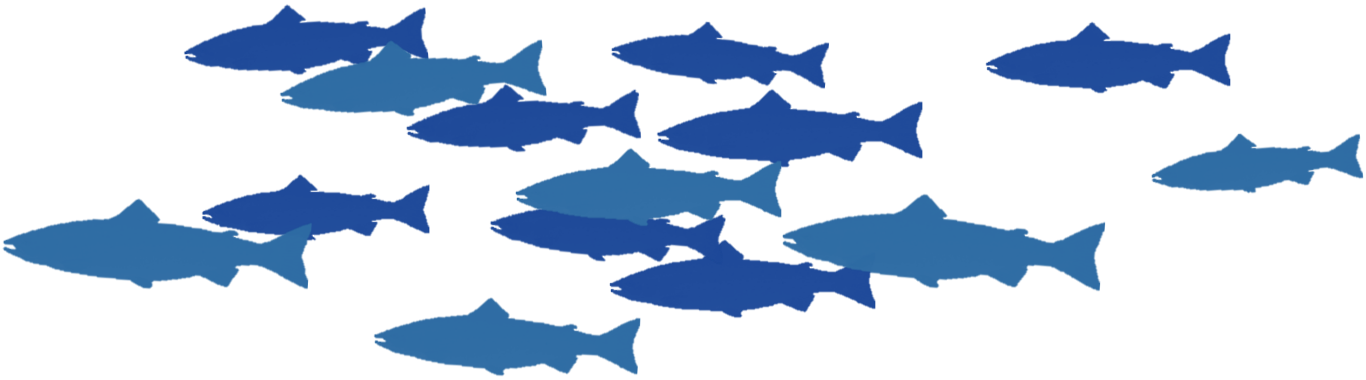
The Return of Fish Migration to the Dutch River Delta



Team 2774
How to make the fish migration river a more attractive environment for migratory and local fish?

Sabine Hoek
Rozanda Jin
Evelien van der Schaar
Sam Shanitbayeva
Matijn de Visser
Niamh Wallace

Dutch Delta Fish Migration River
D.D.F.M.R.

Commissioners: Leen Berke and Huub Lavooij, Delta21
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Contact details of commissioner:

ir. H.A. Lavooij

T: +31 (0)6 37 64 43 12

E: h.lavooij@delta21.nl

Contact details of team secretary:

S. Hoek

T: +31 (0)6 54 61 32 19

E: sabine.hoek@wur.nl

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Executive Summary

Habitat modification and artificial barriers can cause impediment to fish migration. Such a situation has arisen in the Netherlands, due to the construction of the Haringvlietdam in 1971. This dam is situated in the Haringvliet and is part of the delta works, with the purpose of protecting the country from floods. This part of the delta used to be an open estuary composed of brackish waters. However, the brackish transition between salt and freshwater disappeared and dominantly became fresh water, post construction of the Haringvlietdam. The estuary used to serve as a vital link between the North Sea and the rivers Rhine and Meuse, being an essential passage, refuge and nursery for migratory fish. The 'Kierbesluit' was created to occasionally allow migratory fish to pass through the sluices. Unfortunately, this decision was not enough to completely restore the natural fish migration. A possible solution to this problem is a fish migration river (FMR), which is a specific type of fish passage. This solution is part of the Delta-21 plan, which this project was commissioned by. The artificially created river would allow an all-year-round open passage for migratory fish to pass the Haringvlietdam barrier and be reintroduced to the area. At the same time, the proposed FMR would provide a suitable salinity gradient to allow for a suitable acclimatisation period for migrating fish, while also mitigating the risk of salt intrusion into the Haringvliet.

This research was necessary to investigate the local environmental conditions, and to study the ecological and hydrological requirements of the target migrating fish species. We aimed to provide advice on making the FMR attractive to local and migratory fish. As part of this, we aspired to give recommendations with the purpose of improving biodiversity in the Haringvliet and restoring part of the brackish estuary environment. This was performed by investigating the core purposes of a fish migration river and the present hydrological and ecological circumstances in the Haringvliet. In addition, the abiotic and biotic requirements and constraint of the target migrating fish were considered, as well as other aspects that need to be incorporated in an FMR design adapted to the Haringvliet area. The core purposes of an FMR were examined and divided into four categories: hydrology, ecology, anthropogenic disturbance and soil characteristics. For the hydrology, we determined turbulence, salinity, current speed, lure current and tidal currents were the most important aspects. Regarding ecology, fish migration type, migration period and cycles, swimming capacity, predation and supporting ecosystems were chosen as most important. Artificial light, sound and fishery were determined to be influential factors of anthropogenic disturbance. Finally, regarding soil characteristics, it is necessary to consider soil composition and sedimentation. All these aspects are required to be considered and integrated in order to make an FMR effective. The core purposes of an FMR were linked to the current conditions in the Haringvliet For the seven target species chosen, we investigated concepts and models that could encourage these migratory species to pass through the FMR.

Based on the findings and local information, we investigated three different scenarios as possible solutions. The first two scenarios include the construction of an FMR, either in the North or South of the Haringvlietdam. The last scenario does not include an FMR, but is in essence a suggestion for the extension of the current Kierbesluit. Advantages and disadvantages of each scenario were discussed and compared to one another. Finally, we provide recommendations for the most optimal scenario and discuss possibilities for further research. Altogether, the implementation of an FMR in the Haringvliet could be a suitable measure for increasing the migration success of migratory fish species.

Table of Contents

1 Introduction

Most of the ocean's inhabitants and their population rates have drastically decreased (World Wildlife Fund, 2018). According to the WWF report (2018), an estimate of 6 billion tonnes of fish have been removed from the oceans within the last 60 years. Other than overfishing and the general intensity of climate change, habitat modification is a notable factor for fish decline as well (Macura *et al.*, 2019). Habitat modification often comes into conflict with fish migration routes. Physical barriers in rivers or coastal areas may lead to spawning areas becoming inaccessible (Beck *et al.*, 2001; Macura *et al.*, 2019).

Throughout the centuries, water-management techniques led to artificial barriers that resulted in barricades for migratory fish. Going back to ancient civilisations, water-management techniques have always been vital to our fundamental lifestyles (Kvitkova, 2021). In efforts of allowing fish to migrate through new anthropogenic constructs, such as hydropower dams or dykes, ideas of artificial fish passages have come into play (Silva *et al.*, 2017). Fish passages can be seen as artificial constructs and are frequently designed to re-establish fish migration around obstacles. These passages are often made in the forms of bypass channels, ladders and ramps (Dang *et al.*, 2015; FAO/DVWK, 2002). The structure of a fish passage is depended on the local geography. Therefore, every fish passage is unique to the environment in which they are created. This makes it hard to apply the concept of a certain fish passage to a new situation. Therefore, the creation of a fish passage starts with seeking a specific location in which the fish experience a problem in migration.

An example of a specific problem in fish migration can be found in the Netherlands. The Netherlands is fundamentally the delta for multiple rivers, including the Rhine and the Meuse (van de Guchte, 2021). Therefore, the Netherlands is a low-elevation country and is especially susceptible to the effects of climate change-induced sea-level rise (van Nieuwenhuizen Wijbenga, 2020). After the significant flooding incident throughout the Netherlands in 1953, the Delta Works flood protection was implemented (Water technology, n.d.). The Delta Works aided in reducing the size of the Dutch coastline and halting large bodies of water by introducing sluices, locks and dams (Water technology, n.d.). One of these well-known sluices is situated in the Haringvliet, south of the city Rotterdam. This part of the delta used to be an open estuary composed of brackish waters. However, with the completion of the Haringvlietdams in 1971, the brackish transition between salt and freshwater disappeared and became freshwater only (Natuurmonumenten, n.d.; Staatsbosbeheer, n.d.). The estuary served as a vital link between the ocean and the Rhine and Meuse rivers because it is an essential passage, refuge and nursery for migratory fish (Smit *et al.*, 1997). Therefore, it is of international interest to restore the migration in the Haringvliet by allowing the fish to pass the Haringvlietdams once again. As a solution, the 'Kierbesluit' is created, which allows the sluices to occasionally stand ajar on specific tidal conditions. However, this decision is not enough to completely restore the natural fish migration. Thus, another solution is needed to achieve and restore fish migration.

A solution to the obstruction in the form of a fish passage is proposed as part of the Delta-21 plan. Delta-21 is a construction plan in development, with the aim to ensure better protection from extreme river discharges, especially in the scenario when floods and storms occur together. As such extreme events likely will not happen often, the short-term goal of the Delta-21 plan will be the construction of an energy storage lake. Its primary use is to contribute to the production and storage of renewable energy, using the tidal forces of the ocean (Lavooij & Berke, 2019). Another objective of the Delta-21 plan is nature restoration. The construction of the Delta-21 plan is situated in the same area where the fish migration is obstructed by the Haringvlietdam; therefore the Delta-21 aims to incorporate a fish migration river (FMR) in the construction. In essence, an FMR is a type of large-scale fish passage. It is an artificially created river that can be used for migrating fish to pass a barrier (in this case, the Haringvlietdam), while providing a suitable salinity gradient for acclimatisation purposes.

The current proposal for this FMR would allow for the reintroduction of local and migratory fish within the area (Baas *et al.*, 2020). The FMR provides an all-year-round open passage for fish while also mitigating the risk of salt intrusion into the Haringvliet. Whilst this proposal offers the solution to the fish migration problem, there is currently a knowledge gap in the local adaptation of this concept. Thus, research is needed to investigate the local environmental properties and to study the ecological and hydrological requirements of the fish which the passage aims to target. This report aims to bring the return of fish migration to the Haringvliet one step closer while also investigating options to improve the natural values of the area.

1.1 Project Purpose

We investigated the possibilities for implementing an FMR in the Haringvliet. We aimed to provide advice on making the FMR as attractive to local and migratory fish as possible. As part of this, we aspired to give recommendations with the purpose of improving biodiversity in the Haringvliet and restoring part of the brackish estuary environment.

1.1.1 Research Questions

This ACT project was set up to answer the main research question: **How can a fish migration river (FMR) in the Haringvliet be made most attractive for local and migratory fish?** To investigate the main question, we explored the following sub-questions: **i)** What are the core purposes of a fish migration river? **ii)** What are the present hydrological and ecological circumstances in the Haringvliet? **iii)** Which are the abiotic and biotic requirements and constraints of the target migrating fish? **iv)** Which aspects should an FMR design adapted to the Haringvliet area incorporate?

For the first question: **i) What are the core purposes of a fish migration river?** We performed a literature study focusing on the key principles of fish passages and, by extension, the FMR. Additionally, we investigated reports of the Kornwerderzand FMR, which is currently under construction near the Afsluitdijk. By doing this, we compiled a list of parameters and requirements that need to be taken into account when designing any fish passage and, specifically, a fish passage at a salt- and freshwater border. After establishing these core principles of an FMR, we studied the local situation where the new FMR is proposed: the Haringvliet, specifically, the Haringvlietdam. This is to explore the second sub-question.

The second subquestion is: **ii) What are the present hydrological and ecological circumstances in the Haringvliet?** For this, we acquired information on the hydrology of the area, such as ocean currents and tides, as well as the river dynamics. Along with the hydrology, we analysed the local ecology in and around the Haringvliet. This includes information on the species currently present, biodiversity of the area and current migratory movements of fish. Before constructing the delta works, the historical situation and the current situation were compared in both the ecological and hydrological aspects. The information acquired here was used to determine the target fish species, those migratory fish species that need to pass the Haringvlietdam to complete their life cycle.

The third sub-question involved researching the ecology of the target fish species: **iii) Which are the abiotic and biotic requirements and constraints of the target migrating fish?** This information is vital for the design of any fish passage. Aspects of the target species' ecology such as their (migratory) life cycle, critical swimming speed and other life-history characteristics need to be considered when designing the Haringvliet FMR.

We used the information gathered from the above questions for answering the final research question: **iv) which aspects should an FMR design adapted to the Haringvliet area incorporate?** Here, we refer to the FMR core purposes established in the first part and use the information about the target fish species and local environment to attain those principles in a locally adapted plan. We discuss three different scenarios for implementing the FMR and compare their advantages and disadvantages from different perspectives, taking all relevant stakeholders into account. Two of these scenarios involve using the FMR as a bypass to the Haringvliet, either North or South of the sluices. The other does not include a bypass but a structural redesign of the Haringvliet near the sluices instead. We chose the one that best incorporated an FMR's core purposes from these scenarios while taking the local conditions into account. Finally, we elaborate on this scenario and provide advice on its execution. Figure 1 provides a general overview of the project activities, visualised in a flowchart.

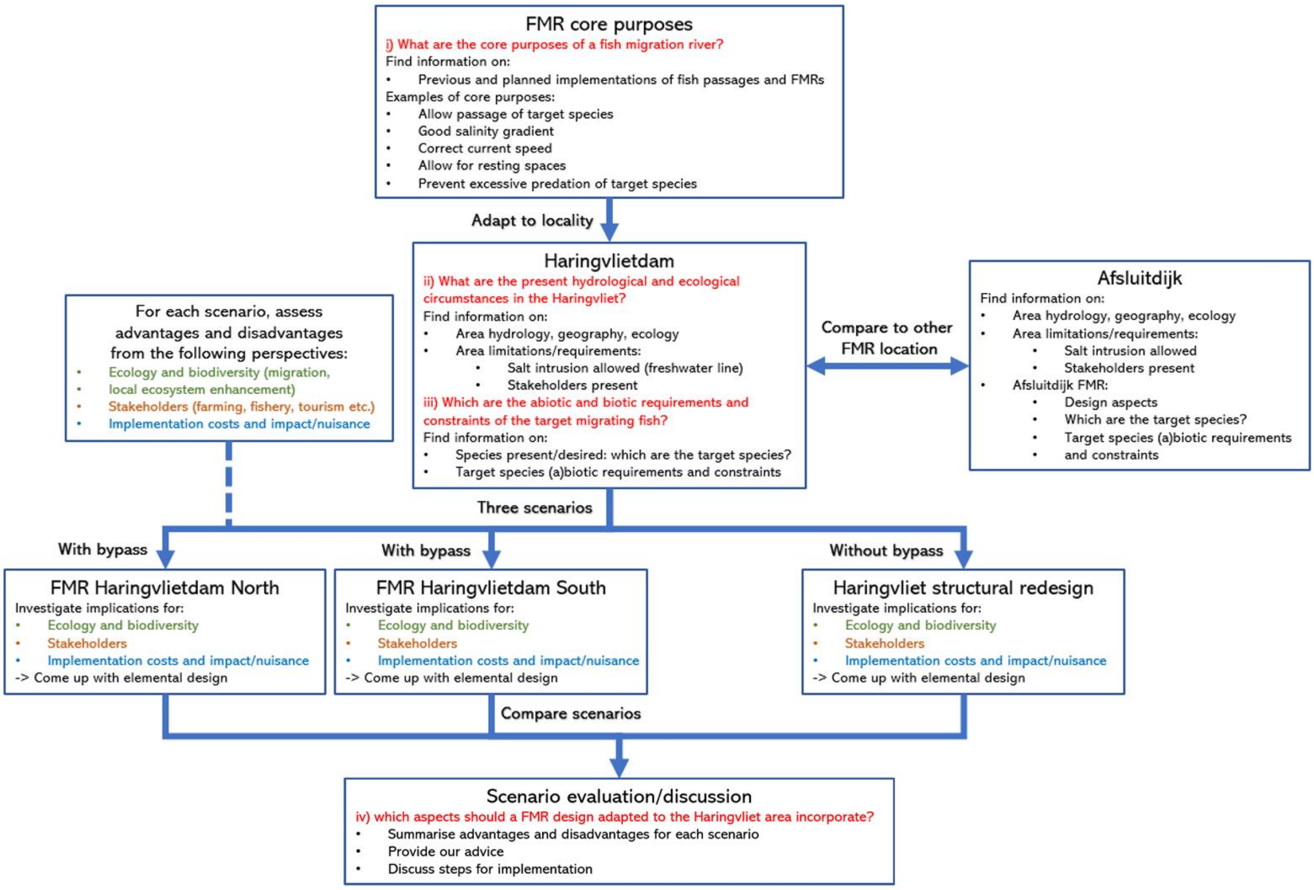


Figure 1. Flowchart of study activities. In chronological order from top to bottom. Each block represents activities that need to be performed in order to gather information on specific subjects. The arrows represent the activities which connect this information. The project research questions are depicted in red. This figure can be seen as a visual overview of the project activities. Appendix A mentions information sources for the activities mentioned here.

1.2 Methodology

Information was obtained from the following sources:
Scientific publications: obtained from scholarly databases such as Scopus, Web of Science, WUR library and Google Scholar.

Relevant project reports: obtained from scholarly databases, report repositories (such as the Delta21 research archive) and interviewees.

Excursion to study site: We visited the Haringvlietdam area to deepen our local knowledge and compare our literature findings to real-world situations.

Personal interviews with experts: We interviewed experts with relevant expertise and knowledge in the field of fish migration in the Haringvliet and Afsluitdijk areas. Interviews were conducted in order to obtain in-depth information and background on the project area's environmental conditions and FMR design strategies. Using a list of predetermined topics and questions, we conducted the interviews in a semi-structured way. Table 1 contains more information on the interviews conducted.

Table 1. Information about conducted interviews, regarding interviewee's name, job description and topics covered in the interview.

Interviewee name	Interviewee job description	Main topics covered in the interview
Wouter van der Heij	Project Leader (Afsluitdijk FMR)	Design concept and functionality of Afsluitdijk FMR. Proposal/scenario discussion of FMR construction in Haringvliet. Discussion of stakeholders in Afsluitdijk.

Reindert Nijland	Assistant Professor (WUR)	Discussion of current environmental & hydrological condition of the Haringvliet & Voordelta areas. Local and migratory fish species present in Haringvliet.
Koen Workel	Adviser ecology and water for Kierbesluit Haringvliet sluizen (Rijkswaterstaat)	Kierbesluit: history and current management/research. How to make the FMR attractive?

2 The Core Principles needed for an FMR

2.1 Brief Overview

An FMR is an artificially created river that can be used for migrating fish to pass a barrier (in this case, the Haringvlietdam), while providing a suitable salinity gradient for acclimatization purposes. An important step to realise the FMR is to explore the core purposes of an FMR and investigate the aspects that make it effective. To achieve this, hydrological, ecological and other requirements of an FMR need to be considered. Firstly, the hydrological aspects are crucial to be recognized in implementing an FMR as different fish species have preferences for distinct currents and turbulence. Similarly, ecological aspects should be taken into account in order to ensure a successful FMR; migration cycles, species' swimming capacity and predation pressure are determinants that could entice or discourage fish into the FMR. Furthermore, anthropogenic disturbance and soil composition in the proposed area are also important aspects that need to be considered. All these aspects are crucial in making the FMR an attractive environment for migratory fish. While reading this chapter, it is recommended to consult table 2, which contains a detailed overview of all the subjects covered here.

2.2 Aim of the FMR

The aim of the FMR is to create an artificial situation similar to an estuary with natural flowing tides, where fish can swim freely through the FMR during the tidal periods. The natural in and outflowing tides create different situations of water levels, currents, turbulence, water temperature, salinity, and other important factors for fish migration that also appear in a natural estuary. As a result, different habitats will be created for fish to use during the transition period from salt to fresh water. Accordingly, there is a suitable period for all kinds of species to migrate (Deafsluitdijk.nl, 2015).

2.3 Hydrology

Hydrology is an important factor for an FMR. A successful fish passage combines biological knowledge about fish behaviour, especially when the fish encounter variable flows, velocity, and turbulence, with expertise in hydraulic and civil engineering to develop appropriate facilities (Williams *et al.*, 2012). Different abiotic factors should be considered. For every factor, the requirements and capacities of the fish can then be assessed. From this assessment, it can be decided if the current design for the fish passage or river will allow the targeted species to pass through it (inspired by: (van Banning *et al.*, 2018; Williams *et al.*, 2012).

2.3.1 Turbulence

It is important to take turbulence into account in the creation of a fish passage. Turbulence can be described as the distortion of the water flow as it encounters solid objects (Neachell, 2014). Turbulence is one of the hydraulic conditions that give the fish cues to seek a migration pathway (Williams *et al.*, 2012). It has even been proposed to use engineered turbulence as a tool to attract migrating juvenile salmonids to the entries of fish passages (Schilt, 2007). However, turbulence is often not desired, as turbulence and vortices impact fish swimming efficiency and sensory acuity (Neachell, 2014). It is known that in cases with very high turbulence, for example, in dams with a Spillway passage, the turbulence can damage fish (Schilt, 2007). Thus, it is important that the maximum turbulence in an FMR is kept under a certain threshold. The matter in which fish experience the negative effects of turbulence depends on the characteristics of the fish, such as the size of the fish and its swimming capacities (van Banning *et al.*, 2018). However, a general threshold in fish passages has been proposed by Marriner *et al.*, 2014. In this paper, K represents the turbulent kinetic energy. K levels of $K \leq 0.05$ m2/s2 are considered 'low', and any value higher is considered as a high amount of turbulence in fish passages.

2.3.2 Salinity

The transition between freshwater and seawater is an important phase in the life history of many fish species. Migratory fish adapt to their environment through physiological mechanisms of osmoregulation. The mechanisms utilized to navigate different environmental salinities are highly conserved across phylogenetically distinct species (Zydlewski & Wilkie, 2012). Fish generally attain salinity tolerance through early development, progressive acclimatization, or adaptation cued by environment or development (Zydlewski & Wilkie, 2012). Although many diadromous fish species can handle a steep salinity gradient (van Banning *et al.*, 2018), other species may need a more gradual transition. For example, the Allis Shad (*Alosa Alosa*) requires a period of acclimatization

(Griffioen & Winter, 2014), and Flounders (*Platichthys flesus*) can develop ulcers in a habitat with large differences in salinity (Vethaak, 2013).

2.3.3 Current Speed

For the realisation of the fish migration river, the speed of the currents in the river needs to stay within a certain threshold so that the swimming capacities of the fish are sufficient to use the passage. The structure and design of an FMR will have a great impact on the current speeds within the river. For example, culverts with high slopes are known to increase the stream velocity, often limiting the passage of fish (Briggs & Galarowicz, 2013). Therefore, it is necessary to run simulations of water going through the proposed river, calculating the current speed at different locations and depths. In the creation of the Afsluitdijk FMR, the critical current speeds of the targeted fish species were studied using literature (van Banning *et al.*, 2018), and compared to the simulated current speeds. It is important to consider that the route chosen by the fish is influenced by the current speed (Standen *et al.*, 2004). Based on a study on adult sockeye salmon (*Oncorhynchus nerka*), it was concluded that at sites with fast-flowing currents, fish increase their speeds to clear the passage. In low or moderate current speeds, fish actively spend time avoiding high currents to save energy. Thus, for the creation of an FMR, it is not necessary for every part of the river to have a slow current. It is sufficient when fish are able to choose a passage with a current speed that matches their swimming capacity.

2.3.4 Lure Current

Migratory fish perceive chemical cues from their environment, which indicate to them which direction they should go in order to return to their spawning ground (Hara, 1992). There is a lack of evidence that odorants specific for freshwater streams serve as guidance to the fish; therefore, it is currently assumed that Salmon are attracted to their native stream by pheromones. Homing adults follow the trails released by juvenile Salmon that reside in the stream (Hara, 1992). For a successful fish passage, there must be an indication for the migratory fish that this path will be a suitable migration route. This makes the freshwater lure current one of the most important properties of a fish migration river. The lure current can be optimised by creating a passage that is as large as possible. This has the additional benefit of bringing in more passive migrants (Odeh *et al.*, 2002). The speed of the lure current and the volume is also of importance, as fish must be able to swim through it (van Banning *et al.*, 2018).

2.3.5 Tidal Currents

The tides affect all of the above-mentioned aspects of hydrology and should therefore be taken into account when doing hydrological simulations. For instance, at the Afsluitdijk FMR, the current speed is highest during low tide (van Banning *et al.*, 2018). Therefore, this is the determining speed to be checked with the species' critical current speed.

2.4 Ecology

Besides hydrological aspects, it is also necessary to consider ecological factors when creating an FMR. First of all, the different types of migration and the different migration periods or cycles of the targeted fish species should be taken into account. To ensure that the fish can use the FMR, it is essential to consider their swimming capacity in combination with the above mentioned hydrological factors. Furthermore, the river itself and the environment should be attractive for the fish species, and predation by other species, like birds, should be minimized. As a start, we first elaborate on the term 'Migration'.

In general, migration consists of animal movements between different habitats that are needed to fulfil the conditions to complete their life cycle (Winter *et al.*, 2020; Deinet *et al.*, 2020; Dorst, n.d.). Fish migrations often consist of large parts of populations with synchronised movements, driven by the availability of key resources in different locations (Deinet *et al.*, 2020; Dorst, n.d.; Lucas & Baras, 2001). Fish migrate large distances between various habitats for refuge, spawning purposes, feeding and growth (Lucas & Baras, 2001). In this way, a fish population can sustain itself. Migratory movements are executed by a large part of the population and often occur regularly and seasonal. The distance over which fish migrate varies for every species, just as the place (Deinet *et al.*, 2020).

