of the river IJssel. Black dashed lines indicate a sufficient water depth of 2.5 m for navigation. The unit of the vertical axis is m above NAP.

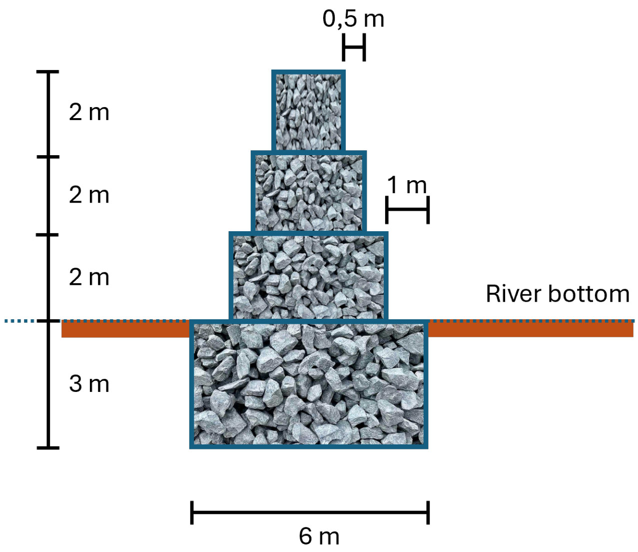


Figure 6.8: The updated design for the cross section of the gabion longitudinal wall. In red scour protection has been indicated (not to scale).

Stability

To calculate the minimum (average) width of a longitudinal training wall that consists of gabion blocks, simplified design guides were used in Chapter 5. To guarantee stability, the structure will be checked for overturning stability. The overturning moment mainly comes from hydrostatic pressure from the navigation channel in case of a difference in water level between the navigation channel and the auxiliary channel. Because of the inlet opening at the beginning of the auxiliary channel, the difference in water level will never be very significant during the life time of the structure. However, there are situations possible in which there is no water in the auxiliary channel, for instance during construction of the wall. In that case, the difference in water level can be equal to the height of the wall at maximum, which is 6 meters. Detailed calculations can be found in Appendix C.

A Factor of Safety against overturning of 1.62 is found. Considering that this calculation was done for an extreme and rare case (maximum water level at the navigation channel, no water level in the auxiliary channel), the factor of safety of 1.62 is safe enough.

The other stability criterion that will be checked is sliding. This will be done according to the following formula:

$$FoS = \frac{f \cdot W}{F_w} \tag{6.7}$$

Detailed calculations can be found in Appendix C.

A Factor of Safety of 2.34 is found, which is very safe and therefore the design that was presented in Chapter 5 will be used throughout this chapter.

For the stones in the gabion boxes, a grading of 90/180 mm is used according to EN13383, as this standard coarse grading is specifically designed to use in gabions (CIRIA, CUR, CETMEF, 2007).

While the previously discussed formulas provide a basic understanding of the stability of a gabion wall, it is evident that detailed structural calculations are required for actual implementation. Moreover, long-term studies on gabion wall performance indicate that, without proper and regular maintenance, there is a considerable risk of scour beneath and next to the structure. This can ultimately lead to the displacement of individual gabions or even the collapse of the longitudinal training wall as a whole (Thompson et al., 2016, Kurokawa et al., 2025). Therefore, scour protection is required to stabilize the riverbed.

Discharge Capacity

To determine the discharge capacity of the gabion structure, the structure is drawn in the model that was described in Section 6.1.1, and the resulting upstream water levels are calculated. This is done for a situation with or without a gabion wall, given a downstream water level. The results can be found in Table 6.7.

Table 6.7: Comparison of upstream water levels (1000 m upstream) for different downstream water levels, with and without a gabion wall. Model results without LTW are used as reference.

Downstream WL [m]	Model (no LTW) [m]	With Gabion Wall [m]	% Difference
3.98	4.05	4.04	-0.25
4.41	4.48	4.47	-0.22
4.88	4.94	4.93	-0.20
5.42	5.47	5.46	-0.18
5.93	6.01	6.00	-0.17
6.44	6.52	6.51	-0.15
6.94	7.01	7.02	0.14
7.38	7.46	7.47	0.13
7.89	7.97	8.00	0.38
8.39	8.50	8.51	0.12

From the results it can be concluded that the water levels in the river do not change significantly between a situation with or without a gabion wall LTW. This indicates that the discharge capacity is roughly the same as well.

6.3.2. Criteria

Permeability of body

The permeability of the structure is closely related to the porosity n_v. For gabion walls, this porosity generally varies between 25 and 35 %, but for calculation practices, a conservative value of 40 % is usually adopted (CIRIA, CUR, CETMEF, 2007). For the calculation of the seepage flow through the dam, Equation 6.1 is used with the following coefficients:

$$K = \text{coefficient that depends on stone shape (-)} K = 0.56 \text{ for crushed stones;}$$
$$C_U = \text{coefficient of uniformity defined as } D_{60}/D_{10} \text{ (-) } C_U = 0.145/0.090 = 1.61;$$
$$e = \text{voids ratio defined as:} e = \frac{n_v}{1-n_v} = \frac{0.4}{1-0.4} = 0.67 \text{ (-);}$$
$$D_{50} = \text{characteristic sieve size of the stone (m)} = 0.135\ m;$$
$$i = \text{hydraulic gradient} = \frac{h_{main\ channel} - h_{auxiliary\ channel}}{L} = \frac{0.20}{2} = 0.1 \text{ (-);}$$

The values for D_{10}, D_{60} and D_{50} were derived from EN 13383. Using Equation 6.1, the seepage flow velocity is calculated to be: 0.208 m/s. This is substantially higher than the seepage flow velocity through the longitudinal training wall as designed in the pilot project.

Wave reflection

The formula presented in Equation 4.2 is not fully applicable for calculating the wave reflection coefficient of the gabion wall, as parts of the structure are vertical, resulting in an infinitely large breaker parameter. It cannot be assumed, however, that the waves are therefore 100 % reflected, because of the permeability of the gabions and the step-wise slope of the gabion wall. Values for the reflection coefficient C_r are presented by (Allsop, N.W.H. and Hettiarachchi, S.S.L., 1988), (Seelig and Ahrens, 1981) for various vertical structures based on their porosity and relative depth h/L. For structures with a porosity between 0.15 and 0.25, reflection coefficients typically range between 0.3 and 0.6. To adopt a conservative approach, a value of $C_r = 0.6$ is selected for this study. This implies that the reflected wave height is, at most, approximately 60% of the incoming wave height.

Flexibility of structure

Gabion structures are flexible because they consist of building units that can be easily replaced with new gabions, as long as they are located at the top layer. Gabion boxes that are located deeper in the wall will require a lot more labor.

The length, width, height and position of the LTW can be changed according to the local conditions. However, the gabions require machinery to be (re)placed because of their weight. Small adjustments are therefore not straightforward.

Width of structure and auxiliary channel

A gabion wall is a relatively thin structure. The maximum width of the structure above the bottom of the river is only 4 meters, which is almost 90 % less than the design in the pilot project. This automatically means that the width of the auxiliary channel is wider, in this case on average 65 meters wide.

Constructability

For the level of constructability, the amount of operations during construction are summed. This is done in broad steps, not in detail, and the steps are based on the Rock Manual and Alsubih et al., 2023.

1. Dredge and level the river soil
2. Add protection layer on the river bottom
3. Prepare the gabions by filling them with stones
4. Place the gabions
5. Interconnect the gabion elements to add stability

These five steps are a simplified summary of the construction process, but still give an idea of the complexity of the construction.

Management and Maintenance
In the Rock Manual, various causes of damages are listed, grouped under 'Hydraulic Actions', 'Biological', 'Chemical', 'Climate', 'Human Action', 'Traffic' and 'Ultra-Violet Light'. During the design phase, preventive measures can be taken to mitigate most types of damage. For this project, biological, chemical, and traffic-related damages are considered the most relevant.
Biological damage may occur due to plant growth in or on the gabion elements. This can lead to a modification of the hydraulic performance and an increase in hydraulic roughness. To prevent this, regular removal of vegetation is necessary.
Chemical damage primarily concerns the corrosion of the steel wire mesh. This is typically mitigated by using galvanized steel, which provides a protective coating against corrosion.
Traffic-related damage, particularly from ship collisions, is also a significant concern. As discussed earlier in this report, the pilot project experienced high repair costs due to a design that was not adequately prepared for such impacts. Gabion walls offer a degree of flexibility, as damaged sections can be repaired by replacing individual stones, mesh, or even entire gabion units. However, if damage occurs to gabions located at lower levels within the LTW, repairs become more complex and costly. In such cases, it may be necessary to remove overlying gabions, and part of the work will need to be carried out underwater, further complicating maintenance operations.
In conclusion, gabion wall need little repair. To minimize the effects on hydraulic roughness, removal of vegetation is needed, which can probably be done manually because of the rectangular form of the gabions. Repair after collisions should also cause little problems, as the steel wire and stone filling can easily be replaced or repaired.

Sustainability
A study on the environmental impact of four different types of retaining walls (gabion wall, crib wall, rubble masonry wall and reinforced concrete wall) concluded that a gabion wall is the most sustainable alternative out of the four (Balasbaneh et al., 2021). It produced the lowest emissions on all assessed environmental criteria: Global Warming Potential, Eutrophication, Fossil Depletion, and Acidification.
The Dutch Environmental Database specifies environmental costs for many different applications. Gabions are not included in the database as a hydraulic structure, but it gives an environmental declaration of a gabion wall used as a noise barrier next to railways. Since the building materials of a gabion wall as a hydraulic structure or as a noise barrier will likely be very similar, this declaration is used to determine the environmental costs of the LTW consisting of gabions:

The gabion wall has a cross-sectional area of 36 m^2. The environmental costs for a gabion wall are €24.79 per m^3 (Nationale Milieudatabase, 2025d). This leads to a cost of €892.51 per meter length. Because this structure specifically needs dredging before it can be constructed, the environmental costs of dredging are added as well. These costs are €0.59 per m^3 (Nationale Milieudatabase, 2025e). The part of the structure that is below the river bottom is 18 m^2, leading to added costs of €10.69 per meter length. The total is then €903.20/m.

Ecology
In this paragraph, the answers are given to the questions that were described in Chapter 4:

1. To what extent can organisms grow on the structure?
Because the gabion wall mainly consists of natural rock, organisms can grow on and in the structure. This should be comparable to a longitudinal training wall consisting of rubble mound. However, due to the relatively small cross sectional area of the gabion wall, the amount of organisms growing on the structure will be lower compared to a situation with a simple rubble mound LTW.
2. Do the structure and corresponding auxiliary channel create an ecosystem with differences in hydrodynamics such that the conditions for different species improve?
Several studies on the physical effects of gabions in rivers suggest that there is no direct positive nor negative effect of gabions on the total fish biomass (Majorošová et al., 2018), (Maughan et al., 1978).. However, these studies focused only on gabions that were used as revetments, not as longitudinal walls that can separate a river in two channels. Generally, it could be stated that a gabion wall creates conditions with differences in hydrodynamics due to its porosity.

3. To what extent does the structure create shelter in the auxiliary channel against the wave conditions in the main channel?
The auxiliary channel is similar to the auxiliary channel in the pilot project design. It provides shelter since the wave energy in the navigation channel dissipate in the gabion wall.

