Let it flow

Analysing the ecological and hydrological requirements of a fish migration river at the Haringvliet

Plan DELTA21: Designing a fish migration river between the Tidal Lake and the Haringvliet

ACT 2665 (group A) – Let it flow entreprises

Arnaud Legrand, Gerrit Assink, Maarten Heijmans, Vivian van 't Westende, Lailatul Rokhmah, Pepijn Vermeiren and Femke van der Drift

Commissioner: Delta21 (Huub Lavooij, Leen Berke and Gijs Kok)

March and April 2021

WAGENINGEN UNIVERSITY & RESEARCH

LIF.e

Contact Details

Delta21

Anker 50

3904 PM Veenendaal

info@delta21.nl

+31 637644312

KVK 71749519

Commissioners

Huub Lavooij (h.lavooij@delta21.nl)

Leen Berke (l.berke@delta21.nl)

Gijs Kok (gijs.kok@upcmail.nl)

Secretary

Pepijn Vermeiren

pepijn.vermeiren@wur.nl

+31 610561910

Source cover page: https://www.triple-bridge.nl/en/fish-migration-river-afsluitdijk/

Executive Summary

The Delta21 project aims to restore the natural values of the south-western delta while simultaneously ensuring freshwater security, water safety and sustainable energy storage. The closing of the Haringvliet from the North Sea had severe consequences for key natural processes. The current situation in the Haringvliet is influenced by the initiation of the Kierbesluit in 2018, whereby the occasional opening of the Haringvliet sluices allows for the temporary removal of physical barriers when freshwater needs to be discharged from the Haringvliet. Although some migrating fish species have been shown to use this passage, natural migration processes remain limited by the lack of a permanent opening to bypass the Haringvlietdam. The commissioner, Delta21, has expressed interest in exploring the potential for a fish migration river (FMR) to further improve the current ecological situation.

In this report, we present our findings on the ecological and hydrological requirements required for a permanently open fish migration river that facilitate the migration of a select number of flagship fish species. These include the Atlantic salmon (*Salmo salar*), European eel (*Anguilla anguilla*), Atlantic herring (*Clupea harengus*), and three-spined stickleback (*Gasterosteus acleatus*), and were chosen considering their potential to serve as indicator species for the other 12 migratory fish species present in the area.

The most important requirements for the FMR are that it has a low enough flow velocity for fish to enter, that a suitable salinity gradient is created for the migrating fish, while at the same time confining this gradient (or any other salt intrusion) to the FMR itself. The FMR would need to have a sufficient water quality, in terms of oxygen, temperature, salinity, acidity, nutrients and clarity. Furthermore, a lure current would need to be created in order to make sure the fish can locate the FMR and thus increase the effectiveness.

To meet these requirements, we would advise a FMR with multiple channels, a minimum length of 6 km and a width of 20-50 meters. One of the channels should have a depth of at least 5 meters. The FMR would need to have an abundance of hiding places for migrating fish, which include sandy/gravelly bedding, rocks, artificial reefs and seagrass and other vegetation. To ensure water quality, shellfish banks and seagrass needs to be located in and around the FMR.

Table of contents

1. Introduction

1.1 Problem Analysis

Since 1970, the Haringvliet estuary has been closed off from the North Sea by the construction of the Haringvlietdam, with serious consequences for natural fish migration. Since 2018, the Kierbesluit was initiated to partly restore this key ecological process. Through the occasional opening of the Haringvliet sluices, the physical barrier to fish migration is temporarily removed and allows for the creation of a brackish zone through the mixing of salt and freshwater. However, in practice the infrequent opening of the sluices does not allow for the creation of a permanent brackish zone necessary for many species on their migration journey. Additionally, fish migration remains limited due to the short windows of opportunity, because most of the time the Haringvlietdam is still closed.

The goal of Delta21 is to restore the natural values of the area while simultaneously ensuring freshwater security, water safety and sustainable energy storage in the South-Western delta. Permanently opening the Haringvliet sluices has been proposed as a solution to facilitate natural recovery in the area with a special focus on the recovery of natural fish migration. This measure would allow permanent brackish conditions to establish and remove the barriers to fish migration between the North Sea and the Haringvliet. This would enhance the recovery of fish species populations such as the Atlantic salmon (*Salmo salar*) and the European eel (*Anguilla anguilla).* However, permanently opening the Haringvliet sluices would jeopardize freshwater provisioning through salt intrusion and has led to severe opposition from key stakeholders from the agricultural sector and drinking water companies such as Evides. For that reason, the commissioner is investigating a second-best measure to restore nature in the area that is still in line with the Delta21 objectives. Hence, they want to explore the idea of designing a river that can facilitate fish migration between the Haringvliet and the North Sea while minimizing salt intrusion. A fish migration river in this scenario would have to be permanently open and provide a gradual transition from saltwater to freshwater through the creation of a stable brackish zone. This would enable fish species to acclimatize at their own pace and bypass the Haringvlietdam to reach their spawning, living, and growing areas further upriver.

However, there is still a lack of knowledge to realize a stable, permanently open fish migration river in the South-Western delta. Defining the ecological and hydrological thresholds to design a successful fish migration river is required before the measure can be executed. Besides, the location for and the design of a fish migration river in the Haringvliet has yet to be determined.

1.2 Team Purpose

An ideal fish migration river should facilitate the migration of many different types of fish species which use the Haringvliet delta and river Rhine for inland migration. For this report we have selected four flagship species which will be a great indicator of the effectiveness of the FMR. This flagship species are selected and used to base the requirements of the fish migration river on. In a fish migration river hourly conditions vary a lot which means that there is a time window for each of the flagship species to pass the Haringvlietdam barrier (Bruins Slot Interview). Similar species are likely to follow if the FMR is suitable for the flagship species. Our purpose is therefore to define the ecological and hydrological requirements of a stable and permanently open fish migration river needed to approach the ecological situation before the closing of the Haringvliet, while fitting in with the other objectives of the Delta21 project. Increasing the biodiversity of both the river itself and the Haringvliet delta can enrich the area in multiple ways. It strengthens and enlarges the food web, increases the water quality, supports fish stocks and increases recreational value.

1.3 Structure of Analysis

In order to achieve our desired objectives, we have defined a sequence of incremental steps that would need to be taken. This report will be structured according to these steps.

1.3.1 Flagship fish species

The first step towards defining the ecological and hydrological requirements of a fish migration river at the Haringvliet will be to identify which migrating fish species should be prioritised in this report. Although a large variety of migrating fish could likely make use of a FMR, an in-depth analysis of each individual species would not be possible within the timeframe attributed for this project. Instead, "flagship" fish species will be chosen based on several factors such as their presence in the surrounding area, threat status, role within food webs, economic importance, cultural importance, charisma and their potential to serve as indicators for other migrating species. The chosen fish species will then be researched in depth to uncover what requirements need to be met by the FMR for their successful migration. This will include exploring their ecological requirements (specific supporting species, predation pressures, key habitat characteristics etc.) as well as their hydrological requirements (salinity gradient, depth, length, width, flow velocity etc.).

1.3.2 Ecological requirements

Once the flagship fish species have been designated, the ecological requirements of the FMR will be examined in more depth. This will be done by analysing the ecology of supporting species, predators of the migrating fish and non-indigenous species to see how they will be integrated into and/or affected by the FMR. Supporting species may be organisms that have a particular importance in setting the right conditions for the migration of our flagship fish species, for instance by providing shelter or food. Non-fish predators are another important aspect to consider as a high concentration of these species near the FMR may limit the survival of migrating fish. In this section, we will therefore consider how a FMR may affect non-fish predators and thereby determine the importance of predation pressures on the flagship fish species in a FMR scenario. Finally, non-indigenous species that have been introduced in local systems by human influence (either accidentally or intentionally) can have significant and potentially overbearing impacts on the structure and functioning of current ecosystems (Mooney *et al*., 2013). As a result, it will be important to consider species that may exert an important influence on the FMR system.

1.3.3 Hydrological requirements

Once the ecological components have been established, we will explore the key hydrological aspects of the fish migration river that are relevant to satisfy these. In addition, this section will also consider the hydrology requirements of the FMR that are important to the different stakeholders in the area, in particular ensuring water safety and limiting salt intrusion to minimise impacts on freshwater extraction and agricultural activities. The mechanisms of the different components important to the FMR design will be explained within the context of the current and desired future state of the Haringvliet hydrological dynamics.

1.3.4 Suggestions for the FMR design

Once the ecological and hydrological requirements have been determined, we will bring together all the information gathered in the first sections of the report to draw insights on the implications for the FMR design. This section will not focus on determining an actual design for the FMR but will rather seek to define how these requirements can realistically be implemented. Conclusions will be drawn on the river's required morphology (depth, width, length, sinuosity) and suggestions for its location will be discussed. This section will draw inspiration from the Afsluitdijk fish migration river design as well as from discussions with Jeroen Lokker and Bart van der Wolff from Hogeschool Rotterdam who are currently working on a design for the Haringvliet FMR in collaboration with Delta21.

1.3.5 Implications for stakeholder awareness

In order to generate greater awareness and support for the Delta21 fish migration river, we suggest sharing some of the information in this report to relevant stakeholders through more popularly accessible means. In this next part of the analysis, we will discuss what information may be relevant to communicate with different stakeholders and make suggestions on the structure and design of an information leaflet. In particular, we compare the three scenarios (Kierbesluit, fully-opened sluices and the fish migration river) with regard to their effect on ecology and hydrology of the Haringvliet and identify this as one of the key elements to communicate to stakeholders.

1.3.6 Discussion

To conclude our analysis, we will discuss the limitations of this report and knowledge gaps that remain to be addressed. In addition, we will discuss and suggest the next steps that could be taken by the commissioner to finalise this project.

2. Background information

2.1 Past Situation

2.1.1 Pre-closing of the Haringvliet

The Haringvliet used to be one of the most important estuaries in the Netherlands, located at the end of the rivers Meuse and Rhine and forming an opening for many migrating fish species. Salt water gradually transitioned into brackish water, before the water turned completely fresh. This salt intrusion from the ocean occurred all the way up to the Biesbosch (Kranenbarg, 2018). The strong influence of tides resulted in a dynamic hydrological system and established the conditions for ecosystems of high diversity (Jager *et al*., 2004). This large estuary was home to more than 50 fish species such as the characteristic Atlantic Herring (Clupea harengus), Atlantic Salmon (Salmo salar), European Sturgeon (Acipenser sturio), European Eel (*Anguilla anguilla*), European Smelt (*Osmerus eperlanus*) and Twaite Shad (*Alosa fallax*). The Haringvliet itself was home to large numbers of these fish species and historic catches from fisheries between 1870 and 1970 were up in the hundreds of thousands (Jager *et al*., 2004). However, this open area was also vulnerable to storms and flooding. People who were living in the deltas, were poorly protected concerning water safety and reached a catastrophical disaster in 1953 called the "Watersnoodramp". The people realised that the water safety in the Haringvliet required strong improvements for the future and the development of the Deltaworks was initiated and separated the Haringvliet from the North Sea with the Haringvliet locks in 1970.

2.1.2 Post-closing of the Haringvliet

The consequences of closing off the Haringvliet are best illustrated with the anadromous fish species European smelt and twaide shad. Both species were declining already because of fisheries and contamination of the rivers. However, their migration behaviour was suddenly interrupted because of the locks which resulted in a rapid decline of the fish stocks. (Jager *et al*., 2004). The salmonid smelt and the herring-like twaide shad were both important to fisheries, just like the Atlantic herring and the European eel. Herring started to disappear from the Haringvliet and the fraction that remained of the total eel population was only 1% (Kranenbarg, 2018). The Haringvliet locks made it impossible for all migratory fish and marine residents to visit the Haringvliet. The fish species composition started to look more towards that of a lake after the water turned completely fresh, dominated by bream, pike, roach and zander (Kranenbarg, 2018). Contamination of the water kept occurring and bioaccumulation of PCBs was the result in many organisms. The closing off of the Haringvliet also had effects on the hydrology and morphology. Due to the construction and closing of the sluices, the Haringvliet area changed from a salt and brackish to a freshwater area. The closing also changed the dynamics of the area. The flow of water stopped completely, changing the type and amount of sediment which were being deposited. At the same time, mudflats and saltmarshes in the area changed due to this change in sediment transport.

2.2 Current Situation

In 2018 the Kierbesluit was implemented by the Dutch government to improve the natural values as well as to promote the migratory fish to swim up into the Haringvliet. The Kierbesluit is expected to have a great effect on migratory species such as the Atlantic salmon and the European eel of which the population is expected to increase. The sluices open ajar when the water level at the Haringvliet is higher than at sea. Since the implementation of the Kierbesluit, saline water has started to intrude into the Haringvliet. Due to the higher density of this saline water compared to freshwater and in the absence of mixing of freshwater and saltwater, this saline water is found primarily at the bottom of the Haringvliet, a so-called salt tongue. The bottom part of the water has a salinity of about 0 – 18 PSU. However, even after the partially opening of the sluices, the Haringvliet remains an important source in fulfilling freshwater needs by providing water for agriculture and drinking water companies. The agriculture has a higher tolerance compared to drinking water companies, but this is crop dependent. The agricultural field near the Haringvliet does not have many salt-sensitive crops (van Rooij et al., 2012). Another consequence is the increase of turbidity (van Wieringen, 2019). These changes in salinity and salinity fluctuations have caused vegetation on the bottom of the Haringvliet to die out completely. Under the current circumstances, no benthic life can survive at the bottom. This causes the bedding of the Haringvliet to be completely dead and muddy at the moment (Tinka Murk, Interview).

3. Flagship fish species

The Haringvliet is populated by many fish with different characteristics. In order to design a FMR that can be used by all fish, species representative have been chosen based on the migration characteristic. Table 3.1 shows the selected flagship species, the ecological requirements for their habitat, and what species they represent.

Table 3.1. Requirements of flagship fish species

Migration characteristics	Species	Requirements	Represent for
Anadromous	Atlantic salmon (*Salmo salar*) 	· Temperature: 10 – 28 °C [1] · Water flow: < 2 m/s [2a] · Dissolved Oxygen: > 6 mg/l [1] · Salinity: 19 – 34 PSU [4] . Sprint speed: 2.44 m/s [10]	· Allis shad (*Alosa alosa*) · Twait shad (*Alosa fallax*) · Houting (*Coregonus oxyrinchus*) · River lamprey (*Lampetra fluviatilis*) · Sea lamprey (*Petromyzon marinus*) · Smelt (*Osmerus perlanus*) · Sea trout (*Salmo trutta trutta*) · Sturgeon (*Acipenser sturio*)
Catadromous	European eel (*Anguilla Anguilla*) 	· Temperature: 10 – 29°C [1] · Water flow: 0.5 m/s [2a] · Dissolved Oxygen: > 2 mg/l [1] · Salinity: ± 36 PSU [5] . Sprint speed: 0.5 m/s (glass eel) [8] . Sprint speed: 1.7 m/s (silver eel) [8]	· Flounder (*Platichys flesus*) · Thinlip grey mullet (*Liza ramada*)
Marine resident in the Haringvliet	Atlantic herring (*Clupea harengus*) 	· Temperature 8 – 12[3] · Water flow: 0.5 m/s [2b] · Dissolved Oxygen: 7 – 11 mg/l [6] · Salinity: 28 – 32 PSU [3] . Sprint speed: 1.5 m/s [9]	· Sea bass (*Dicentarchus labrax*) · Sprat (*Sprattus sprattus*)
Migratory form	Three-spined stickleback (*Gasterosteus aculeatus*) 	· Temperature: 4 – 20°C [1] · Water flow: 0.3 m/s [2b] · Dissolved Oxygen: ± 8 mg/l [7] · Salinity: 5.1 – 5.9 PSU [7] . Sprint speed: 0.7 m/s	-

1)van Emmerik, 2016 ; 2) Waterstaat, 2001 ; van der Wolff & Lokker, 2021; (2b) Gemeenschap, 2005; van der Wolff & Lokker, 2021; (3) Stevenson & Scott, 2005; (4) Byrne et al., 2018; (5) Politis et al., 2018; (6) Reid, 1999; (7) Glippa *et al.* 2017; (8) Klein Breteler & van Emmerik, 2005; (9) Brevé, 2007, (10) Laak *et al.* 2007

3.1 Atlantic salmon (Salmo salar)

In the Netherlands, there was a healthy Atlantic salmon population in the Rhine River until 70 years ago, before the closure of the sluices (Groot, 1989). Some attempts have been made to restore the different migratory species, including Atlantic salmon, that get through the North Sea to Rhine River by Germany, France and Switzerland. Considering the Haringvliet is the largest tidal barrier in Europe, it negates many of the possible positive effects by these countries. One of the important species would be the Atlantic salmon. Moreover, the Atlantic salmon spends a short period in the Haringvliet since this fish is able to acclimate rapidly and thus can be a representative species to other anadromous species such as allis shad (*Alosa alosa*), twait shad (*Alosa fallax*), houting (*Coregonus oxyrinchus*), river lamprey (*Lampetra fluviatilis*), sea lamprey (*Petromyzon marinus*), smelt (*Osmerus perlanus*), sea trout (*Salmo trutta trutta*) and sturgeon (*Acipenser sturio*). Atlantic salmon and sturgeon have some similarities on their life cycles and habitat requirements. The maximum size of sturgeon is 600 cm with 400 kg weight, and the length at maturity is about 165 cm (FishBase, 2021a). Each life stages of the sturgeon require specific habitat, according to Auer (1969), the larvae are hatched on the river and remains on the gravel until the yolk is totally absorbed and then moving to downstream, meanwhile, when they reach juvenile stage, the preferred habitat is on fine sediment. The adult sturgeons spend their life on estuary and sea to forage and continue growing. The mature adult sturgeons migrate to upstream and usually spawn between May and August on the fast-flowing water in the Rhine River. The sturgeon is a slow-growing species which is expected to have a lifespan up to 50-years-old and reach maturity at about 10 to 20-years-old, making this fish an important indicator of the river health and changes on the ecosystem. Besides, the sturgeon is a charismatic fish species with precious historical and cultural values which is a flagship species in conservation. For these reasons, the European sturgeon should be introduced.