2.4.1 Migration Types

The goal of a fish passage or migration river is to re-facilitate migration between certain water bodies. As migration can take place on different scales and between different types of waterbodies, it is important to consider this. To be able to do this, we need to know the different types of migration. There are roughly three different categories to distinguish (Figure 2): oceanodromous (1), potamodromous (2) and diadromous (3) (Binder *et al.*, 2011). Oceanodromous fish migrate solely in saltwater, and potamodromous fish migrate only in freshwater to complete their life cycles. Diadromous fish need salt and freshwater for their different life stages (Deinet *et al.*, 2020; Dorst, n.d.). Therefore, these diadromous fish have the ability to adapt to different salinity gradients (Winter *et al.*, 2014). The latter category can also be subdivided into three subcategories: catadromous (3.1), anadromous (3.2) and amphidromous (3.3) (Binder *et al.*, 2011; Nagelkerken, 2009). Catadromous fish migrate from freshwater to saltwater for breeding, and anadromous fish migrate from saltwater to freshwater to spawn (Deinet *et al.*, 2020; Dorst, n.d.). Amphidromous fish migrate from freshwater to saltwater when juvenile, but they are not driven by breeding (Binder *et al.*, 2011). By knowing the migration category of the target species, their migration timing and direction can be predicted. This in turn, allows management of the fish passage to ensure suitable conditions are met at the right time to allow for passage.

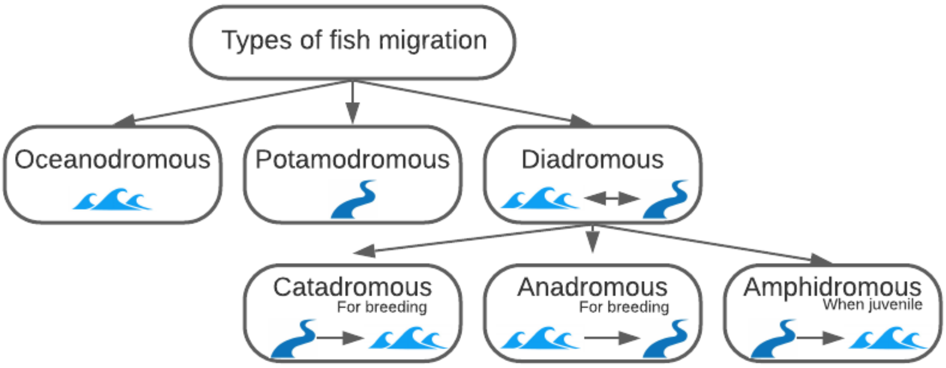


Figure 2. Schematic overview of the different types of fish migration. The waves symbolise the salt seawater and the river symbolises the fresh river water. The arrows indicate the direction of the migration.

2.4.2 Migration Periods and Cycles

Migrations are often triggered by external and internal cues, like for example (water) temperature, day length, season, maturation stage, lunar phase and so on (Tillotson & Quinn, 2017; Binder at al., 2011). In temperate regions, there seems to be a correlation between day length and water temperature that triggers migration (Binder *et al.*, 2011). In tropical regions, fish evolved to begin migration with the start of the rain season and the induced floods, as these ensure higher primary productivity, and thus food, in the floodplains (Nagelkerken, 2009). However, in general, peaks in migration are often associated with the spawning time and the moment that the juvenile fish leave their spawning sites (Rolls, 2009). During these migration periods, the fish can migrate during different times of the day or at night (Winter *et al.*, 2014; Winter *et al.*, 2020). This depends on the specific species and on the local circumstances, such as the exact location or the perceived risk of predation, which may be more present during the day than the night (Winter *et al.*, 2014; Winter *et al.*, 2020). Furthermore, migration periods can shift during the years due to the disappearance of migratory cues by obstructions in the upstream rivers (Lin, 2017). As each fish species has its preference and timing to execute its migration, it is important to make sure that these are considered, so the targeted fish species can optimally use the passage or FMR.

2.4.3 Swimming Capacity

Swimming capacity is an important factor that determines the survival and the ability of a fish to fulfil its life cycle. Swimming capacity includes passive and active swimming, critical swimming speed and energy expenditure and efficiency. It is also connected to reproduction, migration and predator-prey interactions, which are important ecological factors (Reidy *et al.*, 2000). For swimming capacity, fish can be subdivided into three categories: tidal migrants, 'poor' swimmers and 'strong' swimmers (Deafsluitdijk.nl, 2015; Tudorache *et al.*, 2018; Winter *et al.*, 2014; Winter *et al.*, 2020). Swimming capacity can also be distinct between different life stages within one species. Strong swimmers usually pass longer routes than poor swimmers, which are more limited in the area which they can cover during their life cycle (Winter *et al.*, 2020). Tidal migrants use selective tidal transport, which is reflected in the vertical movements of these fish during the tidal cycle (Bruijne *et al.*, 2016;

Deafsluitdijk.nl, 2015; Winter *et al.*, 2014). They essentially move like passive particles without directional swimming movements. Tidal migrants follow the currents during high tide and use it as a way of transportation. Whereas, during low tide, they find shelter in the available sediments and sometimes bury themselves in the soil. Additionally, active and strong swimmers can also use selective tidal transport but are not dependent on it. Meaning they can also transport themselves during low tide. Examples of strong swimmers are Atlantic salmon, sea trout, and twaite shad. Fish like the sea and river lamprey have a poor swimming capacity. The swimming capacity of fish also depends on the flow speed of the water (Bruijne *et al.*, 2016; Deafsluitdijk.nl, 2015; Winter *et al.*, 2014). Fish have an optimal swimming speed when their energy expenditure per distance covered is the lowest (Videler, 1993). The adaptation of different fish species to particular habitats and lifestyles can be compared with regard to energy metabolism and swimming capacity (Tudorache *et al.*, 2008). Knowledge of the swimming capacity of the target migrating fish is essential when designing a fish passage. Current speed through the passage should be low enough so even the poorest swimmers can pass, at least during regular windows of time. Furthermore, for tidal migrants, tidal transport through the passage should be strong enough to allow for their passage. Therefore, hydrological aspects of the passage, such as current speed and tides, should be closely compared to the target species' swimming capacity.

2.4.4 Predation

Occasionally, fish need to remain in a certain area due to high currents, salinity gradients and acclimatisation time. Fish orientate via different stimuli and wait for the right moments to migrate (Banning *et al.*, 2018; Winter *et al.*, 2014). When fish are waiting to pass the FMR due to these factors, high local densities of migrating fish may occur. This is reinforced by the fact that fish are forced to gather in a relatively small area when passing through a fish passage. In these situations, migrating fish are especially vulnerable to predation. However, this may be partly alleviated by the fact that fish can adjust their behaviour and migrate during other periods of the day. For example, fish may opt to move at night instead of the day in order to avoid predation (Banning *et al.*, 2018; Winter *et al.*, 2020). Understanding temporal and spatial predation dynamics, including the abiotic and biotic drivers in an area, is fundamental in managing prey-predator interactions and populations. This is particularly beneficial in situations where humans manage ecosystems and control certain conditions to influence predation dynamics, such as an FMR (Michel *et al.*, 2020). In addition, various fish species detect and respond differently to predator cues. In order to avoid predators, they may seek refuge or decrease their swimming activity (Lehtiniemi, 2005). Therefore, habitat features, such as shelter availability, influence predation risk (Michel *et al.*, 2020). Taking this into account could help make an FMR more effective. Ensuring plenty of hiding and resting spaces in and around the FMR can be considered to limit the effects of predation. Ways in which to incorporate such hiding places will differ depending on the local circumstances and the target species. Different fish species have need different vegetation to hide and rest in (Lehtiniemi, 2005). Suitable hiding places, such as vegetation, need to be selected based on the target species' requirements.

2.4.5 Supporting Ecosystem

Fish populations depend on a suitable ecosystem and habitat with features that differ between life stages and species (Katopodis, 2005). Migratory fish need to pass certain obstacles, such as dams, to reach their spawning grounds for successful recruitment. Furthermore, it is important to consider migratory fish, which are bidirectional, who need to have an upstream and downstream passage to complete their life cycle (Pompeu *et al.*, 2012; Silva *et al.*, 2018). For instance, diadromous fish are able to use the salinity gradient as a que for the entrance or exit of a river (Winter *et al.*, 2014). Therefore, it is crucial to consider that migratory fish need to be able to detect the entrance of an FMR to swim through it (Cada & Jones, 1993). Nevertheless, fish travelling through an FMR does not necessarily indicate that the FMR is a success. To make an FMR effective and attractive for the different species of interest, the FMR needs to be heterogeneous and incorporate different habitational features. For this reason, it is crucial to consider habitat features in and around an FMR, which support the local ecosystem. The aim of an FMR should incorporate the spatial distribution of critical habitats, for instance, nursery areas and reproduction sites at the beginning and end of the FMR (Pompeu *et al.*, 2012). Habitational features of importance are macrophytes and ecosystem engineers that modify or create habitats (Brückner, 2021). Macrophytes are important in representing rearing habitats or as a refuge for migratory fish, such as salmonoids. Macrophytes also reduce water velocity, resulting in an overall reduction of energy consumption for upstream swimming fish (Lusardi *et al.*, 2018). Therefore, taking macrophytes into consideration at the beginning and end of the proposed river could increase the effectiveness of an FMR. Ecosystem engineers are also an important aspect to consider, as they adjust resources and assist in the survival of co-existing species in the area, such as migratory fish. Moreover, they can destabilise or stabilise sedimentation, which could influence the composition and visibility of certain habitats (Brückner, 2021). This would also affect the migration of fish. Thus, it is important to consider ecosystem engineers and their role in creating an attractive FMR. To conclude, it is crucial to take into account habitat features in the areas at the entrances of an FMR in order to make it attractive for migratory fish.

2.5 Anthropogenic Disturbance

The necessity of diadromous fish to move through a chain of different habitats increases their vulnerability to threats and disturbance, and those species that cover great distances are especially vulnerable (McDowall, 1999). An obstacle many migrating fish face when migrating up or downstream are barriers in the river, such as dams and sluices. In a variety of ways, human disturbance can influence a migrating fish's ability to successfully pass such a barrier. This section discusses some of the relevant sources of anthropogenic disturbance fish may encounter when migrating and their effects on individual behaviour and migration success. Potential sources of human disturbance should be taken into account when designing a fish passage, and by extension, the FMR.

2.5.1 Artificial light at night

For many organisms, light is an extremely important source of information. Hence, artificial lighting may have perturbing effects on the behaviour of many animal species (Falcón *et al.*, 2020), causing disruption of important ecological functions such as feeding, migration and reproduction (Perkin *et al.*, 2011; Pulgar *et al.*, 2019). In fish as well, exposure to artificial light at night (ALAN) has been shown to result in changes in physiological performance (Pulgar *et al.*, 2019). With regard to fish migration through sluices and fish passages, behavioural changes caused by ALAN may affect a fish's ability to pass a barrier successfully. For instance, when migrating fish are attracted to a light source, large numbers of fish may congregate at one location, allowing predators to more easily capture them (Winter *et al.*, 2020). There is also experimental evidence suggesting ALAN affects the migration of specific species of migratory fish. Atlantic salmon (*Salmo salar*) for example, show differences in migration timing when exposed to ALAN (Riley *et al.*, 2012). The European eel (*Anguilla Anguilla*) is more likely to reject an illuminated migration route, preferring the darker option, and passes upstream through an illuminated route more quickly than through a non-illuminated route (Vowles & Kemp, 2021).

In conclusion, although studies about species-specific responses to ALAN are rare, it is clear that it can cause undesired changes in fish migratory behaviour and timing. Excessive ALAN near a fish passage may alter fish behaviour in unpredictable ways, thereby decreasing the migration success of certain species. Thus, in the design of fish passages, it is prudent to limit local sources of ALAN.

2.5.2 Sound

There remains significant uncertainty about the impact of anthropogenic noise on fish behaviour (Mickle & Higgs, 2018; Popper, 2003; Popper & Hastings, 2009; Slabbekoorn *et al.*, 2010). However, several studies have shown artificial sounds to alter fish behaviour in certain ways. Fish may be 'distracted' by anthropogenic noise, making them more vulnerable to predation (Simpson *et al.*, 2016). They may show alterations in breeding, social and predator defence behaviour (Bruintjes & Radford, 2013). Some fish species have also been shown to be deterred by artificial sounds (Jesus *et al.*, 2019; Murchy *et al.*, 2017). This especially is relevant to the effectiveness of fish passages: migrating fish should not be deterred by any noise produced by the sluices or any other structures near the passage. There are some observations which suggest fish may be deterred by river structures. At the Ijmuiden pumping station (Dutch: Ijmuiden maal- en spuicomplex) fewer European eel have been observed when the station is operating at full capacity than at half capacity, sound production most likely having a deterrent effect on the fish (Spierts, Vis, & Kemper, 2010). Thus, although the impact of anthropogenic sound on fish migratory behaviour is highly unpredictable, artificial sounds can bring about unwanted behavioural changes in fish. Therefore, frequent occurrence of loud noises near a fish passage could hamper migration success of certain fish species. A potential location for a new fish passage should be investigated for the presence of loud noise producing sources. It would be wise to avoid noisy areas, or otherwise take measures to mitigate excessive noise near the fish passage.

2.5.3 Fishery

Compared to other migratory riverine fish species, diadromous fish are at an increased risk of capture by fishing in estuaries (McDowall, 1999). Fish that are migrating up or downstream are notably vulnerable to the effects of fishery near barriers in the river. When migrating fish encounter a barrier, they are likely to exhibit searching behaviour, attempting to find passage upstream (Boubée *et al.*, 2008; Brevé , 2019; Klopries *et al.,* 2018). Although not much is known about the specifics of this searching behaviour (Bunt, 2001; Bunt *et al.,* 1999), at narrow passages or migration barriers, fish may spend considerable time searching for passage (Winter, 2009). In turn, this can cause high local concentrations of fish near barriers, making the migrating fish especially vulnerable to the effects of fishery near barriers (Winter, 2009). Not only can these fish more easily be caught, other disruptive effects from a fishery, such as noise created by fishing boats, may also negatively affect fish behaviour (as discussed in the section 'Sound'). Overall, it seems probable that fishery near fish passages will lead to reduced migration success of the target species. Fishing restrictions in close proximity to a barrier or narrow passage may alleviate these consequences.

2.6 Soil

The physical properties of soil is a key aspect to look into when reshaping the land. Globally, geology varies greatly between regions. In the Netherlands, rivers were one of the main influencers of the country's shape; during seasonal floods, deposition of clay, sand and gravel arose in coastal areas (Lamé *et al.*, 2014). The central area of The Netherlands is composed of river clay, whereas the east area is more sand based. When looking into specific regions, the soil composition and sedimentation need to be taken into account in order to grasp what kind of aesthetics can be applied to a fish migration river. Previous interviewees have indicated that the sedimentation and silt within the area is relatively high. These factors can play a role in the success of the fish migration as large quantities of sedimentation can lead to unfavourable conditions, such as clogging of the gills and elevated turbidity, reducing the vision in the waters (VFA, 2021).

2.7 Summary

Core Purposes

Altogether, the efficacy of an FMR requires the integration of numerous disciplines and is dependent on site-specific considerations to make it attractive and successful. One of the critical characteristics to consider is hydrology. Fish need to be able to overcome particular turbulence and current speeds to enter and pass the river. Therefore, the turbulence and the current speed should be adjusted to the swimming capacity of the targeted fish species. Other critical hydrological factors are the lure current and salinity gradient, which attract fish to the passage. The second aspect that should be considered is ecology. Diadromous fish species will mainly use a passage like an FMR as they migrate between salt and fresh water. Furthermore, the specific migration period of the targeted species should be considered. As migration is often related to the moment of spawning, the FMR should be fully accessible during these periods. Also, the swimming capacity of the targeted fish is essential to consider as this determines, together with the current speed of the river, if the targeted fish can pass through the FMR. Lastly, predation should be minimized in the area of the FMR, and the surrounding ecosystem should be attractive to create an optimal environment for migrating fish. The third aspect that is crucial to take into account is a disturbance. Human disturbance can have a negative influence on a migrating fish's ability to successfully pass a barrier or fish passage, thereby reducing the migration success of the target species. Soil is another vital aspect to take into consideration for ensuring a successful FMR, investigating what soil type is needed prior to constructing the FMR. In correspondence, looking at favourable sedimentation conditions would be ideal in terms of fish health and whether fish favour certain sedimentary conditions. When these core aspects of a fish passage or FMR are considered together with the site-specific conditions, the conditions should be in favour of successful migration.

Table 2 contains an overview of all aspects which should be considered for the design of a fish passage or FMR. In chapter 3, the hydrological, ecological and morphological conditions in the Haringvliet are discussed. Furthermore, the core purposes, as discussed in this chapter, are applied to the local situation.

Table 2. Overview table that summarizes the above information about the core purposes of a fish passage. The subject column contains important aspects to be taken into consideration for the design of a fish passage, subdivided into four main categories: hydrology, ecology, anthropogenic disturbance and soil characteristics. The second column contains a description of each aspect, and the third column discusses each aspect's relevance for fish passage design. Lastly, the fourth column suggests some specific considerations to be taken for each of these aspects in the design of a fish passage. This table is directly applicable for an FMR design as well.

Subject	Description	Relevance	Consideration
Hydrology	Those factors which are related to the distribution and movement of water and water condition.	Directly related to a fish's ability to pass a barrier. Affects suitability of environment for different species.	Hydrological parameters should be fine tuned for target species
a. Turbulence	The distortion of the water flow as it encounters solid objects	Has impact on fish swimming efficiency and sensory acuity. High turbulence may damage fish.	Should be kept under a certain threshold ($K \leq 0.05$ m2/s2).
b. Salinity	Amount of salt dissolved in a body of water.	Diadromous fish have need of a gradual transition in salinity in space and time. Transition period is species specific.	Suitably smooth salinity gradient is essential. Should be designed with target species in mind.
c. Current speed	Speed of movement of water from one location to the other.	Fish species and life stages differ in their ability to swim at specific speeds for a sustained period of time (critical swimming speed: U(crit))	Current speed through passage should not be higher than critical swimming speed of slowest target species (at least at regular windows of time).
d. Lure current	Artificially created water current with the purpose of luring migrating fish to fish passage.	Effectiveness of lure current affects ability of migrating fish to locate fish passage (homing). Affects migration success.	Lure current should be substantial enough for fish to locate. Lure current should be situated close to passage opening.
Ecology	The relations of organisms to one another and to their physical surroundings.	Needs to be considered to ensure target species migration success and survival.	Local ecology needs to be suitable for target species. Target species ecology needs to be incorporated into fish passage parameters.
a. Migration categories	The different categories migratory fish can be divided into, based on the salt and freshwater requirements during different life stages.	Determines direction of migration of species during different life stages. Directly related to location of spawning grounds.	Direction of migration of target species should be considered: passage should be suitable for migration both upstream and downstream, depending on species migration category.
b. Migration periods & cycles	Temporal patterns in fish migration.	Determines at which times target species have need of passage. This includes at which time of the year as well as the time of day (e.g. day or night).	Information necessary to make predications on migration timing of target species. Allows managers to know during which periods a passage should be open and the conditions required.
c. Swimming capacity	Factors related to a fish's ability to swim such as: passive or active swimming, critical swimming speed, energy expenditure and efficiency.	Determines fish's ability to pass a barrier. Determines energetic/fitness cost for passage.	Directly related to current speed (see hydrology section above). In the case of tidal migrants: tides through passage should be sufficient for tidal transport.
d. Predation pressure	Factors related to predation risk to migrating fish.	Amount of predation occurring affects migration success and thus recruitment of target species. High local fish densities often occur near barriers, in these situations, fish are more vulnerable to predation.	Measures to mitigate excessive predation of target species: • Increasing passage size decreases local fish density • Ensuring enough shelter/hiding places for target species
e. Supportive ecosystem	The extent to which a fish passage's surrounding environment can support migrating species (through e.g. food availability, shelter by vegetation or other organisms).	The suitability of the surrounding ecosystem may affect migration success of target species through: • Number of fish attracted to area • Physical condition of target species	Information on target species ecology is needed to ensure supportive ecosystem. May be improved by introduction of keystone species (reef-building organisms such as oysters or certain macrophytes (e.g. seagrass)).
Anthropogenic Disturbance	Disturbance of human origin.	May influence fish' ability to pass a barrier. May bring about undesired behavioural changes in target species.	Limit sources of anthropogenic disturbance where possible.
a. Artificial light at night	Artificial sources of light at night.	May increase target species vulnerability to predation near barrier. May affect species migration timing. Target species may reject illuminated routes.	Limit sources of artificial light at night near fish passage.
b. Sound	Artificial sources of sound.	May alter fish behaviour. May deter target species from passage.	Area should be investigated for loud noise sources. Loud noise sources should be avoided near passage.
c. Fishery	Impact of fishery on target species.	High local densities of migrating fish often occur near barriers. In these situations, fish are more easily caught by fishermen.	Implement fishing restrictions in close proximity to fish passage.
Soil	Pedology within the area and effects of sedimentation.	Needs to be considered to ensure area is an ideal place for passage construction and favoured conditions for migratory fish.	Local soil type needs to be suitable for target species.
a. Soil composition	Pedology of different soil layers which serves as an important tool for nutrient management.	Types of soil found within the area that can influence dredging and other necessary construction components.	Type of soil layering needs to be taken into account for construction.
b. Sedimentation	Particles that settle at the bottom of a body of water.	Can affect target species health. Affects visibility for target species.	Ensure sedimentation levels are not too high.

3 The Principles of the Haringvliet FMR

In this chapter we are first discussing the past, present and future conditions of the study location, which is the Haringvliet. The conditions of the Haringvliet will be analysed to understand the context and the necessity of an FMR. Next, the target species will be chosen to represent the migratory fish that were found in the Haringvliet area in the past and present. For each target species, their migration cycles, life cycles and hydrological requirements will be explained. After which, the current hydrology values in the Haringvliet will be determined. The soil composition and its effects will also be considered. Then there will be an explanation of the role of supportive ecosystems. The core purposes of an FMR in the previous chapter will be applied to our study location. The ecological and hydrological requirements of an FMR and its relation to the target species will be examined. Finally, we will investigate innovative ideas for increasing the attractiveness and effectiveness of the FMR for the target species.

3.1 Ecology: Past, Present, and Future

This section will review the past, present, and future occurrences of fish species inhabiting the Haringvliet to make a historical reference point for our study.

Unrestricted access to the habitats is one of the requirements to fulfil the life cycle process for riverine fish populations, particularly for diadromous fish species. This applies to downstream and upstream migration to and from nursery and spawning areas and interchange between salt, freshwater, and estuarine ecosystems in the Haringvliet. The construction of the Haringvlietdam (1971) puts sea influence to an end in the former fresh-salt gradient estuary. Several authors identified the closure of the estuary as a major cause of declining diadromous fish (Larinier 2001; Breve *et al.*, 2019). In the case of the Haringvliet estuary, which was closed off by a dam for flood protection, typical estuarine species were almost disappeared (Brink *et al.*, 2018). Figure 3 presents the sluice management protocol, explaining primarily drivers and impacts made to the area after the dam construction in 1971.

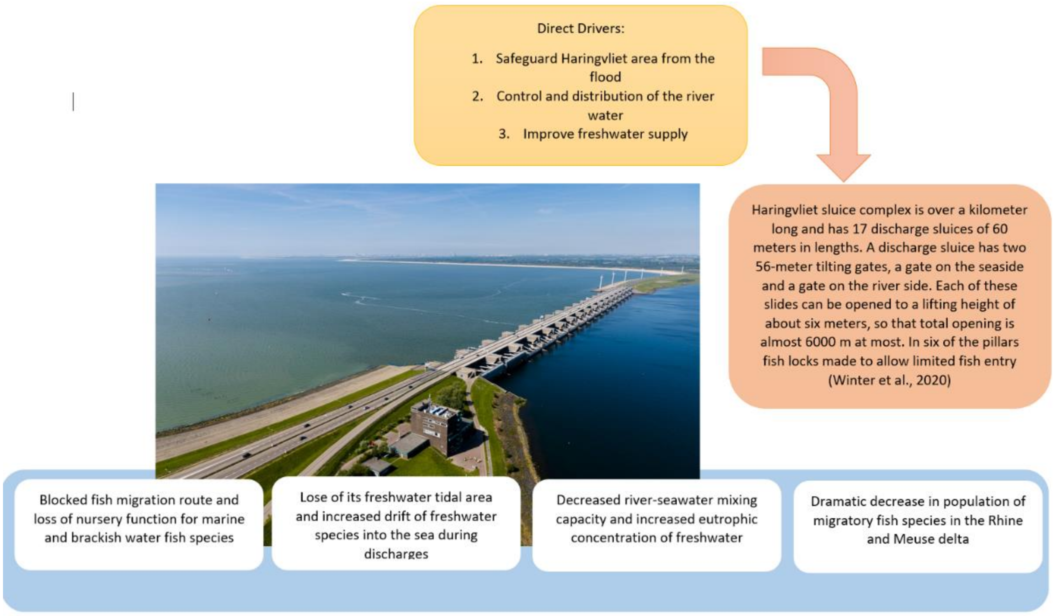


Figure 3. Overview of the Haringvliet sluice complex with an indication of main drivers and impacts on the local habitat of the estuary.