6.3.3. Costs

The costs of this alternative are calculated in the same way as in Section 6.1.3. The results can be found in Table 6.8.

Table 6.8: Cost breakdown per meter for the gabion wall (Source: Haskoning)

Activity	**Unit Cost**	**Cost per meter**
Excavation for gabions, transport and disposal	€ 68 / m^3	€ 4113
Supply of gabions including rock fill	€ 135 / m^3	€ 8165
Installation of gabions	€ 55.00 / m^3	€ 3326
Total		**€ 15,604**

In the estimation of the costs, a volume of 36 m^3 was used per meter length. For the *supply of gabions including rock fill*, the costs are uncertain due to the limited application of gabions in the Netherlands, but a range between € 120 and € 150 per m^3 was provided by a Haskoning employee.

6.3.4. Summary

A brief summary of the scores per criterion is given in Table 6.9.

Table 6.9: Brief summary of all criteria for the design of the gabion-based longitudinal training wall

Criterion	Summary	Qualitative Result
Permeability	The gabion wall is very slender, resulting in a relatively high seepage flow velocity.	Seepage flow velocity = 0.208 m/s
Wave reflection	Due to limited data on vertical structures, a conservative reflection coefficient was chosen.	C_r = 0.6
Flexibility	Minor adjustments are feasible only for gabions in the top row; deeper modifications are labor-intensive and costly.	Not applicable
Width of structure	The structure is slender, as the gabion boxes hold the rocks together.	Width at bottom level = 4 m
Width of the auxiliary channel	The auxiliary channel is relatively wide compared to other alternatives.	Maximum width ≈ 65 m
Constructability	Construction is complex and involves multiple steps.	Main construction steps = 5
Management and Maintenance	Minimal maintenance is required unless the structure is damaged by ship collisions. Underwater repairs may be necessary.	Not applicable
Sustainability	Environmental costs are calculated for the gabion boxes.	Environmental cost per meter = €903.20
Ecology	The gabion wall offers limited ecological growth but provides hydrodynamic variation and wave shelter in the auxiliary channel.	Not applicable
Costs per meter length		€ 15,604

6.4. Alternative design 3: Xstream blocks

6.4.1. Requirements

Width of navigation channel

The longitudinal wall consisting of Xstream blocks is positioned such that the navigation channel is at least 40 meters wide during OLR conditions. A visualization can be found in Figure 6.9. The width of the Xstream LTW at bottom level is approximately 15 meters.

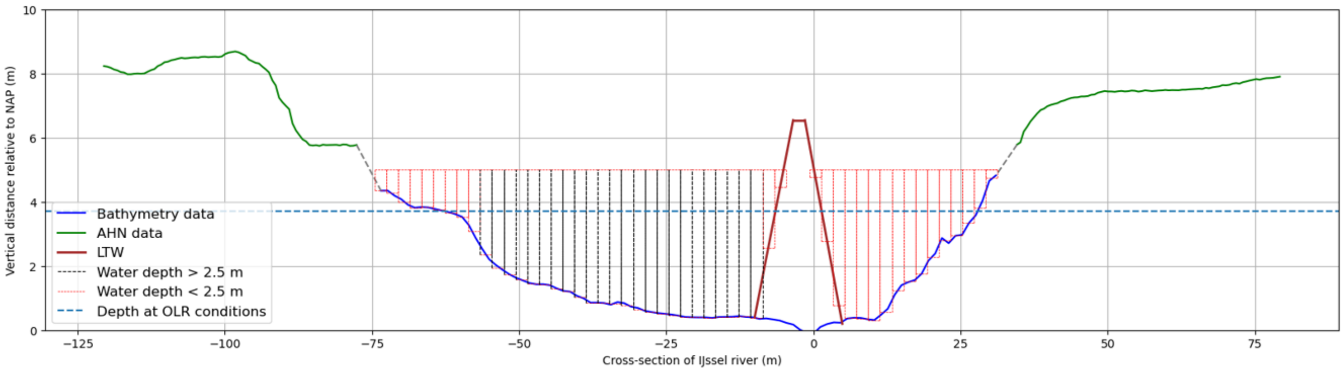


Figure 6.9: Visualization of the gabion LTW in a cross section of the river IJssel. Black dashed lines indicate a sufficient water depth of 2.5 m for navigation. The unit of the vertical axis is m above NAP.

Stability

Xstream blocks are a new concept and are only applied to 'flexible' groynes in the river IJssel in the Netherlands. The information on stability of individual blocks and the structure as a whole is therefore limited. However, conclusions can be drawn from the evaluations of the flexible groynes by Deltares. In this project, regular groynes are substituted by groynes that are built with Xstream blocks. The results show that both during low and increased discharge, the flexible groyne was stable and a filter layer between the blocks and the river bottom is unnecessary (Buschman and Kosters, 2021). However, the results also show that a scour hole with a depth of 'a few decimeters' has formed at one of the three flexible groynes. In a later evaluation, this scour hole was measured to be at maximum 1.6 meters deep. Research indicates that this scour hole will stabilize and eventually be smaller than scour holes near traditional groynes in the same river stretch as the flexible groynes (Buschman et al., 2024). However, monitoring will be required to check this assumption, as the steep slope might cause unexpected effects and deeper scour holes.

Discharge capacity

The discharge capacity requirement was checked in the same way as the other alternatives by using the Python model and comparing the computed water level upstream with data from “Waterstandsduurlijnen Rijn 2022”, 2022. The results can be found in Table 6.10. The difference in water level with verified data for a case without a LTW is relatively small, which can be expected due to the small cross sectional area of the Xstream LTW. A maximum increase of the water level of 1.34 % is observed, which is within acceptable limits. However, it should be noted that for these calculations, it was assumed that no water can flow between the main and auxiliary channel. Since the Xstream elements are rather porous, this assumption can only hold if a change is made to the design, such that no water can flow through the longitudinal wall. This could be a subject of further research.

Table 6.10: Comparison of upstream water levels (1000 m upstream) for different downstream water levels, with and without an Xstream wall. Model results without LTW are used as reference.

Downstream WL [m]	Model (no LTW) [m]	With Xstream Wall [m]	% Difference
3.98	4.05	4.10	1.23
4.41	4.48	4.54	1.34
4.88	4.94	4.99	1.01
5.42	5.47	5.51	0.73
5.93	6.01	6.05	0.67
6.44	6.52	6.57	0.77
6.94	7.01	7.06	0.71
7.38	7.46	7.50	0.54
7.89	7.97	8.03	0.75
8.39	8.50	8.54	0.47

6.4.2. Criteria

Permeability of body

The Xstream blocks have a high porosity of roughly 60 % (Buschman et al., 2024). This can lead to high velocities through a dam that consists only of Xstream blocks. Deltares reports that the average flow velocity of water through the flexible groynes is at maximum 6 % of the velocity next to the groyne in the navigation channel. Tests of the velocity through the groynes showed velocities ranging from 0.006 m/s (at a discharge of 265 m^3) to 0.06 m/s (at a discharge of 671 m^3). Although Equation 6.1 should normally be used for rockfill structures, it is used in this case to compare it with the results from the flexible groynes project. The following assumptions are made:

1. K, the coefficient that gives a correction for the stone shape, it is assumed that it is similar to crushed stones (0.56).
2. Coefficient of uniformity (C_U): Assumed to be 1, as all gabion blocks are considered identical in size.
3. The porosity is assumed to be 60 %, or $n_v = 0.6$
4. The characteristic sieve size D_{50} is chosen to be the smallest dimension (height/width/length), which is 320 mm (Figure 6.10).
5. The seepage length L is assumed to be the average width of the LTW, which is approximately 6.7 meters, based on a crest level of 5.7 meters and a crest width of 2 meters.

This leads to a seepage flow velocity of 0.297 m/s, which is in between the results from the flexible groynes.

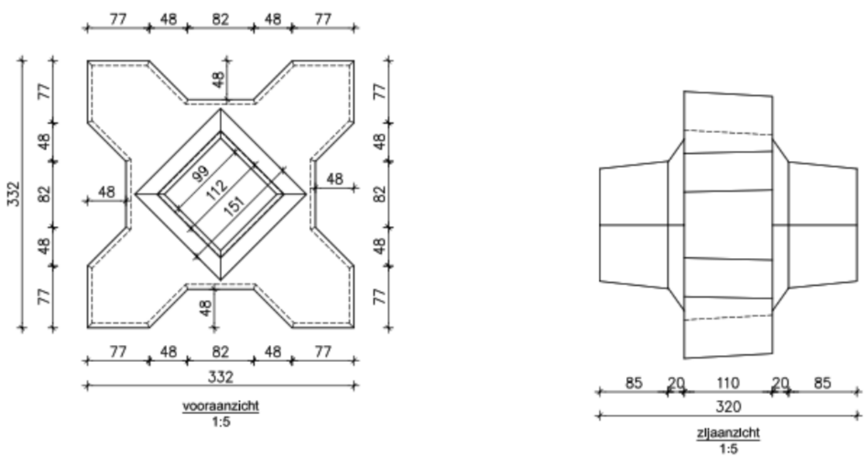


Figure 6.10: Dimensions Xstream-element (Buschman and Kosters, 2021)

Wave reflection
The wave reflection of a LTW with Xstream elements can be calculated by Equation 6.2 and Equation 6.3. Allsop and Hettiarachchi, 1989, give values for the coefficient c and d for concrete armour units, such as Tetrapods. Although Tetrapods have much larger dimensions than Xstream blocks, their shape has similarities to the Xstream blocks. To give an indication of the wave reflection, the known values for Tetrapods are used for Xstream blocks, which are: c = 0.48 and d = 9.62. Using Equation 6.3, the result is: $C_r = 0.193$. This result is supported by the research of Wetser (2016), that found values between 0.15 and 0.32 for C_r (Wetser, 2016).

Flexibility of structure
A longitudinal training wall composed of Xstream blocks provides a high degree of flexibility, due to the small size of the individual elements and the ease with which they can be handled using a polyp grab. Furthermore, changing the geometry of the dam or its inlets during construction or design life, does not require dry conditions (Buschman et al., 2024). Compared to traditional groynes, the adaptation of LTWs composed of Xstream blocks is far less labour-intensive and economically more efficient.

Width of structure and auxiliary channel
The width of the structure is substantially less than the width of the LTW in the pilot project design due to its slope of 1:1 compared to 1:2.5. The width of the structure at river bottom level is approximately 15 meters. The maximum width of the auxiliary channel (assuming a water level equal to the crest height of the LTW) is 38 meters at the level of the LTW crest.

Constructability
As described earlier, the Xstream elements are easy to handle by crane. They can be placed on the river bottom without filter layer and have a low construction time of around 1 hour per meter length (Buschman et al., 2024). There is only one step in the production process:

1. The Xstream elements are lifted from the hopper of the crane vessel using a grab and carefully placed layer by layer at the designated location.

Although the construction process is easy and fast, it will still result in an obstruction to shipping operations on the IJssel. To reduce navigational hindrance, the construction process can be planned to include scheduled interruptions during which vessel traffic is allowed to pass through the work area.