Figure 3.1: Sturgeon (source: Google image)

The current status of Atlantic salmon (*Salmo salar*) is defined as a lower risk and least concern (LC) species by the IUCN (World Conservation Monitoring Centre, 1996). Atlantic salmon is an anadromous species, defined as fish that spawn in freshwater, migrate to the ocean to forage and mature, and return to freshwater to spawn and begin the cycle again, in which most of the population mature for the first time at age 1 – 3 years with a length of about 73.1 cm and the maximum length approximately 120 cm for females and 150 cm for males (FishBase, 2021b). The smolt, a young salmon which has silvery colour and ready to migrate to the sea, is going to the sea to forage and once they are sexually mature, they will return to their home rivers to spawn (Chaput, 2012). The adult can live in a water temperature ranging from 10 – 28 °C, the dissolved oxygen > 6 mg/l and salinity from 19 to 34 PSU (Byrne et al., 2018). The temperature plays important role in migration process. The high temperature difference between seawater and saltwater results in poor smolt seawater challenge performance (Rusell et al., 2012). According to Moore et al. (2012), the temperature influences the timing of freshwater entry and the activity on the estuary. Furthermore, during migration going upstream, the minimum water depth needed is ranging from 0.18 until 0.24 metres (Bell 1986; Bjornn & Reiser, 1991), and the maximum velocity is ideally < 2 m/s (Waterstaat, 2001; van der Wolff & Lokker, 2021) or about 2.13 up to 2.44 m/s (Thompson, 1972; Bjornn & Reiser, 1991). The swimming speed decreases with temperature when it exceeds optimum temperature (16°C) and increase with a temperature lower than the optimal (Salinger and Anderson, 2006). Furthermore, Armstrong et al. (2003) state that several requirements such as boulders covers, overhung banks and deep pools are essential to avoid sunlight and protection from predators.

Figure 3.2: Atlantic salmon (source: Google image)

3.2 European eel (Anguilla Anguilla)

The European eel is placed as 'critically endangered' on the red list of the IUCN (Freyhof & Kottelat, 2010). Across all of Europe, this species has trouble migrating towards fresh waters on the continental shelf (Cresci, 2020). This is also true for the Netherlands since the building of the Haringvliet locks, the Eel population has decreased by a significant proportion (Klein Breteler & van Emmerick, 2005). With regards to achieving the Natura2000 and Kader Richtlijn Water (KRW) goals, restoring the migration activity of the Eels will be of most importance for the FMR. Next to the legal obligations, Eel could form an important income for fisheries because of its delicacy. The European eel represents other catadromous species, defined as fish that spawn in saltwater, migrate to the river or estuary to forage and mature, and return to the sea to spawn and begin the cycle again, like flounder (*Platichys flesus*) and thinlip grey mullet (*Liza ramada*).

The catadromous European eel spawns in the Sargasso Sea, where the larval stage called Leptocephali will make a 5000 km long journey towards African and European coast lines (Miller *et al*., 2015). The Leptocephali develops into a Glass eel before the moment it arrives at the coastlines. In order to find estuaries, they make use of their internal magnetic compass and lunar- and tidal cycles (Jellyman & Lambert, 2003; Cresci *et al*., 2017). Glass eels wait in front of the estuary until it becomes ebb. They possess an exceptionally good olfactory system, with which they can sense chemical cues and salinity differences (appendix 1) coming from the freshwater outflow of the river (Huertas *et al*., 2008). Their susceptibility towards chemical cues depends on the stage of their life cycle, environment and sex (Cresci, 2020). Besides chemical cues and salinity differences, the glass eel also sense pheromones from conspecifics living in fresh water (Schmucker *et al*., 2016).

Figure 3.3: European eel (source: Google image)

When eels finally reach estuaries, they need a couple of weeks of acclimatization before they can enter fresh waters (Rankin, 2009). After this moment, Glass eels decide to stay in the estuary, which can take a few weeks till a couple of years, or they move upstream in the rivers. This mainly depends on their body condition, when this condition is relatively high, they will choose for freshwater nursery grounds upstream and otherwise will stay in the brackish area until they migrate back to the ocean (Edeline et al., 2006). Their ability to swim against the current of the river they will migrate to, depends on tidal activity in the estuary (McCleave & Kleckner, 1982; Dou & Tsukamoto, 2003). Glass eels rely on flooding of the estuary, because they only have a critical swimming speed (U_{crit}) of 10-12 cm/s which eels can maintain only for a short moment (Langdon & Collins, 2000; Wuenschel & Abel, 2008). It is observed that eels will burrow into the sandy bottom during ebb (Trancart et al., 2012).

Finally, glass eels will pigment into elvers during their upstream migration and further into yellow eel and silver eel while foraging in the freshwater parts. The silver eel stage will stop eating and makes its return home to the Sargasso Sea.

3.3 Atlantic herring (Clupea harengus)

The Atlantic herring has an important historical and cultural value and represents the marine juveniles in the Haringvliet. Other marine juveniles in the Haringvliet are sea bass (*Dicentarchus labrax*) and sprat (*Sprattus sprattus*). Eating maatjes herring is a cultural tradition for Dutch since 14th century. Besides, the Atlantic herring holds important role in food web since it is a prey for many marine mammals and birds.

Figure 3.4: Atlantic herring (source: Google image)

The current population of Atlantic herring (*Clupea harengus*) shows a positive trend, since the enforcement of fisheries regulation, and least concern (LC) status, according to the IUCN (Herdson & Priede, 2010). The maximum length of Atlantic herring is about 40 cm, with length at maturity about 16.7 cm at 2 until 9 years (FishBase, 2021c). The adults spawn at sea at the depth 20-40 metres. As the larvae grow, they perform vertical migration and swim actively. The larvae metamorphose to juvenile stage in the spring season. Furthermore, the juveniles migrate to the Haringvliet as nursery ground to forage and leave the nursery ground at age 1 until 3 years, and then join the adult schooling to migrate to the spawning grounds (Dickey-Collas, 2005). The juveniles prefer temperatures ranging from 8 - 12°C and shows physiological stress when the temperature drops below 4°C and raises above 16°C. The preferred salinity of the juveniles is about 28 – 32 PSU (Stevenson & Scott, 2005) and the dissolved oxygen between 7 – 11 mg/l (Reid et al., 1999). In addition, the preferred salinity is temperature dependent. When the temperature is lower than 10°C, they prefer the habitat with salinity higher than 29 PSU, while shows no preference on the temperature above 10°C (Stickney, 1969; Stevenson and Scott, 2005). Based on Gemeenschap (2005) and Van der Wolff & Lokker (2021), the water flow for Atlantic herring is 0.5 m/s. Furthermore, according to Eggers et al. (2015), mature Atlantic herring conduct annual migrations for wintering, feeding and spawning in different areas. Most of the Atlantic herring population in the North Sea starts to spawn at the beginning of September. The Atlantic herring spawners aggregate the eggs on the shells and gravels, which is usually an area with high flow velocity (Petitgas et al., 2010).

3.4 Three-spined stickleback (Gasterosteus aculeatus)

Being one of the most common fish species in the Netherlands, the three-spined stickleback will be found almost everywhere in Dutch waterbodies. There are three different morphological forms distinguished, one living permanently in fresh water (*Leiurus*), an anadromous form (*Semiarmatus*) and one spending their life entirely in salt or brackish water (*Trachurus*). The red list of IUCN indicates this species as 'least endangered', however this is only true for the *Leiurus* forms (NatureServe, 2019). The *Semiarmatus* and *Trachurus* forms have shown declines in population numbers in the past years due to migration barriers like the Afsluitdijk and the Haringvliet (Emmerik & Nie de, 2006). The stickleback also contributes to the Haringvliet serving as bulk food for migratory species like salmonids and piscivorous birds (Griffioen et al., 2017; Reeze et al., 2017).

Figure 3.5: Three-spined stickleback

The *Semiarmatus* form will migrate between February and May to freshwater areas to spawn and juveniles will return to sea around June-September. The FMR at the Haringvliet's main purpose will be a corridor function for the *Semiarmatus* form (anadromous), nursery grounds in the brackish area for the *Trachurus* form and spawning habitat for the *Leiurus* form in the freshwater areas. The stickleback have no problems with acclimatization between fresh and salt water, as this time period is relatively short and forms no migratory problems (Grøtan et al., 2012). The spawning areas in the Haringvliet can be brackish or fresh water and will need a sandy substrate with enough vegetation and cover to build their nests (Reeze et al., 2017). With the Haringvliet locks ajar, the prognose for these species are relatively good. The population of the *Leiurus* sticklebacks can thrive towards stable numbers and the migratory sticklebacks can make a return with the opportunity of a fish migration river (Griffioen et al., 2017).

4. Ecological Requirements

4.1 Predators

This section will describe the effects of a FMR on fish predators, and how this will affect the fish crossing the FMR. The last subsection will discuss the predation risks of different predatory species on the migrating fish, and how these predation risks can be limited within the design of a FMR.

4.1.1 Marine mammals

Two different seal species live in the Voordelta: the harbour seal (*Phoca vitulina*) and the grey seal (*Halichoerus grypus*). Both seal species need sandbanks to rest, to give birth and to nurture their young. Also, human disturbance needs to be absent and seals should have direct access to deep water (Hoekstein et al., 2019). The most important sandbank for the seals in front of the Haringvliet locks is the Hinderplaat, but seals also use the sandbanks Slufter en Oogeiland, Kwade Hoek and Garnalenplaat (Figure 4.1 and 4.2) (Hoekstein et al., 2019; Schop et al., 2018). The FMR is expected to reduce these important sandbanks from eroding in comparison to fully opening the sluices, while still allowing seals to migrate in and out of the Haringvliet at all times which is not possible within the current Kierbesluit.

Figure 4.1: Sandbanks (Kwade Hoek, Garnalenplaat, Hinderplaat, and Slufter en Oogeiland) in front of the Haringvliet locks that are utilized by the harbour seal, the grey seal, and all kinds of bird species. Source: Google Earth.

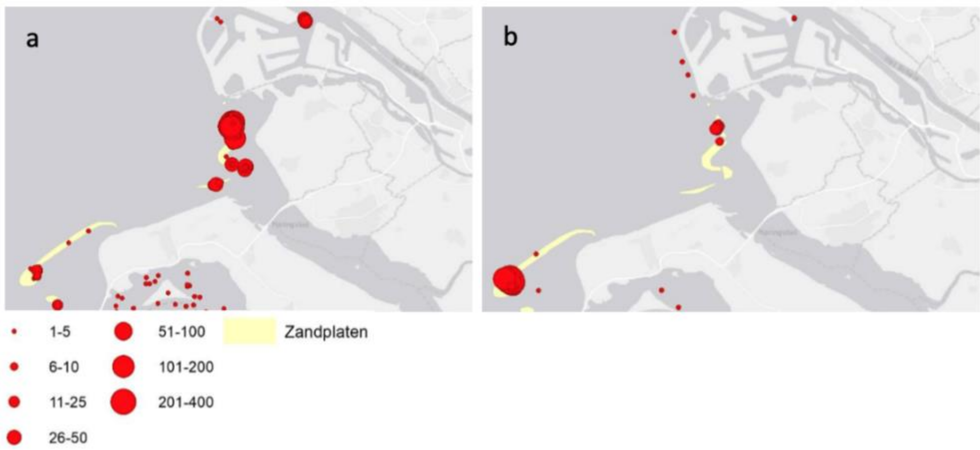


Figure 4.2: Distribution of the use of sandbanks by two seal species around the Haringvliet: adult harbour seals (a) and adult grey seals (b). Based on counts in season 2018-2019. Source: Hoekstein et al., 2019.

Next to harbour seals and grey seals, harbour porpoises (*Phocoena phocoena*) are occurring in the Voordelta. Harbour porpoises are by far the most numerous cetaceans in the North Sea. It is estimated that there are around 250.000 animals in the North Sea (Hammond et al., 2002; Macleod, 2008).

Seals and porpoises can occur in freshwater environments such as the Haringvliet. The species are currently only occurring occasionally to the east of the Haringvliet locks. When emerging in the Haringvliet however, seals and porpoises often have a difficulty returning to their usual foraging grounds in the North Sea. The fact that the species cannot always return and might need to survive for a long time in freshwater might eventually lead to death of the seal and the porpoise, because of a lack of locally available food sources. By creating a FMR there will be a permanent opening for the seals and the porpoises to move between the North Sea and the Haringvliet (Schop et al., 2018). Besides, seals and porpoises will profit from the increase in fish abundance due to a FMR (Van Wieringen, 2019).

A FMR might cause a higher presence of seals in the Haringvliet. It is predicted that seals will more often cross a barrier with a permanently open connection to the sea compared to when there is no permanent opening (Schop et al., 2018). This expected increase in the occurrence of seals will increase their predation pressure on the migrating fish. However, seals are currently able to easily predate on the fish species that are stuck in front of the Haringvliet sluices (Winter et al., 2020). A FMR might make it more difficult for seals to catch the migrating fish, because the FMR is expected to reduce the fish density compared to the current situation without a permanent opening for the migrating fish. The same might also apply to porpoises, but no literature is available on this. It is however important that the FMR is designed in such a way that shelter such as seagrass is provided for the migrating fish, and that there is enough space for the migrating fish to escape from predation. The predation risk is an important factor that should be taken into account when the depth, the width, and the length of the FMR are determined (Section Predation risks).

4.1.2 Birds

Birds visit the Haringvliet area to roost, to forage and to breed. The closure of the Haringvliet from the North Sea however severely affected the presence of birds. Mainly wading birds and piscivorous birds have declined in numbers over the years. The decrease in wading birds such as the Kentish plover (*Charadrius alexandrinus*) and the ringed plover (*Charadrius hiaticula*) is predominantly related to the disappearance of a brackish habitat. The decline of piscivorous birds such as the sandwich tern (*Thalasseus sandvicensis*) and the common tern (*Sterna hirundo*) has mainly to do with a decrease in the supply of fish (Vergeer et al., 2016). The FMR would enhance fish migration and increase both the fish availability and the diversity of fish from which piscivorous birds will benefit. Moreover, piscivorous birds that are hunting on sight might benefit from a higher transparency of the water, because of the low flow velocity of the water within the FMR (Noordhuis, 2017). However, many fish can adapt to this by migrating during the night.

However, the FMR might also make it more difficult for piscivorous birds to catch fish compared to the current situation without a permanent connection where the fish can get stuck in front of the Haringvliet sluices. To prevent a high fish density in a small spot, it is important to design a FMR that limits high concentrations of fish accumulating in one spot of the FMR (section Predation risks).

The presence of sandbanks in the Voordelta are next to being important to seals, also important to all kinds of bird species (Figure 4.1). For instance, the sandbanks are used by cormorants, wading birds, ducks, and migratory water birds. In some periods, more than 20 000 water birds are present at the Hinderplaat (Hoekstein et al., 2019).

The creation of a so-called "bird island" in the FMR could function as an additional breeding area for birds from which a species such as the common tern will benefit. This island can also be used by wading birds as a refuge area to forage and to roost during high tides. This will have a positive effect on wading bird populations such as the ringed plover. These bird islands are often made of shells and gravel.

Taking the FMR Afsluitdijk as an example, the bird island should be made in a way that it can occasionally be flooded by salt water. The salt water will prevent the development of vegetation on the island which will ensure that the island remains a suitable breeding area (Van Banning et al., 2018; Mulder, 2017). It is however important that the bird island does not flood during the breeding season. Besides, the banks of the FMR can provide additional roosting, foraging and breeding areas from which bird species such as oystercatchers, gulls, lapwings, and titlarks might benefit.

4.1.3 Predation risks: shape and hiding places

When fishes are crossing the FMR, they are susceptible to all kinds of predators such as piscivorous birds, seals, porpoises, and predatory fish. Predation is a natural process, but a FMR that is from an ecosystem point of view relatively small might cause an increased predation pressure on the migrating fishes. Making sure that the predation pressure on the migrating fishes will not strongly increase is an important aspect to consider when designing a FMR.

The presence of predatory fish in the FMR can be a risk factor to the fishes crossing the FMR. However, because of the strong salinity dynamics within the FMR, it is unlikely that marine predatory fish will stay in the FMR for a long time (Winter et al., 2014). A way for migrating fish to escape from predation by predatory fish is by hiding. Therefore, it is important for the fish crossing the FMR that hiding places are provided within the FMR. This will enable migrating fish to hide for not only predatory fish, but also for piscivorous birds, porpoises, and seals. For instance, by working with a sandy subsurface in the FMR, fish species such as glass eels (*Anguilla anguilla*) and flounders (*Platichthys flesus*) can hide in the sand to escape from predation. The FMR Afsluitdijk makes use of such a sand-based system for instance. Another example of shelter would be the inclusion of reed banks in combination with a shallow depth (<60 cm) to prevent predation by diving piscivorous birds. Diving piscivorous birds will avoid this area to predate on fish in order to prevent their beaks being buried in the sand. This will provide a safe haven for fish species such as the stickleback and the glass eel (Bruins Slot Interview). The inclusion of seagrass and shellfish beds can also provide shelter to different species. Besides, rocks can function as a hiding place for fish against predation by diving piscivorous birds such as cormorants and grebes (Winter et al., 2014). However, rocks can also be used as a hiding place by predatory fish which can affect the non-predatory, migrating fish again.

A previous ACT group proposed another type of shelter which was the inclusion of artificial reefs within the FMR (Figure 4.3). Three different types of artificial reefs were proposed: reef balls, layered cake, and piles of basaltic rock. In addition to providing hiding places, these artificial structures can also provide hard substrate for the establishment of shellfish (section Benthic species). Reef balls however are not attractive for (smaller) fish to hide from predation as there is only a single large shelter opportunity, while layered cakes and piles of basaltic rock contain multiple layers and therefore provide much more hiding places. The layered cakes are constructed from concrete and the rock piles are made from natural basaltic rocks (Hylkema et al., 2020). A study conducted by Hylkema et al. (2020) proved that structures that provide more hiding places will sustain a higher fish abundance and fish biomass. These artificial reef structures will increase the fish biomass, the fish abundance, and the species richness compared to a barren sand system (Hylkema et al., 2020). Therefore, the subsurface of the FMR must contain at least some of the above described hiding places for the migrating fish.

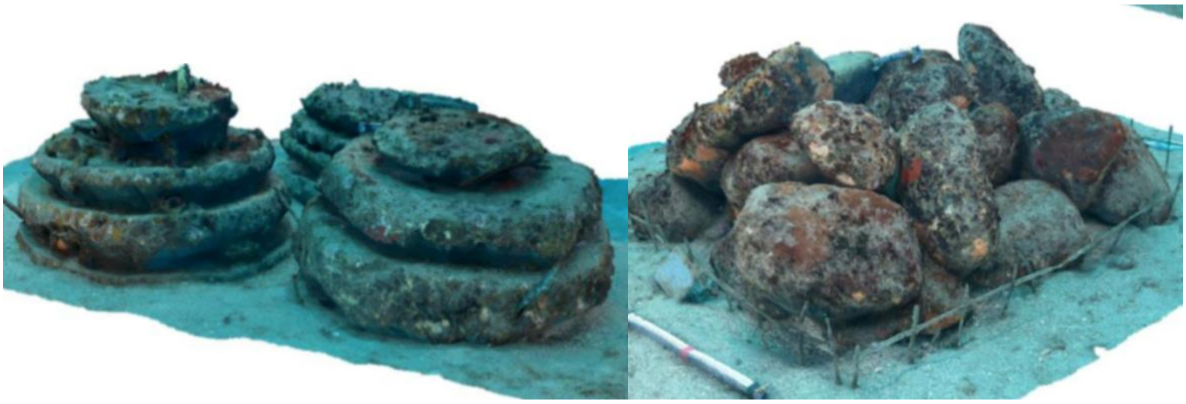


Figure 4.3: Two types of artificial reefs that can be used by the migrating fish crossing the FMR to hide for predators. From left to right: layered cake and piles of basaltic rock. Source: Hylkema et al., 2020.