3.1.1 Fish Stock and Composition before Enclosure (1870-1970)

Before the dam construction, the Haringvliet was known as an area of great natural value. Several nature reserves existed in this area, but most of the marshes were exploited as reeds and as willow coppices or as beds of bulrushes by the community. The management of the Haringvliet estuary was constrained to nautical matters, coastal defence and fisheries (Fergusson and Wolff, 1984). Quak (2016), using fisheries statistics, made a historical study of the fish stock in the Haringvliet from 1870 to 1970. The author states that the estuarine system was discovered to be functional for a significant number of species, for estuarine species (smelt, flounder, eel, herring) as juvenile migratory fish, in addition serving as a gateway for spawning places for upstream fishes (salmon, allis shad, twaite shad, river lamprey). The report was based on the 16 target species developed by the Dream Fund Project Haringvliet. According to Raat (2001), in the Dutch part of the Rhine, 53 fish species have been recorded since 1900. Data analysed by Schaminee *et al.* (2019) confirm that in nine fishing trips, Vaas (1968) recorded at least 35 species in the Haringvliet and Hollands Diep right before it was closed off. Out of these 35 species, five classified as diadromous (smelt, eel, allis shad and three sticklebacks) and nine as estuarine residents (goby, fathead, sea snail, glass goby, lesser pipefish, sea bullhead), and six marine juveniles and seasonal guests, and six freshwater species (roach, bream, kolblei, alver, gudgeon perch). It is important to note that the decline of most migratory fish populations occurred due to an increase in organic and chemical contaminations and deterioration of water quality. As Quak (2016) mentions, between 1930-1970, water contaminations significantly contributed to the degradation of the fish stock, rather than the construction of the dam in 1970. Other studies by Admiraal *et al.* (1993) suggest that salmon (*Salmo salar L*.) have disappeared, and populations of allis shad (*Alosa alosa (L*.), twaite shad (*Alosa fallax (Lac.),* sea lamprey (*Petromyzon marinus L*.), and river lamprey (*Lamp Barbel* (*Barbus barbus* (L.)), dace (*Leuciscus leuciscus (L.)),* minnow (*Phoxinus phoxinus (L.)),* and burbot (*Lota lota (L*.) decreased dramatically. Appendix B represents fish species based on Quak (2016) and Hop *et al.* (2011) included in the analysis showing a historical fish estimate of abundance in the Haringvliet before the closure of the dam. This table represents 16 relevant species based on current policy strategies (Natura 2000 & EU Water Framework Policy) designed for the Voordelta and Haringvliet (Quak, 2016). These fish species primarily represent diadromous fish, as these species are highly vulnerable to migration barriers.

3.1.2 Fish Stock after Closure

The estuary closure abruptly halted estuarine geomorphological processes, transforming it into a lagoon-like system with only shallow currents and rapidly degrading sand and mudflats. The tide movements were drastically decreased to a few decimetres, eliminating critical ecological elements in fresh and brackish water tidal (Nienhuis, 2008). Consequently, anadromous fish species such as twaite shad (*Alosa fallax*) disappeared except for the catadromous flounder (*Platichtys flesus*) and a few smelt (*Osmerus eperlanus*). Common freshwater species like perch (*Perca fluviatilis*), roach (Rutilus rutilus), and bream (*Abramis brama*) quickly colonised the area. In 1974, perch took over the roach dominance that has existed since 1972. Since 1976, pike perch (*Stizostedion*) has become a popular sport fish (Smit *et al.*1997). Between 1991 and 2015, in Haringvliet, the water quality has improved, contributing to the richer occurrence of freshwater species (Bos *et al.* 2018; Schaminee *et al.* 2019).

3.1.3 The Fish Stock Situation in the Haringvliet/Voordelta before and after Kierbersluit

According to the report performed by Hop *et al.* (2016), summarised by Griffioen *et al.* (2017), there was active and passive fish monitoring of the Haringvliet and Voordelta areas carried out in the period 2006-2015 to gain insight into the composition of the present-day fish stocks. A total of 54 species were found in the Voordelta, compared to 53 species in the Haringvliet; over the years, there are 82 in total found in Haringvliet and Voordelta. There is a clear difference in the fish stocks' species composition for both areas caused by the differences in salt gradient. The size of the fish stock in the Voordelta is approx. 60 kg/ha, whereas in the Haringvliet 41 kg/ha and 361 heads/ha. In the Voordelta, the largest biomass (27%) consists of sprat, followed by pikeperch (14%) and (9%) flounder and (4%) houting. The 12 diadromous species were found both in the Voordelta and the Haringvliet. The diadromous species include eel, twaite shad, houting, river lamprey, sea lamprey, smelt, and Atlantic salmon. Less frequently encountered species are three-spined stickleback, allis shad and sturgeon for both the estuarine species (12), marine juveniles (12), marine seasonal guests (6) and marine species (7). The report estimates that the fish stock in the Haringvliet is dominated by bream (57%) based on biomass. Other species with a relevant share in the total biomass are zander (11%), roach (10%), houting (7%), eel (6%), carp (4%) and perch (3%). Based on the result of the catches, Hop *et al.* (2016) conclude the complete freshwater character of the Haringvliet, as results indicate the absence of the saltwater fish species in the trap catches. There was another sampling activity carried in 2018 by Ploegaert *et al.* (2019) in Haringvliet West and Voordelta, wherein Haringvliet West fish composition per estuarine was recorded over guilds (4) for diadromous, (1) estuarine resident, (1) marine juvenile, and (13) freshwater species were 19 species caught in total. Whereas in Voordelta, 25 species spread over six estuarine guilds: diadromous (7), estuarine residents (4), marine juveniles (4), marine vagrants (2), marine visitors (2), and freshwater (6). For both sampling trials, it is clear that in 2018 Haringvliet was still completely composed of fresh water, translating into the absence of marine juveniles and seasonal visitors as locks were still barely ajar.

3.1.4 Fish Fauna and Future Prognosis for the FMR

Our analysis of the prognosis for the target fish species for FMR is based on the Griffioen *et al.* (2017) prognosis of the migratory fish population for the Haringvliet and Voordelta. The original prognosis covered 16 species published in the "fish migration calendar" developed by Reeze *et al.* (2017). The summary of the overview made by Griffioen *et al.* (2017) is incorporated in the last column of Appendix B to use as a reference for our study.

The usefulness of an FMR in the Haringvliet can be examined using the Habitat-Corridor function in figure 4. For some species, access and migration from salt to fresh water through the corridor is vital to complete its life cycle; on the other hand, for some other species, access to the Haringvliet is of little importance.

For species like twaite shad, both the functions of corridor and habitat are significant, as shown in figure 4. For the twaite shad, the Haringvliet is important as a nursery for juveniles and provides passage to spawning grounds for adults. The effect of the FMR implementation for open migration is paramount to complete its life cycle and improve its current population, but at the same time, if the estuarine conditions in the Haringvliet are also comfortable because spawning takes in downstream stretches of the estuaries. For the three-spined stickleback, the importance of the FMR is great, because it can be used as a corridor for the migratory type of that group. The migratory type grows up in the sea and uses freshwater for the purpose of spawning. The population of the three-spined stickleback is expected to improve using the FMR corridor to access Haringvliet. The fish is expected to pass FMR between March and July for spawning or migration when the juvenile stays or returns to the sea from July to September. In the past, during monitoring works, three-spined sticklebacks were barely caught around Voordelta and Haringvliet (Hop, 2016). For the Atlantic herring, the importance of the Haringvliet is relatively small because the current population in the North Sea is relatively high, and the herring is expected to use the FMR to the Haringvliet estuary for foraging and growing purposes, especially for young juveniles.

For this reason, the expectation that FMR will improve the current herring population is minimal; however, the growing stock of the herring in the Haringvliet is important for predatory birds and fish. The FMR is very important for the river lamprey because it allows access to the upstream rivers for spawning. The population of the river lamprey is expected to improve significantly with the introduction of the FMR if the passage and habitat for growing juveniles are provided in the Haringvliet/Hollands Diep. For the flounder, the importance of the FMR is relatively insignificant because the larva, the juvenile, migrate to shallow coastal waters, sometimes further up the freshwater with the period of upstream migration from April/May to June/July and migrate downstream mostly for the foraging. For this reason, access to the Haringvliet is not crucial for the population of the flounders; the current prediction is that flounders will mainly use the FMR for growing and foraging purposes. Accessing the Haringvliet for the Atlantic salmon via the FMR is significant as it is migratory fish. Because the adult salmon will need an FMR to swim upstream between June and August, where the spawning takes place in November and December, and continue to live as larvae and leave the river as juveniles and returning finally to the river it was born. However, for the recovery of the population, the FMR is not sufficient as the only conservation measure, so other constraints limiting the salmon migration on the way to upstream rivers shall be addressed as well. For the European eel, the Haringvliet is one of the estuaries where the glass eel can grow up. The period of upstream migration for the eel is dependent on the availability of food and climatic conditions. For this reason, access to the Haringvliet via the FMR is significantly essential for the fish to complete a full life cycle; however, it is still unclear and unknown how the FMR will contribute to the whole population recovery.

Figure 4. Representation of the degree of importance of an estuary to provide corridor (Y-axis) and habitat (X-axis) functions (Griffioen *et al.*, 2017)

3.1.5 Summary

Study area: the Haringvliet

The introductory part of the section gives information on the original condition of the Haringvliet estuary before the enclosure with the dam in 1971. Then it is followed with an overview of the Haringvliet sluice complex with an indication of main drivers and impacts made from the dam construction on the local habitat of the estuary. We provided the historical data on the fish abundance in the study area before the closure of the dam based on the studies of Quak (2016) & Hop *et al.* (2011). Then this data was expanded with an analysis on the presence of fish stock before and after the Kierbesluit based on the report of several authors, Hop *et al.* (2016), Griffioen *et al.* (2017), and Ploegaert *et al.* (2019). Finally, the section concludes with a prognosis for the fish species based on the analysis conducted by Griffioen *et al.* (2017). All the data about the past and present occurrences and the future prognosis of the 16 fish species inhabiting the study area are presented in Appendix B.

3.2 Target Species and their Ecology

3.2.1 Target Species Selection

To realise the FMR and maximise it to its full potential, ecological conditions need to be adjusted to the specific needs of the target species that will be selected. Previous ACT groups already selected target species using different criteria. In the report of van den Tweel *et al.* (2021), they chose the target species from a list of 16 main migratory fish species that are found in the Haringvliet and the Voordelta (Appendix B) by the Haringvliet Dream Fund Project and Wageningen Marine Research (WMR, previously Institute for Marine Resources & Ecosystem Studies (IMARES)) (Reeze *et al.*, 2017; Winter *et al.*, 2020). They then selected their target species based on the same strategy that WMR performed to select their target species for the FMR in the Afsluitdijk based on several criteria (Griffioen *et al.*, 2014; Van Banning *et al.*, 2018; Van Calsteren & Stoop, 2015). The criteria that van den Tweel *et al.* (2021) used for selecting the target species were the current distribution, current location and conservation status. On top of that, they ensured that the species had an anadromous and catadromous migration in order to take the large range of ecological requirements into account. The current distribution of species was based of the period between 2015 and 2021 (NDFF, 2021). The status of the fish species was determined by a number of policies in Europe and the Netherlands, which are: Wet natuurbescherming, EU Habitat Directive, the Nieuwe Rode Lijst, IUCN Red List, Natura2000, Eel Management Plan and the Bern convention (van den Tweel *et al.*, 2021). The policies are based on different criteria, such as ecological importance, geographic distribution and rate of decline. This is again correspondent to the policy strategy used at the FMR in the Afsluitdijk (Van Calsteren & Stoop, 2015). Eventually, they chose five targe species consisting out of the Atlantic salmon, European eel, Twaite shad, European flounder and the European river lamprey (van den Tweel *et al.*, 2021). These five target species were selected because they were a priority for conservation for at least three of the chosen policies and for their potential of using an FMR. Legrand *et al.* (2021) selected four different target species during their ACT project, which are: Atlantic salmon, European eel, Atlantic herring and Three-spined stickleback. These target species were chosen based on several characteristics such as migration, current presence, role within the food web and economic and cultural importance. They also made the assumption that these species serve as indicators for other species (Legrand *et al.*, 2021). As the species lists from both ACT groups are based on and overlap with the before mentioned list of 16 main species found in the Haringvliet and Voordelta, we decided to use the species suggested by our previous ACT colleagues (Reeze *et al.*, 2017; Winter *et al.*, 2020).

To conclude, the seven species, as two species overlap, we defined as target species are: Atlantic salmon, European eel, twaite shad, flounder, European river lamprey, Atlantic herring and three-spined stickleback. These seven target species have a high FMR user potential, based on passage through the locks that are ajar as a consequence of the Kierbesluit and their presence in the Voordelta (NDFF, 2021; Ploegaert *et al.*, 2019). They also have a high conservation value and serve as indicator species (van den Tweel *et al.*, 2021; Legrand *et al.*, 2021). As the overall goal of the FMR is to reconnect the North Sea with the Haringvliet area, it indicates that the FMR is essential for diadromous fish as target species because they migrate between salt and fresh water to fulfil their lifecycle (Deinet *et al.*, 2020; Dorst, n.d.). With an open migration route, marine juveniles and estuarine fish that lived in the brackish border between salt and freshwater will also be supported again. As the hydrological and ecological conditions of the FMR are based on the requirements of these target species, we will now specify their ecological needs in order to make the FMR as effective as possible for these species (also see table 3).

3.3 Target Species

3.3.1 Atlantic salmon (*Salmo salar*)

The Atlantic salmon is an anadromous fish that spends most of its adult life at sea and spawns upstream in the rivers (Laak *et al.*, 2007). The Atlantic salmon is an active migratory fish (Laak *et al.*, 2007; van Emmerik, 2016). This indicates that the salmon is not dependent on selective tidal transport and are, therefore, 'strong' swimmers. Temperature is an important cue for the initiation of migration (van den Tweel, 2021; Aas *et al.*, 2010; Deelder, 1984; Maitland & Hatton-Ellis, 2003). afsluitdijk.nl, 2015; Winter *et al.*, 2020). They start migrating during late spring, summer or autumn to rivers upstream. The spawning period is from November until December. After spawning, a part of the adults pass away, and other adults migrate back to the sea to get stronger and to potentially take part in reproduction again. The juveniles remain in streams close by the spawning ground until they are a maximum of seven years old. During this period, the juveniles are in the smoltification process to prepare them for the transition to salt water. These smolts then grow up in the sea for one to three years, after which they will migrate back to the rivers to spawn (Laak *et al.*, 2007;

Winter *et al.*, 2014). The lifespan of Atlantic salmon is approximately 13 years (Froese & Pauly, 2021). Salmon usually migrate during the night, but depending on predation risk and hydrological conditions, they can also migrate during the day (Kennedy *et al.*, 2013; Laak *et al.*, 2007; Aas *et al.*, 2010; Winter *et al.*, 2014). Furthermore, they have a swimming capacity of approximately 4.0 - 7.8 m/s (Laak *et al.*, 2007; van Emmerik, 2016; Winter *et al.*, 2014). The velocities that are needed for the Atlantic salmon are: 0.3 - 0.8 m/s in their reproduction stage, 0.05 - 0.25 m/s in their juvenile stage and a maximum of 2 m/s in their adult stage (Laak *et al.*, 2007; van Emmerik, 2016; Winter *et al.*, 2014). Salmon are present in a habitat with gravel, sand, boulders and stones. They can use that as a refuge or a resting place. For a refuge, they also prefer obstacles for the predator and hiding places, such as shallow banks, vegetation and potholes (van Emmerik, 2016). The salt tolerance also differs per life stage. The eggs and larvae do not have salt toleration as this increases during the smoltification process they undergo as juveniles, when becoming an adult, they are completely tolerant (Laak *et al.*, 2007; van Emmerik, 2016; Winter *et al.*, 2014). Salmon feed on plankton in their larval phase; insects, juvenile herring, shrimps in their juvenile phase; and other fish during their adult phase (Laak *et al.*, 2007; van Emmerik, 2016). They need a dissolved oxygen level of > 6 mg/l (Legrand *et al.*, 2021; van Emmerik, 2016). Finally, the salmon need a temperature of 1.5 - 9 °C for their reproduction stage, between 13 – 20 °C in their juvenile stage, and for an adult, the optimum temperature is 18 – 22 °C, whereas 28 °Cl is lethal (Froese & Pauly, 2021; Laak *et al.*, 2007; van Emmerik, 2016; Winter *et al.*, 2014).

3.3.2 European eel *(Anguilla anguilla)*

European eels spawn in saltwater and travel to freshwater to forage and become mature before returning to the sea to spawn between September and November (van den Tweel, 2021; Van Emmerik, 2016). Glass eels have a swimming capacity of 10-12 cm/s over brief intervals (Langdon & Collins, 2000; Legrand, 2021; Wuenschel & Abel, 2008). Because of this, eels heavily rely on tidal activity and flooding within estuaries. (Dou & Tsukamoto, 2003; Langdon & Collins, 2000; McCleave & Kleckner, 1982). Glass eels have a swimming speed of 0.4 m/s, whereas in later stages, their swimming speed increases; yellow eel has an average swim speed of 0.43 m/s, and the silver eel has a swimming speed of 0.66 m/s (Legrand, 2021; Quintella *et al.*, 2010). As the glass eel does not swim actively, it uses the incoming tides to migrate more efficiently (Legrand, 2021). Eels are able to endure low oxygen levels as they can burrow themselves underneath the sedimentation, creating excellent hiding spots from predators (Maes *et al.*,2007). In addition, these resting spots are also used when eels are acclimatising to the salinity gradient throughout rivers; this can take up to 3 weeks (Cresci *et al.*, 2020; Rankin, 2009). In terms of predation, eels tend to stay near rocks and underneath other objects to hide for predatory fish and birds (van den Tweel, 2021). The alteration in temperature is one factor that drives the eels to migrate upstream, this usually occurs around February to June (van den Tweel, 2021). The majority of eels move upstream when temperatures reach about 9-11°C (Deelder, 1984; Solomon & Beach, 2004).

3.3.3 Twaite shad (*Alosa fallax*)

The Twaite shad is an anadromous fish with an unclear status in the Netherlands (Froese & Pauly, 2021; Laak, 2009; van Emmerik, 2016). Their lifespan is approximately 12 - 13 years (Froese & Pauly, 2021; van Emmerik, 2016). The Twaite shad is dependent on the tidal current. Thus, they are tidal migrants who migrate during high tides (Aprahamian *et al.*, 2003; Laak, 2009; van Emmerik, 2016). The shads that are ready to spawn are gathering together in April or May in an estuary. After they gather, they migrate upstream from April until June. They spawn above the gravel and coarse sand. The juveniles start gathering in an estuary in the summer and the start of autumn. From there, they will migrate to the sea from July to November (Aprahamian *et al.*, 2003; Laak, 2009; van Emmerik, 2016; Winter *et al.*, 2014). The shad migrates during the day and night, but especially during the day (van Emmerik, 2016; Winter *et al.*, 2014). The swimming capacity of the shad is 1.9 - 5.7 m/s for the adults and approximately 21 km/day (van Emmerik, 2016). The shad spawns in calmly flowing water, which needs to have a velocity of 0.2 - 0.5 m/s. The juveniles also stay in 0.2 - 0.5 m/s velocities. When the shads turn into adults, they can be in velocities until 2 m/s (Aprahamian *et al.*, 2003; van Emmerik, 2016). The salinity needs to be 0.3‰ for the shads that are spawning because the eggs do not have a tolerance for salt yet. When the fish are at the juvenile stage, then they can have a salinity of 0.3 - 35‰. Furthermore, the adults can tolerate 35‰, which means that they can swim in salt sea water (Laak, 2009; van Emmerik, 2016). Shads are eaten by otters, dolphins and pikes (Laak, 2009). Shads consume zooplankton, plants, insects, crustaceans and other fish (Aprahamian *et al.* 2003; Froese & Pauly, 2021; van Emmerik, 2016). The shad start migrating to spawning ground when the temperature of the water is 10 - 12 °C. They spawn at approximately 15 °C. The larval phase can tolerate 17 - 25 °C. Furthermore, juveniles migrate back to the sea when the temperature is below 19 °C (Aprahamian *et al.*, 2003; Froese & Pauly, 2021; Laak, 2009; van Emmerik, 2016). Juveniles need at least dissolved oxygen levels of 4 mg/l, otherwise they will avoid areas with dissolved oxygen levels below 4 mg/l. The preferred dissolved oxygen levels are at approximately 9 mg/l (Aprahamian *et al.*, 2003).

3.3.4 European flounder (*Platichthys flesus*)

The European flounder is a catadromous flatfish that is common in the Dutch estuarine waterbodies (Reeze *et al.*, 2017). This species is the only West-European flatfish that migrates far into fresh water (Griffioen *et al.*, 2014). Historically it could be found in German parts of the river Rhine, but due to the many introduced obstacles, this is not possible anymore (Griffioen *et al.*, 2014). The adults migrate seawards during winter to spawn and return from April until July (Reeze, 2017; Griffioen *et al.*, 2014). Water temperature does not play a role as the migratory cue, and it should be under 28 °C (van den Tweel, 2021; van Emmerik, 2016; Skerrit, 2010). The flounder has a low swim capacity (Griffioen *et al.*, 2014). Juveniles can swim 0.17 – 0.27 m/s when cruising and 0.47 – 0.77 m/s when sprinting (van den Tweel, 2021; Videler, 1993; De Boer, 2001). Because of its low swim capacity, they also use the tidal current to move to their spawning or feeding sites (van den Tweel, 2021; Reeze, 2017; Griffioen *et al.*, 2014). The preferred current speed is not known for these fish. Flounders are tolerant of salinity transitions as long as they are not abrupt (van Emmerik, 2016; Reeze, 2017). Juvenile flounder feeds on plankton and insect larvae, adult fish feeds on small fishes, benthic fauna and small invertebrates (Froese & Pauly, 2021).

3.3.5 European river lamprey (*Lampetra fluviatilis*)

The morphology of the European river lamprey is unlike most other fish. It is an anadromous species and has an eel-like appearance. This lamprey seeks freshwater during spawning phases and migrates inland through rivers such as the Dutch Rhine and Meuse. The swim capacity of the lamprey is approximated to be around 0.01 to 0.5 m/s (De Boer, 2001). During resting periods and strong currents, lampreys tend to attach themselves to rocks or other objects; more so, they share a low tolerance for turbulence. Lamprey has a somewhat peculiar life cycle. Juveniles, also known as ammoecetes, remain in fresh water silt beds for up to three to six years (van den Tweel, 2021). The ammocoetes have the proficiency to survive with low oxygen levels as they burrow underneath silt beds (Potter *et al.*, 1970; van den Tweel, 2021). Once they gain sex organs and features such as the eyes and teeth, they migrate to the sea; here, they remain for two to three years before returning to the rivers for spawning (Docker, 2015; van den Tweel, 2021). Adult lamprey usually migrate upstream around September and November time (Pereira *et al.*, 2019). Migration upstream usually has temperatures between 15 and 19 degrees (van den Tweel, 2021).

3.3.6 Atlantic herring (*Clupea harengus*)

The Atlantic herring has become a substantial part of Dutch traditions in terms of consumption. Remarkably, herring spawn their eggs onto small objects such as shells. These objects move at relatively high-speed velocity through rivers such as the Rhine and Meuse. Unlike the Atlantic salmon, herring has a slower swimming capacity of 0.5 m/s. The juveniles reside around the Haringvliet and remain there at ages one to three years old; once the juveniles become adults, they join the schools of adult herring and migrate vertically to freshwater spawning grounds (Dickey-Collas, 2005; Legrand, 2021). These juveniles and adults have different preferences for optimal surrounding temperatures of 8-12 degrees and 13-15 degrees, respectively (Dickey-Collas, 2005; Legrand, 2021; Stevenson & Scott, 2005). Whereas the ideal salinity concentration for juvenile herring would be around 28-32 PSU (Legrand, 2021; Stevenson & Scott, 2005). Nevertheless, there seems to be a correlation between temperature and the desired salinity levels; when temperature decreases (< 10°C), the preference towards higher salinity conditions increases to ~29 PSU (Legrand, 2021; Stevenson & Scott, 2005). Dissolved oxygen requirements for juvenile herring is approximately 7-11 mg/l (Legrand, 2021; Reid *et al.*, 1999).

3.3.7 Three-spined stickleback (*Gasterosteus aculeatus*)

The Three-spined stickleback population consists out of small fishes with non-diadromous or anadromous subpopulations (Emmerik & Nie de, 2006; Legrand *et al.*, 2021; Reeze *et al.*, 2017). The anadromous Three-spined stickleback used to be very abundant in Dutch waterways until the Afsluitdijk and the Delta works were completed (Reeze *et al.*, 2017; van Emmerik, 2016). It had great importance in the food web as they are predated on by migrating salmon and birds (Legrand *et al.*, 2021; Griffioen *et al.*, 2014 & 2017; Reeze *et al.*, 2017). These fish can sprint for 0.7 – 0.9 m/s and the maximum current speed should be 0.2 m/s, the cruising speed is unknown (van Emmerik, 2016). They feed on small crustaceans, insects and small fishes (Froese & Pauly, 2021). Their tolerance to salinity is unknown, but as they are anadromous, they should be able to tolerate the transition from fresh to salt water (van Emmerik, 2016). Optimal water temperatures are between 4 – 20 °C. The Three-spined stickleback migrates to the river from February until May and returns from July until September (van Emmerik., 2016).