Management and Maintenance
Since Xstream elements are relatively new, long-term research on the necessary maintenance of structures that are composed of these blocks has not yet been performed. However, the evaluations of the 'Flexible groynes' by Deltares show that maintenance to the groynes is easier compared to traditional groynes. Xstream blocks can be easily added in case of damage to the structure, whereas a traditional groyne requires careful restoration of the (filter) rock layers.
On the necessity of vegetation removal is not enough data available yet, but it is plausible that this should be performed regularly.

Sustainability
Quantifying the sustainability of Xstream longitudinal training walls is performed with the Environmental Indicator Costs. For the flexible groynes project, different cement mixtures were compared. The mixture with the lowest environmental impact while maintaining sufficient properties, was a CEMIII/A mixture. According to Deltares, the environmental costs for this mixture are €14.06 per m^3 (Buschman et al., 2024). It is not known which exact CEMIII/A mixture is used, but the report mentions that for each m^3, 300 kg CEMIII/A was used. In the National Environmental Database, environmental costs vary between roughly 35 and 60 €/m^3, but this applies to mixtures with a density of 2400 kg of cement per m^3. Converted to 300 kg/m^3, the environmental costs would be lower than the €14/m^3 mentioned above. A conservative estimation is made using €14.06/m^3. The cross-sectional area of the longitudinal training wall with Xstream elements is 55 m^2. This means that the total environmental costs per meter length are: €773.30.

Environmental costs for transportation of the Xstream elements from the production plant to the construction site are not included. However, these costs are expected to remain relatively low, as the Xstream elements can be produced at a nearby facility located along the IJssel River, approximately 17 kilometers upstream from the construction site (Buschman et al., 2024, De Meteoor Beton B.V., n.d.).

Ecology
In this paragraph, the answers are given to the questions that were described in Chapter 4:

1. To what extent can organisms grow on the structure?
   Inital results from the pilot project 'Flexible groynes' show that the Xstream elements have primarily been colonized by species that easily attach to hard substrates, this is clearly visible in Figure 6.11. Examples of species that have colonized the Xstream blocks are the Zebra mussel, Fresh water sponge and snails (Buschman et al., 2024).
2. Do the structure and corresponding auxiliary channel create an ecosystem with differences in hydrodynamics such that the conditions for different species improve?
   In the analysis of the permeability of a LTW composed by Xstream elements, the seepage flow was found to be relatively high. This will make it more challenging for species to find shelter within the longitudinal training wall. However, the flow velocities in the LTW are still relatively small to those in the main channel and the second evaluation by Deltares indicates that the voids in the LTW are used as shelters by fish and smaller organisms (Buschman et al., 2024).
3. To what extent does the structure create shelter in the auxiliary channel against the wave conditions in the main channel?
   The auxiliary channel provides shelter against waves in the navigation channel. The relatively high flow velocity through the voids in the wall can cause problems for limnophilic species, but will provide good accommodation for rheophilic fish (Grift et al., 2006).

Figure 6.11: Xstream blocks that were retrieved from a groyne in the pilot project 'Flexible groyne show clearly that species have colonized the elements (Buschman et al., 2024).

6.4.3. Costs

The costs of this alternative are calculated in the same way as in Section 6.1.3. The results can be found in Table 6.11.

Table 6.11: Cost breakdown per meter for the Xstream wall (Source: Haskoning)

Activity	**Unit Cost**	**Cost per meter**
Transport and delivery of Xstream elements	€ 120 / m^3	€ 11,088
Placement of Xstream elements	€ 15 / m^3	€ 1386
Total		**€ 12,474**

In the cost estimation, a volume of 55 m³ per meter length was assumed. Since Xstream elements are a novel concept and are not yet produced by multiple suppliers, estimating their cost is challenging. To provide a preliminary estimate, the unit cost of a concrete block mattress has been doubled.

6.4.4. Summary

A brief summary of the scores per criterion is given in Table 6.12.

Table 6.12: Brief summary of all criteria for the design of the Xstream-based longitudinal training wall

Criterion	Summary	Qualitative Result
Permeability	The Xstream elements have a high porosity, resulting in a relatively high seepage flow velocity.	Seepage flow velocity = 0.297 m/s
Wave reflection	No specific data is available for Xstream blocks; values are based on similar armour units such as Tetrapods.	C_r = 0.193
Flexibility	The LTW has high flexibility, as individual Xstream blocks can be easily replaced.	Not applicable
Width of structure	The 1:1 slope results in a relatively slender structure.	Width at bottom level ≈ 15 m
Width of the auxiliary channel	The auxiliary channel is relatively wide compared to other alternatives.	Maximum width ≈ 38 m
Constructability	Construction using Xstream elements is relatively simple and requires only one main step.	Main construction steps = 1
Management and Maintenance	Xstream elements require minimal maintenance.	Not applicable
Sustainability	Environmental costs are calculated for the use of Xstream elements.	Environmental cost per meter = €773.30
Ecology	The structure supports colonization by hard-substrate species and provides partial shelter, though high seepage flow may limit suitability for some species.	Not applicable
Costs per meter length		€ 12.474

7 Multi-Criteria Analysis

In this chapter, a multi-criteria analysis is performed to come up with the most promising alternative for a longitudinal training wall or multi-channel system in the river IJssel. A sensitivity analysis is added to investigate the impact of weighting factors on the final outcome. In the last part of this chapter, a cost-benefit analysis is performed to make a final design choice that is financially viable.

7.1. Assessment Methods per Criterion and Alternative

Based on Chapter 6, each alternative gets a score per criterion. However, first an overview is given of each assessment method per criterion and alternative. The different nature of the alternatives made it impossible to use only one formula or method per criterion. To take this into account in the multi-criteria decision making, a thorough overview is given in Table 7.1.

Table 7.1: Assessment Methods per Criterion and Alternative

Criterion	Design from Pilot Project	Multi-Channel System	Gabion Wall	Xstream Wall
Permeability	$U_v = KC_U^{-0.26}\sqrt{2geD_{50}i}$	Expert judgement	$U_v = KC_U^{-0.26}\sqrt{2geD_{50}i}$	$U_v = KC_U^{-0.26}\sqrt{2geD_{50}i}$
Wave Reflection	$C_r = c\xi^2/(d+\xi^2)$	Qualitative assessment (expert judgment)	$C_r = c\xi^2/(d+\xi^2)$	$C_r = c\xi^2/(d+\xi^2)$
Flexibility of structure	Available literature	Expert judgment	Expert judgment	Available literature
Width of Structure	Derived from geometry	Based on design guidelines	Derived from geometry	Derived from geometry
Width of Auxiliary Channel	Derived from geometry	Based on design guidelines	Derived from geometry	Derived from geometry
Constructability	Available literature and expert judgment: number of steps in construction process	Expert judgment: number of steps in construction process	Available literature and expert judgment: number of steps in construction process	Available literature and expert judgment: number of steps in construction process
Management and Maintenance	Qualitative: Deltares evaluation document; repair costs quantified	Quantitative: literature and expert judgment	Quantitative: literature and expert judgment	Qualitative: Deltares evaluation document
Sustainability	Environmental cost assessment			
Ecology	Three questions answered based on available literature			
Costs per meter length	€ 14,750	€ 2,018	€ 15,604	€ 12,474

From Table 7.1, it can be concluded that, especially for alternative 1: multi-channel system, it was difficult to quantify the scores on the criteria. The other alternatives and the design of the pilot project are evaluated in a similar way.

7.2. Scores per criterion and alternative

To compare the different alternatives, the scores on the various criteria are discussed one-by-one in this section. As there are 4 alternatives (pilot project design, multi-channel system, gabion wall and Xstream wall), a score between 1 and 4 will be assigned to each alternative, based on the results from Chapter 6). In Table 7.2, an overview is given of the scores for each alternative per criterion. In addition, the weighted scores are added, based on the weight factors from Chapter 4.

Table 7.2: Scores and weighted scores for each alternative per criterion

Criterion	**Weight**	**Pilot project design**		**Multi-channel System**		**Gabion Wall**		**Xstream Wall**	
	Factor	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**
Permeability	1	3	3	4	4	2	2	1	1
Wave reflection	2	3	6	2	4	1	2	4	8
Flexibility	2	3	6	1	2	2	4	4	8
Width of structure	1	1	1	4	4	3	3	2	2
Width of auxiliary channel	3	1	3	3	9	4	12	2	6
Constructability	3	4	12	1	3	1	3	4	12
Management and Maintenance	1	3	3	1	1	2	2	4	4
Sustainability	1	2	2	4	4	1	1	2	2
Ecology	2	3	6	4	8	2	4	2	4
Total		23	42	24	39	18	33	25	47

The following conclusions can be drawn based on Table 7.2:

- The design with an Xstream wall has the highest score with and without weight factor. Based on this multi-criteria analysis, this alternative has the most potential, but a cost-benefit analysis will be required to make a final decision.
- Without weight factors, the difference between the design from the pilot project and the Xstream wall is small. This difference is enlarged by including the weight factors.
- Although the gabion wall is a very slender structure and results in a relatively wide auxiliary channel, its total score is significantly lower than the other alternatives. In combination with the fact that this design is not commonly used in the Netherlands, this leads to the conclusion that this alternative can definitely be ruled out as a viable option.
- The pilot project design also performs relatively well in this MCA. However, its structural width significantly restricts the available space for an auxiliary channel. Maintaining a sufficiently wide channel would require substantial additional excavation, making this alternative likely too complex and impractical to be considered a feasible solution.

7.3. Elaboration of scores

In the following section, a brief explanation is given of the scores per criterion.

7.3.1. Permeability

Table 7.3: (Quantitative) results for permeability

Design from Pilot Project	Multi-Channel System	Gabion Wall	Xstream Wall
Seepage flow velocity = 0.077 m/s	Sand body: seepage flow velocity $\approx$ 0 m/s	Seepage flow velocity = 0.208 m/s	Seepage flow velocity = 0.297 m/s

A low permeability leads to a high score for the permeability criterion. The multi-channel system might introduce some issues with changes in the groundwater flow, but the impact this will have can be minimized by using existing streams in the floodplains. Based on the results that are summarized in Table 7.3, the following scores are assigned:

7.3.2. Wave reflection

Table 7.4: (Quantitative) results for wave reflection

Design from Pilot Project	Multi-Channel System	Gabion Wall	Xstream Wall
Coefficient of reflection C_r = 0.3	No reflection from structure, but cross-currents might have a negative impact on the navigability	Coefficient of reflection C_r = 0.6	No exact information is available, but based on available information from similar protection unit, C_r = 0.2

Although their will be no direct wave reflection from the auxiliary channel in the multi-channel system, the navigability can be negatively impacted by potential cross-currents at the outlet openings. This has led to the choice for a relatively low score for the multi-channel system. The other designs get a score based on their coefficient of reflection (**??**).

7.3.3. Flexibility of structure

Table 7.5: Results for flexibility of structure

Design from Pilot Project	Multi-Channel System	Gabion Wall	Xstream Wall
High flexibility	Low flexibility: changes in geometry are labor intensive and costly	Low flexibility: lower gabions cannot be replaced without moving the upper gabions as well	High flexibility, Xstream elements can be easily repositioned or replaced

Although the pilot project design and Xstream wall both score high on flexibility, the Xstream wall receives the highest score because the shape of the Xstream elements makes it very easy to change the geometry.