In the FMR not only hiding places should be included to prevent migrating fishes from being predated upon, but fishes should also be given sufficient space to escape from predators within the FMR. To reduce the predation pressure from piscivorous birds such as gulls and terns, that catch fish in the upper water layers, the FMR should be at least a few meters deep. This will allow fishes to escape from predation by these birds. However, this will not affect the predation pressure of bird species such as cormorants and grebes, because these species are not limited to the upper layers of the water column (Noordhuis, 2017; Winter et al., 2014). As described in the paragraph above, fishes could hide behind rocks, in artificial reefs or in reed banks for instance to find shelter against these bird species.

Moreover, fish-eating predators are attracted by large concentrations of fish, also called prey hotspots. Therefore, it is of importance to make sure that the FMR is nor too narrow neither too shallow (at least a few meters deep), and as long as possible. These elements are essential to give fish species a chance to escape from predation, and to reduce the accumulation of fish in a small spot to limit an additional loss of fish biomass by predation.

4.2 Supporting species

To ensure the fish migration river is suitable to live in and not only to pass through some non-fish species can be used to create a lively river. Sea grass will function as the lung of the river and make sure the oxygen levels stay above the threshold mentioned above. Sea grass not only generates oxygen, but it can also function as a food source, a hiding place, a breeding ground or a nursery area (Boström et al., 2006). For instance, young cod need the seagrass as a nursery so they are safe from predators. To ensure that seagrass survives, the river should meet the parameters in which seagrass can grow and survive. One of the most important requirements for sea grass is that the water is clear. Important species that can facilitate sea grass and make sure the water is clear enough are shellfish (Fitzsimmons et al., 2019). Their ability to filter the water is necessary to allow enough sunlight into the river for the seagrass to grow. Other benefits of shellfish beds are providing shelters, surfaces, a rich nutrient source and feeding grounds, reducing wave energy, denitrification and stabilising the substrate (Figure 4.4).

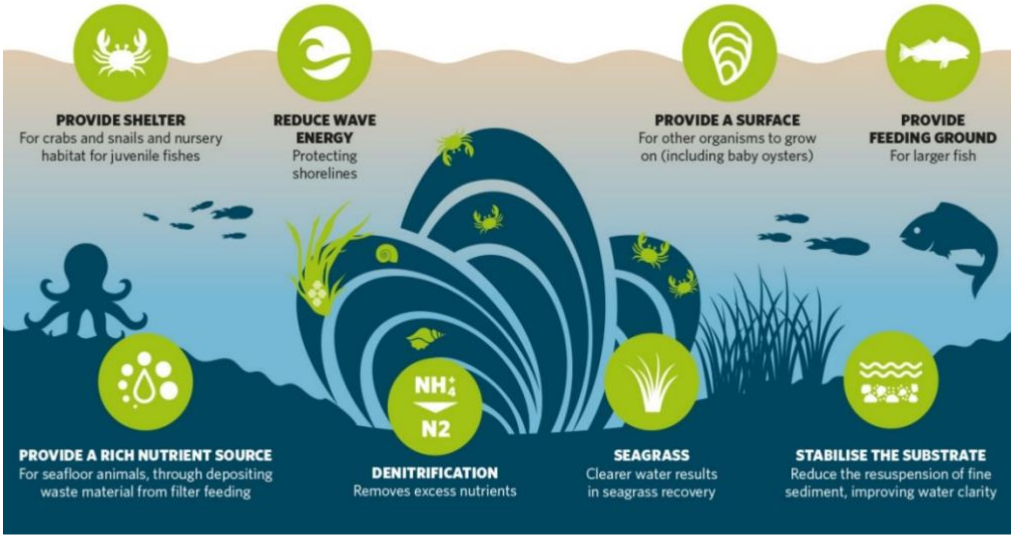


Figure 4.4: The benefits of a shellfish reef (Fitzsimmons et al., 2019).

4.2.1 Seagrass

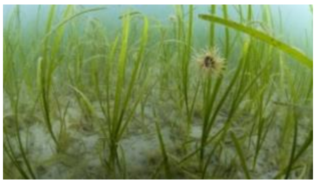
The reintroduction of seagrass in the Waddensea area could be used as an example for the FMR. The species present in the Waddensea are dwarf eelgrass (*Zostera noltei)* and common eelgrass *(Zostera marina),* both the annual and perennial kind (Katwijk, 2012). Seagrass can survive in a depth range between 0 and 15 meters depending on the species. Dwarf eelgrass can survive in intertidal areas and up to 15 in depth while common eelgrass can live in depths from 0 to 5 meters. These shallower depths are more optimal since more sunlight can penetrate here, which will allow them to grow better. If the waterflow of the river is too fast, the seagrass might not be able to root and stay rooted (Tyler-Walters, 2008a). This should be considered when constructing the river, otherwise sea grass would not be able to be present in the river. The flow should ideally be lower than 0.5 m/second. If there are waves coming into the fish migration river, the orbital should be less than 0.5 m/ second. Substrates ranging from mud or sand are the most ideal since seagrass cannot root if the substrate is too loose, too dense or too hard (Tyler-Walters, 2005; Tyler-Walters, 2008a). If there are fish, benthic species or plants that require another substrate, the fish migration river should be divided into different substrate areas. Seagrass also has a preferred salinity range. Both probably need to be closer to the sea entrance, so they are further away from the freshwater. The PSU that is most suitable for dwarf eelgrass is between 30 and 40 PSU but they can survive in salinities ranging from 18 to 40 PSU (Tyler-Walters, 2005). For common eelgrass there are two optimal ranges of PSU. The low salinity variant prefers 6 to 20 PSU and the high salinity variant prefers 10 to 25 PSU (Salo *et al.*, 2014). Their tolerance gradient varies from 2 up to 40 PSU.

4.2.2 Shellfish species

Shellfish and sea grass go hand in hand. If there are no filter feeders present, it is unlikely the water is clear enough for sea grass to survive. A healthy mussel or oyster population will be essential for a well working food web in the Haringvliet area. In a previous ACT report, shellfish beds composed of the European flat oyster (*Ostrea edulis*), the Pacific oyster (*Magallana* (previously *Crassostrea*) *gigas*) and the blue mussel (*Mytilus edulis)* were suggested as an important component of healthy seagrass habitat in a potential fish migration river at the Haringvlietdam (Baas *et al.*, 2020). As the report failed to provide detailed explanations of the hydrological and ecological requirements of these species, we examine this here to determine how these species could be integrated into the FMR design. The flat oyster and blue mussel can create shellfish reefs on soft or hard substrate by using their byssal attachment (O'Donnell *et al.*, 2013). This way they can form large reefs that can filter the water and be used as a food source. Both species can handle a large range of salinities, the flat oyster can survive in water up to 5.5 PSU (Colsoul *et al.*, 2021) and the blue mussel can withstand salinities up to 4 PSU (Eymann *et al.,* 2020). They also have a high sediment tolerance and can handle variability in exposure to sediments (Somers, 2019; Perry *et al.*, 2017; Tyler-Walters, 2008b). If sea grass is to be implemented in the river itself there should also be shellfish nearby. The blue mussel *Mytilus edulis* can attach itself to the leaves of eelgrass. Therefore, this species might help to ensure the water is clear enough for eelgrass to survive. Most shellfish are pretty sturdy and will close their shells when the salinity drops below a certain point. This will cause them to be shut when fresh water pours in the direction of the ocean and to open when saltwater streams into the fish migration river. If the river were to be closed off, or there is a special tide, some of the individuals can die due to being exposed to fresh water for too long.

4.2.3 Summarizing requirements table

Table 4.1: The requirements for the mentioned supporting species.

Species	**Requirements**
Dwarf eelgrass (*Zostera noltei)* 	Temperature between 12 °C and 23.2 °C Depth ranging from intertidal to 15m. Produce between 97.5 and 1001.3 mg of oxygen/m/h Prefer substates of mud, muddy sand and sandy mud. Tidal strengths between 0 and 1.5 m/sec. PSU of 18 to 40, ideally 30 to 40
Common eelgrass (*Zostera marina)* 	Depth ranging from 0m to 5m. Prefers substrates of gravel/shingle. Muddy gravel, muddy sand and sandy mud Tidal strengths between 0 and 0.5 m/s PSU of 2 to 40, the low salinity variant prefers 6 to 20 PSU and the high salinity variant prefers 10 to 25 PSU.
Blue mussel *(Mytilus edulis)* 	Acclimated to temperatures ranging from 5°C to 20°C, with an tolerance limit of 29°C for adults. Depths ranging from intertidal to 5m. Prefer substrates of artificial reefs, bedrock, biogenic reef, caves, crevices/fissures, large to very large boulders, mixed muddy gravel, muddy sand, rockpools, sandy mud, small boulders and under boulders. Tidal strengths between 0 and 3 m/s. Tolerant of PSU 4 to 40 with a preference for salinities >18PSU.
Flat oyster (*Ostrea edulis*) 	Highest filtration at 18 °C to 24°C, with lethal temperature at 36°C. Depths of 0 to 80m Prefer substrates of bedrock, cobbles, gravel/shingle, large to very large boulders, mud, muddy gravel, muddy sand, pebbles and small boulders. Tidal strengths between 0 and 0.5 m/s PSU of 5.5 to 40 with a preference for 30-40

4.3 Non-indigenous species

Non-indigenous species can sometimes be very successful in invading new ecosystems and in those cases they can sometimes cause significant alterations to native environments (Mooney et al., 2013). In this section, we aimed to identify species that are not originally native to the Haringvliet or the surrounding areas but may have an important influence on the current and/or future system. Although this section does not aim to offer a completely comprehensive list of such species, it identifies some of the species which could have an important effect on the specific ecological and hydrological aspects outlined in the previous sections of this report. In order to fully assess the potential impact of non-indigenous species on a FMR at the Haringvlietdam, a more detailed analysis would be necessary.

4.3.1 Chinese mitten crab (Eriochir sinensis)

This species of crab is well known worldwide for its high potential to cause significant ecological, economic and social damages yet such appears not to be the case in the Netherlands (Bouma & Soes, 2010). This species has been present in Dutch waters since at least 1931 and occurs at the highest densities in coastal areas and estuaries in the downstream stretches of the Rhine, which includes the Haringvliet (Bouma & Soes, 2010). As a euryhaline species, it is able to thrive in waters of various salinities and completes a catadromous life cycle. Adult mitten crabs first migrate from freshwaters to estuaries to mate in brackish and salt waters. Brooding females then continue towards the sea, where they release the eggs that will eventually develop into the juveniles that migrate back into freshwater systems further inland (Bouma & Soes, 2010). Although the mitten crab's ability to migrate over land (Bouma & Soes, 2010) suggests that the Haringvlietdam may not serve as an important obstacle to its reproductive cycle, a fish migration river and the formation of a brackish water zone is likely to facilitate their reproduction and enhance their densities in the surrounding areas. Although the current impacts of the Chinese mitten crab remains of low concern in the Netherlands (Bouma & Soes, 2010), potential increases in densities may lead to the species becoming more problematic within the Dutch territory. Additionally, their ecology and behaviour may directly affect the migration of fish species.

The presence of Chinese mitten crabs in the fish migration river could lead to significant changes to a FMR's carefully designed morphological and hydrological characteristics. The burrowing behaviour of this species can cause significant damages to human infrastructures by stimulating erosion and can also precipitate the release of phosphates and pollutants from the sediment and decrease water clarity (Bouma & Soes, 2010). Additionally, heavy preying on invertebrates suggests that this species may affect invertebrate community composition and dynamics, with potential effects on energy flows (Rosewarne et al., 2016). Through their opportunistic feeding habits, Chinese mitten crabs can also interfere with recreational and commercial fishing through bait-stealing, damage to traps and captured fish and increasing handling time (Bouma & Soes, 2010). Through predation of eggs, they may also affect fish reproduction further upstream although actual records are lacking (Bouma & Soes, 2010). Recent studies have confirmed that given the opportunity this species will show egg-feeding behaviour with a preference for larger eggs (1-6mm) such as those of the Atlantic salmon (Webster et al., 2015). This species has been observed in far upstream stretches of the Rhine (Bouma & Soes, 2010), suggesting that their densities may also increase at the spawning grounds of fish species that reproduce further inland. Altogether this suggests that this species may become more abundant due to the creation of a brackish transition zone and may have important effects on the FMR itself through its burrowing behaviour and predation of macroinvertebrates.

Higher future abundances of Chinese mitten crab may be somewhat controlled by the expected increase in the densities of natural predators. Various natural predators have been reported to feed on Chinese mitten crabs in nearby Germany, including mammals, birds and fish (Bouma & Soes, 2010). Eels may serve as an important predator of the smaller individuals in Dutch waters (Bouma & Soes, 2010), and could therefore exert important top-down control if their own densities are successfully increased by the FMR. Additionally, expected positive effects of the FMR on local bird densities could also help control Chinese mitten crab populations as several common Dutch species such as the grey heron, stork, ducks, crows and sea gulls have been reported to predate on this species (Bouma & Soes, 2010). Humans are thought to be the most important predator of this species yet in the Netherlands they are only consumed on a small scale (Bouma & Soes, 2010). This suggests that densities may still increase despite higher predator densities. Monitoring of the densities and impacts of this species within the FMR may be needed to determine if additional control measures are needed to curtail potentially important impacts on the river's ecology and/or morphology.

4.3.2 Non-indigenous shellfish

As discussed previously, shellfish beds may play an important role in the FMR by acting as shelters for benthic species, food sources and facilitating the establishment of seagrass habitat through water filtration (section 4.2.2). Determining what non-indigenous species may establish in the FMR can be important to determine their relative roles in the future system. Figure 6.1 summarises the potential distribution of the species explored in this section according to salinity tolerance.

4.3.2.1 Non-indigenous Mussels

Non-indigenous mussels have been repeatedly recorded in Dutch waters and may either carry out those beneficial functions in the FMR or may instead lead to significant ecological and economical damages at high densities.

A non-indigenous species of mussel that could influence the composition of shellfish reefs in the FMR is Conrad's false mussel (*Mytilopsis leucophaeata*). This species is adapted to brackish environments, with a high salinity tolerance (0.1-26.4PSU) as well as optimal salinity (0.75-20.9PSU) (Verween *et al.,* 2010). They have been found to occur in the estuarine delta of the Rhine (Verween *et al.,* 2010) and although true seawater is outside of their survival range, the development of a brackish habitat may create conditions that facilitate their spread and establishment in the FMR. They require artificial or natural hard substrates such as stone, woody debris and oysters to attach and establish (GISD, 2021). Given their occurrence in nearby locations and their tolerance of brackish conditions and wide fluctuations in salinity, this species could become an important component of shellfish reefs that establish in the FMR. It may be important to monitor their occurrence within the newly create brackish zone as *M. leucophaeata* can cause important biofouling problems by settling on hard substrates in high densities (Verween *et al.,* 2010). Although this may not affect the FMR itself, it may become an issue if the brackish transition zone is located near the Haringvliet sluices or the Delta21 infrastructure as this may lead to biofouling of these key infrastructures.

Zebra mussels (*Dreissena polymorpha*) have been found to co-occur with *M. Leucophaeata* in the estuarine delta of the Rhine (Verween et al., 2010), which suggests that they may also be able to colonise the FMR. The zebra mussel is a non-native species currently found in important densities in the Haringvliet (Figure 4.5, Schonenberg & Gittenberger, 2008) and could therefore potentially integrate sections of the FMR where there are lower salinity levels. If it does spread into the FMR, this species can rapidly reach high densities and has been reported to cause significant changes to local macroinvertebrate abundance and diversity with potential knock-on effects on ecosystem processes (Ward & Ricciardi, 2007; bij de Vaate *et al.*, 2010). Similarly to *M. Leucophaeata*, zebra mussels are known to cause important biofouling issues and lead to significant financial costs (bij de Vaate *et al.,* 2010). It is unlikely to spread further than the sections of the FMR that will be closest to the freshwater inflow given it generally tolerates salinity levels up to 6 PSU (Verween *et al.,* 2010). Establishment of this species in the FMR and brackish transition zone is unlikely to be an issue due to the species' low tolerance for relatively low salinity levels >6 PSU, especially considering that the Haringvliet is no longer fully freshwater due to the Kierbesluit opening.

Figure 4.5: *A mussel bed specimen from the Haringvliet taken in 2006. All but one specimen are Zebra mussels (Dreissena polymorpha). Figure taken from Schonenberg & Gittenberger, 2008).*

4.3.2.2 Pacific Oyster (Magallana gigas)

The non-indigenous Pacific oyster (*Magallana* (previously *Crassostrea*) *gigas*) has been found expanding in the nearby Westerscheldt estuary (Wijnhoven, 2017) and Wadden sea (Fey et al., 2010) and are cultivated in the closed-off Oosterscheldt and Grevelingenmeer (van Houcke et al., 2016). This species has also been proposed as a potential actor in the shellfish reefs of the Haringvliet FMR by a previous ACT group (Baas et al., 2020) and in reefs can host high macrofaunal diversity and abundances (van Broekhoeven, 2005). Pacific oysters can establish on hard substrata or on hard pieces in soft substrates, using the first established individuals as hard substrate to subsequently build on (van Broekhoven, 2005). Despite their expansion over beds of native blue mussels (*Mytilus edulis*), they can also have positive effects on the establishment of this native species by providing a hard substrate for the bivalves to colonise (Fey et al., 2010; Wijnhoven, 2017, Reise et al., 2017). Although

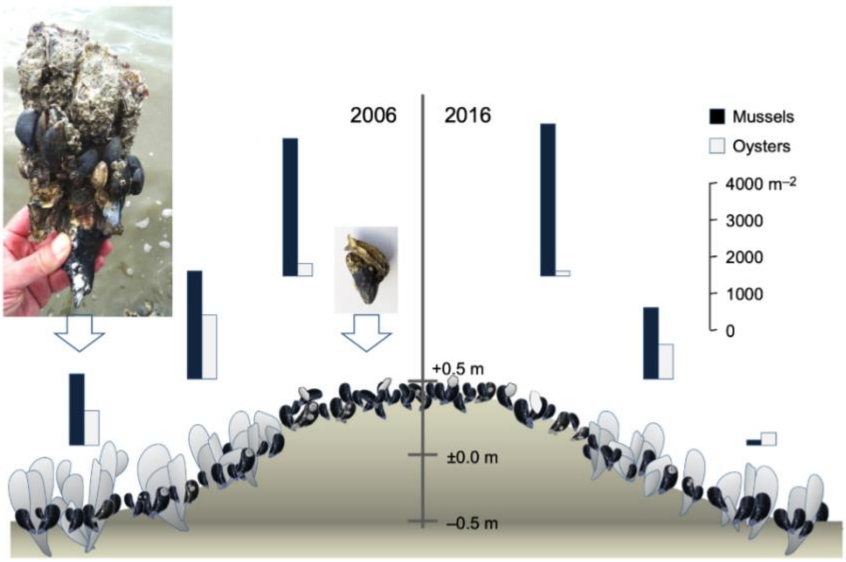


Figure 4.6*:* Observed dominance patterns of shellfish beds by the non-indigenous Pacific oyster (M*agallana crassostrea*) and native blue mussel (*Mytilus edulis*) in the Wadden Sea. Figure from Reise et al., 2017.