Table 3. Seawater has a salinity of 35 ‰ (Laak, 2009; van Emmerik, 2016). When NA is filled in the information is not available or, for example, at current speed, it can mean that the species is using tidal transport and does not swim actively in that moment (Legrand *et al.*, 2021; van der Tweel. All information is from van der Tweel *et al.* (2021) & Legrand *et al.* (2021) unless stated otherwise. (1) van Emmerik, 2016, (2) Cresci *et al.*, 2020, (3) Reeze *et al.*, 2017 (4) Laak *et al.*, 2007 (5) Winter *et al.*, 2014 (6) Froese & Pauly, 2021 (7) Langdon & Collins, 2000 (8) Wuenschel & Abel, 2008 (9) Aprahamian *et al.*, 2003 (10) Quintella *et al.*, 2010 (11) Skerrit, 2010 (12) Videler, 1993 (13) de Boer, 2001 (14) Pereira *et al.*, 2019 (15) Dickey-Collas, 2005 (16) Stevenson & Scott, 2005

Species	**Life stage**	**Water temperature for optimal migration (°C)**	**Swimming capacity (m/s)**	**Current speed needed in FMR (m/s)**	**Strong/weak swimmer?**	**Salinity Tolerance**	**Migration period**	**Time of day during migration**
Atlantic salmon (*Salmo salar*)	Juvenile	13 – 20 [1/4/5/6]	NA	0.05 – 0.25[1/4/5]	Strong[1/4]	None/acclimatization[1]	NA	Night
	Adult	18 – 22	4.0–7.8[1/4/5]	< 2.0 [1/4/5]	Strong[1/4]	Tolerant[1]	Around summer	Mainly night
European eel (*Anguilla Anguilla*)	Juvenile	9 – 11	0.1 – 0.12 [7/8]	0.4	Weak	Tolerant[1]	NA	Suggest night
	Adult	20	0.43 – 0.66 [10]	NA	Weak	Tolerant[1]	Sept - Nov	Night
Twaite shad (*Alosa fallax*)	Juvenile	< 19 [1/4/6/9]	-	0.2 – 0.5 [1/9]	Weak [1/4/9]	0.3 – 35 ‰[1]	July – Nov	Mainly daytime
	Adult	+/- 15 [1/4/6/9]	1.9 – 5.7 [1]	< 2.0 [1/9]	Weak [1/4/9]	35 ‰[1]	April - May	Mainly daytime
European Flounder (*Platichthys flesus*)	Juvenile	Not determinant, < 28 [1/11]	0.17 – 0.77 [12/13]	NA	NA	Tolerant[1], but need acclimatisation[3]	NA	Mainly daytime (1)
	Adult	Not determinant, < 28 [1/11]	NA	NA	NA	Tolerant[1], but need acclimatisation[3]	Winter	Mainly daytime (1)
European river lamprey (*Lampetra fluviatilis*)	Juvenile	NA	NA	NA	NA	Acclimatization[1]	NA	Mainly daytime
	Adult	15 – 19	0.01 – 0.5 [13]	NA	NA	< 12 g/l[1]	Sept – Nov [14]	Mainly daytime
Atlantic herring (*Clupea harengus*)	Juvenile	8 – 12[15/16]	NA	NA	NA	28 – 32 ‰	June - July	NA
	Adult	13 - 15 [15/16]	0.5	NA	NA	NA	May - June	NA
Three-spined stickleback (*Gasterosteus aculeatus*)	Juvenile	5.6 – 20[1]	NA	NA	NA	Unknown	July – Sep [1]	NA
	Adult	4 – 20	NA	0.2[1]	NA	Unknown	Feb – May [1]	NA

3.3.8 Summary

Target fish species

The selected target species are based on the reports from Tweel *et al.* (2021) and Legrand *et al.* (2021). They used different criteria and characteristics to determine these target species. In total there were seven target species selected: Atlantic salmon, European eel, twaite shad, flounder, European river lamprey, Atlantic herring and three-spined stickleback. These seven target species have a high FMR user potential, based on passage through the locks as a consequence of the Kierbesluit and their presence in the Voordelta. They also have a high conservation value and serve as indicator species for other migratory fish species. The FMR is essential to reconnect the North Sea with the Haringvliet area. Hence, the FMR will provide a passage for diadromous fish to migrate between salt and freshwater to complete their life cycle. The hydrological and ecological conditions of the FMR are based on the requirements of these target species. Therefore, the ecological needs are specified for each of the target species, to make the FMR as attractive and effective as possible for these species.

3.4 Hydrology

The hydrology of the Haringvliet has recently changed due to the decision to keep the sluices ajar on occasions, in an effort to restore the fish migration (Noordhuis, 2017). The execution of the Delta-21 plan and the creation of an FMR will change the hydrology as well. The following sections will explain the current hydrological parameters in the Haringvliet and around the sluices, so this information can be considered in the creation of the FMR. The information for the hydrology is based on the report from Noordhuis (2017). As described in the previous chapter, the turbulence and lure current are important hydrological components of the FMR. These components are not specifically related to the current situation in the Haringvliet but should be considered when the design for the FMR is tested with hydrological simulations. The parameters that will be described are salinity, current speeds and tides.

3.4.1 Tidal Information

The tidal situation in the Haringvliet only experienced small changes due to the Kierbesluit. As of 2004, the tidal waves outside of the Haringvlietdam (seaside) were about 2.35 m high (Leeuwen *et al.*, 2004). In 2017, it was expected that these tidal waves would decrease to 2.29 meters as a result of the Kierbesluit (Noordhuis, 2017). Multiple waves coming from different directions bring forth processes of interference, making the period of high tide shorter than the period of low tide. The period in which the water level of the sea is higher than the water level of the Haringvliet only lasts about four hours. In the Haringvliet, the tidal waves are about 30 cm up to the Biesbosch. The tidal difference does not decrease towards the Eastern direction of the water body, because the tides are mostly regulated by the Nieuwe Waterweg. The opening of the sluices for the Kierbesluit is partly dependent on the tides. In periods of low tides, the sluices remain 200 m2 wider in comparison to high tide conditions. If there is a small amount of water disposal of less than 100 m3/sec, then the sluices close for the high tide as well as the low tide. Thus, the sluices may be closed for longer periods of time during dry years. According to simulations, in approximately 30% of the years there will be situations during the fall where this small disposal lasts longer than a month, with maxima of two or three months during the years with the least amount of precipitation. If there is a high amount of water to be disposed of more than 2500 m3/sec, then all the sluices open for the low tide, but probably never during high tide (Noordhuis, 2017).

3.4.2 Current Speed

Besides the fish migration, the opening of the sluices also influences the current speed. The current speed was measured in 1997 as part of the salt-intrusion trials (Noordhuis, 2017). When the sluices opened to the height of 90 cm, then the speed of the current was 0,6 m/s. When the sluices opened to 450 cm, then the current speeds increased to 3,8 m/s. During water disposal (spuien), the speeds at the same sluices were between 0,5 and 1,5 m/s. The current speed is influenced by the depth of the water body. Particularly during the high tide period, the current speed farther from the sluices was higher towards the surface compared to the seabed. The current close to the bottom is a stream of return flow towards the sea during the majority of the period of high tide. It is expected that the kierbesluit will not have an incredibly significant effect on the current speeds, with an expected increase of 1-2 cm/s (Noordhuis, 2017).

3.4.3 Salinity

The effects of the introduction of the Kierbesluit on the salt intrusion are mainly driven by the changes in the flow rate distributions in the Haringvliet. An increase in flood flow rate will increase the maximum length of salt intrusion. When the residual discharge is increased (outflow minus inflow) then the length of the area, over which the salt intrusion shifts (varies) during a complete low tide and high tide period, shifts towards the sea (van Leeuwen *et al.*, 2004).

The research of Noordhuis (2017) found that salt water will intrude farther inland along the south bank than along the north bank. This salt intrusion consists of two phases. The first phase occurs at limited inlet flow rates, in which the inflowing saltwater fills the deep wells directly behind the Haringvliet locks. When these wells are full, the second phase begins, in which the saltwater spreads further over the bottom ground of the Haringvliet (Tiessen *et al.*, 2016). The saltwater follows the deepest parts, therefore distribution on the south side of Haringvliet takes place faster and further than on the north side, where there are shallower sandbars between the deep wells (Tiessen *et al.*, 2016). In the south it reaches the deep well at Middelharnis within a few days via the old tidal channel. On the north side, seawater is first collected in the deep well between the Haringvliet locks and Hellevoetsluis approximately 1.5 - 2.5 km behind the lock complex, after which it further intrudes into the Haringvliet (Noordhuis, 2017). During low tide, a portion of this water will be washed out again, especially the upper part, and a dynamic equilibrium will be formed (Tiessen *et al.*, 2016).

The Kierbesluit stipulates that the salt intrusion may not extend further east than the Spui-Middelharnis line. According to Noordhuis (2017), the salt intrusion did not infiltrate any further than the Spui-Middelharnis line. However, this is not guaranteed for the future. The Kier adapted this through the relationship between the river flow rate and the size of the opening. Furthermore, the Kier also adapted this via the "freshwater flushes" preceding periods with low flow rates (Noordhuis, 2017).

The effect of how far the salt intrudes in the Haringvliet will also determine the amount of mixed salt and freshwater, known as brackish water (Jacob *et al.*, 2003). After the inflow of the salt water, limited mixing takes place over the entire water column, but only close to the locks. Then an area is created with a vertical salt gradient, which further from the locks ends abruptly in a "plungeline". This "plungeline" is an abrupt boundary between brackish or salt water and fresh river water, which is stronger when the river discharge is greater compared to the flood current (Jacob *et al.*, 2003).

Considering that saltwater is slightly heavier than fresh water, the saltwater drops under the fresh water of the river when it enters during a flood period. This means that the mixed water also has a higher density than the fresh water and slides under the fresh water in the form of a density current. As a result, there is stratification east of the plunge line. Salt will remain in an area, due to the difference between the inflow and outflow location. During discharge, stratification also occurs on the outside of the locks, and when it is let in again, particularly the cargo of fresh water from the top layer will enter (Jacobs *et al.*, 2003).

Research done by Jacobs *et al.* (2003) indicated that when the water was mixed over the entire water column – the salinity in Haringvliet reached approximately 1000 mg/l. A few kilometers from the lock, the water in the top layer remained fresh. The salt intrusion suggests that the mixing zone extended to about 3 km upstream of the locks during a flood period midway through the salt intrusion. Salt in the lower layer was measured along the southern edge up to 7 km from the locks, where the salinity was 350 mg/l. The top layer was fresh water (Bol, 1996).

3.4.4 Adapting the Current Hydrology to a Haringvliet FMR

The Haringvlietdam is of profound influence on the hydrology in the Haringvliet. The main purpose of the Haringvlietdam is water management and land protection. This means that the opening of the sluices is done very carefully. The amount of water disposal, the tides and the time of year can all limit the amount of time that the sluices are opened for fish. For the creation of the FMR the limitations of the Haringvlietsluices can be considered. If the FMR can stay open in situations where the sluices are closed, then the FMR can facilitate that the Haringvliet is more accessible for fish at any time.

According to earlier mentioned research, the lowest measured current speed in the Haringvlietsluices was 0,5 m/s during water disposal. If this is truly the lowest current speed, then certain migratory fish species won't be able to swim through the sluices, such as the European eel (swimming capacity: 0.1 - 0.12 m/s). More information about targeted fish species and their swimming capacities can be found in chapter 3.3 "Target Species". The current speeds and the turbulence in the FMR can be adapted to the needs of the targeted fish species in the design. When a specific design is proposed, hydraulic simulations can be used to calculate the current speeds in the various parts of the FMR. From these simulations, it can be concluded whether every target species will be able to find a route where the currents are not too strong for their swimming capacity. If it is found that certain species do not have a route that they can use, then the design can be adapted. For example, if the depth of the FMR is increased, the current will be weaker in these parts, and fish with a weaker swimming capacity can use that route. This makes the FMR accessible for all targeted fish species, and thus a great addition to the current migratory route through the Haringvlietsluices.

The lure current in the Haringvliet FMR should be easily detectable by fish. Detectability is increased when the lure current reaches beyond the entrance of the FMR and when the lure current is as large as possible. Considering the tides will also increase the effectiveness of the FMR. The tide waves can help fish that are not strong swimmers to use the FMR. Therefore, the entrance of the FMR must be as wide as possible and in a location where the waves of the high tide can enter.

The salinity in front and behind the locks are important to consider in order to incorporate this in the FMR. The difference in salinity values is crucial to decide how salt and freshwater can be mixed to create a brackish area. The target species can acclimate in the brackish area before they migrate up and downstream. Each target species has its own acclimatisation time. This needs to be considered in implementing the FMR. The acclimatisation time of the target species in brackish water will provide information about what the length of the FMR should be, in order to make it effective.

In the end, most of the hydrological properties of the FMR will result from the design. Therefore, hydraulic simulation and civil engineering will be necessary for the creation. However, the information above provides a summary of all the aspects that require consideration in the hydrology of an FMR.

3.4.5 Summary

Hydrology

The hydrology of the Haringvliet has recently changed due to the decision to keep sluices ajar on occasions, to restore fish migration. The execution of the Delta-21 plan will also have a large impact on the current hydrology. The opening of the sluices partly depends on the tides. In periods of low tides, the sluices remain wider opened than in periods of high tide. The sluices facilitate the water disposal of water that enters the Haringvliet from the rivers. In dry years, the sluices will be closed for longer periods of time. The opening of the sluices affects the intrusion of salt water in the Haringvliet. Salt water is heavier than fresh water, and so the saltwater drops under the fresh water of the river when it enters.

In the adaptation of an FMR to the current Haringvliet hydrology, it must be considered that the lure current is detectable by the fish. The FMR can be a great addition to the Kierbesluit if it can remain open in times where the sluices are closed. The current speed of the flow through the sluices is higher than the swimming capacity of some target species, giving another reason to supply the Kierbesluit with an FMR. The length of the FMR should allow for proper water mixing, the target species should have enough time to acclimatize. Before the FMR comes to a final design, extensive hydraulic testing is needed to make sure the hydrology suits the need of the targeted fish species.

3.5 Soil

3.5.1 Soil Composition

The Netherlands comprises a large range of soil types across the country, ranging from sandy soils in the East and clay-like soils in the West. Coming to terms with the type of soils found within the area could aid in foreseeing the abiotic conditions that will be present in the proposed FMR. As the FMR can be proposed for different locations, becoming acquainted with the requirements needed in terms of site clearance, bearing capacity and dredging is vital; thus, we can refer to the Civil engineering procedure, 7th edition, published by the Institution of Civil Engineers (ICE) to get a better grasp of aspects involved in water construction works (Institution of Civil Engineers, 2015).

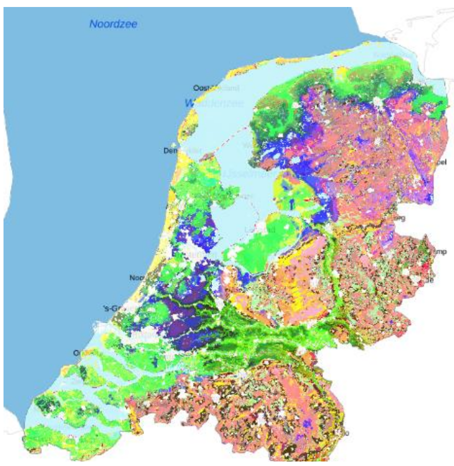


Figure 5. Soil composition found across The Netherlands, including podzol soils (pink), peatlands (blue) and calciferous/azonal soils (green) (DINOloket, 2021).

<u>Dutch Soil Composition</u>

The Netherlands consists of 3 main dominant soils, the podzol soils, peaty soils and clay-like soils. A Dutch database for soils (*DINOloket*) was used for a thorough understanding within the area (DINOloket, 2021). The pink area found in figure 5, consists of podzol soils ("*veldpodzolgronden"*).

Podzol soils encompasses a large range of sandy subgroup soils; these soils are composed of a thick humus layer at the top and thick colloidal humus layer in the subsoil (Van Heuveln, 1980). The area has formed into a podzol area through deforestation and excessive grazing (Van Heuveln, 1980). The bright blue areas indicated in figure 5, are known as the peatlands in The Netherlands ("*veengronden*") and also consists of several subgroups. Peat consists of partially decomposed plant matter and stocks-up a large amount of carbon; its characteristics is known as water saturated, acidic, and low nutrient environments (Verhagen *et al.*, 2009). The green areas seen in figure 5 is known as azonal soils ("*vaaggronden*") and is composed of silty/clay soils. The azonal soils are primarily found towards the coastal provinces and in the Haringvliet area.

<u>Haringvliet Area Soil Composition</u>

The Haringvliet area is mostly surrounded with azonal soils ("*vaaggronden*"). Azonal soils can be seen as fresh youthful soils that did not yet have the time to develop into complete horizontal layers; due to this, the soil is particularly silty due to high amounts of sedimentation and has a clay-like structure (McLintock, 1966). Both the colours yellow and green in figure 6 represent a subgroup of azonal soils, "*nesvaaggronden*" and "*poldervaaggronden*" respectively. Nesvaaggronden are composed of weak bottom layers with clay on top and are often calcareous (de Bakker *et al.*, 1989). Whereas, poldervaaggronden are composed of silty and clay-like soils with peat deeper than 80cm underground (de Bakker *et al.*, 1989). A main distinction between these azonal soils is that poldervaaggronden are fully matured (de Bakker *et al.*, 1989).

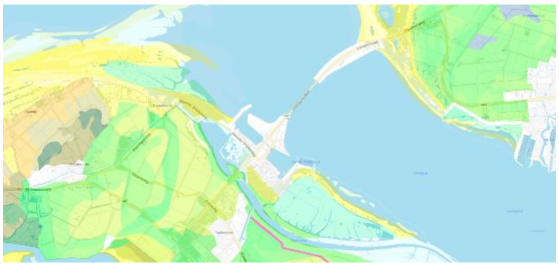


Figure 6. The soil composition found around the Haringvliet, both green and yellow colouring are azonal soils, with subgroups "poldervaaggronden" and "nesvaaggronden" respectively (DINOloket, 2021).

3.5.2 Sedimentation near The Haringvliet

The Entrance and Exit

An inlet can be referred to a connection between the sea and an opening within the shoreline, leading to an entrance towards a river or lake (Harrison *et al.*, 1964). The morphological shape of an inlet is partly dependent on the littoral drift that occurs from the seaside inwards (Wegman *et al.*, 2015). Several factors are involved in the sediment transport along an inlet, such as tidal amplitude and both the direction and strength of a wave (Chen *et al.*, 2015). Sediment transport along the coastline could block the inlet if these factors are not strong enough (Zimmerman *et al.*, 2009). This is an aspect to keep into account when choosing a desirable location for the FMR in the Haringvliet, which will be covered in chapter 4 ("scenario evaluation").

Throughout the River

Without going into detail on types of dredging, the process of extending or making a new river would most likely involve mechanical and hydraulic dredging (Anish, 2021). It is predicted that the proposed FMR river will be composed of high silt and sedimentation levels due to the low currents within the area behind the dam. As dredging also involves the removal of sedimentation, it would be ideal for there to be at least partial sedimentation, as some target species have a preference. Target species such as the flounder prefer azonal soils as they are then able to burrow themselves underneath the muddy layers (Aas *et al.*, 2010; Foulds *et al.*, 2013; van den Tweel *et al.*, 2021). In contrast, the river lamprey prefers to remain on solid structures during resting stages, and the Atlantic Salmon prefers resting near boulders (Deelder, 1984; van den Tweel *et al.*, 2021). Thus, an ideal situation would be to have a complete dredged area and a partly dredged area, which still composes a sediment environment. Likewise, forming pothole-like structures that allow increased silty areas, for species such as flounders could make the river diversifiable for fish preferences.

3.5.3 Summary

Soil

Getting acquainted with the soil in the area is a vital part that determines the FMR construction. The Netherlands is made up of a diverse set of soils, ranging from sandy to extreme muddy properties. This chapter reviewed the types of soils near the Haringvliet – dominantly being azonal soils ("vaaggronden") of which subgroups are "nesvaaggronden" and "poldervaaggronden". Furthermore, this chapter covers the type of sedimentation that might occur near the FMR, and the ideal soil conditions for the different target species.

3.6 Supportive Ecosystem

A supportive ecosystem is an environment which provides the target species with sufficient possibilities for foraging and shelter, and can function as a nursery or spawning ground. As discussed in chapter 2, a supportive ecosystem may improve the efficiency of a fish passage or FMR. A supportive ecosystem around the FMR could increase the migration success of the target species in two ways. Firstly, a supportive ecosystem will be more attractive to the target species, which will likely result in more individuals being attracted to the vicinity of the FMR. This, in turn, increases the chance an individual of the target species will find the entrance to the FMR and successfully pass through it, resulting in more individuals successfully migrating. Secondly, having a supportive ecosystem around the FMR, with high food availability and the possibility for shelter, will logically improve the physical condition of migrating fish. It stands to reason that healthier individuals, those with a sufficient energy storage and the ability to avoid predators, will be more successful in passing the FMR. For these reasons, insuring a supportive ecosystem should be part of the Haringvliet FMR design. In this part, we will discuss the possibilities for this in the Haringvliet area, and provide information on how to implement these.

3.6.1 How to Create a Supportive Ecosystem

A more biodiverse habitat offers more possibilities for foraging and shelter than an area which is species poor. Therefore, increasing biodiversity around the FMR will create a more supportive ecosystem. Additionally, the area should contain biodiversity that is specifically attractive to the target species. One way of increasing biodiversity is by introducing or restoring certain species, which play an essential role in the creation of suitable, biodiverse habitats to the area. Examples of these are so-called keystone species and ecosystem engineers. Keystone species being those species which the integrity and stability of the ecosystem depend on (Paine, 1969), while ecosystem engineers are species which play a role in 'the creation, modification and maintenance of habitats' (Jones *et al.*, 1994). Additionally, the term 'foundation species' is often used in close relation to these, meaning those species with a strong contribution to the structure of a community (Dayton, 1972). An example of a foundation and keystone species is the common eelgrass, *Zostera marina* (Jahnke *et al.*, 2018), a widespread macrophyte on coastlines of the Northern hemisphere. The flat oyster, *Ostrea edulis*, is a prime example of an ecosystem engineer. It creates biogenic reef habitat, important for numerous ecosystem services and functions (Pogoda *et al.*, 2019). Both of the species mentioned here are native to Dutch coastal waters and could provide the habitat needed for a supportive ecosystem near the Haringvliet FMR. Previous ACT teams have already looked into the possibilities of these particular species for an FMR. However, they envisioned the introduction of oyster reefs and seagrass meadows *inside* the FMR. We believe this is not a realistic scenario for two reasons. Firstly, based on current salinity data of the Haringvliet, we believe salinity inside the FMR will not be high enough to support these organisms. Secondly, the placement of large structures such as oyster reefs (or even eelgrass meadows), can have an unpredictable influence on hydrology inside the FMR: deviations in current speed and direction, turbidity and sedimentation may occur (van der Heij, W., personal communication, September 10, 2021). This may result in incorrect hydrology parameters for the target species and additional maintenance of the FMR (e.g., to prevent sedimentation clogging up areas of the river). Therefore, we suggest any measures to be taken in the area surrounding the sea-side entrance of the FMR. This will increase natural values of the area and increase the FMR's effectiveness, while not interfering with the FMR hydrology. There may also be possibilities for the creation of a supportive ecosystem near the freshwater entrance of the FMR, but this is beyond the scope of this part, whose focus is on the saltwater environment of the Haringvliet. The remainder of this chapter is focused on the ecology and restoration strategies of the candidate species, the common eelgrass and flat oyster.

3.6.2 The Candidate Species

Here, we will discuss specifics about the ecology, requirements, ecosystem functions and services and restoration efforts of the candidate species separately. Additionally, information on species viability for the Haringvliet area and restoration tactics are provided. We have chosen the common eelgrass and flat oyster as candidate species, because of their beneficial role in the local ecosystem, the fact that they are native to this area and considerable information being available on restoration efforts. We believe these species are among the most promising, but other species may be suitable for this role as well (e.g., the blue mussel, *Mytilus edulis*).

3.6.2.1 Common eelgrass, *Zostera marina*

In the Dutch Wadden Sea, the common eelgrass (*Zostera marina*) was widespread before the 1930s, but has rapidly declined since (De Jonge *et al.*, 2000). In lake Grevelingen as well, common eelgrass has shown a steep decline since 1980 (Kamermans *et al.*, 1999). This is worrying, for in the archipelago of the Swedish Skagerrak, a decline in the areal extent of *Z. marina* by 60% coincided with decreased fish biodiversity and biomass in the affected areas (Pihl *et al.*, 2006). With *Z. marina*'s decline, the Dutch coastal waters and estuaries have most likely experienced a similar loss of important ecosystem functions and services which the species supplied.

Among marine ecosystems, eelgrass systems are one of the most productive in the world (McRoy, 1977). Many marine species benefit from the presence of eelgrass beds as a source of refuge, foraging and spawning areas (Plummer *et al.*, 2013) (see figure 7 for an example of an eelgrass bed). *Z. marina* meadows have an important function as nursery and spawning grounds for many fish species, including commercial species (Bertelli & Unsworth, 2014; Lazzari *et al.*, 2003; Polte & Asmus, 2006). The increased habitat complexity and hiding places offered by *Z. marina* meadows reduce the vulnerability of juvenile fish to predation (Shoji *et al.*, 2007). The species benefitted by the presence of *Z. marina* include species common in Dutch waters and specifically the Haringvliet area, making it an interesting candidate for inclusion in the FMR project. Examples of relevant benefitted species are the three-spined stickleback (Gagnon *et al.*, 2019; Rybkina *et al.*, 2017) and Atlantic cod (Lilley & Unsworth, 2014; Warren *et al.*, 2010). In addition, although no evidence has been found for the Atlantic salmon, other salmonids have been shown to use *Z. marina* meadows as spawning and foraging grounds (Hughes *et al*, 2021; Kennedy *et al.*, 2018; Rubin *et al.*, 2018). The same applies to the Atlantic herring: distribution of the related Pacific herring is positively related to *Z. marina* beds (Lewandoski & Bishop, 2018). Thus, we expect the introduction of *Z. marina* beds to the Haringvliet area to positively affect local biodiversity and habitat suitability to the target species.

Figure 7. A bed of common eelgrass, *Z. marina*, here partially exposed in low tide. Photo by Frank Kruk. Obtained from de Leeuw, C. 2018. https://www.waddenacademie.nl/wetenschap/wadweten/wadweten-2018/zeegrasherstel.