7.3.4. Width of structure

Table 7.6: (Quantitative) results for width of structure

Design from Pilot Project	Multi-Channel System	Gabion Wall	Xstream Wall
Width = 30 m	No structure: minimal spatial impact	Width = 4 m	Width = 15 m

Once again, the multi-channel system is different from the other designs, as it has no hydraulic structure in the river. In this case, this means a minimal spatial impact on the river view, resulting in a high score for this criterion. For the other designs, a smaller width of the structure leads to a higher score for this criterion:

7.3.5. Width of auxiliary channel

Table 7.7: (Quantitative) results for width of auxiliary channel

Design from Pilot Project	Multi-Channel System	Gabion Wall	Xstream Wall
Width = 28.5 m: additional excavation is required	Width = 10.38 m	Width = 65 m	Width = 38 m

The width of the auxiliary channel is the widest for a gabion LTW. For the design of the pilot project, additional excavation is required to maintain a flow in the auxiliary channel. The width of the auxiliary channel in the multi-channel system is relatively small, but this is optimized based on the research of van Denderen, 2019. However, because the gabion wall leaves so much space for the auxiliary channel, it gets a higher score than the multi-channel system for this criterion.

7.3.6. Constructability

Table 7.8: (Quantitative) results for constructability

Design from Pilot Project	Multi-Channel System	Gabion Wall	Xstream Wall
1 step in construction process	2 steps in construction process, but legal issues can cause problems	5 steps in construction process	1 step in construction process

The number of steps in the construction process is of course a substantial simplification of the processes that are needed. Site preparation and transport of materials are not included in the overview. The multi-channel system and gabion wall both get a score of 1 for this criterion, as they are both difficult to construct.

7.3.7. Management and Maintenance

Table 7.9: Results for management and maintenance

Design from Pilot Project	Multi-Channel System	Gabion Wall	Xstream Wall
Little maintenance is required, similar to regular groynes. Costs are relatively high	Regular monitoring is required to prevent sedimentation or erosion of the main and auxiliary channels	Little maintenance is required, repair works are costly and labor-intensive	Little maintenance is required

The most detailed information is known for the LTW design that was used in the pilot project in the Waal. For the other alternatives, expert judgment was used in combination with available literature. In **??**, the scores can be found.

7.3.8. Sustainability

Table 7.10: Environmental costs per meter of length for sustainability criterion

Design from Pilot Project	Multi-Channel System	Gabion Wall	Xstream Wall
€ 629.61	€ 28.17	€ 903.20	€ 773.30

Based on the costs per meter length for constructing the different designs, scores are awarded in **??**. Because the difference between the multi-channel system and the other alternatives is so big, no score of 3 is given to any of the alternatives, and both the Xstream wall and pilot project design get a score of 2.

7.3.9. Ecology

Table 7.11: (Qualitative) results for ecology

Design from Pilot Project	Multi-Channel System	Gabion Wall	Xstream Wall
The structure provides shelter against waves from the main channel and organisms can colonize on the natural rock	An ecosystem is created with favorable conditions for many different species	The structure provides shelter against waves from the main channel, but the high seepage flow through the wall limits the positive effects	The structure provides shelter against waves from the main channel, but the high seepage flow through the wall limits the positive effects

The multi-channel provides the best conditions for species to find shelter against the hydrodynamic conditions of the main channel. The positive effects of the gabion wall Xstream wall are limited by their relatively high permeability. Because all alternatives provide some sort of shelter and habitat to species, no alternative will receive a score of 1.

7.3.10. Sensitivity analysis

A sensitivity analysis was performed to investigate the effects of the weighting factors on the result. Three different approaches were used for this analysis:

1. Assign a random value between 1 and 3 to each criterion. Iterate 10,000 times and calculate the percentage that each alternative has the highest score.
2. Randomize the current weighting factors on the criteria. Iterate 10,000 times and calculate the percentage that each alternative has the highest score.
3. Use the weighting factors assigned by the experts to the criteria during the brainstorming session (Table 4.1). Determine the best alternative for each of the 4 configurations.

Based on these three approaches, the following results were obtained. The scripts can be found in appendix

1. The Xstream wall is the best alternative in 63.7 % of the iterations. The multi-channel system is best in 39.2 % and the pilot project design in 4.7 % of the iterations. The gabion wall gets the highest score in 0.0 % of the iterations.
2. The Xstream wall is the best alternative in 65.5 % of the iterations. This is 40.2 % for the multi-channel system, 2.7 % for the pilot project design and 0.0 % for the gabion wall.
3. In Table 7.12, the MCA scores can be found for the different weighting factors. The scores are higher compared to those in Table 7.2 because values between 1 and 9 were used instead of 1-3.

Table 7.12: Total MCA scores, based on the weighting factors that were assigned by the three experts that joined the brainstorming session (Table 4.1.

Experts	Design from pilot Project	Multi-Channel System	Gabion Wall	Xstream Wall
Expert 1	112	108	92	129
Expert 2	116	126	92	120
Expert 3	122	107	89	134
Author	114	122	97	121

7.4. Cost-Benefit analysis

To determine the best alternative, based on the criteria and costs, the final step in the evaluation is a cost-benefit analysis. This is done by dividing the values, which are the results from the MCA, by the costs per alternative. The results can be found in Table 7.13.

Table 7.13: Results of Cost-Benefit Analysis

Alternative	Value (from MCA)	Costs	Value-Cost ratio
Pilot project design	42	€ 14,750	0.0028
Multi-Channel system	39	€ 2,018	0.019
Gabion wall	33	€ 15,604	0.0021
Xstream wall	47	€ 12,474	0.0037

From the value-cost ratios, it can be concluded that the multi-channel system is the best alternative based on the criteria and its costs. This is the result of the significantly lower costs compared to the other alternatives. Although the Xstream wall LTW had the highest score in the Multi-Criteria Analysis, it is only second in the cost-benefit analysis.

8 Morphological impact

In this research, little attention has been given to the morphological impact of the different designs. Although it was chosen to leave this subject out of the main scope of this research, the morphological impact of the designs largely decides whether it is suitable or not as a solution for the degradation of the riverbed in the IJssel river. Therefore, some remarks about the morphology are made in this chapter:

- Morphological changes can often take decades to fully develop. Especially effects on large spatial scales can take large amounts of time (Mosselman et al., 2021). Furthermore, the morphology of a riverbed is influenced by various factors, such as the sediment supply and width of a river but also the occurrence of flood events. This indicates that, for the new designs in this research, laboratory tests should ideally be combined with in situ tests to monitor the response of the river to new implementations.
- The evaluation of the pilot project with longitudinal training walls in the Waal river shows that sedimentation occurs at the upstream end of the longitudinal walls, with on average a riverbed height increase of 10 cm’s. However, flood events disturb this trend and the problem of riverbed erosion is not fully solved by the LTWs according to Deltares (Mosselman et al., 2021). This indicates that implementation of longitudinal walls should always be combined with other measures, such as sediment nourishment projects. Other research also shows that combining LTWs with lowering of groynes can be effective in limiting river bed erosion (ten Brink, 2024. Changing the discharge distribution in the Rhine branches is also mentioned as one of the measures to limit bed erosion.
- Research shows that a bifurcation that is formed by a longitudinal training wall is inherently unstable (Le et al., 2018). This research also shows that if the starting location of the longitudinal training wall is optimized, the change in morphology will be slow and takes years. Especially if the width of the two channels (main and auxiliary) is more or less the same, channel maintenance can be minimized.

  For this research, slender designs that leave more space for the auxiliary channel in the river cross section will therefore possibly cause a system in which morphological changes are slow and manageable. The Xstream and gabion wall designs will potentially lead to a system that requires less morphological maintenance than the design with a wide rubble mound design.
- For the design of the multi-channel system, the research from Van Denderen (2019) was used to give dimensions to the auxiliary channel. However, in practice, auxiliary channels that flow through the floodplains are generally much wider, according to an expert at Haskoning. This is done to limit the aggregation of sediment in the auxiliary channel. Therefore, further research into the optimal dimensions of the auxiliary channel is required to limit the necessary maintenance.

9 Discussion

The results of the research are discussed in this chapter. During the research, assumptions were made to simplify the process. In addition, limitations apply to methods and data that were used. This chapter aims to address these and discusses the applicability of this research to other river sections.

9.1. Width of main channel

For the width of the main channel, the current Dutch guideline is applied, which states that the navigation channel in the IJssel should be at least 40 meters wide under OLR conditions. This width is used as a minimum requirement for the alternatives. However, this 40-meter width represents an absolute minimum. While it may be theoretically sufficient for vessels to pass each other, it is likely to cause practical difficulties, especially in curved sections of the river where a longitudinal training wall is applied. This concern is supported by the evaluation of the pilot project with longitudinal training walls in the Waal, where ship operators reported the wall felt uncomfortably close and obstructive. Therefore, it is essential to assess whether this minimum width is truly sufficient, in consultation with the navigation sector.

9.2. Criteria

The choice of criteria has had a major impact on the final design choice. The criteria were selected based on reference projects and consultations with experts at Haskoning. Although the criteria give a broad view of the advantages and disadvantages of the alternatives, the choice for criteria remains subjective. Adding a weighting factor to the criteria even increases this subjectivity, which was also visible in the different weights that were assigned by the Haskoning experts to the criteria.

However, subjectivity will remain an intrinsic part of design processes. The preferences of the client and designer will significantly impact the outcome of such a process. During this research, experts with different backgrounds were consulted to generalize the process. One expert assigned more weight to *Sustainability* and *Ecology*, whereas another professional focused on the structural criteria *Permeability* and *Wave reflection*. During a design process for a structure, it will always remain important to thoroughly discuss the preferences of a client, as this will have a major impact on the outcome.

9.3. Multi-channel system

Due to its inherently different nature compared to the other alternatives, evaluating the multi-channel system proved to be complex. In particular, morphological aspects, being outside the direct scope of this research, need to be taken into account in further research. Although the research of van Denderen, 2019, gave useful insights to determine the basic geometry of the auxiliary channel, the effects of local conditions need further research. In addition, the impact of cross-currents at the auxiliary channel outlets should be further investigated and mitigated to minimize potential disruption to navigation.

Currently, the alternative with a multi-channel system scores low on the criteria *flexibility*, *constructability* and *management and maintenance*. However, it is important to note that these scores are based on current policy and land-use regulations. If future policy were to shift —towards more nature-based or adaptive river management strategies— the multi-channel concept could score significantly higher on several criteria. The Dutch Room for the River 2 programme (Ruimte voor de Rivier 2) has already laid the groundwork for such a shift, by prioritizing spatial solutions that combine flood safety with ecological and spatial quality. In that context, the multi-channel system could become more favorable in future multi-criteria analyses, especially when long-term ecological and hydro-morphological benefits are taken into account.