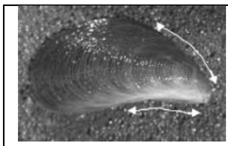
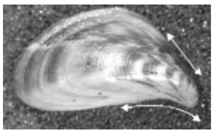
the establishment of blue mussels does not completely depend on the presence of Pacific oyster reefs, their overlap in occurrence suggests a high overlap in their ecological requirements. Additionally, although the two species co-dominate on slopes, blue mussels are still able to dominate shellfish beds above the mean tide level (Reise et al., 2017, Figure 4.6).

Although their optimal salinity is recorded to be between 20-25 PSU, the sites at which Pacific oysters were found in the Western Scheldt showed a large salinity gradient from approximately 0 PSU to >30 PSU (Wijnhoven, 2017). The species prefers firm substrates but can also be found on mud or sand-mud bottoms and can establish from the lower intertidal zone up to 40m depth (Reise et al., 2017; FAO, 2021). This suggests that this species may colonise the full length of the FMR and can aid in forming the basis of the shellfish reefs by providing hard substrate for other species such as the blue mussel to establish. Reef-building bivalves, and the Pacific oyster specifically, are known however to locally enrich the sediment through mass production of fecal matter (van Broekhoven, 2005), which may cause deterioration of the surrounding aquatic environment (Wijnhoven, 2017). Additionally, the space taken by the formation of dense Pacific oyster reefs in the FMR could have an effect on the hydrological dynamics within, for instance by slowing flow velocity. In the Dutch Wadden Sea, Pacific oysters have been found predated upon occasionally by crabs and birds such as herring gulls and oystercatchers (Fey et al., 2010) although the only significant predation pressures comes from human consumption, which is not possible when the individuals are established in reefs (Fey et al., 2010). Altogether, this suggests that Pacific oysters may be able to naturally colonise a FMR at the Haringvliet and form the basis of shellfish reefs, thereby establishing the conditions suitable for the establishment of other shellfish and seagrasses. Considering that they also have a very wide saline tolerance, this species may be interesting to artificially establish in the FMR to facilitate and kickstart the development of desirable benthic habitat. However, due to their tendency to create large, dense, unharvestable reefs, it may be important to monitor their densities and effects on the FMR system, for instance their domination of the benthic system or effect on water quality through defecation.

4.3.3 Summary of non-indigenous species ecology

Table 4.2: Overview of key information for the four non-indigenous species focused on for this report.

Species	Status	Effects	Requirements
Chinese mitten crab *(Eriochir sinensis)*  Image: Bouma & Soes, 2010	Currently low impact in Netherlands but brackish transition zone could increase local abundances *Monitor in FMR*	**<u>Positive</u>** (low) predation by birds and fish; (low) demand for consumption. **<u>Negative</u>** Burrowing (erosion, release of pollutants, lower water clarity); Feeding (lower macroinvertebrate diversity, lower fish reproduction, effect on recreational and commercial catch).	Wide salinity tolerance; Mating in brackish and salt waters; Catadromous life cycle; Able to migrate via land.
Conrad's false mussel (*Mytilopsis leucophaeata)*	Found in estuarine delta of Rhine	**<u>Positive</u>** Water column filtration, structural habitat component (shelter, food).	Wide salinity tolerance: 0.1-26.4PSU; Optimal salinity: 0.75-20.9PSU; Requires hard substrates to establish

 Image: Verween et al., 2010		**Negative** Potential biofouling of Haringvliet sluices and Delta21 infrastructure.	.
Zebra mussel (*Dreissena polymorpha)*  Image: Verween et al., 2010	High densities in Haringvliet, found in estuarine delta of Rhine	**Positive** Water column filtration, structural habitat component (shelter, food). **Negative** Significant changes to macroinvertebrate community; Potential biofouling of Haringvliet sluices and Delta21 infrastructure.	Low salinity tolerance: up to 6 PSU; Unlikely to show important abundances in FMR.
Pacific oyster (*Magallana Crassostrea*)  Image: Reise *et al.,* 2017	Increasing in nearby Western Schedlt estuary and in Wadden Sea *Potential benthic habitat kickstarter;* *Monitor in FMR*	**Positive** Water column filtration, structural habitat component (shelter, food); Allows for establishment of native blue mussel (*Mytilus edulis*); Harvested if not in dense reefs; (Low) predation by birds and crabs. **Negative** Decrease in water quality through local enrichment; Can create large, dense, unharvestable reefs.	Wide salinity tolerance: near 0 to >30PSU; Optimal salinity: 20-25 PSU; Requires hard substrate to establish (can then build on already established individuals); Mud or sand-mud bottoms.

5. Hydrology

When looking at an FMR, hydrological requirements need to be taken into account to ensure functionality and function. Species using the FMR need certain conditions to survive and thrive. In this chapter, the hydrological requirements like flow velocity, morphology and salinity will be discussed. We will try to give an overview of the factors and their influence on both the FMR and the local environment. We will not be looking at the political side of these requirements and the way these stakeholders should be prioritized.

5.1 Flow velocity

In large parts of the FMR the flow velocity will likely be variable, due to the variable discharge of freshwater and the influence of the tides. When designing a permanently open fish migration river, this changing flow velocity must be taken into account. The flow velocity is important for a number of reasons. The flow velocity is important for fish and other wildlife, for morphology and salt intrusion.

The flow velocity is of great importance to fish, as they need to be able to swim upstream. They need to be able to enter the fish migration river either permanently, or by using the tidal current. Thus, the critical swimming speed of fish needs to be taken into account. Adequate measures need to be taken to make sure the flow velocity does not continuously exceed this critical swimming speed. Furthermore, the flow velocity is important for the morphology of the FMR. A too high flow velocity will cause erosion and a too low flow velocity will cause sedimentation. In the ideal situation there will be no nett sedimentation or erosion in the final form of the FMR system. Either nett erosion or nett sedimentation would require additional maintenance which is not desirable. It is however a different story in the start-up phase of the FMR. In the beginning, a morphologically stable state needs to be reached. This may take some time. It is also possible that sedimentation is required to construct certain parts of the FMR. This depends on the final design and should not influence the functioning of the FMR. The flow velocity, more specifically the discharge, should be high enough at high tide to keep salt water out. It also needs to be high enough to flush out the saline water from the river part of the fish passage, or at least far enough back, so that is does not intrude into the Haringvliet during the next high tide. This is important to prevent salt intrusion. If the discharge is not high enough and salt water intrudes too far into the FMR, it might need to be closed to prevent the saline waters from reaching the Haringvliet. This is of course not a desirable outcome. The length of the FMR is in this case very important, since a longer length means the salt water has more space and thus time to mix with the fresh water. It also enhances the distance salt may intrude and as a result, the timespan over which lower then desired discharge can occur is extended.

5.2 Morphology and sedimentology

The critical flow velocity for sediments is dependent on the grainsize figure 5.1. The sedimentary composition found at the mouth of the Haringvliet has changed after the construction of the Haringvliet locks. Before the construction, it was mostly sandy. After the construction of the locks a clay layer has been deposited on most of these sandy deposits (TNO Dinoloket, 2021). From figure 5.1 it can be gathered that the critical erosion velocity for sands is ~0.2 m/s. However, this is in the case of no coverage by vegetation, shellfish or artificial reef structures. In more recent documents (Sweco, 2018) this number has been raised to 0.3 m/s. This would mean that a flow velocity above 0.3 m/s would lead to erosion in the FMR and as a consequence sedimentation elsewhere (possibly also in the FMR). Thus, to create a morphologically stable system, it is crucial that the flow velocity does not exceed this limit of 0.3 m/s anytime during a regular (non-storm event) tidal cycle. It is however very unlikely that this can be prevented at all times and all along the FMR. Thus, at places where this limit is exceeded, the riverbed needs to be reinforced, either naturally (vegetation cover, mussels) or artificially (concrete reinforcement). A too low flow velocity is also not desirable, since this could cause particles which had previously been suspended in the water to settle (sedimentation). Furthermore, it could cause the water quality to drop significantly, since the water is not being filtered by filter feeders, nutrients may build up and oxygen levels in the water may drop.

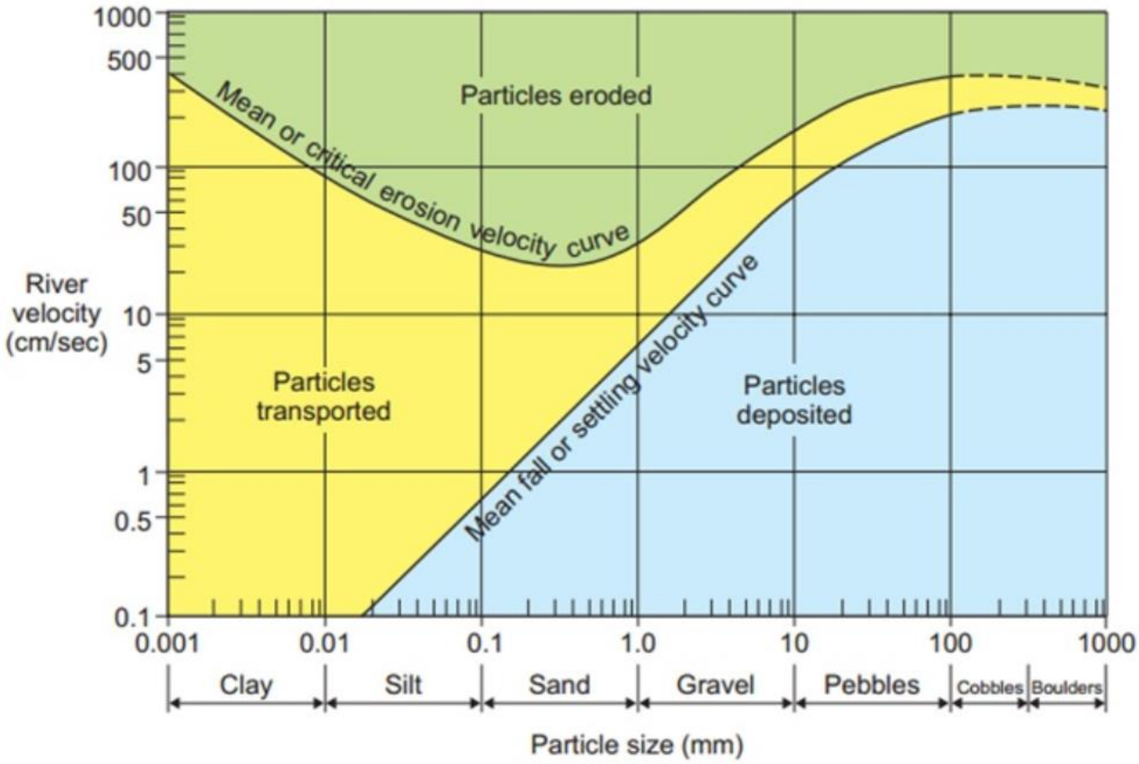


Fig 5.1: Hjülstrom diagram, showing the critical velocity for erosion and/or sedimentation of particles.

5.3 Discharge

The discharge is an important factor to take into account when looking at salt intrusion and at the possible dimensions for the FMR.

$$Q = u \times A \tag{1}$$

Wherein: *'Q'* is the discharge [m^3/s], *'A'* the cross-sectional area of the river [m^2] and *'u'* the flow velocity [m/s].

The discharge is directly related to the width and depth of the fish migration river. The maximum and minimum possible discharge need to be taken into account when designing the river. This is because a minimum flow is still required to keep the saline water out. The source of the water which is being discharged through the Haringvliet is the Rhine. However, most of the fresh water from the Rhine needs to be discharged via the *Nieuwe Waterweg* to prevent salt intrusion there, since it is in open connection with the sea. This means only a limited amount of water discharge is available for the Haringvliet. In times of higher discharge, this is not a direct problem. It may however become troublesome during times when the discharge of the Rhine is low, for example during summer. Over the last few years, there have been periods where discharge through the Haringvliet has been very limited or even negative. In figure 5.2, we see that in the last few years, the discharge through the Haringvliet has been above ~100 m^3/s most of the time. We can use this number as an estimate for the discharge which is available for the FMR. If we use a maximum flow velocity of 0.5 m/s (section 5.2), the cross-sectional area of the river could be a maximum size of $A = \frac{100}{0.5} = 200m^2$.

In times of high discharge, their needs to be a way to deal with the excess of fresh water. If too much fresh water is discharged through the FMR, this could lead to a too high flow velocity and a change in salinity. This could cause problems for species using or living in the FMR. To deal with this discharge, another way for the fresh water to leave the Haringvliet is needed. Looking at the FMR being built at the Afsluitdijk could present a potential solution. At that location, excess water is discharged through pumping the water out, called “Spuien”. The location of these Spuien needs to be carefully considered, since the discharge of extra fresh water into the sea could mess with the navigation of migrating fish. This could cause them to not be able to find the entrance to the FMR (section 5.5).

Furthermore, flood safety is also a concern. The purpose of the Haringvliet sluices is to secure flood safety. By constructing a FMR, this flood safety would become compromised. In order to keep this flood safety, measures should also be taken in the FMR. In the FMR, a locking mechanism should be in place in case of emergency situations. Emergency situations include storms or other extreme high water events.

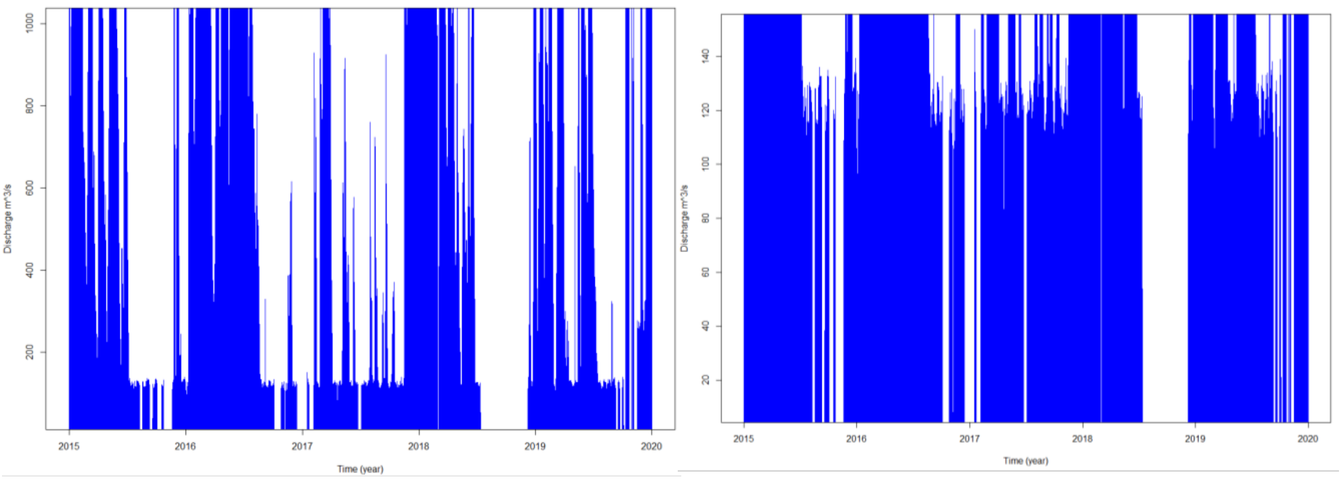


Fig 5.2: Discharge through the Haringvliet in the years 2015 to 2020 (data: https://waterinfo.rws.nl)

5.4 Salinity

The FMR river needs to form a place for migratory fish to travel from salt to fresh water and vice versa, while also offering a place to adjust to the different conditions. For this reason, a suitable salinity gradient needs to be present and no salt wedge may form. A salt wedge occurs when no mixing occurs between fresh and saline water and the freshwater flows on top of the saline water, as illustrated in figure 5.3. In this way, saline water is able to intrude far inland. Thus, sufficient mixing needs to occur. At the same time, in the interest of the drinking water provisioning and surrounding nature areas, the salt must not intrude inland or into the Haringvliet. Thus, in order for migrating fish to utilize the FMR in an optimal way, the saline and fresh water must mix sufficiently over a large enough length, so that a suitable salinity gradient forms. This will give fish the opportunity to adapt to the change in salinity. For this gradient to be present, it is important that no salt wedge forms. In the interests of the freshwater provisioning, saline water must not intrude too far into the Haringvliet. Currently, with the Kierbesluit, the maximum salt may intrude is to the line Middelharnis-Spui. Ideally, this line is pushed back again to (close to) the Haringvliet sluices. As a minimum requirement, this line should not be exceeded. Water is considered fresh with a PSU value of 0.45 (Practical Salinity Units). In order to provide a suitable salinity gradient for the fish, mixing of salt and fresh water needs to be stimulated. Furthermore, sufficient mixing length must be present. The length of the FMR also plays a role in preventing salt water from intruding into the Haringvliet.

To create a salinity gradient, mixing needs to occur. Mixing between the salt and fresh water can happen in two ways: Dispersion and turbulent mixing. Turbulence thus needs to be stimulated to promote mixing. At the same time, turbulence causes stress for some fish species, and completely washes others away. It can also effect the structure of the FMR in a negative way. Turbulence is thus something which needs to be monitored well and has both an upper and a lower limit. For fish, the value which is seen as undesirable is at 0.05 m^2/s^2.Turbulance can be stimulated by adding resistance. Resistance is dependent on the bed structure. An irregular bed, for example with boulders or artificial reefs, stimulates active mixing.