3.6.2.2 *Z. marina* Ecology and Requirements

Information on the ecology and requirements of the species is essential in order to evaluate the possibilities for its establishment in the Haringvliet. Here, we provide information on some of the most important parameters related to *Z. marina* settlement and growth.

Light availability is arguably one of the most critical factors limiting *Z. marina* distribution. The lack of recovery of *Z. marina* populations in the Wadden Sea after 1930 is thought to have increased turbidity as one of the main causes (De Jong & De Jong, 1992; Giesen *et al.*, 1990a, 1990b; van den Hoek *et al.*, 1979). Increased turbidity limits light availability, and *Z. marina* suffers damage or population loss after a prolonged period of increased light attenuation (Giesen *et al.*, 1990a). Turbidity is positively related to the amount of sediment in the water, which is dependent on soil/silt erosion and human activities in the area, such as construction or dredging (Giesen *et al.*, 1990a). Another cause of increased turbidity is an increased number of algae in the water column, which in turn can be brought about by an increased nitrogen load in the system (Giesen *et al.*, 1990a; Hauxwell *et al.*, 2003).

This brings us to the next important parameter: nutrient enrichment. Although a short-term increase in nutrient enrichment seems to have a positive effect on *Z. marina*, prolonged exposure negatively affects it (Boyton et al., 1996; Short & Wyllie-Echeverria, 1996; Taylor *et al.*, 1995) *Z. marina* populations. Nutrient enrichment also seems to have an interactive effect with salinity: *Z. marina* tolerates a high nutrient concentration better at relatively low salinities than at higher salinities (M. Van Katwijk, Schmitz, Gasseling, & Van Avesaath, 1999) *marina* tolerates a high nutrient concentration better at relatively low salinities than at higher salinities (van Katwijk *et al.*, 1999).

Regarding salinity, estimates vary widely for the tolerated and optimal salinity range of *Z. marina*. One study found a positive relationship between salinity and eelgrass productivity in Danish eelgrass meadows (Pinnerup, 1980) with salinity ranges from 13 to 31‰, yet another study found no such relationship for a salinity range of 9 to 23‰ (Wium-Andersen & Borum, 1984). Other proposed salinity tolerance ranges are 18 to 40‰ (Tyler-Walters, 2008) and 10 to 39‰ (Davison & Hughes, 1998). Based on these data, it seems that *Z. marina* may tolerate a salinity of 9‰ on the low end and 40‰ on the high end.

Lastly, *Z. marina* is able to grow in depths from 0 to 5 meters and requires an environment sheltered from wave exposure, with a tidal strength of less than 0.5 m/s. A muddy, sandy or gravel substrate provides an optimal habitat (Tyler-Walters, 2008).

3.6.2.3 Possibilities for *Z. marina* Implementation in Haringvliet

As mentioned, light availability may be the most important limiting factor to *Z. marina* settlement potential. It is therefore essential for turbidity not to be too high in the proposed introduction sites. Ways to prevent high turbidity include: limiting nutrient enrichment in the area (runoff from local farmland may have a large impact here), reducing water pollution (e.g., from industry), limiting major construction and dredging activities where possible and reducing silt erosion in the area. As discussed, prolonged periods of nutrient enrichment have a negative effect on *Z. marina*, yet another reason to prevent excessive enrichment. Additionally, there may be ways to actively reduce turbidity and nutrient enrichment in the area. A good example being the utilisation of shellfish reefs such as oysters. Through their ability to filter substantial amounts of water, oyster reefs decrease suspended solids and nutrients in the water and thus turbidity (Newell & Koch, 2004). Subsequently, they have a positive effect on light penetration (Cressman *et al.*, 2003; Grabowski & Peterson, 2007; Newell & Koch, 2004). In addition to this, just like mussel banks, oyster reefs can have a stabilising effect on sediments (van Katwijk *et al.*, 2000), decreasing the amount of suspended sediment in the water. Even smaller populations of healthy oysters may significantly decrease turbidity in the area (Newell & Koch, 2004).

The possible distribution of *Z. marina* in the Haringvliet is further limited by salinity, as *Z. marina* most likely does not survive in salinities below 9‰. Figure 8 shows a map containing simulated and measured salinity in the Haringvliet in 1997, obtained from Groenenboom *et al.* (2016). *Z. marina* will only be able to grow in the relatively deep-red coloured areas, which according to this map, limits its potential distribution to the area where the Haringvliet widens into the North Sea. Furthermore, restoration attempts should occur in areas of the Haringvliet sheltered from heavy wave exposure and strong tidal currents.

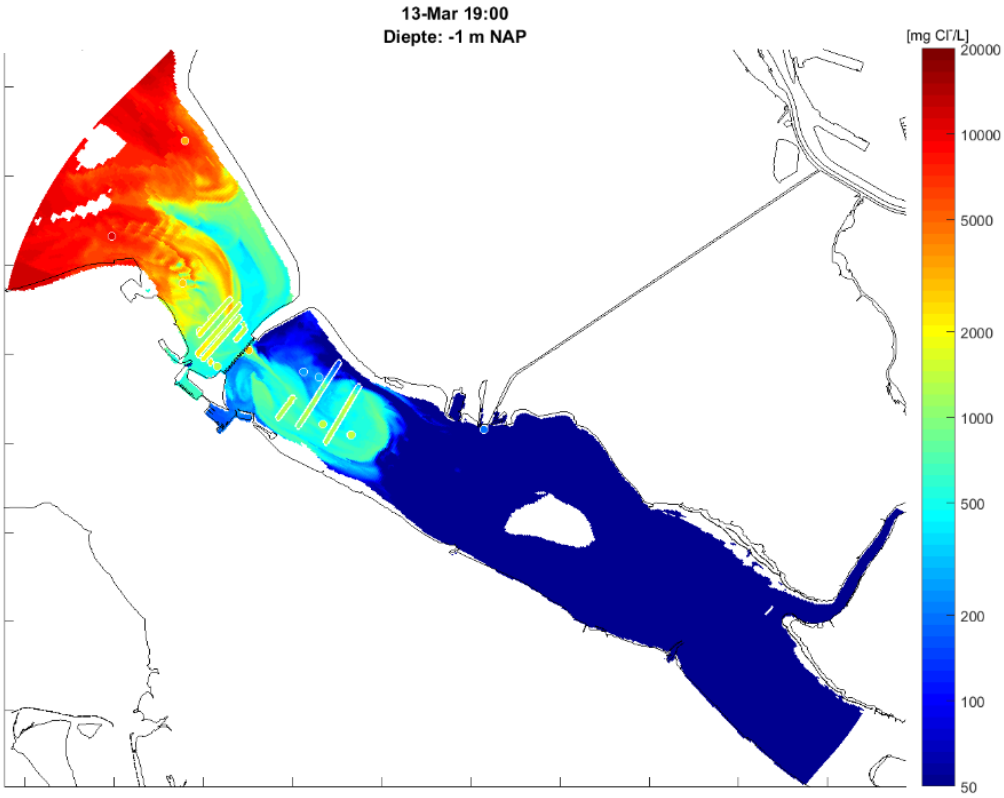


Figure 8. Map of calculated and measured salinity (mg Cl-/L) on March 13, 1997 in the Haringvliet (near the Haringvlietdam), measured at 1m beneath NAP. Logarithmic scale from low salinity (deep blue colour, 50 mg Cl-/L) to high salinity (deep red colour, 20 000 mg Cl-/L). 1‰ salinity is equivalent to 1000 mg Cl-/L. Calculated salinities are displayed in the white-encircled areas of the map. Obtained from Groenenboom *et al.* 2016.

When the above requirements and constraints are taken into account, we believe suitable areas for *Z. marina* restoration can be identified in the Haringvliet estuary.

3.6.2.4 *Z. marina* Restoration Strategies

Here, we briefly go over some of the previous work done on eelgrass restoration. There has been interest in the restoration of seagrass habitats in the Netherlands for some time. From 1995 to 2000, several studies were published on eelgrass restoration in the Wadden Sea. These studies agree that *Z. marina* restoration will only be successful in carefully selected, undisturbed and sheltered areas. Specifically, areas free from fishery and mussel and cockle culture (De Jonge *et al.*, 1996; van Katwijk *et al.*, 2000). Implementation of structures that reduce wave exposure and improve shelter is recommended (De Jonge *et al.*, 2000). These could be structures created by humans, however, shellfish reefs may provide a natural solution as well. An effective strategy for eelgrass transplantation is the anchoring of *Z. marina* rhizomes to small stones and superficially burying these in the substrate (Zhou *et al.*, 2014). In addition, reintroduction using seeds shows promise as well, but this method still needs more research (Infantes *et al.*, 2016). Lastly, the choice of donor population should be carefully considered, taking into account the population's genetic diversity, sensitivity to disease and plasticity to environmental conditions (De Jonge *et al.*, 2000).

3.6.3 Flat oyster (*Ostrea edulis*)

O. edulis used to be a common occurrence in shallows of the Atlantic coast, Mediterranean Sea and Black Sea until the 20th century, but only small relic populations remain today (Lapegue *et al.*, 2006; Ranson, 1948; Strauch & Thüry, 1985). Overexploitation is thought to be the main reason for their local extinction, although various other factors may have also played a role (Drinkwaard, 1998; Gercken & Schmidt, 2014; Hagmeier & Kändler, 1927; Möbius, 1877; Thieltges, 2003). Currently, the bonamia parasite (*Bonamia ostraceae*) is likely the most important factor limiting *O. edulis* recovery. Since its first recorded presence in 1979 (Bucke & Feist, 1985), *O. edulis* populations have achieved some resistance to the disease. Nonetheless, resistant individuals are still at significant risk of sustaining damage or dying (Cigarria *et al.*, 1995; Elston *et al.*, 1987). Despite this, small populations have recently been found in Dutch coastal waters (Kerckhof *et al.*, 2018), including near the coast of Zeeland (Sikkema, 2016), suggesting that the circumstances may still be suitable.

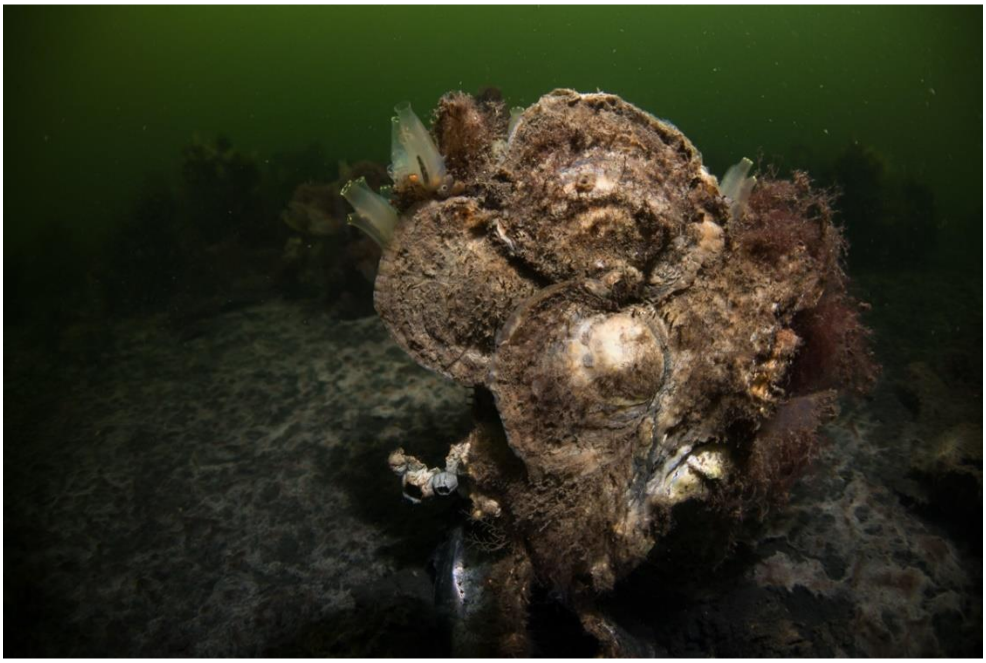


Figure 9. A flat oyster reef in the Voordelta, showing flat oysters and species of seaweed, ascidians and barnacles. Photo by Youri van Es. Obtained from Kamermans, P. (2016) https://www.wur.nl/nl/nieuws/Wilde-platte-oesters-op-rif-Voordelta-produceren-zelf-oesterlarven.htm.

Flat oyster beds have an important ecosystem function: they provide a hard substrate in otherwise sandy or muddy environments, allowing for a species-rich benthic community (Coen *et al.*, 2007; Houziaux *et al.*, 2011; Kamermans *et al.*, 2018; Möbius, 1877; Pogoda, 2019; Kamermans *et al.*, 2018; Möbius, 1877; Pogoda, 2019) (see figure 9 for an example of a flat oyster reef). Just like *Z. marina*, *O. edulis* can be considered a keystone species, able to provide many organisms with foraging grounds and refuge, and contributing to benthopelagic coupling (Coen *et al.*, 2007; Kent *et al.*, 2017; Kent *et al.*, 2017). Hereby, they increase local biodiversity (Grabowski & Peterson, 2007); historic *O. edulis* reefs were characterised by their high species richness (Caspers, 1950; Korringa, 1954; Möbius, 1877). As mentioned in the section on *Z. marina*, in great abundance, *O. edulis* reefs also increase local water clarity (Cressman *et al.*, 2003; Grabowski & Peterson, 2007). Thus, by increasing light availability, *O. edulis* reefs facilitate the settlement of macrophytes such as seagrasses. In conclusion, the successful introduction of *O. edulis* beds to the Haringvliet estuary would increase local biodiversity and structural diversity, hereby providing migrating fish with foraging grounds and shelter. In the long term, their introduction could improve local water quality, hereby facilitating settlement of other species such as *Z. marina*.

3.6.3.1 *O. edulis* Ecology and Requirements

Here, we provide an overview of the ecology of *O. edulis*, going over the most important requirements for their settlement and growth.

As a filter feeder which acquires food from particles in the water, moderate nutrient enrichment will most likely have a positive effect on food availability for *O. edulis* (Jackson & Wilding, 2003). However, sustained and/or high levels of eutrophication can still have detrimental effects (Jackson & Wilding, 2003). For instance, algal blooms brought about by excessive nutrient enrichment are known to cause mortality in *O. edulis* (Shumway, 1990). *O. edulis* can also be negatively affected by high quantities of suspended sediments, which cause a decreased filtration rate (Hutchinson & Hawkins, 1992; Korringa, 1952; Moore & PG, 1977) and reduced growth (Grant, Enright, & Griswold, 1990). Although estimates vary, *O. edulis* needs a relatively high salinity, normally above 30‰, although populations in estuaries tolerate shorter periods of 16 to 19‰ (Gercken & Schmidt, 2014; Hutchinson & Hawkins, 1992). Other sources list 18 to 40‰ salinity (Jackson & Wilding, 2003) and 15 to 20‰ on the low end for larval growth (Gercken & Schmidt, 2014; Lapegue *et al.*, 2006). Rödström and Jonsson (2000) recorded permanent damage to oyster spat at salinities below 16‰. To stay on the safe side, salinity in the area should be at least 20‰ and preferably higher most of the time.

O. edulis are prevalent in depths of 0 to 20m, but may be found in depths of up to 50 (Gercken & Schmidt, 2014; Lapegue *et al.*, 2006) or even 80m (Jackson & Wilding, 2003). Adults can be found on soft and hard substrates such as sand, mud, gravel and rocky surfaces (Jackson & Wilding, 2003; Lapegue *et al.*, 2006; Möbius, 1877), but the larvae require a hard substrate to settle on (Jackson & Wilding, 2003), which may also be provided by the surface of conspecifics. Lastly, *O. edulis* also has need of areas relatively sheltered from wave exposure and with a low tidal strength (<0.5m/s) (Jackson & Wilding, 2003).

3.6.3.2 Possibilities for *O. edulis* Implementation in Haringvliet

Just as *Z. marina*, *O. edulis* is negatively affected by high levels of suspended sediments. When selecting suitable sites, turbulent areas with frequent sedimentation should be avoided. As discussed in the section on *Z. marina* implementation, increased turbidity can be prevented by various measures. Additionally, the filter-feeding capabilities of oysters can aid in settlement of macrophytes by improving light penetration. By the same mechanism, oysters also facilitate themselves: by filtering excess suspended matter, they improve circumstances for their conspecifics. Only sites with a suitable salinity can be considered for the introduction of *O. edulis* in the Haringvliet. As discussed, salinity should be at least 20‰. Consultation of figure 8 leads to the conclusion that *O. edulis* restoration can only be considered at the Westerly edge of this map and further towards the North Sea. Lastly, *O. edulis* needs protection from heavy wave exposure and strong tidal currents, initial introduction should take place in relatively sheltered areas. Once a successful population has settled, the growing reef structures will have a stabilising effect on the elements, further improving conditions for oyster settlement.

Taking its ecology into account, we believe successful restoration of *O. edulis* could take place off the Haringvliet coast and near the estuary entrance. Healthy flat oyster reefs would increase the Haringvliet's attractiveness for local and migratory fish.

3.6.3.3 *O. edulis* Restoration Strategies

In recent years, many studies have been published on *O. edulis* restoration in the North Sea (Bennema *et al.*, 2020; Kamermans *et al.*, 2018; Kerckhof *et al.*, 2018; Maathuis *et al.*, 2020). Here, we provide a promising method for *O. edulis* restoration, based on strategies discussed in recent articles.

The first step in *O. edulis* restoration is to establish a small population of varying age classes, which should at least partly be protected by predators (Pauline Kamermans *et al.*, 2018). Protection could be achieved by placing oysters in cages, which also allows for easy monitoring. Alternatively, nearby commercial oyster farms can be used as a source of larvae (R. J. Kennedy & Roberts, 2006). Once a healthy population has settled, the second step is to provide a suitable substrate for the larvae to settle on (P. Kamermans *et al.*, 2018). In experimental trials, it was found that *O. edulis* larvae settlement is the most effective on shells of conspecifics (Rodriguez-Perez *et al.*, 2019). However, in the case of a small, isolated population, this will not prove very effective. Fortunately, larvae also settle on marine stones with habitat-associated biofilms at a high success rate (81% settlement after 45 hours) (Rodriguez-Perez *et al.*, 2019). For the Haringvliet, instalment of marine stones near established populations may be the best option. In addition, marine stones would likely decrease wave exposure and tidal strength, further improving local conditions. Once enough populations have settled, further expansion of existing populations could take place via larval dispersal and subsequent settlement on conspecifics. An interesting option could also be to combine *O. edulis* restoration with wind farm development, a subject which has come to recent attention (Buck *et al.*, 2006; Buck *et al.*, 2017; Kamermans *et al.*, 2018; Sas *et al.*, 2018).

It is essential to consider that the bonamia parasite is widespread in wild *O. edulis* populations, it is present in the nearby lake Grevelingen as well (Engelsma *et al.*, 2010). Before transplantation, oysters can be tested for the parasite (Jacobs *et al.*, 2020), ensuring a disease-free population. However, the introduced populations would still be vulnerable when come into contact with bonamia. A solution may be found in the thirty-year long selection program by Lynch *et al.*, which has yielded a *O. edulis* population highly resistant to bonamia (Lynch *et al.*, 2014). Restoration using individuals from a resistant population would greatly decrease mortality in the case of a bonamia outbreak. Resistance to bonamia aside, wild European *O. edulis* populations are mostly genetically similar (Saavedra *et al.*, 1995; Saavedra *et al.*, 1993). Thus, in case of introduction, the source of the population is not essential to consider (Laing *et al.*, 2006).

Table 4 shows an overview of the candidate species' requirements and constraints, as well as a summary of their potential benefits to the ecosystem. Both species provide different, complementary benefits, promoting biodiversity and the production of the system. Their restoration would increase the natural values of the area, while improving conditions for local and migratory fish by providing refuge, foraging, spawning and nursery grounds. In turn, this will have a positive effect on the physical condition of migratory fish and the number of individuals and species attracted, hereby increasing the FMR's effectiveness. This chapter can be seen as a simple framework for the restoration of *Z. marina* and *O. edulis* in general, containing an overview of their ecology and examples of restoration strategies. In addition, it provides applied information for their restoration in the Haringvliet area. We recommend more research to be done in this area, as we were limited in our access to sources of local information. In particular, more detailed salinity measurements of the area are a necessity to investigate suitable sites for both species. Detailed information on the current, local ecology of the Haringvliet estuary can also be used as an indication for suitable restoration sites (e.g., existing reef structures or vegetation indicate suitable settlement circumstances for the candidate species). To conclude, we believe *Z. marina* and *O. edulis* make for a synergistic combination, and could have a positive effect on the FMR effectiveness. More research into the interplay between these species and its benefits could be promising.

Table 4. Overview of *Z. marina* and *O. edulis* requirements and sensitivity to certain factors, as well as their benefits to the ecosystem.

	Z. marina	*O. edulis*
Turbidity	Highly sensitive to light attenuation caused by turbidity	High quantities of suspended sediment decrease filtration rate and growth
Nutrient enrichment	Positively affected by short-term increase Negatively affected by prolonged exposure	Positively affected by moderate levels Negatively affected by prolonged, high levels of exposure
Salinity	9‰ - 40‰	20‰ - 40‰ Should regularly be higher than 20‰
Depth range	0 – 5m	0 – 20m. Up to 80m
Wave exposure	Highly sensitive. Sheltered area needed.	Sensitive. Sheltered area needed
Tidal strength	< 0.5 m/s. Sheltered area needed	< 0.5 m/s. Sheltered area needed
Substrate	mud/sand/gravel	Adults: sand/mud/gravel/rocky surfaces Larvae: hard substrate, preferably conspecifics or rocks with biofilm
Benefits	Important nursery, spawning and foraging grounds Provides refuge/shelter Highly productive	Important foraging grounds High species richness Provide hard substrate Contribute to benthopelagic coupling

It is important to consider that we provided this advice based on information of the current situation in the Haringvliet. The construction involved in the Delta21 plan will likely have substantial effects on many of the factors discussed above, such as turbidity, salinity, wave exposure and tidal characteristics. Plans for the introduction of the candidate species cannot be made without knowledge of the new situation. Predictive (modelling) studies may provide insight into the new conditions. Regardless, the new area conditions will have to be measured after completion of the Delta21 construction in order to determine suitability of the area to any restoration attempts.

3.6.4 Summary

Supportive Ecosystems

A supportive ecosystem is an environment which provides the target species with sufficient possibilities for foraging and shelter and can function as a nursery or spawning ground. A supportive ecosystem around the FMR could increase the migration success of the target species by: 1) attracting more individuals and species to the FMR and 2) improving the physical condition of the migrating fish. There are specific species that can play a large role in the creation and maintenance of a supportive ecosystem, such as the common eelgrass (*Z. marina*) and the flat oyster (*O. edulis*). Here, we provided relevant information on their ecology and their potential benefits for the Haringvliet area and FMR effectiveness. Additionally, we present recommendations for potential restoration sites and strategies in the Haringvliet and discuss important considerations. We believe these two species make for a synergistic combination, which could provide substantial benefits to the area, improving the natural values and increasing the FMR's effectiveness.

3.7 Making the FMR Attractive for Target Species

3.7.1 Hydrology & Velocity - The Tesla Valve

3.7.1.1 Current

Nikola Tesla, known for his innovative concepts of electrical circuits, also developed a design known as the valvular conduit or formerly, the Tesla valve (Keizer, 2016). The tesla valve permits fluids and gasses to pass through a one-way system, similarly to valves found within a heart (Keizer, 2016). As previously stated in Chapter 3, current can be a major determinant for fish being able to pass through the FMR. The Tesla valve is designed in such a way to create variation in currents, which includes resting places through creating the pond-stream-pond structure seen in Figure 10. Figure 10 also indicates the overall flow through the valves, as well as the arrows depicting its hydraulic flow pattern. These factors are relevant for incorporating different currents for different target species. Experimentation with incorporating the Tesla valve design into a fish passage has previously been done by a TU Delft student, K. Keizer. His work indicated that this valve design can allow a range of fish with varied current preferences to pass through; herring favours slower currents and salmon can withstand strong currents. This can be an interesting concept to partly apply in areas in the FMR to combat hydrological challenges for fish.

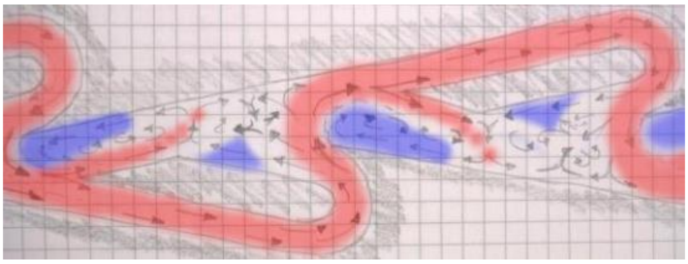


Figure 10. Direction of flow (from left to right), where red indicates high flow area and blue indicates a stagnant area. (Image obtained from Keizer, 2016).

3.7.1.2 Velocity

Migratory fish cannot withstand flow velocities greater than 1 m/s (Kiezer, 2016; Monden & Kroes, 2005). Flow velocities tend to increase in the loops of the Tesla valve if the slope gradient increases. It is assumed that there would not be any substantial slope gradient involved throughout the FMR, thus situations like these would not arise. In contrast, velocity near the Haringvliet sluices can be higher than 1 m/s at the surface when sluices are ajar (see Hydrology chapter 3.4). One way of decreasing these current speeds is by increasing the depth of the water. Fortunately, as mentioned in Chapter 3.4 ("Hydrology"), the current speeds near the kierbesluit will not have a great significant effect on the FMR itself. Hence, introducing the Tesla valve would not hinder favoured flow velocities *for the fish.*

3.7.1.3 Resting

The Tesla valve also introduces areas of stagnant water for the migratory fish, as can be seen in Figure 11. While swimming upstream, migrating fish have regular need for resting spaces, which could be provided by the stagnant areas inside the Tesla valve. Thus, another reason why looking into tesla valves and incorporating it in our proposed FMR could be ideal. To summarise, incorporating a Tesla valve into the FMR would contribute to the several aspects listed above.