9.4. Verification of alternatives

During the verification and scoring of alternatives, simplifications were made, making it possible to give a broad comparison between 4 different alternatives. Key points that need consideration are mentioned below:

- Several calculations were only performed for extreme scenarios, such as permeability and stability, resulting in a conservative and potentially costly design. A full probabilistic analysis could be used to gain insight into the structure's behavior under regular conditions. Calculating the failure probability can support design optimization by helping to find a balance between acceptable risk and costs.
- The model used to estimate discharge capacity is a fast and practical method that compares upstream water levels with and without a structure, given a downstream water level. It provides a good indication of relative differences in water levels and thus discharge capacity. However, the model lacks complexity: for example, it assumes a single cross-section for the entire stretch over which the water level difference is calculated. While this approach is useful for comparing alternatives, a more detailed model is needed to accurately assess other effects. A more advanced model could incorporate spatial variability and provide a better understanding of local flow dynamics.

  In addition, the assumption was made for this model that no water can flow through the longitudinal walls. In reality, water can flow between the main and auxiliary channel in case of a relatively slender and porous wall, such as the gabion and Xstream wall. However, to realize a higher water level in the main channel than in the auxiliary channel during low discharge events to improve the navigability of the river, no water should be able to flow through the walls. Therefore, instead of changing the model, the designs should be improved so that the walls are less permeable.
- The formula proposed by Martins and Escarameia (1989) for estimating average seepage flow velocity is particularly suited for rubble mound structures, making it applicable to the pilot project and gabion-based alternatives. However, it was also used to estimate flow through the Xstream element wall, where the smallest element width was taken as the D_{50}. Given the regular and uniform shape of these elements, this assumption may not be appropriate. Ongoing research by Deltares aims to better quantify flow velocities through these elements and improve the accuracy of such estimations.

9.5. Dimensions of inlet openings and morphology

In this study, no specific attention has been given to the design of inlet openings, inter-wall notches, or outlet openings of the longitudinal training walls. However, these features significantly influence the volume and velocity of water entering the auxiliary channel and are therefore important design aspects that should be addressed in future research.

9.6. Best scoring alternative

In the Multi-Criteria Analysis, the Xstream wall LTW was the best scoring alternative with a score of 47, followed by the pilot project design (42) and the multi-channel system (39). However, the costs of the multi-channel system are estimated to be significantly lower than the costs of the other alternatives. In the cost-benefit analysis, this resulted in a much better value-cost ratio for the multi-channel system than the Xstream wall LTW and the other alternatives. So, based on these analyses, the multi-channel system is the best scoring alternative for this research.

However, several important nuances must be considered. Firstly, as previously mentioned, comparing the multi-channel system with the other alternatives proved to be complex. This raises the question of whether the conclusion that it is the most suitable option can be drawn solely from the steps taken in this research. Secondly, there is currently no concrete information available regarding the costs of the Xstream elements, as they are still in a pilot phase and only one supplier exists at this time. A presumably conservative cost estimate was made by doubling the price of a concrete block mattress. In practice, however, these costs could be lower if the Xstream elements are mass-produced and become more widely available. In summary, although the multi-channel system emerged as the most favorable alternative based on the cost-benefit analysis, the Xstream element LTW remains a promising solution and should not yet be ruled out.

9.7. Applicability in other river sections

This research aimed to develop a design that is not only suitable for the relatively straight section of the IJssel between Doesburg and Zutphen, but also potentially applicable to other stretches of the river. By including the criterion of flexibility, the selected alternative is designed to be easily constructed in various locations and adaptable to local conditions. Additionally, specific attention was given to minimizing the spatial impact on the navigation channel, which is particularly relevant given the limited available space in the IJssel.

Nevertheless, each location along the river presents unique challenges. In more curved sections, flow patterns may develop that negatively affect both navigation and riverbed stability. In addition, enough space needs to be available for the multi-channel system to construct an auxiliary channel. Therefore, while the proposed design offers a starting point, it cannot be directly applied elsewhere without modification. Site-specific adjustments will be necessary, and the feasibility of implementation should be assessed in close collaboration with the navigation sector.

10 Conclusion and Recommendations

This chapter provides answers to the research question and gives recommendations for further research.

10.1. Conclusion

The research question of this design research is: ”What is the optimal design for a longitudinal wall in the IJssel river to enhance flood safety, mitigate bed erosion, and maintain navigability”. To answer this question, three subquestions were answered first, these answers can be found below. The subquestions focus on (1) the requirements and criteria that form a basis of design, (2) the advantages and disadvantages of the pilot project design and (3) how the pilot project design and three alternative designs compare based on the criteria.

A Multi-Criteria Analysis (MCA) and a Cost-Benefit Analysis (CBA) were conducted to address the main research question. The design incorporating Xstream elements achieved the highest scores across the defined evaluation criteria, indicating strong performance in terms of ecological value, constructability, and technical feasibility.

However, the multi-channel system demonstrated significantly low implementation costs, primarily due to the minimal material requirements and the fact that most expenses are related to excavation. As a result, despite its lower ranking in the MCA, the multi-channel system emerged as the optimal alternative in the Cost-Benefit Analysis.

This conclusion is worked out further in the answers to the subquestions, as defined in Chapter 1.

10.1.1. Answering of subquestions

The first subquestion reads: ”What are the relevant criteria and boundary conditions for the location, dimensions and materials for the structures in the IJssel river and how can they be quantified? To answer this question, the area of interest was first analyzed to understand local conditions and their implications for potential designs. One of the key findings is the limited spatial availability in the IJssel. The average river width between the banks ranges from only 95 to 110 meters. This constraint is further emphasized by the relatively short groynes currently in place—shorter than those in the Waal—to avoid obstructing navigation.

The primary functions of the river—flood safety, navigation, and ecology—must be preserved, and the design criteria and boundary conditions should be aligned with these functions. The requirement for a minimum navigation channel width of 40 meters under OLR conditions is based on these considerations and forms a key constraint in the design process. Additionally, the criteria concerning the *width of the structure* and the *width of the auxiliary channel* are specifically aimed at minimizing spatial impact while still achieving a positive effect on bed erosion. Although the selected design aims to be *flexible and adaptable*, these spatial limitations highlight the importance of tailoring the design to local conditions. Since this research focuses on developing a structurally sound design, structural stability was included as one of the key design requirements. This requirement largely determines the dimensions of the proposed alternatives. In addition, the alternatives were designed to minimize their impact on the river’s discharge capacity, ensuring that flood safety is not compromised.

The remaining criteria were selected based on the primary functions of a river and also on potentially changing local conditions. To minimize disruption to navigation, the *permeability of the body* should be as low as possible. This ensures that during low discharge conditions, only a limited amount of water flows into the auxiliary channel, thereby slightly increasing the water depth in the main channel. Additionally, *wave reflection* should be kept to a minimum to reduce the reflection of ship-induced waves, which could otherwise lead to unsafe situations for vessels navigating near the structure. The criteria *sustainability* and *ecology* ensure that the final design not only minimizes environmental impact, but also actively contributes to enhancing the natural environment and local ecology. Finally, the criteria constructability and management and maintenance ensure that the design can be effectively implemented in practice, while also minimizing the risk of issues arising in the short or long term due to high maintenance costs. These criteria help guarantee that the solution is both technically feasible and economically viable throughout its lifecycle.

The second subquestion is: ”What are the advantages and disadvantages of the current design approach for longitudinal walls, as applied in the pilot project near Tiel, when considered in the context of the IJssel River?

The primary advantage of the design approach applied in the pilot project near Tiel lies in its proven effectiveness. This design has previously been implemented along the Waal River, where it successfully mitigated bed erosion and contributed to a slight increase in water levels in the main channel during periods of low discharge. This empirical evidence supports its potential applicability in similar river systems, such as the IJssel.

Moreover, the use of natural rock as the primary construction material offers practical benefits. Natural rock is a commonly used material in Dutch hydraulic engineering, which means that extensive additional research or testing is unlikely to be required for its application elsewhere. This enhances the feasibility of scaling the design to other locations. Additionally, the design scores relatively high on other evaluation criteria, including *permeability*, *wave reflection*, *flexibility*, *management and maintenance*, and *ecology*.

However, the design also presents notable disadvantages. The most significant drawback is its spatial footprint. Due to the 1:2.5 slope on both sides, the structure reaches a width of over 30 meters at the riverbed for a height of approximately 6 meters. Given that the legally required minimum width of the navigation channel is 40 meters, this leaves limited space for the secondary channel. Research indicates that wider secondary channels tend to perform better in terms of ecological and hydraulic functioning (Czapiga et al., 2022), which may be compromised by this design.

Finally, the environmental costs associated with this design are relatively high. Natural rock for armour stones is often not locally available in the Netherlands and must be imported from abroad, resulting in significant transportation-related emissions and resource use. This reduces the overall sustainability of the solution, particularly when compared to alternatives that utilize locally sourced or more environmentally friendly materials.

The final subquestion is: ”Which alternative construction materials can be used for longitudinal walls, and how do they compare based on the criteria defined in the first sub-question?”

To explore alternative construction materials for longitudinal walls, a brainstorming session was organized with experts in the field. This session led to the identification of three promising alternatives:

- A multi-channel system with one secondary channel in the floodplain
- A longitudinal dam constructed with gabions
- A longitudinal dam composed of Xstream elements

Each of these alternatives was evaluated using the same set of criteria applied to the pilot project design. A multi-criteria analysis (MCA) was then conducted to compare their performance.

The gabion-based design performed the worst in the MCA. Its low scores were primarily due to poor performance on criteria related to navigational safety, such as permeability and wave reflection. Additionally, gabions are rarely used in Dutch hydraulic engineering, and their implementation poses practical challenges, making this alternative less feasible.

The Xstream element design emerged as the most promising alternative in the MCA. It scored highly across most criteria, but a solution will need to be found for the problem with its porosity: the quantity of water that can flow from the main to the auxiliary channel and vice versa is too high and makes it impossible to set up any water level differences between the channels. Positive about this design is that the Xstream elements are easy to install and interlock, allowing for a steep slope of 1:1, which significantly reduces the spatial footprint. However, it is important to note that the Xstream concept is still in its early stages and has only been applied in a pilot project involving flexible groynes. As such, detailed information on long-term performance and costs is still limited.

The multi-channel system ranked third in the MCA and appears less promising based on the defined criteria. Its main drawbacks include high expected maintenance costs due to the risk of sedimentation in the secondary channel, and limited flexibility compared to the other alternatives. Nevertheless, the cost-benefit analysis revealed that the multi-channel system is the most cost-effective option. This is primarily because it requires minimal construction materials, with most costs associated with excavation. As a result, despite its lower MCA ranking, the multi-channel system achieved the highest score in the cost-benefit analysis.