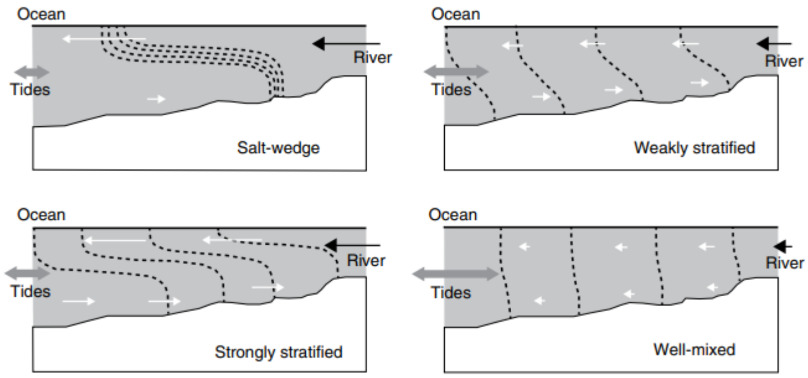


Figure 5.3: Classification of estuaries based on the vertical structure of salinity. Different types of stratification (solid black lines) are controlled by the relative strength of tidal versus riverine flow as illustrated by the length of the arrows in the four models. Adapted from Valle-Levinson, 2010

In order to increase mixing and lessen the intrusion, groynes can be installed in the river (fig. 5.4). Research from Arcadis (2018) indicates that these both increase hydraulic resistance and decrease salt intrusion. From this same research, it can be gathered that the groynes can be placed in both the bends and the straight parts, with a limited difference in salt intrusion but a higher difference in flow velocity, turbulence and depth. We would advise to use groynes in the straight parts with a reinforced riverbed between the groynes.

Figure 5.4: Example of groynes in a river to stabilize the channel and its banks. (Rijkswaterstaat)

5.5 Lure current

To attract the fishes to the seaside entrance of the fish migration river, a lure current will have to be created. This is especially important when the brackish zone is mainly located within the FMR. In that case, migratory fish need to be able to find the entrance of the FMR when they are swimming along the Dutch coastline. Fish can sense fresh or brackish water that exits the FMR and have a natural instinct to swim upstream. Without a lure current, fish tend to not find entrances of fish passages (Kroes & Monden, 2000). There are different requirements the lure current has to meet.

Firstly, the flow rate of the current has to match the swimming speed of the species that make use of the fish migration river. Based on the flagship species, the flow rate of the lure current should drop below 0.2 m/s during high tide, to make sure all species are able to enter the FMR. However, during high tide the flow rate can be higher, in order to reach as far away from the entrance of the FMR as possible and attracting fish from further away.

Secondly, the current cannot be too turbulent. Smaller migratory species might easily get disoriented and become an easy prey to predators like birds when they get pushed to the surface of the water.

Lastly, it is important to choose a suitable location for the lure current. The lure current should reach far out from the entrance of the FMR in order to attract as many fish as possible. Besides, other waterflows have to be taken into account too, since they can both disrupt or enhance the lure current. When excess fresh or brackish water is being discharged into the North Sea, migrating fish will group at the location of the discharge. In this case it is important that the lure current is as close to the discharge as possible, in order for the fish to be able to find the entrance of the FMR (scenario 1 figure 5.5).

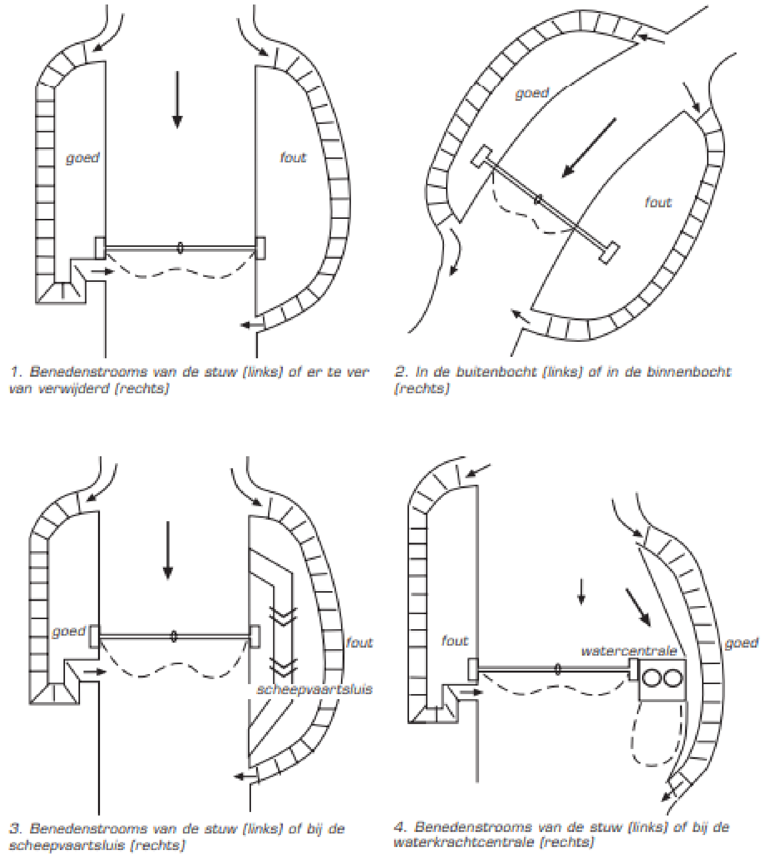


Figure 5.5: Possible situations for the location of the entrance to the FMR in relation to sluices,weirs and other sources of freshwater. Source: Kroes & Monden, 2000.

On the other hand, discharged water can also amplify the effect of the lure current. In the FMR that is currently being constructed through the Afsluitdijk, discharged excess water is going to be used to enhance the lure current (van Banning et al., 2018). During the times the Haringvliet sluices are being opened, as agreed in the Kierbesluit, excess fresh water is being discharged into the North Sea, so this situation might be recreated and benefit the FMR at the Haringvliet (Griffioen et al., 2017).

However, the discharge of excess water can also be dangerous for fish. The huge amounts of fresh water might cause heavy turbulence, and cause fishes to either get disoriented and be eaten or might even pull the fish away from the actual entrance of the FMR. In the last case, the entrance of the FMR, and thus the lure current, can be placed on the side of the discharge point, just before the area where the turbulence is too strong for the migratory fish species. In this way the fish can still enter the FMR, but experience less turbulence (Kroes & Monden, 2000).

6. Suggestions for the FMR design

To construct a functional FMR with limited impact on quantitative and qualitative (salinity) water safety, measures need to be taken in the design of the FMR. In this chapter, measures which could be taken to make sure these requirements are met will be discussed. Below is a short overview of these requirements.

6.1. Overview of the requirements

6.1.1. Ecology

- Temperature
  - For a successful migration for fish, a gradual temperature range of 4°C to 25°C should be respected during the different seasons.
- Salinity
  - The salinity gradient has to drop gradually and no salt wedges must be formed, as the fish can adapt properly during their acclimatization period.
  - Most of the flagship species can maintain themselves at salinity gradients of up to 36 PSU. For stickleback it is still unknown which salinity levels they can tolerate, but the studies of Arai et al. (2020) suggests that anadromous stickleback can easily live in and around brackish environments and in close distance within the sea from brackish waters.
  - Apart from species that travel through the river there will also be species that have a more permanent and set location in the FMR. These species may occupy different sections of the FMR according to their salinity tolerances, as displayed in figure 6.1.
- Acidity
  - Salt water usually has a stable pH value of 8.2, whereas river water may fluctuate between 6.5 and 8.5 pH. The tolerable pH range for Atlantic salmon and eel are known and rang from 6.2 - 8.5 and 5.0 - 8.0 respectively.
- Swimming speed
  - Atlantic salmon are strong and endurable swimmers and can reach a maximum speed of 2.44 m/s.
  - Herring can also swim against relatively strong currents as they can reach an U_{crit} of 1.5 m/s.
  - The European eel's swimming ability depends on their form. The glass eel is a weak swimmer and will find more trouble to keep up with stronger currents as their sprint speed is only 0.5 m/s. Silver eel have much more endurance and strength than glass eel with a swim speed up to 1.7 m/s.
  - The three-spined stickleback can reach a maximum speed of 0.7 m/s and thus, just like glass eel, need weaker currents to migrate in the FMR.
  - Resting spots with relatively stagnant water, can provide resting places for migrating fish to rest.
- Dissolved oxygen
  - The critical mortality threshold for most organisms is < 2 mg/l dissolved oxygen. Fish will not be able to survive under these conditions.
  - The flagship species need at least 2 mg/l (preferably 6-8 mg/l) dissolved oxygen for a successful migration.
- Shellfish
  - The presence of the shellfish would increase the water quality through filtration, however, in very high density shellfish can lower the water quality through mass defecation.
- Vegetation
  - Seagrass can provide shelter and nursery ground, and reduce the water flow as the migratory fish in the Haringvliet prefer a flow < 2 m/s.

- The introduction of seagrass is needed to enhance the dissolved oxygen and create a stable temperature. The eelgrass can be introduced on the FMR close to the saltwater since its salinity preference is relatively high (Figure 6.1).

- Hiding places
    - Artificial reefs such as layered cakes and rock pile shapes (Figure 4.3) provide hiding and resting places for (small) migratory fish. These reef structures can also function as a hard substrate for the establishment of shellfish.
    - Hard substrate such as gravels and rocks are important to allow migratory fish to hide from predators such as diving piscivorous birds (e.g. cormorants and grebes).
- Substrates
    - Sandy and muddy substrate are needed to grow seagrass and provide a burrowing place for e.g. eel and flounder.
    - Gravel and rocks substrates are essential to initiate shellfish to adhere. The establishment of larger species such as the Pacific oyster can then provide additional hard substrate for reefs to build on.
- Bird islands
    - A FMR also gives the opportunity to enhance bird populations in the area. By constructing bird islands in the FMR design additional breeding, foraging and roosting areas will be provided for birds.

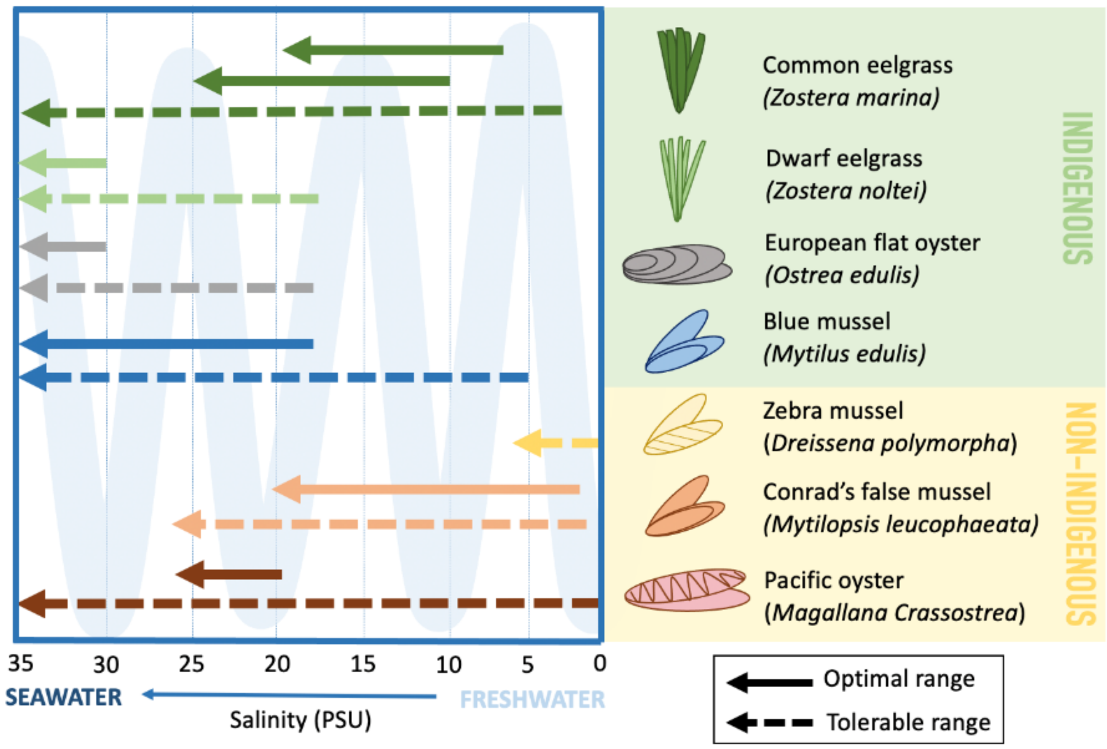


Figure 6.1: Expected distribution of key indigenous and non-indigenous supporting species within the Haringvliet FMR according to their respective optimal and tolerated salinity preferences. The common eelgrass (*Zostera marina*) may diverge in their optimal salinities according to the specific population's native salinities (Salo *et al.,* 2014).

6.1.2. Hydrology

- Flow velocity
    - Regularly below 0.2 m/s during high tide so all fish can enter.
    - During low tide, flow velocity may be higher but at places where it is higher than 0.3, the riverbed needs to be reinforced by either natural or artificial means to prevent erosion.

- For common eelgrass the flow velocity should be below 0.5 m/s, while dwarf eelgrass can handle flow velocities up to 1.5 m/s.
- For bigger fish (salmon, sturgeon), the flow velocity during low tide can be as high as 1.5 to 2 m/s.

- Discharge
  - The discharge of freshwater should be sufficient to keep saline water out of the Haringvliet. During low tide, the discharge must be high enough to flush saline water from further upstream in the FMR.
  - There should be a way to deal with excess discharge. This opening, sluice or spui should be located in a way so that it does not negatively impact the working of the FMR.
  - The discharge should create a lure current, so that migrating fish are able to find the entrance to the FMR.
- Salinity
  - Active mixing should occur between salt and fresh water to ensure a salinity gradient. No salt wedge must form.
  - Turbulence should be present to ensure mixing, but it should not exceed 0.5 m^2/s^2 as to not negatively impact fish, flat oysters and common eelgrass.
  - The salt water must not intrude into the Haringvliet, which means that the mixing must take place primarily, if not completely, in the FMR.
- Dimensions
  - The length should be sufficient to create a suitable salinity gradient and prevent salt water from reaching the Haringvliet. For the FMR at the Afsluitdijk, this was a length of at least 6 kilometres to completely prevent water from entering the Ijsselmeer. The final length of that FMR is 4 km (Arcadis, 2018).
  - The width depends on the available water to be discharged through the Haringvliet. It should preferably be a minimum of around 20 meters, to lessen predation. The width is most variable and depends on the amount of discharge available for the FMR.
  - The depth should be around a minimum of 5 meters to prevent predation by bird species (e.g. gulls and terns) and lessen predation in general.

6.2. Measures in implementation

6.2.1. Location and general structure

An important factor in the development and construction of a FMR is the location. Broadly speaking, there are three possibilities for the FMR: at the north side of the sluices, through the sluices, or the south side of the sluices. The advantage of a FMR at the north side, is that previous research into this location has been done. However, there are a lot of recreational activities on the north side (badstrand Rockanje, holiday parks). Thus, a FMR at this location would disturb or hinder these businesses, which could lead to more social resistance to the plan.

The south side has the advantage of a pre-existing body of water (Zuiderdiep). This body of water has no destination or purpose as of writing (Huibert van Rossum, Interview WSHD), so it could be restructured to form a basis for the FMR. Furthermore, at the moment, migrating fish are primarily using the south side of the sluices to pass through, which would suggest a southern FMR would be more effective (Interview Bruins Slot). On the south side of the Haringvliet there are also 2 ports and a set of sluices that connect these. This human activity could potentially disrupt the fish migration, but at the same time, the fish migration river could disrupt the port activities. This is something that should be taken into account if the decision is made for a FMR on the south side. One option would be to construct the entry to the FMR parallel to the port entry so that they have less interference with one another.

The option for the FMR to pass through the sluices is currently being researched by students of the Hogeschool Rotterdam. The advantage of this option is that it already has a locking mechanism in place. Furthermore, this option could potentially be beneficial to the lure current, as all fresh water would be discharged close to this spot. At the seaward side of the FMR, the entrance to the river could even be located close to the energy storage lake, since recent developments of “fish friendly pumps” can prevent high risks of fish mortality (Interview Lavooij, Kok & Berke). The downside is that it would need restructuring of the sluices, and that the construction of the FMR in the current path of fish migration could be damaging to the fish.

Whichever location is chosen in the end, it is important to make sure the surroundings are also fish friendly. This would mean gill netting should not be allowed along the migration routes and for this case specifically, near the entrance of the FMR, since this would defeat the purpose of the FMR (Tinka Murk, Interview).

To ensure the specific optimal conditions of different species are present in the FMR, multiple channels could be constructed. This way, variations in water depth and flow velocity could be implemented. This would allow for more optimal conditions for the wide variety of species living in and utilising the FMR. There is also the option to construct multiple FMR’s, for example one on the north side and one on the south side. This option has however no clear added value. However, the disadvantage of multiple FMR’s is that the total discharge through these FMR’s is the same, so if multiple FMR’s are constructed, the individual size of these FMR’s will decrease drastically, which would make it harder to meet the required ecological conditions to best enhance the creation of a brackish transition zone and the process of fish migration, for example by increasing predation risks.

6.2.2. Kierbesluit

With the construction of the FMR, the Kierbesluit might need to be reconsidered. The Kierbesluit was initially implemented to allow for the migration of fish. With the construction of a FMR, this purpose would expire. People might not want to roll back the Kierbesluit, since it took many years to finally bring about. Furthermore, the Kierbesluit has been recorded to facilitate the passage of various fish species (Binsma, 2021) so keeping the sluices partly open can also help facilitate fish migration. Also, keeping the Kierbesluit in place allows a way for excess discharge to exit the Haringvliet. It is important to note that this option to use it as a way to discharge excess water could lead to a disruption of the lure current for the FMR (section 6.2.3). At the same time, if the Kierbesluit is stopped, salt intrusion into the Haringvliet would likely lessen, which is the point on which the decision for the Kierbesluit was stuck.

6.2.3. Discharge and lure current

To attract migratory fish to the seaside entrance of the fish migration river, a lure current will need to be created. This lure current will disperse fresh or brackish water which can be sensed by migrating fish into the North Sea. The lure current will need to have a flow velocity that drops below 0.2 m/s during high tides so that weaker swimmers, like the European Eel, can also swim into the FMR. During low tide, the discharge and flow velocity of fresh or brackish water will be higher.

If fresh water from the Haringvliet is discharged in another way than through the FMR, this could also have an influence on the lure current. The discharge of excess fresh water can both enhance the range of the lure current but can also have a negative influence by creating too much turbulence or drawing fish away from the entrance of the FMR. An important point here is the location where this excess discharge enters the sea (section 5.5).

6.2.4. Resistances

To facilitate mixing, objects which cause resistance should be added to the water to lower the flow velocity and to ensure sufficient mixing of the saline and fresh water. There are several possibilities to add resistance. One would be the shape of the river. Meanders in the river add resistance to the flow and create turbulence. An added benefit of adding these meanders would be that it compacts the size of the FMR without compromising the length.

Mixing is also increased by resistances on the bed of the river, like gravel, boulders or other structures. Possible structures that could be placed in the FMR to increase resistance on the river bed are artificial reefs (section 4.2.3). These artificial reefs would add bed friction and thus slow flow velocity and stimulate mixing as denser saltwater rises to mix with freshwater. The added benefit is that it works as a shelter for fish and a settling ground for shellfish.