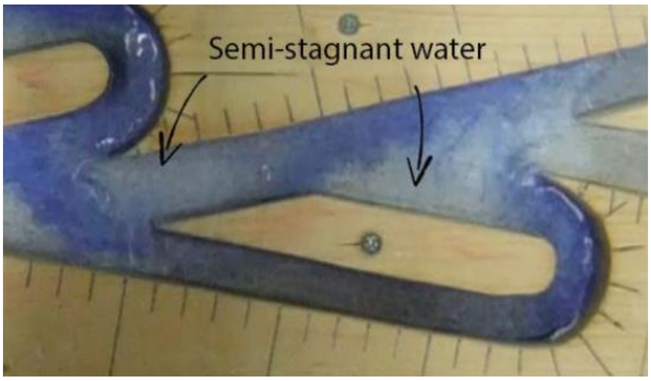


Figure 11. Tesla valve - High flowing water can be seen with blue dye, and stagnant areas can be seen as white shaded areas (Keizer, 2016).

3.7.2 Salinity

The salinity is a very important factor to consider when designing an FMR. Each specific fish species has its own preference and tolerance for salinity (see table 3). Meaning that the FMR needs to consider the different salinity tolerances and preferences of the target species. The current salinity values can be found on "Rijkswaterstaat Waterinfo" (2021). In order to incorporate salinity in the FMR, certain factors need to be taken into account. These include the swimming capacity of the target species and their acclimatisation period in brackish water, and the current speed and salinity gradient in the FMR. When these factors are considered, this will provide information about the required length and salinity gradient of the FMR. First, an area needs to be found where the salinity gradient is appropriate for the target species to acclimatise in. Then, the swimming capacity of the target species and the current speed at the location, need to be considered in order to obtain information about the length of the FMR. A species' swimming capacity minus the current speed will indicate how fast the fish will be able to pass the river. However, the current speed depends on the depth of the water body (Noordhuis, 2017). This will result in fluctuations in current speed during different tidal periods. After this calculation, the species' acclimatisation period needs to be considered in order to determine the required length of the FMR. Some fish species need three weeks to acclimatise, such as the European eel (Cresci *et al.*, 2020; Rankin, 2009), while other species only need 24 hours to acclimatise, such as the Atlantic salmon (van Emmerik, 2016). The actual swimming speed, minus the current speed, of a certain species, will be multiplied with the acclimatisation time of that species. This will result in the length that is needed in the FMR, for the specific fish to acclimatise in. As an example, the European eel has a swimming speed of approximately 0.4 m/s (van Emmerik, 2016). Currently, the current speed at the Haringvliet locks range from 0.5 - 3.8 m/s (Noordhuis, 2017). When the swimming speed and current speed are subtracted, it will result in a negative value. This also means that the current speed in the FMR needs to be adjusted to make the FMR more effective. However, if the current speed in the FMR would be lower, for instance, 0.3 m/s, then the actual swimming speed of the fish would be 0.1 m/s when attempting to pass the FMR. The European eel needs to acclimatise for three weeks before they have sufficient salt tolerance (Cresci *et al.*, 2020; Rankin, 2009). After the calculations, this would result in an FMR with a required length of 181440 meters, which is not realistic. Therefore, it is essential to consider resting places in the FMR to let the target species acclimatise. However, it is not this simple in deciding how long the acclimatisation length in the FMR should be. The salinity gradient also needs to be considered, because it is not a perfectly smooth gradient throughout the length of the FMR. The length of the FMR, consisting out of the salinity gradient, for the target species to acclimatise in, should be as long as possible. This way the FMR can consider the target species with the longest acclimatisation time and lowest swimming speed. However, this is not realistic to implement in the FMR and therefore, other solutions, such as resting and hiding places should be incorporated to compensate this. Thus, it is important to have an FMR that consist out of diverse abiotic factors, that will be available for various target species to be able to pass the FMR. To conclude, the length of the brackish water area needs to be calculated for the target species. This length is needed for the acclimation time of the target species and thus, needs to be incorporated in the FMR.

3.7.3 Soil

It has become clear that the target species share a range of preferences for soil type. The European eel favours more sandy areas for optimal movement, whilst the European flounder favours high silty/muddy levels for hiding. Common eelgrass grows optimally in 0.5 m, as advised in chapter 3.3 "Supportive Ecosystems". Consequently, implementing eelgrass in the FMR would contribute to sediment deposition, as waves travelling from deep to shallow waters result in slower flow; when the velocity reduces, sediment will start to deposit (Fondriest Environmental, 2014). Due to this occurrence, sediment and fine gravel such as silt can be found in higher quantities surrounding the common eelgrass; hence, creating a favourable environment for migratory fish that favour silty surroundings.

On a different note, flat oysters (the other candidate species), favour sandy areas/solid structures as their filtering capabilities can then be optimal (Sas *et al.*, 2019). Similarly, the European eel and the Atlantic Salmon seek more solid structures with a less silty environment. With the implementation of flat oysters and common eelgrass, a variety of target species can experience diverse and ideal environments.

3.7.4 Predation

Predation in and around an FMR can happen on different levels. On the one hand, we have natural predation by other inhabitants of the river and sea and on the other hand we have non-natural predation such as fishing. As the FMR facilitates migration again, it will mainly be used by reproducing individuals on their way to the spawning grounds and by the newly hatched generation travelling to the feeding grounds. Therefore, it would not be wise to allow fishing activities up and down stream of the FMR, as this directly influences the restoring fish populations. As a whole fishing ban is probably not feasible a possible solution for this can be that fishing is not allowed during the migration peaks of the fish. It might also help to distinguish between younger spawning fish and older fish when catching, but this might be too complex.

Natural predation will generally happen on three places: downstream of the FMR, in the FMR or upstream the FMR. Downstream of the FMR, on the seaside, predators will likely be bigger piscivorous (fish eating) marine fish and other marine animals like seals that will predate on, for example, salmon when they start to migrate upstream. Also, smaller piscivorous fish and piscivorous birds will predate on the juveniles returning from their nursing areas. The same, but then vice versa, will happen in and upstream of the FMR. Bigger migrating fish will encounter others on which they predate. Salmon for example, are known to feed on three-spined stickleback that also migrates upstream (Legrand *et al.*, 2021; Griffioen *et al.*, 2017; Reeze *et al.*, 2017).

As bigger marine mammals probably will not use the FMR, there is more opportunity for birds to catch fish in the calmer river water of the FMR and the rivers upstream. To tackle these problems, it is vital that we ensure that there is rich vegetation cover at the up and downstream side of the FMR. Once the fish have passed the FMR they can immediately find shelter in the vegetation. At the seaside of the FMR, this can be done by incorporating seagrass as mentioned in 3.5 supporting ecosystem. Upstream there should be more freshwater plant species around the opening of the FMR. The usage of fish hotels can also increase the amount of shelter places around the openings of an FMR. As predation will also happen when fish are passing the FMR it is important to have a large variety of vegetation around the FMR, so the possible predators have difficulty reaching the FMR. This is especially important because in the FMR itself the conditions for plant growth will not be favourable due to the different current speeds. Also, the current speed is designed to be optimal for the fish that will likely use the FMR, and any adjustments in the FMR by plants or fish hotels will alter the carefully designed currents. Lastly, the FMR should be accessible during the whole night and day as species prefer to migrate on different times of the day.

3.7.5 Food

Availability of food resources is needed for the migratory fish to regain and store energy to complete their migration. Each target fish species has different consumption needs. They usually feed on plankton and other fish. For instance, flounders consume plankton, insect larvae, small fishes, small invertebrates and benthic fauna (Froese & Pauly, 2021). Another example is the shad that consumes zooplankton, plants, insects, other fish and crustaceans (Aprahamian *et al.* 2003; Froese & Pauly, 2021; van Emmerik, 2016). Habitats need to have a high biodiversity, in order to have food availability and increase foraging success. Usually, these habitats also have resting places where the fish can forage and regain energy before they move on with their migration. Therefore, it is important to consider the biodiversity and incorporate availability of food in and around the FMR, to attract the target species. This will also increase the migration success of the target species.

3.7.6 Resting

Migratory fish sometimes need to stop to regain energy or to hide from predators. This can occur in resting places. Resting places consist out of different kinds of substrates or macrophytes, such as rocks, gravel, sand, the flat oyster (*Ostrea edulis*) and eelgrass (*Zostera marina*). The flat oyster is an ecosystem engineer and eelgrass are keystone species. The details and specific roles about these ecosystem engineers and keystone species were explained in chapter 3.6 "Supportive Ecosystem". These resting places are also called supportive ecosystems, which will help in increasing the passage efficiency for the target species to pass the FMR and improve their migration success. The resting places could be implemented in different ways to improve migration success. First, the instalment of resting places around and in the FMR could help to attract the target species. This would increase the chances of the target species finding the entrance of the FMR and successfully migrating through it. Secondly, a resting place can increase food availability, which will help the fish regain their energy. Thirdly, resting places could also provide shelter, which will decrease predation risk. These aspects of resting places will enhance the physical condition of the migratory fish, which will result in a more successful migration through the FMR.

To create effective resting places in and around the FMR, habitats need to have a high biodiversity. Habitats with higher biodiversity have more potential to be a resting place than habitats with a poor number of species. The reason for this is because it offers more options for foraging and shelter. Furthermore, the habitats that have potential to be a resting place, need to be attractive to the target species. Each species has its own preference in selecting their resting habitat. This selection could depend on the substrate type and water temperature in the located area (Meese & Lowe, 2019). For instance, the Atlantic salmon prefers habitats with sand, gravel and stones to hide and rest in. Furthermore, they also prefer shallow banks, potholes and vegetation to avoid predation (van Emmerik, 2016). Some fish species prefer to rest near the bottom of shallow banks, especially at night where there is less visibility and predation activity (Emery, 1973; Keats & Steele, 1992). This aspect could be important to consider, while implementing the FMR. Furthermore, the Tesla valve could also be an option as a resting place, due to its stagnant areas as mentioned before. Another option that could be a resting place is the so-called "fish hotels" in and around the FMR, where migratory fish can rest in, before they move on with their migration (Murk, 2019). These fish hotels could be interesting for the European eels, because they are nocturnal animals and prefer dark enclosures (Dou & Tsukamoto, 2003). However, it is still important to consider the effects of placing these resting places in the FMR. As mentioned before, the placement of structures could alter the hydrology inside the FMR. To create these suitable habitats around the FMR, certain species that play a crucial role, need to be restored or introduced. For example, the flat oyster and eelgrass. To conclude, the areas surrounding the FMR need to have heterogenous resting places with high biodiversity to attract the different target species and increase migration success to make the FMR effective.

3.7.7 Summary

Making an FMR Attractive for Target Species

Different measures are proposed to make the FMR as attractive as possible for the targeted species. The concept of the Tesla valve can be applied to the FMR to facilitate different current speeds. The Tesla valve also introduces areas of stagnant water for the migratory fish, and thus this can provide resting spaces. To allow the fish to acclimate to the salinity gradient, the FMR should be as long as possible. The length of the brackish water area should be determined with calculations, to suit the needs of the target species. The targeted species have a range of preferences regarding the soil. We propose implementing flat oysters and common eelgrass, as this will bring forth diverse environments for the fish to experience. It is important that no fishing is allowed near or in the FMR. Natural predation can occur in all parts of the FMR, thus we propose to incorporate vegetation cover to provide the fish natural shelter. An unhindered water flow in the FMR is of great importance, thus vegetation cover should be focused on the entrance and not in the river itself. In the Haringvliet, fish hotels can be placed to facilitate dark resting spots. In general, the attractiveness of the Haringvliet will be improved if the biodiversity is increased.

3.7.8 Anthropogenic Disturbance

In chapter 2 we discussed the general effects different sources of anthropogenic disturbance can have on fish behaviour and migration. In this chapter, we apply this knowledge to the situation in the Haringvliet. We discuss the relevance of these different sources to the implementation of the Haringvliet FMR, and give recommendations for taking these effects into account.

3.7.8.1 Light

As discussed in chapter 2, artificial light at night (ALAN) may have undesired effects on fish migratory behaviour and timing. Studies suggest this is also the case for at least two of our target species: the Atlantic salmon (*Salmo salar*) and the European eel (*Anguila anguila*). Eel, specifically, seem to avoid illuminated migration routes. In order to not deter the European eel and potentially other species, excessive ALAN at and around the FMR should be prevented as much as possible. Fortunately, there are ways to mitigate the effects of ALAN. For streetlights and other sources of public lighting, lights can be placed in such a way to reduce light spillover (Kinzey *et al.*, 2017) and lights can be shielded using vegetation or constructions (Pauwels *et al.*, 2021). Most importantly, artificial light sources should be kept to a minimum around the FMR.

3.7.8.2 Sound

In chapter 2, we discussed the effects noise of anthropogenic origin may have on fish behaviour. Although there is not much information on the effect of sound on migratory behaviour of fish, one study did suggest one of our target species may be deterred by artificial sounds: the European eel.

Regarding the Haringvlietdam, the discharge of large amounts of water through the sluices (Dutch: 'spuien') may produce loud turbulent sounds, which could have an effect on migrating fish (Winter *et al.*, 2020) delete (Winter *et al.*, 2020), such as the eel. For this reason, it would be prudent for the entrances of the FMR not to be placed in close proximity to any areas with frequent high level water discharges (such as areas with frequent 'spuien').

3.7.8.3 Fishery

Fishery near fish passages can have a negative effect on the migration success of the target species. Taking into account that it is a relatively narrow passage, the Haringvliet FMR is also likely to experience high local concentrations of migrating fish near the entrances of the river. Thus, fish queuing to enter the FMR will be especially vulnerable to fishing. The Haringvliet is often visited by small fishing vessels originating from the nearby fishing port, Stellendam. In order to make the FMR a success, it is essential that clear agreements are made with local fishermen about fishing near the FMR. In addition, under the current regulations of the Kierbesluit, high local densities of migrating fish are likely to occur near the Haringvliet sluices. Thus, to allow for more successful fish migration in the Haringvliet, we recommend the implementation of fishery restriction zones near the entrances of the FMR and in the close vicinity of the Haringvlietdam.

3.7.8.4 Disturbance caused by Delta21 Construction

The latest version of the Delta21 plan will involve large scale construction and sand suppletion in the Haringvliet delta. These activities will most likely interfere with current migration routes of diadromous fish moving from the ocean to the Haringvliet delta or the other way around. Current migration routes may be blocked, and migrating fish may be faced with altered water currents and sedimentation patterns. Cues needed by fish to find their native spawning ground may change, which in turn may cause certain species to be unable to find the Haringvliet entrance. Therefore, even when measures are taken to improve fish migration success near the Haringvlietdam, such as the FMR, it is very well possible that Delta21 as a whole could have a negative effect on fish migration for years until after its implementation. We suggest research to be done into the effects Delta21 construction could have on fish migration patterns and ways in which to mitigate these.

3.7.9 Summary

Anthropogenic Disturbance

Anthropogenic disturbance could affect the effectiveness of the Haringvliet FMR in multiple ways. Artificial lighting could deter certain migratory species such as the eel and cause changes in migratory behaviour of Atlantic salmon. Fish may also be deterred by loud sounds, such as produced by the discharge of large amounts of water through the sluices. Disturbance caused by artificial light and sound near the FMR should be prevented by limiting their occurrence and mitigating their disturbing effects. Near the FMR, migrating fish are especially vulnerable to fishery. We recommend implementing fishery restricted zones in the FMR and near the entrances of the FMR. Lastly, it should be noted that the execution of the Delta21 plan will unavoidably cause considerable disturbance to migrating fish. We suggest research to be done into the effects Delta21 construction could have on fish migration patterns and ways in which to mitigate these.

4. Scenario Proposal

4.1 Introduction to Scenarios

In this chapter, the findings from the previous chapters, together with local information, are applied in a scenario evaluation. We discuss three different scenarios, all with the same aim of increasing fish migration and increasing natural values of the Haringvliet. A detailed description and background is provided for each scenario, and we explain our reasoning for choosing these scenarios. The advantages and disadvantages of each scenario are summarised from three different perspectives: ecology and biodiversity, stakeholders, and implementation costs and local impact. For ecology and biodiversity, we assessed the consequences of the scenario for fish migration, biodiversity and the natural values of the area. For the stakeholders, we investigated the consequences for the stakeholders involved. For implementation costs and local impact, we made an estimate of the project costs and local impact to the area, indicated by the amount of construction involved and consequent hindrance to inhabitants. In the next section, the three scenarios are briefly introduced.

The first two scenarios involve the construction of an FMR in either of two locations: at the North side of the Haringvlietdam (scenario 1) or at the South side of the Haringvlietdam (scenario 2). For the first scenario, an FMR would be built from scratch, in a similar fashion as the Kornwerderzand FMR currently under construction at the Afsluitdijk. This scenario can be seen as a local adaptation of that design. For the second scenario, the FMR would be built using existing structures: the 'Zuiderdiep' and 'het Spui'. These are existing waterways which would be adapted to function as an FMR going around the Haringvlietdam. The third scenario does not involve an FMR, but is in essence a suggestion for the extension of the current Kierbesluit. It proposes measures which limit salt intrusion into the Haringvliet, enabling a further and more frequent opening of the sluices. Figure 12 shows the location under consideration for each of the scenarios on a map of the Haringvliet area.

As a conclusion to this chapter, we summarise the advantages and disadvantages of each scenario and compare these to one another. Finally, we provide our recommendations for the most optimal scenario and discuss possibilities for further research.

Figure 12A. Scenario 1 is the creation of an FMR on the north side of the Haringvliet. This FMR will be inspired by the Afsluitdijk FMR.

Figure 12B. Scenario 2 is utilizing water bodies already present to allow fish migration. This FMR will be on the south side of the Haringvliet take fish through the 'Zuiderdiep' and adjacent river.

Figure 12C. Scenario 3 involves developing the Haringvliet further to improve fish migration. It expands on the current Kierbesluit.

4.1.2 Scenario One, Haringvlietdam North

This scenario involves the construction of an FMR in one of the locations proposed by the commissioner and previously investigated by ACT teams: the North side of the Haringvlietdam (see figure 12A). In essence, the FMR proposed in this scenario would be a locally adapted version of the Kornwerderzand FMR currently under construction at the Afsluitdijk. Therefore, a brief overview of the Kornwerderzand FMR is provided here.

The Kornwerderzand FMR is the first of its kind and was the inspiration for the idea of a Haringvliet FMR. It was designed with the purpose of reconnecting the IJsel Lake with the Wadden Sea, allowing migrating fish to move between these areas, while maintaining the Afsluitdijk's original purpose of water safety and the IJsel Lake's freshwater characteristics (van Banning *et al.*, 2018). Its design is supposed to mimic a natural estuary situation, and therefore has a sandy interior (van Banning *et al.*, 2018). Figure 13 contains a schematic map of the Kornwerderzand FMR. The FMR forms a passage between the Wadden Sea (North) and the IJsel lake (South), and flows through the Afsluitdijk (the broad, gray dike). It has a total length of 4000 meters, taking the meandering into account (van Banning *et al.*, 2018). The design can be subdivided into three functional regions: the seaside estuary, the river side estuary and the river section (see Figure 13) (van Banning *et al.*, 2018). The seaside estuary forms the entrance from the Wadden Sea into the FMR and faces the 'spuisluizen' in the East, which ensures its vicinity to a suitable lure current. It has brackish characteristics (6.0 – 10.0‰ salinity) and leads into the passage through the Afsluitdijk (the coupure). The riverside estuary flows from the coupure to the start of the meandering part of the river. It also contains brackish water, albeit more on the freshwater side (2.0 – 8.0‰ salinity). The greatest part of the FMR consists of the river section, which forms the entrance from the IJsel Lake to the FMR and has a length of 2750 meters. It contains the remainder of the salinity gradient, from brackish (0.5 – 4.0‰ salinity) to freshwater (> 0.5‰ salinity). Only freshwater enters the IJsel Lake through the FMR (van Banning *et al.*, 2018). The design also includes the construction of two sandy bird islands, one in the seaside estuary and one in the river side estuary, which provide suitable habitat for different species of bird (van Banning *et al.*, 2018).

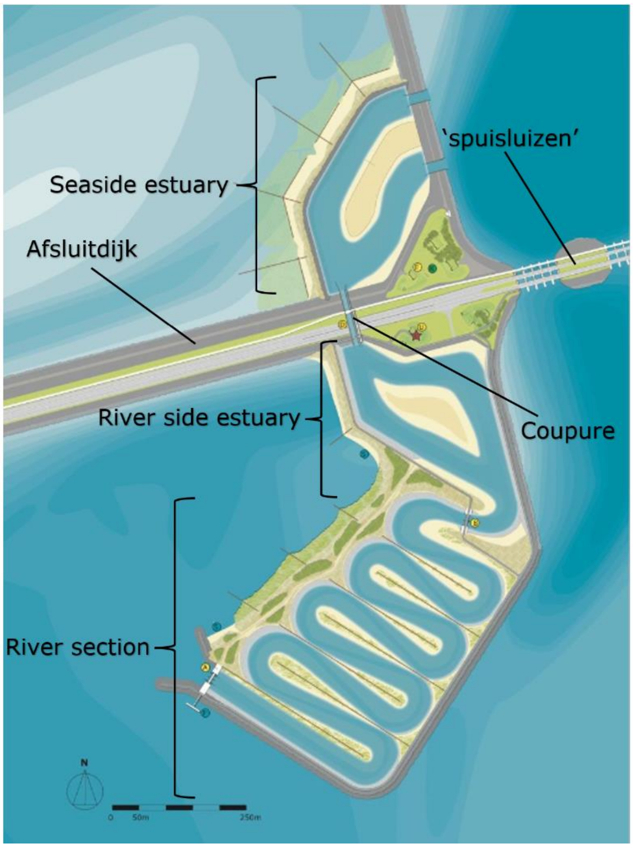


Figure 13. Schematic map of the Kornwerderzand FMR. The three functional regions are indicated by brackets. The location of other structures such as the Afsluitdijk, coupure and 'spuisluizen' is also given. Obtained from Bruins Slot (n.d.).

Although there are differences between the situation at Kornwerderzand and the Haringvliet, the essentials of the Kornwerderzand FMR design could also be applied to the study area. As a suggestion for the possible location of the Haringvliet FMR in this scenario, Figure 14 shows the dimensions of the Kornwerderzand FMR mapped onto the Haringvlietdam area. Some small changes were made in order to adapt the structure to the Haringvliet, but the same functional regions present in the Kornwerderzand FMR are present here. The sea-side estuary is located on the West side of the Haringvlietdam, and its entrance is just North of the sluices, so as to ensure the vicinity of a suitable lure current. The seaside estuary functions to attract and 'collect' fish migrating from the sea to the Haringvliet, and leads to the passage through the dam: the coupure. The coupure opens into the East side of the Haringvlietdam: the river side estuary, a sizeable area where further mixing of brackish and freshwater takes place. Finally, the river side estuary leads to the river section of the FMR. The river section ensures a smooth gradient from brackish to (largely) freshwater and makes up the bulk of the FMR's length. This section meanders strongly in order to compress its considerable length into a smaller area. At the end, the river section opens into the Haringvliet and functions as the entrance for fish migrating from the river to the North Sea. Its opening faces the South, towards the sluices, in order to 'collect' fish searching for an opening through the sluices. Just like in the Kornwerderzand FMR, the coupure can be closed off in case of extreme water levels. At Kornwerderzand, it was estimated that closure of the fish passage will only be needed for 4 to 5 days per year on average (van Banning *et al.*, 2018). The design of the Haringvliet FMR should strive not to exceed this estimate. Lastly, the inclusion of bird islands into the design could be considered as well, which could increase the natural values of the area. However, it should be taken into account that attracting piscivorous birds could have a higher predation pressure on the migrating fish as a consequence. After all, fish passing through a fish passage (the FMR in this case) are especially vulnerable to the effects of predation, as discussed in Chapter 2.4.4 ("Predation"). Therefore, it may be preferential to not incorporate bird islands in the FMR itself, although their presence in the surrounding area may not pose a problem.

Naturally, there are relevant differences between the situation at Kornwerderzand and the Haringvliet. An especially important difference between the two areas is the amount of salt intrusion allowed in their respective freshwater bodies. For the IJsel Lake, no salt intrusion is allowed of any kind. As explained above, the Kornwerderzand FMR's design reflects this: the water that enters the IJsel Lake is completely fresh. For the Haringvliet, salt intrusion is allowed to a certain extent. As agreed in the Kierbesluit, salt water should not be present beyond the Spui-Middelharnis line, about 12 kilometers upstream from the Haringvlietdam. This allows for some more freedom when designing the Haringvliet FMR, as some brackish water is allowed to enter the Haringvliet. Because of this, there may be possibilities for an extended brackish estuary environment inside the Haringvliet FMR when compared to Kornwerderzand. Hydrological simulations can provide information on the extent to which brackish water could enter the Haringvliet via the FMR, ensuring the Kierbesluit agreements are not breached. There are also different stakeholders in both areas and the eventual design should incorporate the wishes of local stakeholders as closely as possible. Logically, different stakeholders means different demands, which leads to different requirements for the FMR in both areas.