10.2. Recommendations

Although this study has identified the most promising design alternatives based on structural criteria and a cost-benefit analysis, several important aspects remain outside the scope and warrant further investigation:

1. **Morphological Impact**
   Further research is needed to assess the morphological impact of the proposed alternatives. This study focused primarily on structural performance and evaluation criteria, but did not include detailed analysis of morphological effects. In particular, the multi-channel system requires additional investigation to understand the potential for sedimentation in the auxiliary channel. Over time, such sedimentation could lead to increased maintenance costs, which may ultimately affect the long-term viability and cost-effectiveness of this alternative.
2. **Gabion wall and Xstream wall**
   Both the gabion wall design and the Xstream wall design require more research. In this preliminary research, both designs score low in the cost-benefit analysis, due to various reasons. For the gabion wall, improvements should be made to the construction process and the porosity. Research is required to make the construction process more efficient. Solutions for the porosity problem might include filling the gabion walls with sand or other material or using a membrane. The same can be done for the Xstream wall design. Another possible measure to make the design less expensive and more environmentally friendly could be the use of Xstones, a smaller version of the Xstream elements that is 2-dimensional instead of 3-dimensional (HOLCIM Nederland, n.d.).
3. **Cost Estimation of Xstream Elements**
   The cost estimate for the Xstream element design in this study was based on an assumption using a comparable material—concrete block mattresses. However, this provides only a rough indication. A more accurate and detailed cost assessment is necessary to properly evaluate this alternative. Additionally, it is recommended to explore the potential for mass production and sustainable manufacturing of Xstream elements, which could significantly reduce both production and environmental costs. This Xstone has a 2D shape, which makes the construction process easier compared to the 3D shape of the Xstream blocks.
4. **Comprehensive Cost Analysis**
   The current cost-benefit analysis considered only construction costs, excluding investment costs and potential long-term economic benefits. For example, reduced flood risk could lead to avoided damages, which would positively influence the overall cost-effectiveness of certain alternatives. Therefore, a more comprehensive economic analysis is recommended, incorporating both direct and indirect costs and benefits over the full lifecycle of the design.

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A Calculation of wave loads and stability

In this chapter, the formulas and calculations for the wave loads that act on the longitudinal training wall are presented. The approach as described in the Rock Manual, sections 4.3.4.1 and 4.3.4.2 is followed (CIRIA, CUR, CETMEF, 2007). In the first section of this appendix, the formulas are presented. In the second section, the calculations for the parameters of this research are worked out.

For the stability equations from the third section, the approach as used in chapter 9 of 'Introduction to Bed, bank and shore protection' has been applied (Schiereck and Verhagen, 2012).

A.1. Ship waves formulas

As described in (CIRIA, CUR, CETMEF, 2007), ship waves can be divided into primary and secondary waves. Technically, the propeller wash should also be considered, however, this is only from interest in situations where ships are berthing. Since the longitudinal training wall is not a berthing place or jetty, only primary and secondary waves are assessed for this situation.

A.1.1. Vessel's submerged cross-section

The vessel's submerged cross-section, A_m (m^2), can be calculated as follows:

$$A_m = C_m B_s T_s \tag{A.1}$$

$C_m =$ midship coefficient related to the cross-section of the ship (-), between 0.9 and 1.0 for inland vessels
$B_s =$ beam width of the ship (m)
$T_s =$ draught of the ship (m)

A.1.2. Limit speed and actual speed

The limit speed of the vessel, V_L (m/s) =

$$V_L = F_L \sqrt{g A_c / b_w} \tag{A.2}$$

$F_L = [\frac{2}{3}(1 - \frac{A_m}{A_c} + 0.5F_L^2)]^{\frac{2}{3}}$
$A_c =$ cross-sectional area of the waterway (m^2)
$b_w = b_b + (2 \cdot slope \cdot h)$: width of the fairway at the waterline (m)
$g = 9.81$ m/s^2: gravitational acceleration

However, the limit speed of the vessel should not be higher than:

$$V_L = (g L_s / 2\pi)^{1/2} \tag{A.3}$$

$L_s =$ ship length (m)

$$V_L = (gh)^{1/2} \tag{A.4}$$

$h =$ water depth of fairway (m)

Now, the actual speed of the vessel, V_s (m/s) can be calculated as a factor of the limit speed:

$$V_s = f_v V_L \tag{A.5}$$

$f_v = 0.9$ for unloaded ships and 0.75 for loaded ships

A.1.3. Primary waves

A primary wave consists of a water level depression, Δh, a front wave, Δh_f, and a stern wave with height z_{max}.

Mean water level depression, Δh and return flow velocity, U_r

The mean water level depression, Δh (m), is calculated in the following way:

$$\Delta h = \frac{V_s^2}{2g}[\alpha_s(A_c/A_c^*)^2 - 1] \tag{A.6}$$

$\alpha_s = 1.4 - 0.4V_s/V_L$: factor to express the effect of the sailing speed V_s relative to its maximum (-)
$A_c^* = b_b(h - \Delta h) + cot\alpha(h - \Delta h)^2 - A_m$: cross-sectional area of the fairway next to the ship (m^2)
$A_c = b_b h + h^2 cot\alpha$: cross-sectional area of the fairway in the undisturbed situation (m^2)
$b_b =$ width of fairway at the bed (m)
$\alpha =$ slope angle of the bank (-)

The corresponding return flow velocity, U_r (m/s) =

$$U_r = V_s(A_c/A_c^* - 1) \tag{A.7}$$

Maximum water level depression, $\Delta\hat{h}$ and return flow, $\hat{U}_r$

The maximum water level depression, $\Delta\hat{h}$ (m/s):

$$\Delta\hat{h}/\Delta h = \begin{cases} 1 + 2A_w^* & \text{for } b_w/L_s < 1.5 \\ 1 + 4A_w^* & \text{for } b_w/L_s \geq 1.5 \end{cases} \tag{A.8}$$

$A_w^* = yh/A_c$ (-)
$y =$ ship position, relative to the fairway axis (m)

The maximum return velocity:

$$\hat{U}_r/U_r = \begin{cases} 1 + A_w^* & \text{for } b_w/L_s < 1.5 \\ 1 + 3A_w^* & \text{for } b_w/L_s \geq 1.5 \end{cases} \tag{A.9}$$

According to the Rock Manual, for ratios of $b_w/B_s > 10$, flow conditions are two-dimensional, which practically means that there is no simple design formula for the maximum return flow, $\hat{U}_r$.

Front wave height, Δh_f and steepness, i_f

The front wave height and steepness can be calculated with the following formula:

$$\Delta h_f = 0.1\Delta h + \Delta\hat{h} \tag{A.10}$$

$$i_f = 0.03\Delta h_f \tag{A.11}$$

Stern wave height, z_{max}, steepness, i_{max} and velocity, u_{max}

The stern wave height, steepness and velocity are calculated by the following formulas:

$$z_{max} = 1.5\Delta\hat{h} \tag{A.12}$$

$$i_{max} = (z_{max}/z_0)^2,\ with : i_{max} < 0.15 \tag{A.13}$$

$z_0 = 0.16y_s - c_2$
$y_s = 0.5b_w - B_s - y$: ship position, relative to the bank (m)
$c_2 = 0.2$ to 2.6

$$u_{max} = V_s(1 - \Delta D_{50}/z_{max}) \tag{A.14}$$

$D_{50} =$ roughness of the bed (m)
$\Delta =$ relevant buoyant density of the material (-)

A.1.4. Secondary waves

The wave height, length and period of secondary waves are calculated with the following formulas:

$$H_i = 1.2\alpha_i h(y_s/h)^{-1/3} V_s^4/(gh)^2 \quad \text{(A.15)}$$

$$L_i = 4.2V_s^2/g \quad \text{(A.16)}$$

$$T_i = 5.1V_s/g \quad \text{(A.17)}$$

α_i = coefficient depending on the type of ship. For a loaded conventional ship, α_i = 1

A.2. Calculation of ship wave loads

In this section, the steps from the previous section are followed, using the parameters corresponding to the IJssel. First, a water depth of 8 meters is used to show the calculations. At the end of this section, a table is included with the results for different values of h. This is done because the design water depth corresponds to the height of the longitudinal training wall.

A.2.1. Vessel's submerged cross-section

For the IJssel, the design ship is a CEMT class Va vessel:
$C_m =$ 1.0
$B_s =$ 12.0 m
$T_s =$ 3.5 m
$L_s = 110$ m

$$A_m = C_m B_s T_s = 1.0 \cdot 12.0 \cdot 3.5 = 37.8\ m^2 \quad \text{(A.18)}$$

A.2.2. Limit speed and actual speed

$h = 8\ m$
$slope = 6.3\ [-]$
$b_b = 75\ m$
$b_w = b_b + (2 \cdot slope \cdot h) = 75 + (2 \cdot 6.3 \cdot 8) = 175.8\ m$ $A_c = ((h \cdot slope) + b_b) \cdot h) = ((8 \cdot 6.3) + 75) \cdot 8 = 1003\ m^2$

Using an iterative calculation process, the following values were found:
$F_L = 0.77$

$$V_L = F_L\sqrt{gA_c/b_w} = 0.77\sqrt{9.81 \cdot 1003/175.8} = 5.73\ m/s \quad \text{(A.19)}$$

The limit speed should not be higher than:

$$V_L = (gL_s/2\pi)^{1/2} = (9.81 \cdot 110/2\pi)^{1/2} = 13.1\ m/s \quad \text{(A.20)}$$

$$V_L = \sqrt{gh} = \sqrt{9.81 \cdot 8} = 8.9\ m/s \quad \text{(A.21)}$$

So, the minimum value for $V_L =$ 5.73 m/s.

The actual speed is then:

$$V_s = V_L f_v = 5.73 \cdot 0.75 = 4.30\ m/s \quad \text{(A.22)}$$

A.2.3. Primary waves

Mean water level depression, Δh and return flow velocity, U_r
$\alpha_s = 1.4 - 0.4V_s/V_L = 1.4 - 0.4 \cdot 5.73/4.30 = 1.1$

Again, an iterative process was followed to find the following values:
$A_c^* = 910.6\ m^2$

$$\Delta h = \frac{V_s^4}{2g}[\alpha_s(A_c/A_c^*)^2 - 1] = \frac{4.30^4}{2 \cdot 9.81}[1.1 \cdot (1003/910.6)^2 - 1] = 0.32\ m \quad \text{(A.23)}$$

$$U_r = V_s(A_c/A_c^* - 1) = 4.30 \cdot (1003/910.6 - 1) = 0.44\ m/s \quad \text{(A.24)}$$

Maximum water level depression, $\Delta\hat{h}$ and return flow, $\hat{U}_r$
$y = 6.25\ m$
$A_w^* = yh/A_c = 6.25 \cdot 8/1003 = 0.050$
$b_w/L_s = 1.6$:

$$\Delta\hat{h} = \Delta h(1 + 4A_w^*) = 0.32 \cdot (1 + 4 \cdot 0.050) = 0.38\ m \tag{A.25}$$
$$\hat{U}_r = U_r(1 + 3 \cdot A_w^*) = 0.44 \cdot (1 + 3 \cdot 0.050) = 0.50\ m/s \tag{A.26}$$

However, this last formula is only indicative, as the value of $b_w/B_s = 14.65$, which is bigger than 10, meaning that 2D flow conditions play a role.