A third option to increase hydrological resistance is to install groynes (Figure 5.4) in the river. These groynes make the channel smaller, which increases turbulence and flow velocity in between (Arcadis, 2018). This could lead to erosion due to the increase in flow velocity (section 5.1). A solution would be to add reinforcements, like the artificial reef or vegetation, to prevent this erosion. The groynes could be added either in the meanders or on the straight part of the river. In the meanders, they would likely increase turbulence to a level at which fish experience negative effects. If the groynes are installed on the straight parts of the FMR, they would lead to an increase in flow velocity, and potentially a deeper channel if this is desired, but that could be prevented by reinforcements. Thus, the negative impact of the groynes could be compensated by other measures. The added effect of the groynes on the mixing is beneficial and would be a good addition to include in the FMR.

6.2.5. Vegetation and supporting species

Seagrass will be introduced in the FMR close to the entrance with the sea (section 4.2.1). To make sure that seagrass will survive, filter feeders such as flat or pacific oysters and blue mussels should be facilitated in the FMR (section 4.2.2). Introducing these species is however only step one, afterwards we should allow for natural succession to occur in the FMR. This way, the FMR stays natural and lively and does become as less static and artificial as possible. The shellfish reefs and seagrass beds can function both as wave protection and decrease the chance of erosion. Common eelgrass is best placed in areas where the flow velocity is lower, since dwarf eelgrass can withstand flow velocities up to 1.5 m/s while common eelgrass can withstand only up to 0.5 m/s. The shellfish reefs can be placed regardless of the flow velocity since mussels and oysters can withstand higher flow velocities relative to the fish species.

6.2.6. Substrates

For the substrate in the FMR, a division can be made between soft and hard substrate. The soft substrate is sandy and/or muddy substrate and is required for seagrass to elongate the rhizomes and fasten the roots. This substrate can be introduced along the FMR or introduced with a higher concentration in the mouth of the FMR close to the seaside to reduce the flow velocity. The soft sediment can also be used by eel and flounder to burrow in order to hide for predators. The hard substrate consists of gravel or rocks and can allow the migratory fish to hide from predators and the shellfish to adhere. The presence of shellfish is essential in increasing water clarity and quality, but their densities should be monitored to prevent negative impacts. The hard substrate can be placed in the mouth of the FMR to facilitate better mixing (section 6.2.5.). Another hard substrate which can be used for the shellfish to adhere to, as well as providing shelter for the migrating fish is the artificial reefs. Altogether, it is important in the design of the FMR to provide different substrate areas or combine both soft and hard substrate, so that migrating fish can find shelter, and both seagrass and shellfish can occur in the FMR.

7. Conveying the advantages of a FMR to stakeholders

In this section, we aim to give insights on how to convey the advantages of a FMR to different stakeholders. The large variety of stakeholders that may be affected by the construction of a FMR have different interests according to the potential consequences the project may have on their respective interests. Additionally, it is important to clarify the added value of an FMR to the current situation (occasional opening of the Kierbesluit) as well as compare it to the proposed permanent opening of the Haringvliet sluices as a method to re-establish natural processes. In this section, we therefore will briefly compare the advantages and disadvantages of these three scenarios with regard to their effects on the ecology and hydrology. In addition, we will explore how to communicate the benefits of a FMR to the stakeholders depending on their interests and stakes in the project. The main conclusion we draw in this section is that a permanently open Haringvliet can lead to important positive impacts on the ecology and hydrology, but this comes with significant consequences for Natura 2000 areas and freshwater provisioning (Table 7.1). Although the effects of an FMR are more limited, its construction would allow to improve the current situation by enhancing the success in achieving the same objectives set by the initiative behind the Kierbesluit (Table 7.1).

Table 7.1: Overview of the potential positive added value (+), negative added value (-) or no added value (0) of two alternative scenarios to the current Kierbesluit system.

	Kierbesluit →Permanently open Haringvliet	**Kierbesluit → Kierbesluit + FMR**
Migratory fish	++	+
Birds	++	+
Marine mammals	++	+
Stable brackish habitat	++	+
Haringvliet Natura 2000 areas	--	+
Freshwater provisioning	--	0
Ecotourism	+	+

7.1. Ecology

7.1.1 Scenario 1: Kierbesluit (current situation)

In the current situation in which the Kierbesluit is operative, fish cannot pass the Haringvlietdam at all times. In this scenario, the sluices are opened to release excess freshwater, creating a lure current to attract migrating fish and removing the physical barrier to migration. However, although the Kierbesluit has been recorded to facilitate the passage of various fish species (Binsma, 2021), this process remains limited as fish are only able to migrate up- or downriver during short windows of opportunity. Although fish currently tend to converge in front of the sluices (Interview, Bruins Slot) this reduces the number of total individuals that can go through. Additionally, some species such as the Atlantic salmon require specific conditions to stimulate migration (section 3.1), meaning that migration may also be limited if the sluices are opened while these conditions are not met. The sluices are also only opened when the Haringvliet water levels are higher than the sea, meaning that it involves high discharges of freshwater into the sea. As some fish species such as the European eel are weak swimmers and depend on the tidal inflow to bring them into riverine systems, this system could limit their migration into the Haringvliet. Besides, fish species will benefit from a brackish transition zone to facilitate their migration between salt and freshwaters (section 3). In this situation, no stable brackish zone is created, because the saline and fresh water can only mix with enough turbulence and while the sluices are opened. Both of these are limited in the current situation, leading to stratification and a salt wedge creeping into the Haringvliet. In addition to the effect on the migrating fish, the occasional opening of the sluices also affects other species such as marine mammals. For instance, seals and porpoises may pass through the opened sluices but may end up stranded in the freshwater system if the sluices close before they are able to return. This means that they cannot return to their usual foraging grounds in the North Sea and remain stuck in freshwater areas where local food availability can be limited (section 4.1.1).

7.1.2 Scenario 2: Permanently open Haringvliet sluices

Permanently fully opening the Haringvliet sluices is the most beneficial option for facilitating fish migration and for creating a stable brackish transition zone. This method would allow for significant volumes of freshwater and seawater to pass through the Haringvlietdam and thereby better approach the natural riverine and tidal dynamics normally present in estuaries. As this approaches the historical situation, we can assume that the physical and hydrological barriers to fish migration will be largely removed. The establishment of these conditions will likely lead to the natural restoration of large areas of brackish habitats as specialist species from the surrounding areas become able to establish in the newly created conditions.

This option may however have a negative effect on the aquatic and terrestrial systems that have developed in the Haringvliet area since its closing. The creation of brackish or even salty environments far into the Haringvliet is in contradiction with the Natura 2000 decree on this area. The habitat types that have to be protected or improved by this decree are muddy riverbanks and moist alluvial forests, which will be threatened by the intrusion of salt water (Directie Natuur & Biodiversiteit, 2015). The decree also protects specific species, of which some can only survive in a fully fresh environment. These are fish species like Bullhead *(Cottus perifretum),* but also two mammals: the Eurasian beaver *(Castor fiber)* and tundra vole *(Microtus oeconomus arenicol*). (Directie Natuur & Biodiversiteit, 2015). Besides threatening the protected habitats and species in the Haringvliet, there is some concern that fully opening the Haringvliet sluices might threaten the Biesbosch National Park which also hosts a wide array of protected habitats and species. Although prior to closure of the Haringvliet saline intrusion was known to reach this area at high tide, under this scenario this is not expected to occur (Figure 7.3).

7.1.3 Scenario 3: Fish migration river

A FMR could serve as a compromise to reconcile the two options. The construction of a FMR would allow to create a permanent opening for the migrating fish to pass the Haringvlietdam. Although the opening will be limited which means that it is more difficult for the migrating fish to find their way up the rivers compared to fully opening the Haringvliet sluices, migrating fish would be able to cross the barrier at all times. Additionally, a FMR could continue to attract migrating fish through the creation of a lure current that could be enhanced by the discharge of water from the Kierbesluit (section 5.5). A carefully designed FMR can also provide the necessary habitat and conditions for fish to migrate upstream, such as shelters to hide from predators or low flow velocities that allow weaker swimmers to make it through. Additionally, it can better create a stable brackish transition zone than the Kierbesluit by stimulating the mixing of salt and freshwater within its confines (section 5.5), although this area will be smaller than if the sluices were fully opened. In addition to facilitating migration of certain fish species, the creation of brackish conditions can allow for the establishment of new brackish habitat and associated species. The FMR can also be adapted to be large enough to allow larger sea mammals to swim back and forth across the dam at all times. Additional foraging opportunities and the construction of bird islands for breeding could also stimulate local bird populations. The FMR could therefore allow for a large improvement in the local ecology as compared to the current Kierbesluit. Additionally, a carefully designed FMR could also serve as an improvement to the full opening of the Haringvliet as by preventing additional salt intrusion, it would prevent large impacts on the nearby Natura 2000 areas. Altogether therefore, the FMR offers an interesting compromise between the two options as it can improve fish migration, provide a stable brackish transition zone (albeit more spatially limited) and stimulate local biodiversity while preventing important damaging effects to Natura 2000 areas.

7.1.4 Stakeholders concerned with nature recovery

A number of stakeholders are primarily concerned with restoring natural fish migration between the sea and the Haringvliet as well as enhancing the natural value of the landscape. This would involve those organisations that took part in the establishment of the Kierbesluit and involved in the Haringvliet Droomfonds project such as Natuurmonumenten, Staatsbosbeheer, Vogelbescherming, ARK, WWF and Sportvisserij Nederland. Reaching this objective in 2018 was a huge accomplishment and is likely to continue to be intensely supported by these organisations. The Haringvliet Droomfonds Project plans to use the hydrological dynamics instigated by the Kierbesluit to stimulate the natural recovery of the estuarine nature around the Haringvlietdam (Haringvliet, 2018). They also highlight their plan to promote visitation to the area for ecotourism and recreational activities such as biking and hiking through the development of a fast boat connection from Rotterdam to Dordrecht (Haringvliet, 2018).

When approaching these stakeholders, it will therefore be important to highlight how the FMR could fit within the existing Kierbesluit arrangement and highlight that it will improve those very same objectives for which the Kierbesluit was implemented. In particular, these stakeholders should be shown how the Kierbesluit continues to limit the migration of certain fish species such as the critically endangered European eel and highlight how an FMR could improve this. It would also be crucial to inform these stakeholders of the added value an FMR could provide to improve the diversity and richness of the landscape. In addition to the FMR's potential to enhance birds and marine mammals, it can also allow for the creation of more stable brackish conditions than the Kierbesluit alone. Brackish habitats are relatively rare in north-western Europe (Tangelder et al., 2017) and communicating the potential for the FMR to restore these in the Haringvliet area would likely generate support for the project from these groups. In addition, the FMR could provide a more unique ecotourism experience by integrating a viewing station to observe the passage of fish through the dam, as will be present at the Afsluitdijk FMR (Arcadis, 2018). Altogether, it will be important to communicate the FMR as a *compromise* that allows to address some of the limitations of the Kierbesluit for nature recovery without the important impacts of saline intrusion that would be caused by permanently opening the Haringvliet sluices.

The added value of an FMR to boost natural recovery is also interesting for parties that would benefit from healthier and richer aquatic ecosystems, for instance commercial and recreational fishing organisations. This group may provide significant resistance to a FMR as they would need to make short term concessions such as terminating gill fishing activities on the seaside of the Haringvlietdam as these can strongly hinder efforts to facilitate fish migration (Murk, 2021 private communication). For this group of stakeholders, we suggest to focus on communicating the potential for long-term returns of an FMR. These parties should be informed of the potential of the FMR to boost depleted fish stocks by further enhancing the reproductive cycle of key species such as the Atlantic salmon and Atlantic herring. It would be beneficial to highlight that in the longer-term facilitating migration could help the recovery of these fish stocks and thereby allow to relax current fishing regulations. Additionally, it will be important to inform these parties of potential indirect positive feedbacks of ecosystem recovery on fish stocks. For instance, improving the migration of the three-spined stickleback, which plays an important role in food web interactions, could help the current systems host higher abundances and diversities of larger fish.

7.2 Hydrology

7.2.1 Scenario 1 Kierbesluit (current situation)

The Kierbesluit opens up only during the tidal ebb, where water levels in the Haringvliet are higher than the sea. The size of the opening can be adjusted according to the river discharge (Baas *et al.,* 2020). The Kierbesluit is specifically designed to allow some saline intrusion into the Haringvliet although this is limited so it does not exceed 0.3g/L Cl beyond the virtual line between Middelharnis and the opening of the Spui (Binsma, 2021; Figure 7.1). This scenario allows for some mixing of salt and freshwater close to the sluices but only when there is enough turbulence and while the sluices are opened. Occasional opening of the sluices does not stimulate mixing itself but rather allows for the creation of a salt wedge whereby the denser saltwater remains stratified beneath the freshwater (Baas et al., 2020). Water safety should not be compromised however as the sluices can still be closed when necessary, for instance during storms. To summarise, the Kierbesluit prevents extensive salt intrusion into the Haringvliet and allows the exchange of freshwater and saltwater but does not restore the tidal dynamics of a brackish area, preventing significant mixing and the creation of a stable brackish zone.

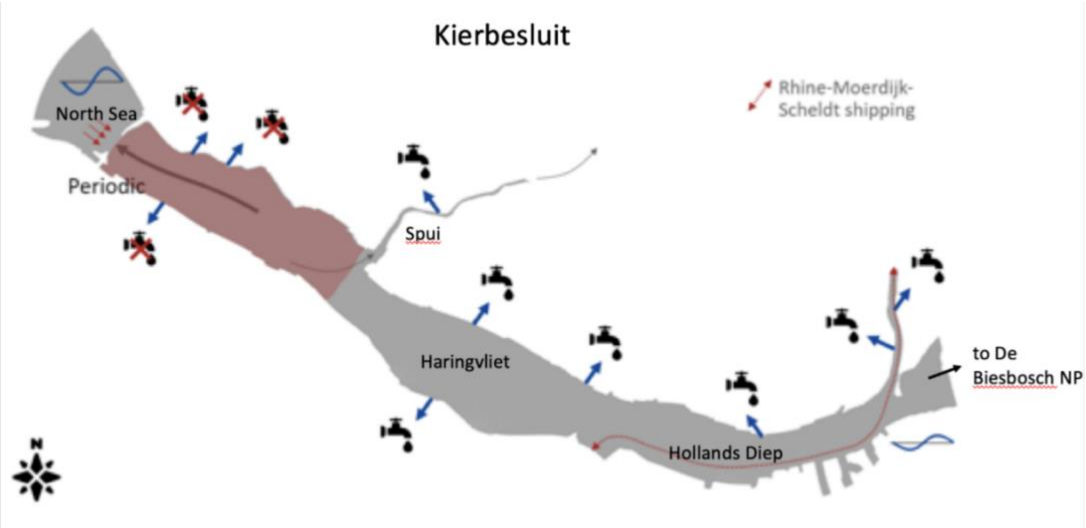


Figure 7.1: Salt intrusion (red) into the Haringvliet as agreed under the Kierbesluit scenario. Figure adapted from Binsma, 2021.

7.2.2 Scenario 2: Permanently open Haringvliet sluices

Fully opening the Haringvliet sluices on a permanent basis would best restore the natural hydrological dynamics and return the Haringvliet to a brackish/saltwater system. Although this is mostly desirable from an ecological point of view, this will lead to much more significant saline intrusion into the Haringvliet system than the Kierbesluit (Figure 7.3). This option has been met by fierce opposition from various stakeholders concerned with the negative effect on freshwater provisioning for human consumption or agricultural activities (Interview Lavooij, Kok & Berke, Interview van Rossum).

Although lesser volumes of water can pass through the open sluices as compared to pre-construction of the Haringvlietdam, this still amounts to significant amounts of water. As a result, under this scenario, changes to water flows within the Haringvliet are also expected, with consequences for the morphology of the water body for instance through changed erosion and sedimentation dynamics (Interview Wil Borm). As with Scenario 1, water safety should not be compromised as the sluices can still be closed when necessary. In summary, this scenario is best for restoring natural hydrological dynamics but is very unlikely to be a feasible option as it would allow undesired levels of saltwater intrusion into the Haringvliet with impacts on natural systems and freshwater extraction.

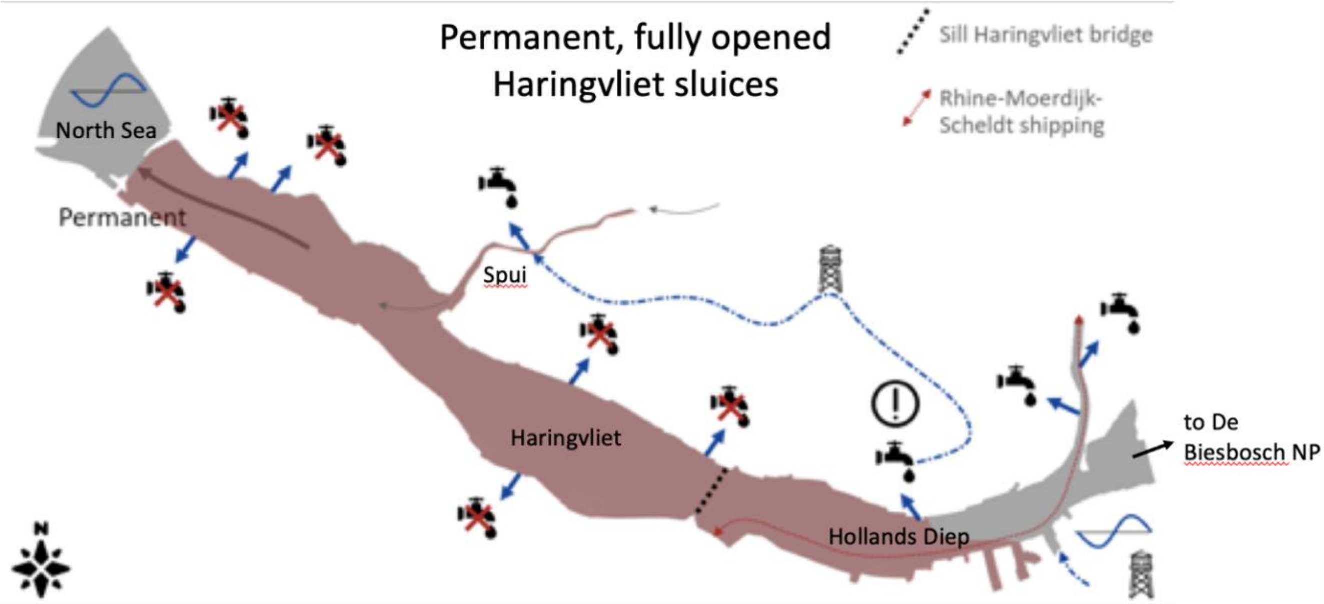


Figure 7.3: Expected saline intrusion (red) into the Haringvliet under the permanent, fully opened sluices scenario. Figure adapted from Binsma, 2021.