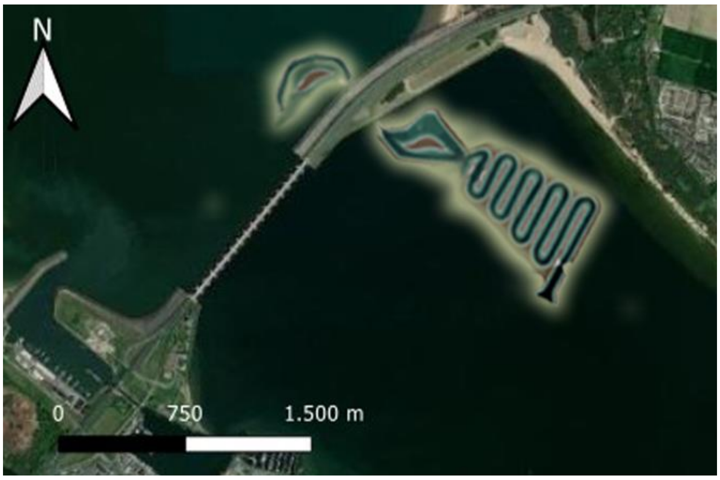


Figure 14. The Kornwerderzand FMR adapted to the Haringvliet, as marked by the glowing penumbra. The seaside estuary is located on the West side of the Haringvlietdam, which leads to the opening through the dam, the coupure. The triangular area directly East of the dam, past the coupure, is the river-side estuary. The meandering part of the FMR is the river section, which eventually enters into the Haringvliet on the East side of the FMR. For this schematic, both the seaside and river-side estuary include a bird island (the brown, sandy area within the estuary).

4.1.2.1 Scenario One Evaluation - Advantages and Disadvantages

Here, we discuss the different advantages and disadvantages of this scenario from different perspectives.

<u>Ecology and Biodiversity</u>
A lot of research has gone into the Kornwerderzand FMR design, which this scenario is based on. Following this design for the Haringvliet FMR will ensure suitable hydrological parameters for allowing passage of the target species.

However, because this FMR design involves the construction of a completely new structure in the river, it is limited in its size (making it larger will increase costs much more). Although its compactness may be an advantage in some respects (less obtrusion for boats and recreation), it limits its effectiveness as a fish migration route. The small diameter causes high densities of fish in migration peaks and there is not much space for the implementation of shallows in the river, which limits hiding places. Both facts increases migrating fish' vulnerability to predation. In addition, its small size limits the number of fish able to pass the FMR at any given time. Thus, when compared to the Haringvliet before its closure, the FMR will be less effective at enabling fish migration.

This scenario also would not add much to the desired estuary characteristics of the Haringvliet (because of its small scale). We expect only a modest effect on increasing the natural values of the area.

Stakeholders
Here we discuss the stakeholders we believe will be impacted most in this scenario.

Fishery: fishery would need to be restricted in the direct vicinity of the entrances of the FMR (fishing inside the FMR will not be allowed). Under the current area legislations (Sportvisserij Nederland, 2019), fishing is not allowed within 50 meters of fish passage entrances, which would be sufficient. However, we have reason to believe that local fishermen do not always comply with these restrictions, in which case enforcement would need to be more strict. Thus, the FMR would take up some area which may have been fishing grounds before and should lead to stronger enforcement of fishing restrictions, neither of which local fishermen would be happy about. However, it should be noted that this will only apply to a relatively small and inaccessible area. Additionally, in the long term, the increased fish migration caused by the FMR would improve the fish stock of the area, which would be of interest to fishermen. Thus, ensuring proper communication with fishermen could help convince them of the FMR's advantages.

Environmental and Nature Organisations: This scenario would increase fish migration in the area, which these organisations would most certainly be in favour of. However, when compared to other possibilities, this scenario would not be a return to the historical estuary characteristics of the area (which would most likely be the optimal outcome for these organisations). As discussed, this version of the FMR also would not be as effective at allowing fish migration when compared to the other scenarios.

Water Boards: There is a very small chance of increased salt intrusion in the Haringvliet, since this FMR was designed in exactly such a way as to not allow any salt water into the area. Since salt intrusion is allowed up to the Spui-Middelharnis line, there is even more leeway here when compared to the situation at the Afsluitdijk. Water boards would most likely be happy with this scenario.

Agriculture: This scenario would not include any form of construction in farmland. For the same reasons as discussed above, there is a very small risk of salt intrusion. We do not expect too much opposition.

Local Businesses: There are local businesses dependent on the nearby beach ('Quackstrand') in the vicinity of the planned FMR location. A good example of this is the EuroParcs Resort: 'Poort van Zeeland'. Construction of the FMR could hamper the view from the beach, temporarily cause hindrance and increase water turbidity. On the other hand, the finished FMR could provide possibilities as a tourism site. Some opposition would be expected and close cooperation would be necessary in order to convince these parties of the FMR's worth to the area.

Implementation Costs and Impact
Costs: According to Rijkswaterstaat, the expected costs of the Kornwerderzand FMR are 55 million euros (Rijkswaterstaat, n.d.). A similar expense could be expected for the Haringvliet FMR in this scenario. When compared to the other scenarios, we believe this scenario would be the most expensive one. It involves the construction of a large-scale, completely new structure in the middle of the Haringvliet and does not make use of existing structures (as is the case with scenario 2 and 3).

Impact: Construction of the FMR would have some consequences for residents and the local ecosystem. Residents living near the beach may be affected as the area's attractiveness will temporarily decrease due to large-scale construction. In addition, the construction would cause hindrance to residents and tourists (loud noises, large vehicles and blocked areas in the vicinity of construction). The local ecosystem at the construction site would largely be destroyed, and there would be disturbance for animals in the surrounding environment. This scenario would have a relatively large impact to the local area when compared to the other scenarios.

4.1.2.2 Overview of scenario One

The main advantage for this scenario comes from the fact that it is based on an extensively studied design (the Kornwerderzand FMR). Thus, research and construction can follow the guidelines from this design, which saves time and research costs and increases the probability of a properly functioning Haringvliet FMR. In addition, we expect most relevant stakeholders to be content with the execution of this scenario. However, regarding the FMR's main function, which is allowing fish migration and increasing natural values of the area, we believe better options exist. Lastly, this scenario is expected to be the most costly of the three, and would cause a greater degree of hindrance and disturbance to the local area.

In principle, previous ACT groups investigated a version of the scenario described here. It is a logical choice, since it is based on the only existing example of an FMR design. However, we believe there are better options for the Haringvliet FMR, for the Haringvliet area offers other possibilities than the Afsluitdijk.

4.1.3 Scenario Two - Haringvlietdam South

This scenario involved utilizing the river Spui and expanding this waterway into the proposed FMR. The area includes the Zuiderdiep which is found towards the southside of river, underneath the Scheelhoek nature preserved area. On the northside of the N57 highway there is a port built which is accessible for small yachts. The Spui leads into this port area where it exits on the coastal side of the Haringvliet sluices. Two possibilities were taken into account – extending the already partly existing Spui river with additional features or extending the river (12 km in length) passed the port and towards the creek side, seen in Figure 15; thus, there are two possible entry points on the coastal side. Furthermore, the other entry point coming from the freshwater side begins at the corner of the town known as Scheelhoek, seen in Figure 15. A student at TU Delft, Esmee van Eeden, had proposed the design seen in Figure 15, along with other propositions for Delta-21. As her plan was valued and taken into consideration, our team would like to include it in our scenario two evaluation. Thus, looking at both portside and coastal side entry points.

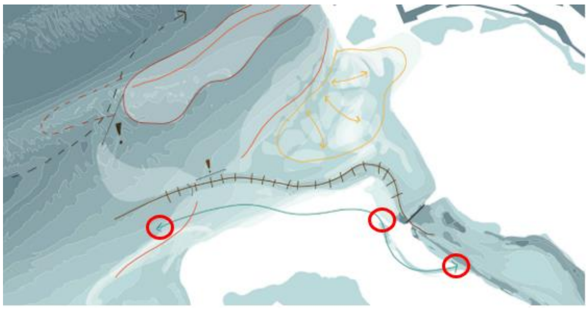


Figure 15. Design made by Esmée van Eeden (TU Delft Student, 2021) The light blue arrow on the bottom of the image is the proposed location of the river and red circles the different entry points into the

In comparison to scenario one, implementing a meandering river on the south side of the Haringvliet dam would not be necessary. The proposed length of the river is much greater, where scenario one is ~4 km and scenario two is ~8 km or 12 km depending on point of entry. Thus, the gradient from fresh to salt water would establish an equilibrium, creating a brackish environment without the need of a meandering structure.

4.1.3.1 Scenario Two Evaluation - Advantages and Disadvantages

Ecology and Biodiversity

The area of the proposed FMR partly surrounds the nature preserve in Scheelhoek. This nature area also contains a bird sanctuary. Since this area is already partly acquainted with wildlife, placing the FMR in this location could add value to these wetlands, taking food webs, mutualistic relationships and the general ecosystem's health into account. More so, the Spui river already exists, so besides modifications, the whole dredging and implementing the river aspect does not need to be done. Less or no dredging contributes to reduced number of disturbances from an ecological perspective.

As indicated above, the river does not need to be in a meandering structure. This can be beneficial in several aspects – less time and costs for dredging as complex structures in a small surface area can be more challenging. As well as less disturbance in existing conserved areas, due to the Spui already been put in place. Interestingly, as mentioned in Chapter 2.3.1 ("Turbulence"), turbulence levels diminish in straight rivers. This is advantageous when comparing to the meandering structure where turbulence can appear.

In contrast, the small port attached to the Spui river could elevate water pollution. This could discourage migratory fish to enter the river. Migratory fish might enter the port and struggle to get out. Attempting to make the FMR on the south side could mean that anthropogenic disturbances might come in play. Anthropogenic disturbances such as noise could arise from the highway and boats nearby. Likewise, the port could also deliver light, an element that could hinder nocturnal species such as the eel from approaching the entrance of the FMR.

Esmee's entry design (coastside) – involves opening an inlet by the coastline, thus sedimentation and silt could be a large factor to keep in mind during implementation (van Eeden, 2021). Furthermore, this area is also between two large channels known as the Slijkgat and Rak van Scheelhoek (Wegman *et al.*, 2015). A large amount of sediment deposition is found amid these channels, which in turn could affect current strengths and could further assist in obstructing the inlet (Koomans *et al.*, 2001; Wegman *et al.*, 2015). When examining Esmee's design, the river-part from the port to the coastline entry point involves going through Kwade Hoek, trespassing a Natura 2000 bird sanctuary area. Taking construction into consideration, this will most likely not be favoured.

Stakeholders

Environmental and Nature Organisations: Realizing an FMR in the area near the wildlife reserve would only further contribute to environmental organisations and their ongoing efforts to make the area "Green". Yet, whilst ongoing construction will take place, some animals could be disturbed. For this, other measures might have to take place for minimizing any damage. More so, Esmee's design could have some repercussions as it involves implementing the river within a Natura 2000 area.

Local Businesses: During construction and after its completion other establishments, such as the company that maintains the port, might have issues with the modifications near the FMR. Some actions might occur where the port could be temporarily closed during FMR modifications. However, additional businesses might come in play, such as visitor centers for educational purposes; bringing awareness to the importance of migratory fish.

Fisheries: Entrance of the proposed FMR (near Scheelhoek) is located in a popular sport fishing zone and commercial dock. Therefore, out of these three scenarios, this one has the most direct impact to fishermen. Although it is assumed that the FMR would not be available for sport fishing, some sport fishers might not oblige, seeing as the Spui is currently being used for this activity. This problem could arise more in scenario two in comparison to the others.

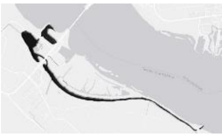
Water Boards: The advantage of the FMR in the south is that it the river will be lengthier (~8 or 12 km), thus the gradient from salt to fresh will happen within the river. Therefore, compared to scenarios, water gradient is not an issue. Yet, scenario one has an already well-developed and existing design for the FMR; when looking at salt intrusion, scenario two might be more unpredictable than scenario one.

Agriculture: The Spui river travels along the northside of several agriculutural land. Incorporating an FMR in this region would establish a brackish environment. This could impact the growing of crops and soil characteristics.

Implementation Costs and Impact

Implementation costs could be relatively low in comparison to other proposed FMR scenarios. Assuming that this scenario will be an extension of the Spui river, the costs could involve expanding and maintaining the original profile of the river. Yet, expanding the width of the river near the port site could be costly and seen as a nuisance for port stakeholders. Extending the entrance could be more costly than anticipated as you would be looking at incorporating both the port entrance and the river entrance with neither being disrupted.

4.1.3.2 Overview of Scenario Two



This scenario entails promising advantages which possibly outweigh the disadvantages, when looking at an environmental disturbance perspective. Designing an FMR for this scenario would mean that a further evaluation of both entry points, the port and coastal side, needs to be done. Although both entry points seem realistic, looking at an economic perspective creating an expansion in only the port area would be more beneficial. It would cost less money to pursue the FMR at the port as no/less dredging would be done, a costly task; it also enhances the chances for the fish to catch the lure current as they wait near the dam area, due to it being geographically closer. However, creating an entrance near the coastal area between the Slijkgat and Rak van Scheelhoek would most likely entail no disturbance of the port. Correspondingly, this entrance could minimize the anthropogenic disturbances, such as light, as this would be more remote.

4.1.4 Scenario Three, Extended Kierbesluit

Rather than creating the fish passage in the form of a migration river, scenario 3 features the optimalization of the current Haringvliet for fish migration. It involves expanding the current Kierbesluit, and developing the Haringvliet area in a way that the sluices can be kept open more often. As aforementioned, the Haringvlietdam primarily functions as protection against flooding. The sluices control the water disposal of the Haringvliet, and it is important to close the sluices in times of little precipitation to keep the water levels at desirable height. Since the construction of the Haringvlietdam, stakeholders have become reliant on the Haringvliet as a source of fresh water. For these reasons, the main goals of structural redesign are to limit the intrusion of salt and protect the land against flooding.

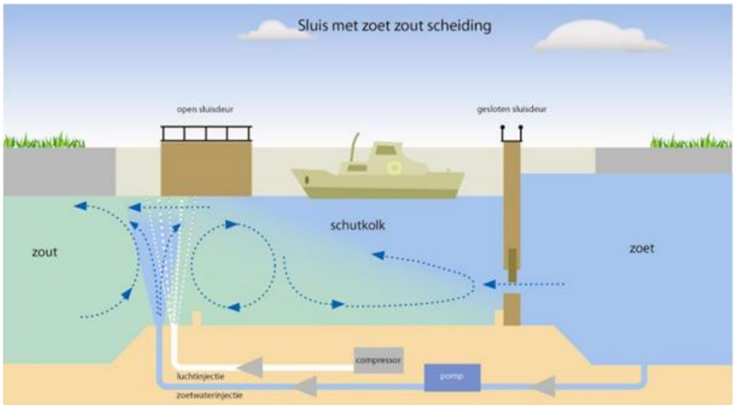
Limiting Salt Intrusion

The basic operational principle of the Dutch sluices limits the salt intrusion. The basin (in this case the Haringvliet) will collect the outflow water of the rivers, and the sluices will open when the water level of the basic exceeds the water level of the sea. The discharge will continue until the water level of the sea and basic are equal (Hong and Stive, 2013). During discharge, the current speed of the water flowing through the sluices will often be too high for fish to pass, as discussed in Chapter 3.4.3 ("Salinity"). The Kierbesluit opens the sluices at times that are different from this basic operational principle, and thus the Haringvliet will suffer more salt intrusion if the sluices are opened more often or wider. Salt intrusion is currently a trending topic in the Netherlands, and ingenious solutions are being deployed in different parts of the Netherlands. Here, some examples are provided to inspire potential measures for the Haringvliet.

Air bubbles

Towards the eastern side of the Haringvliet, there is a body of water called the Volkerak. In the years 1970-1987, the Volkerak had an open connection to the (then) salt water of the Oosterschelde. Several methods were used to limit the salt intrusion through the Volkeraksluices through which the ships pass. In particular, it was found that the creation of a screen of air-bubbles was very effective in stopping the intrusion of salt. Recent studies found available methods for increased efficiency, such as a better and more dense dispersal of air over the entire width of the canal, and by supplying the screen of bubbles with injection of fresh water (Uittenbogaard *et al.*, 2011).

This could be a promising solution for the salt intrusion for the sluices that open for the Kierbesluit. This idea would need a lot of hydrological testing, and it must be biologically confirmed that the fish can pass the screen of air bubbles. Besides this, the construction will be a complicated and costly affair. The principle of the air bubble screen implemented in the Volkeraksluices is displayed in Figure 16.



Source: Uittenbogaard *et al.*, 2011

Figure 16. An example of measure to limit salt intrusion. Displayed here is a sluice with underwater barriers, a screen of bubbles and a yet that propels fresh water.

<u>translation of key words</u>
-Sluice met zoet zout scheiding = sluice featuring separation of fresh water and salt water
- zout = salt water
- zoet = fresh water
- luchtinjectie = jet propelling air bubbles
- zoetwaterinjectie = jet propelling fresh water
- schutkolk = lock chamber

<u>Underwater Salt-wedges</u>
Another possible measure for limiting the amount of salt intrusion is to create a subsurface barrier. This barrier will utilize the properties of seawater. The heavier salt water will flow closer to the bottom and get stuck behind the barrier. The brackish- and freshwater will flow closer to the surface and is not limited by the subsurface barrier. The principle is currently researched and utilized in many parts of the world. Extensive research has been performed in Japan to investigate the best design to stop seawater intrusion (Sugio *et al.*, 1987). In Latakia, Syria subsurface barriers are explored as a solution to seawater intrusion due to excessive pumping of groundwater (Allow, 2012). The principle is already applied in numerous Dutch sluices (Uittenbogaard *et al.*, 2011).

In the Haringvliet, the creation of a sub-surface barrier could greatly reduce the salt intrusion. This barrier would expand on the current barriers that are present in the sluices. The barrier would have to be a distance from the sluices, and it would span the entire width of the Haringvliet. The fish migration should not be limited by a salt water intrusion barrier (Uittenbogaard *et al.*, 2011). There may be possibility for the underwater barrier to be combined with the creation of a bird island, allowing for the Haringvliet ecosystem to be developed further, and improve the current biodiversity.

4.1.4.1 Scenario Three Evaluation - Advantages and Disadvantages

<u>Ecology and Biodiversity</u>
Implementing scenario 3 could have a very positive impact on the biodiversity of the Haringvliet. It is already known that the kierbesluit has led to migrating fish entering the Haringvliet again, (source: intervewee Koen). Therefore we assume that if the sluices are able to stay open more thanks to structural measures, the result will be more fish migration.

The implementation of underwater salt-wedges can be combined with the creation of bird islands. There are already several bird islands in the Haringvliet, and they have all been very successful in providing a safe space to breed for different sea bird species. We also mentioned improving the attractiveness of the Haringvliet for fish, by structures such as fish hotels or plants. In this manner the biodiversity of the Haringvliet can be improved on multiple levels in the ecosystem.

The downside of this concept is that without an FMR to complement the Kierbesluit, the fish passage will be completely closed every time the sluices must be closed. In periods of great water disposal, the fish also won’t be able to enter the Haringvliet.

<u>Stakeholders</u>
Here we discuss the stakeholders we believe will be impacted most in this scenario.

<u>Fishery:</u> The structural redesign of the Haringvliet as described in this scenario may affect the fisheries. Fishermen may experience some new legislations, for migration restoration to be effective we may need to protect the spawn of certain species. The underwater construction may lead to disturbance to the local infrastructure.

Environmental and Nature Organisations: This scenario provides an opportunity to restore the historical ecosystem of the Haringvliet. Nature organisations will most likely be in favour of opening the sluices more, if this can be done in a safe manner. Not only will this scenario benefit the fish migration, there is also possibility to improve upon the avian and plant biodiversity.

Water Boards: Increasing the opening of the sluices will be met with resistance from the water boards. Out of the three scenarios this one has the largest risk of more salt intrusion. This is why it is important for all measured named above to be tested thoroughly through simulations and experiments. This scenario will require more research for informed decision-making.

Agriculture: The kierbesluit was met with some resistance from farmers. Further opening of the sluices is central in this scenario, and so more opposition can be expected. That said, If the salt intrusion is managed, then we expect no interference with farmlands or farmers who require fresh water.

Local Businesses: We do not expect the structural redesign of the Haringvliet to have a large effect on the local businesses.

Implementation Costs and Impact
Costs: Creating barriers against salt intrusion will be costly. The implementation can be difficult, because these structures need to be built underwater. We do expect this measure to be less costly than creating an FMR on the North side, because there is less to be constructed.

Impact: It may also require the main road over the Haringvliet to be closed. There are no significant long-term issues expected with the implementation of this scenario, as fish and boats will still be able to pass through the Haringvliet.

4.1.4.2 Overview of Scenario Three

This scenario brings a new way of thinking about the restoration of biodiversity in the Haringvliet. Instead of creating a river, we discussed the possibility of redesigning the Haringvliet to facilitate fish migration. This scenario expands on the Kierbesluit which is currently in place and considers ways of limiting the salt intrusion so the sluices can be opened more. There are risks involved with this scenario, because the sluices have a key role in protection and water disposal, meaning the fish migration will not always be forst priority. It is critical that the salt intrusion limitation measures work, because of the stakeholders requiring the Haringvliet to stay the freshwater body it is now. Therefore this scenario requires a lot of research.

4.1.5 Scenario Ranking Tables

As a way of evaluating the advantages and disadvantages of the three scenarios, we created ranking tables. This allowed us to quantify the advantages and disadvantages by providing ranks to aspects of the different perspectives which the scenarios where evaluated for. A separate ranking table was made for each of the three different perspectives: ecology and biodiversity (Table 5a), stakeholders (Table 5b) and implementation costs and impacts (Table 5c). For the ecology and biodiversity perspective, we evaluated the three scenarios for the following aspects: fish migration, biodiversity and estuary characteristics. For the stakeholders, we assigned a rank to the consequences for the relevant stakeholders: fisheries, agriculture, water boards, environmental organisations and local businesses. Lastly, for implementation costs and impact, we evaluated the following aspects: implementation costs, local ecological impact and local hindrance. For each combination of perspective aspect and scenario, we provided a rank of 1, 2 or 3. A '1' meaning this scenario provided the most optimal outcome for this aspect compared to the other scenarios, and a '3' meaning the least optimal outcome for the aspect in question. Lastly, we included a summary ranking table for each of the scenarios. For this table, the ranks for the different aspects of each perspective were averaged for each scenario, resulting in a table with one average rank from each perspective per scenario (Table 5d). For the summary table, the lower the score, the more optimal the scenario from that specific perspective.

Table 5a. Ecology and biodiversity ranking table. For each combination of scenario (1,2 and 3) and aspect (fish migration, biodiversity and estuary characteristics), a rank was provided from 1 to 3. A '1' meaning this scenario provided the most optimal outcome for this aspect compared to the other scenarios, and a '3' representing the least optimal outcome for the aspect in question.

Scenario	Fish migration	Biodiversity	Estuary Characteristics
1: FMR North	3	3	3
2: FMR South	1	1	2
3: Extended Kierbesluit	1	2	1

Table 5b. Stakeholders ranking table. For each combination of scenario (1,2 and 3) and aspect (fisheries, agriculture, water boards, environmental organisations and local businesses), a rank was provided from 1 to 3. A '1' meaning this scenario provided the most optimal outcome for this aspect compared to the other scenarios, and a '3' representing the least optimal outcome for the aspect in question.

Scenario	Fisheries	Agriculture	Water boards	Environmental organisations	Local businesses
1: FMR North	2	1	1	3	3
2: FMR South	3	3	2	2	3
3: Extended Kierbesluit	1	2	3	1	1

Table 5c. Implementation costs and impact ranking table. For each combination of scenario (1,2 and 3) and aspect (implementation costs, local ecological impact and local hindrance), a rank was provided from 1 to 3. A '1' meaning this scenario provided the most optimal outcome for this aspect compared to the other scenarios, and a '3' representing the least optimal outcome for the aspect in question.

Scenario	Implementation costs	Local ecological impact	Local hindrance
1: FMR North	3	2	3
2: FMR South	1	3	2
3: Extended Kierbesluit	2	1	1

Table 5d. Scenario summary ranking table. For this table, the ranks for the various aspects of each perspective were averaged for each scenario, resulting in a table with one average rank from each perspective per scenario. The lower the score, the more optimal the scenario from that specific perspective.

Scenario	Ecology/biodiversity	Stakeholders	Implementation costs and impact
1: FMR North	3.0	1.9	2.6
2: FMR South	1.5	2.5	2.0
3: Extended Kierbesluit	1.5	1.6	1.3

The differences between the ranking of the 3 scenarios were statistically tested, using Friedman's test. In the software R (version 4.1.2) run in the interface of Rstudio (version 1.3.1093) All values from table 5a, 5b and 5c were considered data points and were all considered to be of equal weight. According to this test, there was no significant difference between the total scores of the scenarios, but there was a trend ($Q=5.64$, $df=2$, $p=0.06$). This test illustrates how every scenario has advantages and disadvantages, and as a result there is not an obvious 'best choice.' The next part will go into detail on the strengths of the different scenarios.

4.1.6 Conclusion

The created ranking tables (tables 5a – 5d) show considerable variation in optimality for the different perspectives and scenarios. As a reminder, the scores from the summary ranking table are ranks from 1 to 3, meaning that a '1' is most optimal, and a '3' is least optimal. When looking at the ecology and biodiversity perspective, scenario 2 (FMR South) and 3 (Extended Kierbesluit) are tied for first place, with an average ranking of 1.5. Which is considerably better than the average rank of 3.0 for scenario 3 (FMR North). From the stakeholders' perspective, scenario 3 performs best (average rank of 1.6), closely followed by scenario 1 (average rank of 1.9). Scenario 2 shows the lowest optimality in this regard (average rank of 2.5), we would expect the most opposition from stakeholders for this scenario. Lastly, regarding implementation costs and impact, scenario 3 seems to be the most optimal (average rank of 1.3), followed by scenario 2 (average rank of 2.0) and scenario 1 (average rank of 2.6).