Front wave height, Δh_f and steepness, i_f

$$\Delta h_f = 0.1\Delta h + \Delta\hat{h} = 0.1 \cdot 0.32 + 0.38 = 0.41\ m \tag{A.27}$$
$$i_f = 0.03\Delta h_f = 0.03 \cdot 0.41 = 0.0123 \tag{A.28}$$

Stern wave height, z_{max}, steepness, i_{max} and velocity, u_{max}
$y_s = 0.5b_w - B_s - y = 0.5 \cdot 175.8 - 12 - 6.25 = 69.7\ m$
$c_2 = 1.0$
$z_0 = 0.16y_s - c_2 = 0.16 \cdot 69.7 - 1 = 10.14$
$\Delta = \frac{\rho_s - \rho_w}{\rho_w} = \frac{2650-1000}{1000} = 1.65$
$D_{50} = 0.002\ m$ (based on coarse sand)

$$z_{max} = 1.5\Delta\hat{h} = 1.5 \cdot 0.38 = 0.57\ m \tag{A.29}$$
$$i_{max} = (z_{max}/z_0)^2 = (0.57/10.15)^2 = 0.0031\ [-] \tag{A.30}$$
$$u_{max} = V_s(1 - \Delta D_{50}/z_{max}) = 4.30 \cdot (1 - 1.65 \cdot 0.002/0.57) = 4.27\ m/s \tag{A.31}$$

A.2.4. Secondary waves

$\alpha_i = 1$

$$H_i = 1.2\alpha_i h(y_s/h)^{-1/3}V_s^4/(gh)^2 = 1.2 \cdot 1 \cdot 8 \cdot (69.7/8)^{-1/3} \cdot 4.30^4/(9.81/8)^2 = 0.26\ m \tag{A.32}$$
$$L_i = 4.2V_s^2/g = 4.2 \cdot 4.30^2/9.81 = 7.91\ m \tag{A.33}$$
$$T_i = 5.1V_s/g = 5.1 \cdot 4.30/9.81 = 2.23\ s \tag{A.34}$$

A.2.5. Results for different values for the water depth, h

Table A.1: Ship wave parameters for different water depths

h **(m)**	**4.5**	**5**	**5.5**	**6**	**6.5**	**7**	**7.5**	**8**	**8.5**	**9**	**9.5**
V_L **(m/s)**	3.88	4.19	4.48	4.75	5.01	5.26	5.50	5.73	5.95	6.16	6.37
V_s **(m/s)**	2.91	3.14	3.36	3.57	3.76	3.95	4.13	4.30	4.46	4.62	4.77
Δh **(m)**	0.21	0.23	0.24	0.26	0.27	0.29	0.30	0.32	0.33	0.35	0.36
U_r **(m/s)**	0.47	0.47	0.46	0.45	0.45	0.44	0.44	0.44	0.44	0.44	0.44
$\Delta\hat{h}$ **(m)**	0.24	0.25	0.27	0.28	0.30	0.32	0.36	0.38	0.39	0.41	0.43
$\hat{U}_r$ **(m/s)**	0.50	0.49	0.48	0.48	0.47	0.47	0.51	0.50	0.50	0.50	0.50
Δh_f **(m)**	0.26	0.28	0.29	0.31	0.33	0.34	0.39	0.41	0.43	0.45	0.46
i_f **(-)**	0.0077	0.0083	0.088	0.0093	0.0098	0.0103	0.0118	0.0123	0.0128	0.0134	0.0139
z_{max} **(m)**	0.35	0.38	0.40	0.43	0.45	0.47	0.54	0.57	0.59	0.62	0.64
i_{max} **(-)**	0.0029	0.0028	0.0028	0.0028	0.0027	0.0027	0.0032	0.0031	0.0031	0.0030	0.0030
u_{max} **(m/s)**	2.88	3.11	3.33	3.54	3.73	3.92	4.10	4.27	4.44	4.60	4.75
H_i **(m)**	0.09	0.11	0.13	0.16	0.18	0.21	0.23	0.26	0.28	0.31	0.34
L_i **(m)**	3.62	4.22	4.83	5.44	6.06	6.67	7.29	7.91	8.52	9.14	9.76
T_i **(s)**	1.51	1.63	1.75	1.85	1.96	2.05	2.14	2.23	2.32	2.40	2.48

A.3. Stability

The stability of a Longitudinal Training Wall will be calculated using the approach of Schiereck and Verhagen, 2012, which gives design formulas for river banks, based on the approaches of Izbash and Hudson.

A.3.1. Primary waves

Stability for primary waves is based on the maximum return flow velocity $\hat{U}_r$ and on the stern wave height z_{max}.

Return flow velocity stability

For the stability against the return flow velocity, the following formula is used:

$$\Delta d_{n50} = 0.47\frac{(U_r(1+3r))^2}{2gK_s} \quad \text{(A.35)}$$

$\Delta = \frac{\rho_s - \rho_w}{\rho_w} = \frac{2650-1000}{1000} = 1.65$
d_{n50}: median nominal diameter $= (m_{50}/_s)^{1/3}$ (m)
$U_r = \hat{U}_r$: design return flow velocity (m/s)
$r = 0.2$
$\alpha = \arctan 1/2.5 = 0.38$: angle of the slope
$\phi \approx \arctan 1 = 0.79$. (For rocks, $tan(\phi)$ is roughly equal to 1).
$K_s = \sqrt{1 - \frac{\sin^2\alpha}{\sin^2\phi}} = \sqrt{1 - \frac{\sin^2 0.38}{\sin^2 0.79}} = 0.85$

Stern wave stability

For stability in the stern wave, the following formula is used:

$$\frac{z_{max}}{\Delta d_{n50}} = 1.8\cot\alpha^{0.33} \quad \text{(A.36)}$$

$\cot\alpha = 2.5$: slope of the LTW

A.3.2. Secondary waves

For secondary ship waves, the following formula is used:

$$\frac{H\sqrt{\cos 55°}}{\Delta d_{n50}} = c_{2nd}\xi^{-0.5} \quad \text{(A.37)}$$

$c_{2nd} = 1.6(\cot\alpha)^{0.33}$
$\xi = \frac{\tan\alpha}{\sqrt{H/L_0}}$: Irribarren number or breaker parameter
H: wave height of secondary wave
$L_0 = \frac{gT^2}{2\pi}$: wave length of secondary wave
T: wave period of secondary wave

A.4. Stability calculation for case: Pilot project design

In this section, the stability calculations that correspond to the design of the pilot project in the Waal river are provided. The water depth that is used for these calculations is 5.5 m. Parameters that are used can be found in **??** and Table A.1.

A.4.1. Primary waves

Return flow velocity stability

$U_r = \hat{U}_r = 0.48$ (m/s)

$$d_{n50} = 0.47\frac{(U_r(1+3r))^2}{2gK_s\Delta} = 0.47 \cdot \frac{(0.48(1+3\cdot 0.2))^2}{2\cdot 9.81\cdot 0.85\cdot 1.65} = 0.010\ m \quad \text{(A.38)}$$

Stern wave stability
$z_{max} = 0.40$ (m)
$\cot\alpha = 2.5$ (-)

$$d_{n50} = \frac{z_{max}}{1.8\cot\alpha^{0.33}\Delta} = \frac{0.40}{1.8\cdot 2.5^{0.33}\cdot 1.65} = 0.10\ m \tag{A.39}$$

A.4.2. Secondary waves

$H = 0.13$ (m)
$c_{2nd} = 1.6(\cot\alpha)^{0.33} = 1.6 * 2.5^{0.33} = 2.165(-)$
$L_0 = \frac{gT^2}{2\pi} = \frac{9.81\cdot 1.75^2}{2\pi} = 4.782$ (m)
$\xi = \frac{\tan\alpha}{\sqrt{H/L_0}} = \frac{\tan 0.38}{\sqrt{0.13/4.782}} = 2.42$ (-)

$$d_{n50} = \frac{H\sqrt{\cos 55°}}{\Delta c_{2nd}\xi^{-0.5}} = \frac{\sqrt{0.13\cdot cos 55°}}{1.65\cdot 2.165\cdot 2.42^{-0.5}} = 0.12\ m \tag{A.40}$$

A.4.3. Predominant d_{n50} and corresponding rock class

The biggest d_{n50} results from the secondary waves: 0.12 m. The rubble mound that is used should thus be at least 5-40 kg (*EN 13383-1*, 2002).

B
Criteria

In this appendix, the tables with relative scores between the criteria are presented. The tables need to be read from left to right. To give an example: if the criterion 1. Permeability is considered less important than Wave reflection, a score of 0 is given in the first green box. To avoid situations in which a criterion gets a weighting factor of 0, the weighting factor, which is the last column of each table, is equal to the sum of each row + 1.

Table B.1: Weighting of criteria according to Expert 1, Haskoning

		Permeability	Wave reflection	Flexibility	Width of structure	Width of auxiliary channel	Management and Maintenance	Sustainability	Ecology	Constructability	sum	weighting factor
1	Permeability		0	0	0	0	0	1	1	0	2	3
2	Wave reflection	1		1	1	0	0	1	1	1	6	7
3	Flexibility	1	0		1	0	1	1	1	1	6	7
4	Width of structure	1	0	0		0	0	1	0	0	2	3
5	Width of auxiliary channel	1	1	1	1		1	1	1	1	8	9
6	Management and Maintenance	1	1	0	1	0		1	1	1	6	7
7	Sustainability	0	0	0	0	0	0		0	0	0	1
8	Ecology	0	0	0	1	0	0	1		0	2	3
9	Constructability	1	0	0	1	0	0	1	1	1	1	4

Table B.2: Weighting of criteria according to Expert 2, Haskoning

		Permeability	Wave reflection	Flexibility	Width of structure	Width of auxiliary channel	Management and Maintenance	Sustainability	Ecology	Constructability	sum	weighting factor
1	Permeability		1	0	0	0	0	1	1	0	3	4
2	Wave reflection	0		0	0	0	0	1	1	0	2	3
3	Flexibility	1	1		0	0	0	1	0	0	3	4
4	Width of structure	1	1	1		1	0	1	0	0	5	6
5	Width of auxiliary channel	1	1	1	0		0	1	1	0	5	6
6	Management and Maintenance	1	1	1	1	1		1	1	1	8	9
7	Sustainability	0	0	0	0	0	0		0	0	0	1
8	Ecology	0	0	1	1	0	0	1		0	3	4
9	Constructability	1	1	1	1	1	0	1	1		7	8

Table B.3: Weighting of criteria according to Expert 3, Haskoning

		Permeability	Wave reflection	Flexibility	Width of structure	Width of auxiliary channel	Management and Maintenance	Sustainability	Ecology	Constructability	sum	weighting factor
1	Permeability		1	0	0	0	0	0	0	0	1	2
2	Wave reflection	0		0	0	0	0	0	0	0	0	1
3	Flexibility	1	1		1	0	0	1	1	1	6	7
4	Width of structure	1	1	0		0	0	0	0	0	2	3
5	Width of auxiliary channel	1	1	1	1		0	0	0	0	4	5
6	Management and Maintenance	1	1	1	1	1		1	1	0	7	8
7	Sustainability	1	1	0	1	1	0		1	1	6	7
8	Ecology	1	1	0	1	1	0	0		0	4	5
9	Constructability	1	1	0	1	1	1	0	1		6	7

Table B.4: Weighting of criteria according to author

		Permeability	Wave reflection	Flexibility	Width of structure	Width of auxiliary channel	Management and Maintenance	Sustainability	Ecology	Constructability	sum	weighting factor
1	Permeability		0	1	1	0	1	1	1	1	6	7
2	Wave reflection	1		1	1	0	1	1	1	1	7	8
3	Flexibility	0	0		0	0	0	1	1	0	2	3
4	Width of structure	0	0	1		0	0	1	1	0	3	4
5	Width of auxiliary channel	1	1	1	1		1	1	1	1	8	9
6	Management and Maintenance	0	0	1	1	0		1	1	1	5	6
7	Sustainability	0	0	0	0	0	0		1	0	1	2
8	Ecology	0	0	0	0	0	0	0		0	0	1
9	Constructability	0	0	1	1	0	0	1	1		4	5

In the table below, the resulting weighting factors from the previous tables are visualized in one table. The average value for each criterion is also given in the last column.