7.2.3 Scenario 3: Fish Migration River

A FMR at the Haringvliet could limit salt intrusion while allowing for the creation of a brackish transition zone, albeit smaller than would be created by a permanent opening of the sluices. The FMR at the Afsluitdijk is specifically designed towards limiting salt intrusion in the Ijsselmeer, for example by means of a technical part to close the river if necessary (Arcadis, 2018). In this scenario therefore, we can expect there to be no additional negative effects of saltwater intrusion in the Haringvliet on freshwater extraction. The FMR can be designed in such a way as to allow for more extensive mixing between freshwater and saltwater than is currently allowed by the Kierbesluit (section 6.2.4). Rather than the entire Haringvliet being subject to natural estuary hydrological dynamics as in the fully opened sluices scenario, these dynamics can be restored within the more limited space of the FMR, allowing for a more stable brackish transition zone than that created by the Kierbesluit. Additionally, a permanent opening can allow for a constant inflow of freshwater from the Haringvliet into the sea. As Delta21 plans to partially close of the marine area right beyond the Haringvlietdam to turn it into a tidal lake, constant inflow of freshwater can also render this entire area less saline, facilitating the transition (Figure 7.4). Finally, the opening of the FMR will be smaller than the fully opened sluices in Scenario 2 and therefore should cause less important changes in waterflow in the Haringvliet and thereby less important impacts on the morphology. With respect to water safety, the FMR design would include a lock mechanism that could be used if the situation requires it. In summary, the FMR can be designed to prevent further saltwater intrusion into the Haringvliet and restore some key hydrological dynamics of a brackish estuary system although these would be largely limited to the smaller area of the FMR itself.

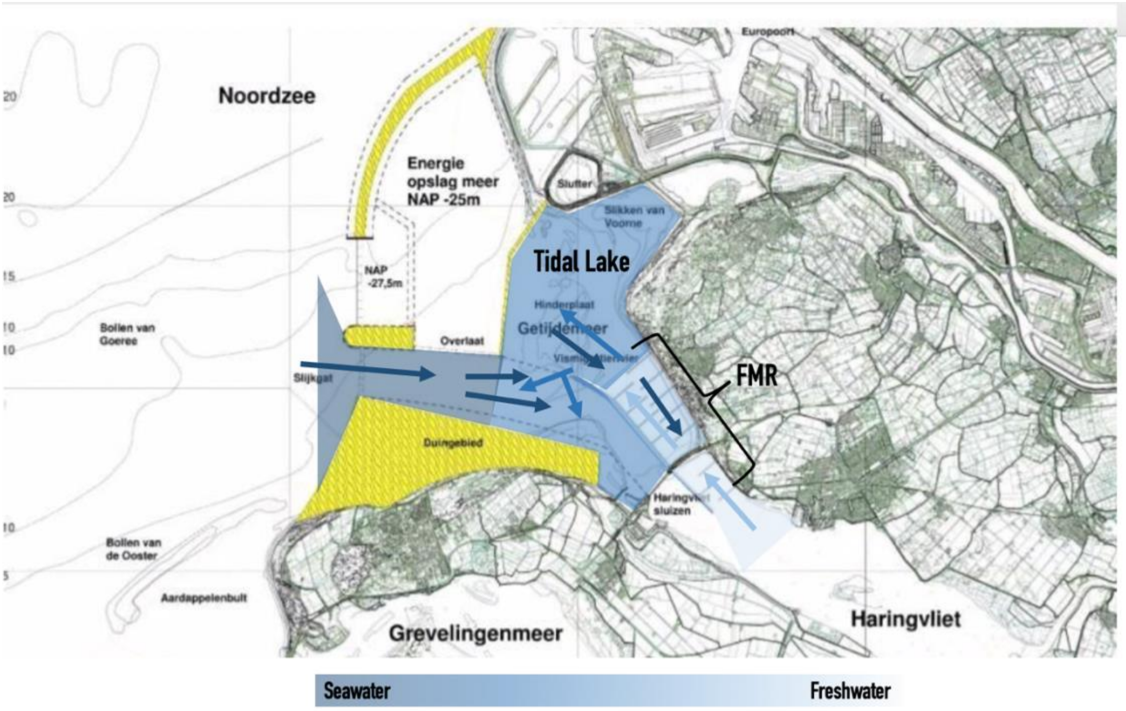


Figure 7.4: Schematic of generalised direction of freshwater and saltwater movement between the North Sea, the Delta21 Tidal Lake and the Fish Migration River (FMR). The location for the FMR is not definite. Original figure provided by the commissioner.

7.2.4 Stakeholders affected by altered hydrology

Some stakeholders such are particularly concerned about saline intrusion past the Spui-Middelharnis limit affecting freshwater extraction stations for drinking and agricultural activities. This factor remains one of the main bases of opposition against the permanent opening of the Haringvliet sluices for the purpose of restoring natural hydrological dynamics. When approaching these actors, it will be important to communicate that the FMR will be constructed in such a way that saltwater intrusion will not breach the level of saltwater intrusion agreed upon with the implementation of the Kierbesluit. In addition, it could be useful to point out that “This has been done before” by using the approved design of the Afsluitdijk FMR to reassure stakeholders that this point will be respected. We expect that these stakeholders may also be more open to the idea of the FMR after the construction of the Afsluitdijk FMR is completed and is (hopefully) shown to mitigate saltwater intrusion into the Ijsselmeer.

8. Discussion

To bring back migratory species in the Haringvliet delta, a fish migration river is proposed. In this report, we analysed and determined the ecological and hydrological requirements necessary to ensure that the FMR enhances fish migration. However, this report does not offer a completely comprehensive overview of all the aspects involved in ensuring the ecological success of this endeavour. In this section, we highlight the main limitations that should be considered by the reader when considering the conclusions draw in this report.

The location of the fish migration river is challenging to define. There are several options for the location of the FMR, each with consequences for its design and different advantages and disadvantages for various stakeholders. Another thing to keep in mind is that the building process should not disturb nature or people too much. This ties into the selection of the location, as some possible locations are now used by either fish, marine mammals, birds or humans. There are 3 scenarios available, which each has pros and cons that equally important. Each of those scenarios also has a risk that can impair the interests of the stakeholders. Therefore, the collaboration and integration between stakeholders and government are very encouraged to minimize the conflict.

To make sure the fish migration river has the desired success, the sustainable and integrated fisheries management should be implemented. The availability of food and the accessibility to the good spawning ground should also be guaranteed. In order to provide the access, the fish-friendly sluices seem a good alternative. If the entry ways remain blocked, the FMR will not yield the wanted effects for the fish stocks. For example, if salmon cannot reach far enough into the delta and rivers to spawn, the goal in bringing back and increasing the number of populations would be difficult to find success. Another example are fish that live their juvenile lives at sea and then migrate upstream to spend their adult life. If they cannot reach these areas, they cannot make the Haringvliet delta their home. Moreover, the areas surroundings the FMR should meet the purposes of migration, such as good spawning ground, low predation risk and high food availability.

For this report we selected only four flagship species to explore in detail due to time restrictions. This choice was influenced by the commissioner's preferences and were presumed to serve as indicators for similar species. However, successfully enhancing the migration of the selected species may not lead to similar effects in the other 12 migratory species. For instance, although the Atlantic salmon and European sturgeon are similar in characteristics, there are likely significant differences in their ecology and life cycle that could lead to differences in the specific requirements. As the sturgeon is still being re-introduced in the area, further insights on their specific requirements may become clearer in the near future. As a result, although the flagship species were chosen to be representative of other migratory fishes in the area, more detailed analysis of their specific requirements would be necessary to ensure they benefit from the FMR.

It is very difficult to predict how the system within the FMR will naturally develop. Even if the circumstances are right, the uncertainty remains, so it will not ensure that certain species will use the river or establish home there. There might also be species that manage to reside in the river even though the circumstances are less than ideal. Additionally, this report only analysed a very limited selection of indigenous and non-indigenous species that could colonise the FMR system. Although this report provides an idea of some of the key species that would likely be part of this new system, other species that were not investigated may also colonise the FMR and influence the development of the new ecosystem. A more comprehensive overview of which species may or may not colonise and influence the FMR ecosystem is required to address this knowledge gap. What the FMR will look like a couple years later is almost impossible to determine. It will depend on many different factors of which many cannot be controlled. For instance, climate change can cause different effects like extreme weather, sea level rise and increased water temperatures. The changes in water temperature might cause an alteration in migration pattern of the species mainly on the timing of migration.

There is a high chance that marine mammals like seals and porpoises will also make use of the FMR. They might use it to hunt for prey, to rest or to enter the delta. Even if this is unwanted, it will be difficult to keep them out. Their presence might attract tourists to the location, since these animals are well-liked by the public. Birds might also be attracted to the FMR as they will be able to use the banks of the FMR for additional foraging, roosting and/or breeding areas. These birds also attract a specific group of people, the birdwatchers. It is thus also an important thing to consider since it brings additional value through tourism, but these species might impair the success of the FMR since the predation might have a larger effect on migration success than anticipated. Monitoring of the effect of predators on fish migration would have to be implemented to determine the significance of this effect.

The FMR can improve the current ecological situation but may not be able to achieve as much as letting nature take back the Haringvliet delta. Whether the river will enhance the migration of fish and allow for the restoration of brackish habitats to the level we expect remains elusive as many uncertainties still exist. However, this report explores in the detail the aspects that would be important to ensure the FMR is a success and offers some initial insights on how these can be integrated into a design. We expect the information contained in this report to be helpful in particular for Jeroen Lokker and Bast van der Wolff from the Hogeschool Rotterdam as their technical design for the FMR will require an ecological perspective to ensure that it achieves the desired results (Interview Lokker & van der Wolff).

9. References

Arai, T., Ueno, D., Kitamura, T., & Goto, A. (2020). Habitat preference and diverse migration in threespine sticklebacks, Gasterosteus aculeatus and G. nipponicus. *Scientific Reports*, *10*(1), 1-15.

Ark Nature (2021). *Sturgeon (image)* https://www.ark.eu/en/projects/sturgeon Accessed on 23 April

2021 at 8.13 PM.

Armstrong, J. D., Kemp, P. S., Kennedy, G. J. A., Ladle, M., & Milner, N. J. (2003). Habitat requirements of Atlantic salmon and brown trout in rivers and streams. *Fisheries Research*, *62*(2). https://doi.org/10.1016/S0165-7836(02)00160-1

Auer, N. A. (1996). Importance of habitat and migration to sturgeons with emphasis on lake sturgeon. *Canadian Journal of Fisheries and Aquatic Sciences*, *53*(SUPPL. 1). https://doi.org/10.1139/cjfas-53-s1-152

Baas, V., Clabbers, N., Moens, J., Schuurke, E., Spierings, J., Termaat, E., & Wolma, A. (2020). *Opening of the Haringvliet, a stream of possibilities*. *Wageningen University & Research.*

van Banning, G., van der Baan, J., & Bruijne, W. de. (2018). Vismigratierivier Afsluitdijk: Hydraulische en ecologische toetsing van het ontwerp. In *Arcadis*.

Binsma, J. (2021) Assessment of future stratification induced by opening of Haringvliet sluices. *Masters Thesis, Delft University of Technology*.

Biodiversiteit, D. N. &. (2018). Ontwerp-wijzigingsbesluit Habitatrichtlijngebieden vanwege aanwezige waarden (DN&B/2018-000). *De Minister van Landbouw, Natuur En Voedselkwaliteit*.

Bjornn, T., Bjornn, T., Reiser, D., & Reiser, D. (1991). Habitat requirements of salmonids in streams. *American Fisheries Society Special Publication*, *August*.

Boström, C., O'Brien, K., Roos, C., & Ekebom, J. (2006). Environmental variables explaining structural and functional diversity of seagrass macrofauna in an archipelago landscape. *Journal of Experimental Marine Biology and Ecology*, *335*(1). https://doi.org/10.1016/j.jembe.2006.02.015

Bouma, S., & Soes, D. M. (2010). A risk analysis of the Chinese mitten crab in The Netherlands. In *Bureau Waardenburg bv* (Issue October 2010).

Brevé, N. W. P. (2007). *Kennisdocument Atlantische haring, Clupea harengus harengus (Linnaeus, 1758)*.

van Broekhoven, W. (2005). *Macrofaunal diversity on beds of souththe Pacific oyster (Crassostrea gigas) in the Oosterschelde estuary (Internal report 05.002)*.

Bruins Slot, E. (2021). Interview 19 April 2021. Technical manager FMR De Nieuwe Afsluitdijk.

Byrne, A. A., Pearce, C. M., Cross, S. F., Jones, S. R. M., Robinson, S. M. C., Hutchinson, M. J., Miller, M. R., Haddad, C. A., & Johnson, D. L. (2018). Planktonic and parasitic stages of sea lice (Lepeophtheirus salmonis and Caligus clemensi) at a commercial Atlantic salmon (Salmo salar) farm in British Columbia, Canada. *Aquaculture*, *486*. https://doi.org/10.1016/j.aquaculture.2017.12.009

Carter, K. (2005). The Effects of Dissolved Oxygen on Steelhead Trout , Coho Salmon , and Chinook Salmon Biology and Function by Life Stage. *Quality*, *August*.

Chaput, G. (2012). Overview of the status of Atlantic salmon (Salmo salar) in the North Atlantic and trends in marine mortality. *ICES Journal of Marine Science*, *69*(9). https://doi.org/10.1093/icesjms/fss013

Colsoul, B., Boudry, P., Pérez-Parallé, M. L., Bratoš Cetinić, A., Hugh-Jones, T., Arzul, I., Mérou, N., Wegner, K. M., Peter, C., Merk, V., & Pogoda, B. (2021). Sustainable large-scale production of European flat oyster (Ostrea edulis) seed for ecological restoration and aquaculture: a review. In *Reviews in Aquaculture*. https://doi.org/10.1111/raq.12529

Cresci, A. (2020). A comprehensive hypothesis on the migration of European glass eels (Anguilla anguilla). *Biological Reviews*, *95*(5). https://doi.org/10.1111/brv.12609

Cresci, A., Paris, C. B., Durif, C. M. F., Shema, S., Bjelland, R. M., Skiftesvik, A. B., & Browman, H. I. (2017). Glass eels (Anguilla anguilla) have a magnetic compass linked to the tidal cycle. *Science Advances*, *3*(6). https://doi.org/10.1126/sciadv.1602007

Degerman, E., Tamario, C., Watz, J., Nilsson, P. A., & Calles, O. (2019). Occurrence and habitat use of European eel (Anguilla anguilla) in running waters: lessons for improved monitoring, habitat restoration and stocking. Aquatic ecology, 53(4), 639-650.

De Groot, S. J. (1989). *Literature survey into the possibility of restocking the River Rhine and its tributaries with Atlantic salmon (Salmo salar) (MO 88-205/89.2)* (Vol. 11).

de Vaate, A. bij, Rajagopal, S., & Velde, G. van der. (2010). The zebra mussel in Europe: summary and synthesis. In *The Zebra Mussel in Europe* (Issue August 2015, pp. 415–421). Backhuys Publishers.

Dickey-Collas, M. (2005). *Desk Study on the transport of larval herring in the southern North Sea (Downs herring) (no. C031/05)*.

Dou, S. Z., & Tsukamoto, K. (2003). Observations on the nocturnal activity and feeding behavior of Anguilla japonica glass eels under laboratory conditions. *Environmental Biology of Fishes*, *67*(4). https://doi.org/10.1023/A:1025894010739

Edeline, E., Lambert, P., Rigaud, C., & Elie, P. (2006). Effects of body condition and water temperature on Anguilla anguilla glass eel migratory behavior. *Journal of Experimental Marine Biology and Ecology*, *331*(2). https://doi.org/10.1016/j.jembe.2005.10.011

Eggers, F., Olsen, E. M., Moland, E., & Slotte, A. (2015). Individual habitat transitions of Atlantic herring Clupea harengus in a human-modified coastal system. *Marine Ecology Progress Series*, *520*. https://doi.org/10.3354/meps11103

van Emmerik, W., & de Nie, H. (2006). *De zoetwatervissen van Nederland*. Vereniging Sportvisserij Nederland.

van Emmerik, W.A.M. (2016). Biologische factsheets trekvissen Haringvliet en Voordelta. Onderdeel van Droomfondsproject Haringvliet. Deelproject Visserij. *Sportvisserij Nederland*, Bilthoven.

Eymann, C., Götze, S., Bock, C., Guderley, H., Knoll, A. H., Lannig, G., Sokolova, I. M., Aberhan, M., & Pörtner, H. O. (2020). Thermal performance of the European flat oyster, Ostrea edulis (Linnaeus, 1758)—explaining ecological findings under climate change. *Marine Biology*, *167*(2). https://doi.org/10.1007/s00227-019-3620-3

FAO. (2021). *Crassostrea gigas (Thunberg, 1793): Species Factsheet*. http://www.fao.org/fishery/species/3514/en

Fey, F., Dankers, N., Steenbergen, J., & Goudswaard, K. (2010). Development and distribution of the non-indigenous Pacific oyster (Crassostrea gigas) in the Dutch Wadden Sea. *Aquaculture International*, *18*(1). https://doi.org/10.1007/s10499-009-9268-0

FishBase. (2021). *Salmo salar Linnaeus 1758*. https://www.fishbase.in/Summary/SpeciesSummary.php?ID=236&AT=salmon

FishBase. (2021). *Acipenser sturio Linnaeus 1758*.

FishBase. (2021). *Clupea harengus Linnaeus 1758.* https://www.fishbase.se/Summary/SpeciesSummary.php?ID=24&AT=herring

Fisher, J. P., Bradley, T., & Patten, K. (2011). Invasion of Japanese eelgrass, Zostera japonica in the Pacific Northwest: A preliminary analysis of recognized impacts, ecological functions, and risks. *Unpublished Report Prepared for the Willapa-Grays Harbor Oyster Growers Association, Ocean Park, WA.*, 25. https://doi.org/10.13140/2.1.2502.9441

Freyhof, J., & Kottelat, M. (2010). *Anguilla anguilla. The IUCN Red List of Threatened Species 2010: e.T60344A12353683*. https://www.iucnredlist.org/species/60344/12353683

GISD. (2021). *Species profile: Mytilopsis leucophaeata*. http://www.iucngisd.org/gisd/species.php?sc=707

Glippa, O., Brutemark, A., Johnson, J., Spilling, K., Candolin, U., & Engström-öst, J. (2017). Early development of the threespine stickleback in relation to water pH. *Frontiers in Marine Science*, *4*(DEC). https://doi.org/10.3389/fmars.2017.00427

Griffioen, A. B., Winter, H. V., & van Hal, R. (2017). Prognose visstand in en rond het Haringvliet na invoering van het Kierbesluit in 2018 (rapport C081/17). In *Wageningen Marine Research*.