When comparing the scenarios taking all perspectives into account, scenario 3 is tied with scenario 2 for ecology and biodiversity, and scores the best on stakeholders and implementation costs and impact. Scenario 2 shares first place for ecology and biodiversity with scenario 3, but is least optimal for the stakeholders category. Scenario 3 shows a middling optimality from the stakeholders' perspective, but is suboptimal to the other scenarios from the other perspectives. Overall, scenario 3 seems the most optimal based on this analysis, followed by scenario 2 and then scenario 1. Surprisingly, our analysis suggests that the best solution for the area may not be an FMR at all, but could come from an extension of the Kierbesluit, as described in scenario 3. This solution offers interesting possibilities from an ecological perspective: a further opening of the sluices would in part return the historical estuary characteristics of the area and open up options for increasing its natural values. Depending on the extent to which the sluices would be opened more, it could also be most effective at allowing migration of fish and other organisms, such as seals (Schop, Cremer, & Brasseur, 2018). However, it should be taken into account that scenario 3 is the least thought out of the scenarios. It is more of a suggestion than anything else, and a considerable amount of research would need to be done to check for its validity. Nonetheless, it shows great promise and could be the optimal solution to the problems discussed in this report.

When comparing the two scenarios which do include an FMR, scenario 1 and 2, we believe scenario 2 shows the most promise. We expect its costs and local impact and hindrance to be considerable lower than scenario 1. Most importantly, it performs much better from an ecology and biodiversity perspective. It offers considerably better possibilities for the return of fish migration, and would increase the natural values of the area to a greater extent than scenario 1. As ecology is the focus of this report, we view this perspective as one of the most important. However, it should be noted that scenario 2 may offer more challenges from the stakeholders' perspective than scenario 1. Its construction would be both near agricultural lands as well as the docks of Stellendam. Opposition from farmers, fishermen and local businesses dependent on the docks is to be expected. Still, this scenario could also offer interesting possibilities for some stakeholders, especially local businesses, for we believe it offers the best opportunities for stimulating tourism. The proposed FMR would be near a nature reserve and would include the return of a small-scale historical estuary. It would be a dynamic and ecologically interesting area, attractive to (rare) bird species and other flora and fauna. Moreover, it would hallmark the return of long-lost migratory fish species. A visitor centre and observation huts are some of the possibilities to be included in this scenario, which could make the area into a valuable tourism site.

To conclude, the Extended Kierbesluit scenario shows great promise, and we recommend to look into its possibilities. Regarding the implementation of an FMR, we believe the South location, making use of the existing waterways there, is the optimal solution.

4.1.7 Summary

Scenarios

In this chapter, we proposed three different scenarios that can implement the fish migration principles applied to the Haringvliet as discussed in chapter three. The first scenario is an FMR inspired by the Kornwederzand FMR, applied to the situation in the Haringvliet. The second scenario utilizes bodies of water already present on the south side of the Haringvlietdam, making them more suitable for allowing fish migration. The third scenario does not involve the construction of a new FMR, but rather expands on the current Kierbesluit by limiting salt intrusion to the Haringvliet, so the sluices can be kept more open.

After every scenario was described, each scenario was ranked to investigate which scenario is best suitable for implementation. For the biodiversity and ecology, we considered the potential improvement in fish migration, the improvement of the general biodiversity and the return of the characteristics of the natural estuary. We then ranked the scenarios based on the potential stakeholder satisfaction of the categories fisheries, agriculture, water boards, environmental organizations and local businesses. We then assumed the hardships of implementation by ranking the relative costs, local ecological impact and hindrance of the construction.

Out of this explorative analysis, we conclude that the extended Kierbesluit (scenario three) is a promising solution to restore fish migration. For the creation of an FMR, the south location using the natural river structure gets a higher score than the creation of a new structure on the north side of the Haringvlietdams. In the end, each scenario has advantages and disadvantages, more research in the shape of hydraulic tests, economical calculations and stakeholder analysis can provide more data to improve upon this preliminary investigation.

5 Conclusion

The aim of this research was to explore the options for the implementation of a Fish Migration River (FMR) in the Haringvliet. In this report we specifically focused on gathering information to make such an FMR attractive for local and migratory fish. We researched the core purposes of an FMR and found three main factors to take into account when creating an FMR: hydrology, ecology and anthropogenic disturbances. Hydrological aspects that are important to consider are turbulence, salinity, current speed, lure current and tidal currents. These factors together determine the accessibility and usability of an FMR for fishes. For example, without a strong enough lure current fish are not able to pick up the chemical cues from the environment that would lead them to the FMR. Once they found the FMR, the other hydrological factors mentioned above should be adapted to the fishes needs so they are able to successfully pass the FMR. These hydrological adaptations should be conducted in consultation with ecological factors. To be able to create the best passage it is vital to know the migration type, migration periods and the swimming capacities of the species for which the passage is intended. In order to help fish pass through the FMR, it is desired to make the surrounding ecosystem as supporting and attractive as possible for fish. This will also help to prevent excessive predation in and around the river. To make an FMR as successful as possible it is wise to consider reducing anthropogenic disturbances caused by sources of artificial light and sound and activities like fisheries.

Having determined the core purposes of an FMR, we investigated the current conditions in the Haringvliet and came up with solutions to adapt the current environment. Using information from past ecological assessments, we compiled a list of sixteen species which originally occurred in the Haringvliet and Voordelta area. Seven species out of this list were chosen as the most important species to base the FMR on, namely: Atlantic salmon, European eel, twaite shad, European flounder, European river lamprey, Atlantic herring and three-spined stickleback. The hydrological characteristics of the FMR should be designed considering the requirements of these target species. First of all it is important for migratory fish that there is an all year round open connection between the sea and the rivers. Additionally, we found that the current speed in a newly created FMR in the Haringvliet will likely be too high. This can be altered by incorporating the Tesla valve concept that creates a variable current and areas with semi stagnant water. Another measure to alter current speeds is to create variation in the depth of the FMR. To ensure that species that depend on tidal transport are able to use the passage, the opening of the FMR should be as broad and as close to the sea as possible. This will also ensure that the lure current that fish need to detect the passage can be most easily detected. As the salinity on both sides of the Haringvlietdams is now different, the implementation of an FMR will provide a gradual transition in salinity changes. This salinity transition zone can be increased by, for example, lengthening the FMR. The sediment around the Haringvliet is mostly composed of silty and clay-like soil. As some target species favour or unfavour that, it is necessary to adapt this to the needs of the different fish species. This can be done by implementing seagrasses and oyster reefs to make sure that sediment will be deposited in which certain species can hide and at the same time create less murky water for other species. Incorporating seagrass and oyster reefs would also increase the amount of shelter and resting places, reduce predation, increase the food availability and would be in line with the idea of a healthy and varied supporting ecosystem around the FMR. Lastly, effects of anthropogenic disturbance can be mitigated by ensuring that there is no excessive light and noise pollution near the FMR. In addition, disturbance by fishery activities should be reduced by, for example, implementing restricted zones or seasonal banning of fishing activities in the surrounding area. All these ideas and solutions will eventually contribute to the effectiveness of the FMR.

After we determined what adaptations are needed or could be incorporated for an FMR in the Haringvliet, we compared three different possible scenarios. Therefore, we made a comprehensive analysis of our proposal in which we looked at options to fit a fish passage into the Haringvliet estuary. Hereby considering various local stakeholders' interests, ecological requirements and biodiversity requirements of the region. Additionally, we have considered the costs of the project realisation in order to investigate the economic feasibility. Our study suggests that extension of the Kierbersluit (scenario 3), is the most optimal variant compared to the scenario 1 and scenario 2 as it suggest further opening of the Haringvliet sluices, which in part can bring back historical characteristics of the area. We proposed this scenario because it offers new and interesting possibilities from an ecological point of view. The proposed extension of the Kierbesluit (scenario 3) shows great promise; however, it requires considerable research and validity. If in case the implementation of an FMR would still be desirable, then scenario 2, which involves the construction of an FMR in the Southern location by using an existing waterway, would be suggested as the best option. Since it is the most preferable and optimal solution that offers better perspectives from the ecological and biological point of view compared to scenario 1.

A great amount of effort and time has been devoted to the comprehensive research done to discover innovative solutions for the FMR; further enabling target species to effectively migrate upstream and downstream the proposed FMR. However, the context of addressing an attractive FMR together with producing minimal hindrance to migratory fish still requires additional research and the use of new technological developments.

5.1 Limitations

Our proposal on the appropriate fish location should be further extended to specific research for site characteristics, comprising topography (i.e. flow pathways) and site geology (i.e. bedrocks) and estuary characteristics (depth/width, discharge and velocity of water throughout the FMR). These properties will have an influence on the design as per the scenario. Currently, we have taken the design of the current Kornwerderzand FMR as a basis; the expansion on each specific scenario is not in the scope of this investigation but instead a more generalised one. As with any major infrastructure construction, the FMR will facilitate direct and indirect economic impacts in the form of income and employment opportunities within the area.

With the construction of the FMR, several migratory species can be introduced within the Haringvliet. Yet, there are negative consequences when implementing an FMR, such as re-/introduction of invasive species. This can alter the advised ecosystem within and surrounding the FMR.

The requirements to implement the FMR are based on past and current abiotic factors, such as hydrology. If the abiotic conditions are changing, for example due to climate change or long-term effects of erosion in the area, then it would alter the hydrological conditions in and around the FMR. Climate change could change the water temperature, salinity gradients and water levels. This will lead to different species composition, passing the FMR. The target species that are now taken into account, could be less attracted to the FMR due to these changed conditions. Furthermore, erosion could change the habitat and soil composition, which also affects the attractiveness for the target species to pass the FMR in the long term. For instance, resting and hiding places could be altered, which makes it less attractive and accessible for the target species. Eventually, these altered conditions could result in less migration success of migratory fish.

5.2 Recommendations

It should be noted that the design and construction of the FMR requires the collaboration of a transdisciplinary team of engineers and biologists during the design phase, to create a design that is both biologically and technologically feasible. This aspect should also take hydrological, ecological and morphological requirements (i.e. erosion effects) into consideration.

Furthermore, for the implementation of the successful FMR, the computational modelling and experimental simulation needs to be performed. Taking into consideration specifics of the proposed locations, hydrodynamic variables (velocity, salinity gradient, tidal flows etc.) of the estuary that possibly may influence the efficiency of the FMR, as the basis to consider simulation carried in Afsluitdijk (van Banning, 2018).

A vital part of this project requires thorough communication with all relevant stakeholders. This includes Governmental Agencies, recreational fishermen, local water suppliers, environmental organisations and the general public. We recommend a separate study to be carried out with the purpose of identifying the costs and benefits associated with the construction of the FMR to the local stakeholders. The FMR may have positive long-term impacts within the local industries such as eco-tourism and travel. An increase in fish populations and other recreational opportunities along the stretch of the estuary may positively affect the values of the nearby properties. But most importantly, based on the decision where to construct the FMR, the economic costs induced by the impacted stakeholders needs to be critically evaluated, especially their loss of income opportunities.

Seven target species were selected for this research. It would be more representable and accurate, if more target species of the list of 16 migratory fish, would have been investigated. Therefore, for future studies, more target species should be investigated, in order to make the FMR as accessible as possible for all present migratory fish. Our team assumes that water quality monitoring is necessary in the Voordelta and in the Haringvliet prior and after the FMR implementation Additionally, fish surveys using different fish survey methods and protocols are necessary to evaluate on site water composition and target species survival, and ensure fish passing efficiency through the FMR.

We believe that the following ACT projects should consider the implications of the introduction of invasive species. This is paramount, as the introduction of invasive species may result in a decline or loss of native species inhabiting the Haringvliet and upstream areas.

Other aspects that are important to consider are the future conditions in the FMR. The FMR is now based on current and past abiotic conditions, which might not be accurate for future conditions, due to climate change and erosion. Therefore, future studies should investigate future conditions, in order to make the FMR more and longer effective. For instance, the FMR can be made dynamic, wherein the hydrological and ecological conditions can be controlled.

Nevertheless, this report contains relevant new insights in implementing an FMR, bringing its realisation a step closer. For instance, the comparison between the three scenarios, including the extended Kierbesluit scenario, which was not mentioned or investigated before. To build on this, the mentioned limitations and recommendations should be incorporated and considered for future studies.

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Appendices

Appendix A: Information sources flowchart

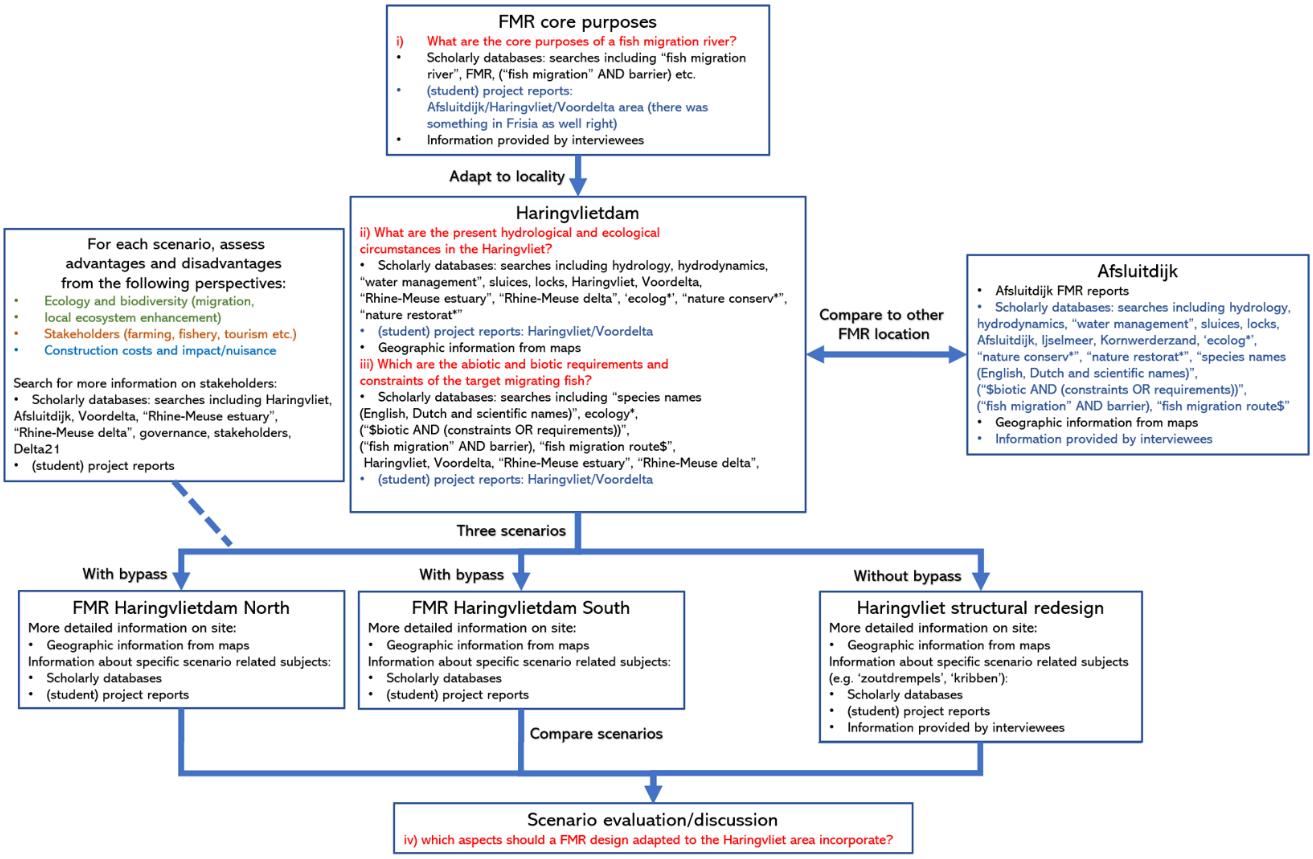
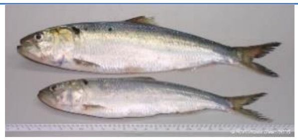


Figure A. Flowchart of information sources. This figure suggests information sources needed for the activities mentioned in figure 1. Each block contains suggestions for relevant information sources. For information from scholarly databases, some important search keywords are mentioned.

Appendix B: Historical Species found within the Haringvliet Area

Table B. Represents the occurrence of 16 fish species in the Haringvliet that are historically used and are expected to use the fresh-saltwater transition zone adapted from the Dream Fund Project retrieved. The third column shows the IUCN Red List status of the mentioned fish species: LC = Least concern; NT = near threatened; VU = vulnerable; EN = endangered; CR = critically endangered; EX = extinct (IUCN, 2021). The fourth column shows the historical estimate of fish abundance in the Haringvliet before the closure by the Haringvlietdam, based on Quak (2016) & Hop *et al.* (2011). +=less common, ++=common, +++=abundant. The fifth column of the Table represents the fish composition result of monitoring works carried b/w 2006-2015 in the Haringvliet and Voordelta by Hope *et al.* (2016) and in 2018 by Ploegaert *et al.* (2018). The last column summarises the overview of the prognosis effect of the Kier on the 16 species by Griffioen *et al.* (2017). (Photo's of species retrieved from: (1) shorturl.at/czEGH; (2) shorturl.at/rEMST; (3) shorturl.at/dCG34; (4) shorturl.at/hBPW6; (5) shorturl.at/hprQ0; (6) shorturl.at/ftBEM; (7) shorturl.at/qwAX8; (8) shorturl.at/dfsuP; (9) shorturl.at/mxBV1; (10) shorturl.at/cmyHX; (11) shorturl.at/dsDPQ; (12) shorturl.at/htwB4; (13) shorturl.at/tACR8; (14) shorturl.at/ceoqO; (15) shorturl.at/dtxyE; (16) shorturl.at/mBER9)

Species	Photo	Guild	IUCN Red List	Historical Reference based on (Quak 2016) & Hop *et al.* (2011)	The present situation of species composition Based on (Hop *et al.*,2016) & Ploegaert *et al.*, 2019)	Prognosis Based on Griffioen *et al.*, 2017 with the opening of the sluices
European eel (*Anguilla Anguilla*)		Diadromous[1]	CR	From fluctuating to very abundant +++* (red eel)	(10) species recorded in Haringvliet & (10) in Voordelta by Hop et al, 2016 (1) sp. recorded in Voordelta by Ploegaert et al, 2019	Open migration is essential for the eel population b/w fresh and saltwater. The importance of the Haringvliet is mainly associated with providing growing ground in fresh water. The eel can migrate upstream depending on the availability of the food. The passage may not be significantly crucial for the silver eel as they use an alternative route at Spui, but it is expected to significantly improve the amount of glass eel coming to an estuary.
Flounder (*Platichtys flesus*)	*Platichthys flesus* 	Estuarine residents[2]	LC	From abundant to very abundant – (adult) (decreased because of fishing efforts) +++* (adult)	(10) species recorded in Haringvliet & (10) in Voordelta by Hop et al, 2016 (171) sp. in Haringvliet & (2580) sp. number/ha recorded by Ploegaert et al, 2019	After spawning in deeper part of the sea, flounders return to an estuary for their foraging areas, and young larvae and juvenile flounders migrate to fresh water or brakish water and/or upstream. Opening the Kier will not crucially affect the population of flounders, but the estuary is a vital as growing and foraging area.

Three-spined stickleback (*Gasterosteus aculeatus*)		Diadromous[3]	LC	+++* (adult)	(3) species recorded in Haringvliet & (6) in Voordelta by Hop et al, 2016	The importance of the Haringvliet is mainly that it functions as a spawning ground and foraging area. Spawning takes place in March and July, in fresh water. The three -spined stickleback either stay in the river, or migrate to the sea. The migratory type may continue to stay in the estuary for this species because they have a high tolerance to freshwater. It is expected the chances for migration and increase in population through the Kier will improve significantly.
Thinlip grey mullet (*Liza ramada*)		Catadromous[4]	LC	No information	(0) Recorded in Haringvliet & (1) sp. in Voordelta by Ploegaert et al, 2019	No information available for prognosis
Allis shad (*Alosa alosa*)		Diadromous[5]	LC	Very abundant – (juvenile & adult) Species amount start to decrease after 1885 to nearly extinction ++* (adult)	(1) sp. was recorded in Haringvliet & (0) in Voordelta recorded by Hop et al, 2016	The importance of the Haringvliet for the allis shad is significant because they use the midstream of the Rhine for the reproduction process, and it is essential to migrate via the dam to reach the the spawning grounds. Shads migrate upstream during the spring period, and the opening of the locks in spring is highly favourable. It is unclear how the Kier affects the restoration of the population.
Twaite shad (*Alosa fallax*)		Diadromous[6]	LC	Very abundant – (juvenile & adult) ++* (adult)	(8) species recorded in Haringvliet & (10) in Voordelta recorded by Hop et al, 2016	The importance of the Haringvliet for migration is paramount as shad use freshwater for spawning purposes. After spawning, adults return to the sea.
Atlantic herring (*Clupea harengus*)		Marine juvenile[7]	LC	Very abundant –(juvenile) to Small amount – (adult) +++ (juvenile)	(2) species in Haringvliet & (10) in Voordelta recorded by Hop et al, 2016 (0) Sp. recorded in Haringvliet & (10357) sp. number/ha in Voordelta by Ploegaert et al, 2019	The importance of the Haringvliet is relatively small. However, herring larvae stock increase in the estuary is essential for predatory fish and birds. Brackish water is preferable over a complete freshwater environment. Migration changes will improve for young herring with the opening of the sluices.

Houting (*Coregonus oxyrinchus*)		Diadromous[8]	EX	From abundant to common – (adult) ++ (adult)	(7) species in Haringvliet & (9) in Voordelta recorded by Hop et al, 2016	The Haringvliet is important as it functions as a corridor for spawning in upstream rivers and returning to the sea. With the opening of the sluices, houting will be able to complete their full life cycle. An increase in population also depends on other constraining factors
River lamprey (*Lampetra fluviatilis*)		Diadromous[9]	LC	From very abundant to abundant – (juvenile & adult) +++* (adult)	(9) species in Haringvliet & (10) species in Voordelta, recorded by Hop et al, 2016	The Haringvliet is important as it functions as a corridor for spawning in upstream rivers. The migration from salt to fresh water is important to complete the full life cycle.
Smelt (*Osmerus eperlanus*)		Diadromous[10]	LC	Abundant (Decrease after WWII) +++* (adult)	(10) species in Haringvliet & (10) in Voordelta recorded by Hop et al, 2016 (0) sp. in Haringvliet & (27) sp. in Voordelta number/ha recorded by Ploegaert et al, 2019	The Haringvliet is important as it functions as a corridor for spawning in upstream rivers. The migration from salt to fresh water is significant to complete the entire life cycle. The population is expected to increase with the sluice opening.
Sprat (*Sprattus sprattus*)		Marine seasonal[11]		+++* (adult)	(3) species in Haringvliet & (10) in Voordelta recorded by Hop et al, 2016 (91)	The importance of the Haringvliet is relatively small. The population is prominent in the North Sea. Similar expectations are similar for the Atlantic herring but increase in population not to an extent as for the herring.
Sturgeon (*Acipenser sturio*)		Anadromous[12]	CR	Hundreds Extinct (rapid decrease after 1885)	(1) species recorded in Haringvliet & (1) in Voordelta recorded by Hop et al, 2016.	The importance of the Haringvliet is not present because sturgeon is extinct. The European sturgeon can reach the spawning grounds upstream in the Rhine. The locks in the Haringvlietdam are currently an obstacle before the migration, but with the Kier, this will undoubtedly improve the population.

Atlantic salmon (*Salmo salar*)		Anadromous[13]	VU	Most abundant – (juvenile), Most abundant in May & August – (adult) (decline since 1890)	(9) species in Haringvliet & (10) in Voordelta recorded by Hop et al, 2016.	The Haringvliet is important as it functions as a corridor for spawning in upstream rivers. The migration from salt to fresh water is significant to complete the entire life cycle. The population is expected to increase with the sluice opening. The migration between salt and fresh water is essential.
Sea bass (*Dicentrarchus labrax*)		Juvenile marine[14]	LC	No information	(4) species on Haringvliet & (10) in Voordelta recorded by Hop et al, 2016. (329) sp. in Voordelta, number/ha recorded by Ploegaert et al, 2019	The Haringvliet/Holland Diep is used by the sea bass as a foraging area. The sea bass can be found in the coastal side and also in the freshwater estuaries. The migratory subpopulation of the sea bass uses use freshwater habitats during the summer periods. The importance of the Haringvliet is not essential to complete their life cycle. Opening of the “Kier” will not significantly impact the North Sea population but improve their occurrence in the Haringvliet.
Sea trout (*Salmo trutta trutta*)		Anadromous[15]	LC	Thousands	(9) species in Haringvliet & (10) in Voordelta recorded by Hop et al, 2016. (1) sp. recorded in Voordelta by Ploegaert et al, 2019	The importance of the Haringvliet is mainly that it functions as a foraging area and for spawning grounds. The carrying capacity of the trout may increase due to the opening of the locks.
Sea lamprey (*Petromyzon marinus*)		Anadromous[16]	LC	No information	(9) species in Haringvliet & (10) in Voordelta recorded by Hop et al, 2016.	The Haringvliet is important as it functions as a corridor for spawning in upstream rivers. The migration from salt to freshwater is significant to complete the full life cycle. Sea lamprey retractability will increase with the opening of the sluices.