Table B.5: Resulting Weighting factors from experts at Haskoning and author

	Expert 1	Expert 2	Expert 3	Author	Average
Permeability	3	4	2	7	4
Wave reflection	7	3	1	8	5
Flexibility	7	4	7	3	5
Width of structure	3	6	3	4	4
Width of auxiliary channel	9	6	5	9	7
Management and Maintenance	7	9	8	6	8
Sustainability	1	1	7	2	3
Ecology	3	4	5	1	3
Constructability	4	8	7	5	6

C Calculations

C.1. Calculation of Overturning and Sliding Stability for Gabion Wall

In this section, the calculations for the overturning and sliding stability of a gabion wall are provided.

C.1.1. Overturning Stability

For the overturning stability, the extreme case is considered in which the water level is at LTW crest level in the main channel and no water is present in the auxiliary channel. The hydraulic force acting on the gabion wall is:

$$F_w = \frac{1}{2} \cdot \gamma \cdot h^2 = \frac{1}{2} \cdot 9.81 \cdot 6^2 = 176.5\ kN/m^2 \tag{C.1}$$

This leads to a resulting moment of:

$$M_{overturning} = F_w \cdot \frac{h}{3} = 176.5 \cdot \frac{6}{3} = 353\ kNm/m \tag{C.2}$$

This overturning moment should be compensated for by the structure. Using the design from Figure 6.8, assuming that only the part that is above the river bottom contributes, the following resisting moment can be calculated:

$$M_{res} = W * a = A * \gamma * a \tag{C.3}$$

$W =$ weight of the structure (kN/m);
$A =$ Area of the wall per meter length (m/m); $= 2 \cdot 4 + 2 \cdot 3 + 2 \cdot 2 = 18$
$\gamma =$ unit weight of the gabion wall $= (1 - n_v) * \gamma_{rock}$;
$n_v =$ layer porosity (-) ≈ 0.4;
$\gamma_{rock} =$ unit weight of rock $\approx 2650 kg/m^3 \approx 26.5 kN/m^3$
$a =$ horizontal distance from center of gravity to the toe $= 1/2 * b = 1/2 * 4 = 2\ m$

$$M_{res} = 18 \cdot (1 - 0.4) \cdot 26.5 \cdot 2 = 572\ kNm/m \tag{C.4}$$

The resulting Factor of Safety is then:

$$FoS = \frac{M_{res}}{M_{overturning}} = \frac{572}{353} = 1.62 \tag{C.5}$$

C.1.2. Sliding Stability

The following formula is used to calculate the Factor of Safety for sliding stability:

$$FoS = \frac{f \cdot W}{F_w} \tag{C.6}$$

Detailed calculations can be foun in Appendix C.

A Factor of Safety for sliding of 2.34 is found, which is well above 1 and therefore safe. W and F_w are both known. f is the friction coefficient that can generally be assumed to be 0.5 (CIRIA, CUR, CETMEF, 2007). This leads to the following calculation:

$$FoS = \frac{0.5 \cdot (18 \cdot (1 - 0.4) \cdot 26.5)}{176.5} = \frac{143.1}{176.5} = 0.81$$

Of course, this factor of safety is too low, but the calculation does not include the passive earth pressure that resists sliding. The design as visualized in Figure 5.11 is embedded for 3 meters in the river soil. The passive earth pressure can be calculated with:

$$F_p = \frac{1}{2} \cdot K_p \cdot \gamma_s \cdot H_e^2$$

where:

F_p = passive earth pressure force (kN/m)
K_p = coefficient of passive earth pressure (-) $= \frac{1+\sin\phi}{1-\sin\phi}$
ϕ = angle of internal friction (°)
γ_s = unit weight of soil (kN/m^3) $\approx 20\ kN/m^3$ (*NEN-EN 1997-1 Eurocode 7*, 2019)
H_e = embedded depth of the structure (m) $= 3\ m$

According to borehole data, the soil in the IJssel consists of 'Sand, medium loose' (DINOloket, 2016). A corresponding friction angle is approximately 30 °, which gives a coefficient of passive earth pressure of 3. This gives the following result for the passive earth pressure force:

$$F_p = \frac{1}{2} \cdot 3 \cdot 20 \cdot 3^2 = 270\ kN/m^3$$

Adding this to the calculation of the stability against sliding gives a FoS of:

$$FoS = \frac{143.1 + 270}{176.5} = 2.34$$

C.2. Calculation of D_{10}, D_{60} and C_U

In this section, the calculations for D_{10}, D_{60} and C_U are provided, based on a standard rock grading of 5-40 kg.

$$D_n = (M/\rho_{app})^{1/3} \tag{C.7}$$

$$D = 1.19 D_n \text{ (Laan, n.d.)} \tag{C.8}$$

M is the mass that corresponds to a certain percentage of the fraction
ρ_{app} is the density of rock, typically 2650 kg/m^3
$M_{10} \approx 9\ kg$;
$M_{60} \approx 29\ kg$;

$$D_{n10} = (9/2650)^{1/3} = 0.14\ m \tag{C.9}$$

$$D_{10} = 1.19 * 0.14 = 0.16\ m \tag{C.10}$$

$$D_{n60} = (29/2650)^{1/3} = 0.22\ m \tag{C.11}$$

$$D_{60} = 1.19 * 0.22 = 0.26\ m \tag{C.12}$$

$$C_U = \frac{D_{60}}{D_{10}} = \frac{0.26}{0.16} = 1.61 \tag{C.13}$$

C.3. Calculation of Seepage Flow U_v

$$U_v = KC_U^{-0.26}\sqrt{2geD_{50}i} \tag{C.14}$$

$$Q = U_v n_v A \tag{C.15}$$

Where:
$K =$ coefficient that depends on stone shape (-);$K = 0.56$ for crushed stone;
$C_U =$ coefficient of uniformity defined as D_{60}/D_{10} (-) $= 1.61$
$e =$ voids ratio defined as the ratio of volume of the voids and total rockfill volume;
$e = \frac{1}{90}(e_0)$ arctan$(0.645 \cdot n_{RRD})$ (Tsirel, 1997)
$e_0 = 0.94$; void ratio associated with single-size particles of different shapes (CIRIA, CUR, CETMEF, 2007)
$n_{RRD} =$ uniformity coefficient; 5.22 for a 5-40 kg grading
$D_{50} =$ characteristic sieve size of the stone = 0.24 (m)
$i = \frac{h_{main\ channel} - h_{auxiliary\ channel}}{L}$; hydraulic gradient (-)
$n_v = \frac{e}{1+e}$; armourstone porosity of the medium
$A =$ the total cross-sectional area (m^2) $=$ height of the wall*thickness of the wall

$e = \frac{1}{90} \cdot 0.94 \cdot$ arctan$(0.645 \cdot 5.22) = 0.77$ (-)
$n_v = \frac{0.77}{1+0.77} = 0.44$ (-)

For the hydraulic gradient, a maximum difference in water level between the main channel and auxiliary channel is assumed to be 0.20 m, based on observations and simulations that were performed at the pilot project in the Waal (Mosselman et al., 2021). The length of the seepage path is assumed to be the average thickness of the dam With the crest height of the dam being approximately 5.7 meters (Chapter 6), a slope of 1:2.5 and a crest width of 2 meters, this leads to a thickness L of 5.7 * 2.5 * 2 + 2 = 30.5 meters.
$i = \frac{0.20}{30.5} = 0.0066$ (-)
$A = (5.7 \cdot 2.5 \cdot 5.7) + 2 \cdot 5.7 = 92.6\ m^2$

$$U_v = 0.56 \cdot 1.61^{-0.26}\sqrt{2 \cdot 0.77 \cdot 9.81 \cdot 0.24 \cdot 0.0066} = 0.077\ m/s \tag{C.16}$$

$$Q = 0.077 * 0.44 * 92.6 = 3.1\ m^3/s \tag{C.17}$$

D Sensitivity Analysis of MCA

This appendix provides the Python script that was used to perform the sensitivity analysis in Chapter 7.

```python
import numpy as np

# Scores per alternative
score_pilot = np.array([3, 3, 3, 1, 1, 4, 3, 2, 3])
score_mc = np.array([4, 2, 1, 4, 3, 1, 1, 4, 4])
score_gabion = np.array([2, 1, 2, 3, 4, 1, 2, 1, 2])
score_xstream = np.array([1, 4, 4, 2, 2, 4, 4, 2, 2])

# Expert weight factors
experts = {
    "Expert 1": np.array([3, 7, 7, 3, 9, 7, 1, 3, 4]),
    "Expert 2": np.array([4, 3, 4, 6, 6, 9, 1, 4, 8]),
    "Expert 3": np.array([2, 1, 7, 3, 5, 8, 7, 5, 7]),
    "Expert 4": np.array([7, 8, 3, 4, 9, 6, 2, 1, 5])
}

# Calculate and print scores for each expert
for name, weights in experts.items():
    total_pilot = np.sum(score_pilot * weights)
    total_mc = np.sum(score_mc * weights)
    total_gabion = np.sum(score_gabion * weights)
    total_xstream = np.sum(score_xstream * weights)

    print(f"{name}:")
    print(f"  Pilot: {total_pilot}")
    print(f"  MC: {total_mc}")
    print(f"  Gabion: {total_gabion}")
    print(f"  Xstream: {total_xstream}\n")

# --- Simulation Part ---

# Initial weight factors
wf_initial = np.array([1, 2, 2, 1, 3, 3, 1, 1, 2])

# Number of simulations
num_simulations = 10000

# Dictionary to count best alternative occurrences
best_counts = {"Pilot": 0, "MC": 0, "Gabion": 0, "Xstream": 0}

# Run the simulation
for i in range(num_simulations):
    # Shuffle the weight factors
    # Case 1: Permutation of expert weights
    # wf_shuffled = np.random.permutation(wf_initial)

    # Case 2: Random weights between 1 and 3
    wf_shuffled = np.random.randint(1, 4, size=9)

    # Calculate total scores for each alternative
```

```
    total_pilot = np.sum(score_pilot * wf_shuffled)
    total_mc = np.sum(score_mc * wf_shuffled)
    total_gabion = np.sum(score_gabion * wf_shuffled)
    total_xstream = np.sum(score_xstream * wf_shuffled)

    # Store scores in a dictionary
    scores = {
        "Pilot": total_pilot,
        "MC": total_mc,
        "Gabion": total_gabion,
        "Xstream": total_xstream
    }

    # Determine the best alternative(s)
    max_score = max(scores.values())
    best_alternatives = [key for key, value in scores.items() if value == max_score]

    # Increment count for each best alternative
    for alt in best_alternatives:
        best_counts[alt] += 1

# Calculate and print percentages
print("Percentage of times each alternative was the best:")
for alt, count in best_counts.items():
    percentage = (count / num_simulations) * 100
    print(f"  {alt}: {percentage:.1f}%")
```

Listing D.1: Python simulation and expert-based scoring