Grøtan, K., Østbye, K., Taugbøl, A., & Vøllestad, L. A. (2012). No short-term effect of salinity on oxygen consumption in threespine stickleback (gasterosteus aculeatus) from fresh, brackish, and salt water. *Canadian Journal of Zoology*, *90*(12). https://doi.org/10.1139/cjz-2012-0121

Hammond, P. S., Berggren, P., Benke, H., Borchers, D. L., Collet, A., Heide-Jørgensen, M. P., Heimlich, S., Hiby, A. R., Leopold, M. F., & Øien, N. (2002). Abundance of harbour porpoise and other cetaceans in the North Sea and adjacent waters. *Journal of Applied Ecology*, *39*(2). https://doi.org/10.1046/j.1365-2664.2002.00713.x

Haringvliet (2018) *The Dream of the Haringvliet.* url:https://haringvliet.nu/english-summary. Accessed

29-04-2021

Herdson, D., & Priede, I. G. (2010). *Clupea harengus. The IUCN Red List of Threatened Species 2010: e.T155123A4717767*. https://www.iucnredlist.org/species/155123/4717767

Hoekstein, M. S. J., Arts, F. A., Lilipaly, S. J., Straalen, K. D. van, Sluijter, M., & Wolf, P. A. (2020). Watervogels en zeezoogdieren in de Zoute Delta 2018/ 2019. *Deltamilieu Projecten*.

Huertas, M., Canário, A. V. M., & Hubbard, P. C. (2008). Chemical communication in the Genus Anguilla: A minireview. *Behaviour*, *145*(10). https://doi.org/10.1163/156853908785765926

Hylkema, A., Debrot, A. O., Osinga, R., Bron, P. S., Heesink, D. B., Izioka, A. K., Reid, C. B., Rippen, J. C., Treibitz, T., Yuval, M., & Murk, A. J. (2020). Fish assemblages of three common artificial reef designs during early colonization. *Ecological Engineering*, *157*. https://doi.org/10.1016/j.ecoleng.2020.105994

Jager, Z., Kranenbarg, J., & Vethaak, D. (2004). Vissen tussen zoet en zout. *De Levende Natuur*, *105*(5), 204–208.

Jellyman, D. J., & Lambert, P. W. (2003). Factors affecting recruitment of glass eels into the Grey River, New Zealand. *Journal of Fish Biology*, *63*(5). https://doi.org/10.1046/j.1095-8649.2003.00220.x

van Katwijk, M. (2012). Zeegras in de Waddenzee. *De Levende Natuur*, *mei*.

Keulen, M. Van. (1998). *Water flow in seagrass ecosystems*. Doctorate thesis, Murdoch University.

Klein Breteler, J. G. P., & van Emmerik, W. A. M. (2005). *Kennisdocument Europese aal of paling, Anguilla anguilla (Linnaeus, 1758)*.

Kranenbarg, J. (2018). *Haringvlietsluizen op een kier: kansen voor vissen*.

Kroes, M. ., & Monden, S. (2000). *Vismigratie Een handboek voor herstel in Vlaanderen en Nederland*. Ministerie van de Vlaamse gemeenschap AMINAL afdeling water.

Laak de, G. A. J., van Emmerik, W. A. M., & Moquette, F. D. (2007). *Kennisdocument Atlantische zalm, Salmo salar (Linnaeus, 1758) (Vol.6)*.

Langdon, S. A., & Collins, A. L. (2000). Quantification of the maximal swimming performance of Australasian glass eels, Anguilla australis and Anguilla reinhardtii, using a hydraulic flume swimming chamber. *New Zealand Journal of Marine and Freshwater Research*, *34*(4). https://doi.org/10.1080/00288330.2000.9516963

Lavooij H., Kok G., & Berke L. (2021). Interview 19 March 2021. Commissioners Delta21 Project.

Macleod, K. (2008). Final Report: Small Cetaceans in the European Atlantic and North Sea (SCANS-II). *SCANS II Newsletter*, *21*(1).

Masselink, G., & Gehrels, R. (2015). Coastal Environments and Global Change. In *Coastal Environments and Global Change*. https://doi.org/10.1002/9781119117261

McCleave, J. D., & Kleckner, R. C. (1982). Selective Tidal Stream Transport in the Estuarine Migration of Glass Eels of the American Eel (Anguilla Rostrata). *ICES Journal of Marine Science*, *40*(3). https://doi.org/10.1093/icesjms/40.3.262

Middleton, D., Sussex Wildlife Trust (2020). *European Eels – slipping towards extinction? (image).*

https://waronwildlife.co.uk/ Accessed on April 23 2021 at 5.22 PM.

Miller, M. J., Bonhommeau, S., Munk, P., Castonguay, M., Hanel, R., & Mccleave, J. D. (2015). A century of research on the larval distributions of the Atlantic eels: A re-examination of the data. *Biological Reviews*, *90*(4). https://doi.org/10.1111/brv.12144

Møller, P. R., (2021). *Atlantic Herring (image).*

https://www.eurekalert.org/multimedia/pub/85638.php?from=286975 Accessed on 23 April 2021 at 5.04 PM

Mooney, H. (2005). *Invasive Alien Species: A New Synthesis (SCOPE Series)*. Island Press.

Mulder, R. (2017). De vismigratierivier : het ecoduct door de Afsluitdijk. *Vakblad Natuur Bos Landschap*, 4–7.

NatureServe. (2019). *Gasterosteus aculeatus. The IUCN Red List of Threatened Species 2019: e.T8951A58295405.* The IUCN Red List of Threatened Species.

Noordhuis, R. (2017). Het Haringvliet na de Kier: Samenvatting van hydrologische prognoses ten behoeve van effectinschattingen op vis en vogels (11200854-010). In *Deltares*.

O'Donnell, M. J., George, M. N., & Carrington, E. (2013). Mussel byssus attachment weakened by ocean acidification. *Nature Climate Change*, *3*(6). https://doi.org/10.1038/nclimate1846

Palstra, A. P., Kals, J., Böhm, T., Bastiaansen, J. W. M., & Komen, H. (2020). Swimming Performance and Oxygen Consumption as Non-lethal Indicators of Production Traits in Atlantic Salmon and Gilthead Seabream. *Frontiers in Physiology*, *11*, (759). https://doi.org/10.3389/fphys.2020.00759.

Perry, F., Jackson, A., & Garrard, S. L. (2017). *Ostrea edulis Native oyster*. MarLIN (Marine Life Information Network): Biology and Sensitivity Key Information Reviews (Online).

Petitgas, P., Alheit, J., Beare, D., Bernal, M., Casini, M., Clarke, M., Cotano, U., Leonie, M. D., Clementine, D., Heino, M., Massé, J., Möllmann, C., Nogueira, E., Reid, D., Silva, A., Skaret, G., Slotte, A., Stratoudakis, Y., Uriarte, A., & Voss, R. (2010). Life-cycle spatial patterns of small pelagic fish in the Northeast Atlantic Editor. *ICES COOPERATIVE RESEARCH REPORT*, *306*.

Politis, S. N., Mazurais, D., Servili, A., Zambonino-Infante, J. L., Miest, J. J., Tomkiewicz, J., & Butts, I. A. E. (2018). Salinity reduction benefits European eel larvae: Insights at the morphological and molecular level. *PLoS ONE*, *13*(6). https://doi.org/10.1371/journal.pone.0198294

Rankin, J. C. (2009). Acclimation to Seawater in the European Eel Anguilla anguilla: Effects of Silvering. In *Spawning Migration of the European Eel*. https://doi.org/10.1007/978-1-4020-9095-0_6

Reeze, B., Kroes, M., & van Emmerik, B. M. W. (2017). *Fish Flows, Migratory fish and migration calendar for the Haringvliet and the Voordelta*. Haringvliet Dream Fund. https://www.haringvliet.nu/sites/haringvliet.nu/files/2017-11/Vismigratierapport_EN-GB_hi-res.pdf

Reid, R., Cargnelli, L., Griesbach, S., Packer, D., Johnson, D., Zetlin, C., Morse, W., & Berrien, P. (1999). *Essential fish habitat source document. Atlantic herring, Clupea harengus, life history and habitat characteristics (NOAA Technical Memorandum NMFS-NE-126).*

Reise, K., Buschbaum, C., Buttger, H., & Wegner, M. K. (2017). Invading oysters and native mussels: From hostile takeover to compatible bedfellows. *Ecosphere*, *8*(9). https://doi.org/10.1002/ecs2.1949

Rijkswaterstaat (2021). Waterinfo. https://waterinfo.rws.nl/ Retrieved: 19-04-2021

Van Rooij, S., B. van Bueren & E. Kuijs. 2012. *Balance Island reduces salt intrusion in the Haringvliet by creating a smooth transition from salt to fresh water while preserving the unique dynamic character of the delta. Delta Alliance Young Professionals Award: Innovative solutions for delta challenges worldwide* (No. 3). Delta Alliance.

Rosewarne, P. J., Mortimer, R. J. G., Newton, R. J., Grocock, C., Wing, C. D., & Dunn, A. M. (2016). Feeding behaviour, predatory functional responses and trophic interactions of the invasive Chinese mitten crab (Eriocheir sinensis) and signal crayfish (Pacifastacus leniusculus). *Freshwater Biology*, *61*(4). https://doi.org/10.1111/fwb.12717

Rossum van, H. (2021). Interview 19 April 2021. Advisor water quality WSHD

Salinger, D. H., & Anderson, J. J. (2006). Effects of Water Temperature and Flow on Adult Salmon Migration Swim Speed and Delay. *Transactions of the American Fisheries Society*, *135*(1). https://doi.org/10.1577/t04-181.1

Salo, T., Pedersen, M. F., & Boström, C. (2014). Population specific salinity tolerance in eelgrass (Zostera marina). *Journal of Experimental Marine Biology and Ecology*, *461*. https://doi.org/10.1016/j.jembe.2014.09.010

Schmucker, A. K., Johnson, N. S., Galbraith, H. S., & Li, W. (2016). Glass-Eel-Stage American Eels Respond to Conspecific Odor as a Function of Concentration. *Transactions of the American Fisheries Society*, *145*(4). https://doi.org/10.1080/00028487.2016.1146164

Schonenberg, D. B., & Gittenberger, A. (2008). The invasive quagga mussel Dreissena rostriformis bugensis (Andrusov, 1879) (Bivalvia: Dreissenidae) in the Dutch Haringvliet, an enclosed freshwater Rhine-Meuse estuary, the westernmost record for Europe D.B. *Basteria*, *72*.

Schop, J., Cremer, J., & Brasseur, S. (2018). Mogelijke effecten van opening van de Haringvlietsluizen op zeehonden (No. C041/18). In *Wageningen Marine Research*. https://doi.org/10.18174/452177

Slater Museum of natural history. (2010). *Three-spined Stickleback (*Image).

https://www.pugetsound.edu/academics/academic-resources/slater-museum/exhibits/marine-panel/three-spined-stickleback/ Accessd on 23 April 2021 at 4.55 PM.

Somers, P. (2019). *Tolerance of the European flat oyster (Ostrea edulis) and the blue mussel (Mytilus edulis) to suspended sediment exposure*. NIOZ Netherlands Royal Institute for Sea Research, Yerseke.

Stevenson, D., & Scott, M. (2005). Essential fish habitat source document: Atlantic herring, Clupea harengus, life history and habitat characteristics_v2. In *NOAA Technical* (Issue July).

Svensen, R. (2019). *Chile salmonid production up 8.5% in first third of year (image).*

https://www.fishfarmingexpert.com/ Accessed on 23 April 2021 at 4.56 PM

Sweco. (2018). *Ontwerpnota Vismigratierivier*, Definitief Ontwerp D6.0. Groningen.

Tangelder, M., Winter, E., & Ysebaert, T. (2017). Ecologie van zoet-zout overgangen in deltagebieden: literatuurstudie en beoordeling van een scenario in het Volkerak-Zoommeer (No. C116/17). In *Wageningen Marine Research*. https://doi.org/10.18174/436428

Tinka, M. (2021) Interview 13 April 2021. Academic Advisor WUR

TNO Geologische Dienst Nederland (2021). DINOloket. https://www.dinoloket.nl/ Retrieved:16-04-2021

Trancart, T., Lambert, P., Rochard, E., Daverat, F., Coustillas, J., & Roqueplo, C. (2012). Alternative flood tide transport tactics in catadromous species: Anguilla anguilla, Liza ramada and Platichthys flesus. *Estuarine, Coastal and Shelf Science*, *99*. https://doi.org/10.1016/j.ecss.2011.12.032

Tyler-Walters, H. (2005). *Zostera (Zosterella) noltei Dwarf eelgrass*. MarLIN (Marine Life Information Network): Biology and Sensitivity Key Information Reviews (Online). https://www.marlin.ac.uk/species/detail/1409

Tyler-Walters, H. (2008). *Mytilus edulis Common mussel*. MarLIN (Marine Life Information Network): Biology and Sensitivity Key Information Reviews, (Online). https://www.marlin.ac.uk/species/detail/1421

Tyler-Walters, H. (2008). *Zostera (Zostera) marina Common eelgrass*. MarLIN (Marine Life Information Network): Biology and Sensitivity Key Information Reviews (Online).

Valle-Levinson, A. (2010). Definition and classification of estuaries. In *Contemporary Issues in Estuarine Physics*. https://doi.org/10.1017/CBO9780511676567.002

Vergeer, J. W., Arts, F. A., Lilipaly, S., Hoekstein, M., & Strucker, R. (2016). Vogels van het Haringvliet. Impressie van vogelwaarden voor en na de afsluiting in 1970 (rapport 2016/09). In *Sovon Vogelonderzoek Nederland*. https://www.sovon.nl/en/publicaties/vogels-van-het-haringvliet-impressie-van-vogelwaarden-voor-en-na-de-afsluiting-1970

Verween, A., Vincx, M., & Degraer, S. (2010). Mytilopsis leucophaeata: The brackish water equivalent of Dreissena polymorpha? A review. In *The Zebra Mussel in Europe* (Issue November).

Ward, J. M., & Ricciardi, A. (2007). Impacts of Dreissena invasions on benthic macroinvertebrate communities: A meta-analysis: Biodiversity research. *Diversity and Distributions*, *13*(2). https://doi.org/10.1111/j.1472-4642.2007.00336.x

Webster, J. M., Clark, P. F., & Morritt, D. (2015). Laboratory based feeding behaviour of the Chinese mitten crab, Eriocheir sinensis (Crustacea: Decapoda: Brachyura: Varunidae): Fish egg consumption. *Aquatic Invasions*, *10*(3). https://doi.org/10.3391/ai.2015.10.3.06

van Wieringen, D. (2019). The impact of sluice management on biodiversity and ecosystem services in the Haringvliet. In *MSC thesis, Wageningen University & Research*.

Wijnhoven, S. (2017). *Non-indigenous species presence and distribution in intertidal hard substrate environments of the Western Scheldt (Report Series 2017-04)*. www.ecoauthor.net

Winter, H., Griffioen, A., & van Keeken, O. (2014). De Vismigratierivier: Bronnenonderzoek naar gedrag van vis rond zoet-zout overgangen. In *Institute for Marine Resources & Ecosystem Studies (IMARES), Wageningen University & Research*.

Winter, H. V., Mulder, I. M., Griffioen, A. B., van Rijssel, J. C., & de Leeuw, J. J. (2020). Herstel van vismigratie in het Haringvliet: kennisvragen, monitoring en wetenschappelijk onderzoek (rapport C061/20). In *Wageningen University & Research*. https://research.wur.nl/en/publications/2625718f-ecfe-4409-a4c3-8d60cc464023

Van der Wolff, B & J. Lokker. 2021. Vooronderzoek Vismigratierivier Delta21. *Hogeschool Rotterdam*.

World Conservation Monitoring Centre. (1996). *Salmo salar. The IUCN Red List of Threatened Species 1996: e.T19855A9026693.* https://www.iucnredlist.org/species/19855/9026693

Wuenschel, M. J., & Able, K. W. (2008). Swimming ability of eels (Anguilla rostrata, Conger oceanicus) at estuarine ingress: Contrasting patterns of cross-shelf transport? *Marine Biology*, *154*(5). https://doi.org/10.1007/s00227-008-0970-7

10. Appendix

Appendix table 1: List of chemical compounds that cause attraction/repulsion in glass eels. The compound, the odour category to which it belongs, and its role in eliciting behaviour in glass eels are shown. The salinity (FW, fresh water; SW, salt water) at which a specific compound elicits a specific behaviour, and the minimum concentration thresholds at which attraction or repulsion was observed are also indicated (Cresci, 2020).

Chemical cue	Odour category	Role	Water	Detection threshold	Reference
Geosmin (trans-1,10-dimethyl-trans-9-decalol)	Earthy odour	Attractant Repellent	FW SW	10^{-13} mg/l 10^{-13} mg/l	Tosi & Sola (1993)
MMP (2-methyl-3-methoxypyrazine)	Green odour	Attractant Repellent Attractant Attractant	FW SW Brackish (30‰) Brackish (15‰)	10^{-13} mg/l 10^{-13} mg/l 10^{-13} mg/l 10^{-9} mg/l	Sola (1995); Sola & Tongiorgi (1996)
ETMCE (2-isobuthyl-3-1-ethyl-2,2,6-trimethylcyclohexanol)	Green odour	Attractant Repellent Attractant Attractant	FW SW Brackish (30‰) Brackish (10‰)	10^{-13} mg/l 10^{-13} mg/l 10^{-13} mg/l 10^{-9} mg/l	
MT (4-methylthiazole)	Green odour	Attractant Repellent	FW SW	10^{-12} mg/l 10^{-11} mg/l	
L-MF (l-2-methylfenchol)	Earthy odour	Attractant Repellent	FW SW	10^{-12} mg/l 10^{-12} mg/l	
D-MF (d-2-methylfenchol)	Earthy odour	Attractant	FW	10^{-9} mg/l	
IBMP (2-isobutyl-3-methoxypyrazine)	Green odour	Attractant Repellent	FW SW	10^{-11} mg/l 10^{-9} mg/l	
TMCE (1,2,2,6-tetramethycyclohexanol)	Earthy odour	Attractant Repellent	FW SW	10^{-11} mg/l 10^{-11} mg/l	
IPMCET (4-isopropyl-7-methycyclohexathiazole)	Green odour	Attractant	FW	10^{-10} mg/l	

Fresh water (0‰)	Salinity difference	Attractant	Eels kept in FW		Tosi *et al.* (1988)
d-glutamine	aa (CS)	Attractant Attractant	FW SW	10^{-7} M 10^{-7} M	Sola & Tongiorgi (1998)
d-glutamic acid	aa (CS)	Attractant Attractant	FW SW	10^{-7} M 10^{-8} M	
d-asparagine	aa (CS)	Attractant Repellent	FW SW	10^{-7} M 10^{-7} M	
d-alanine*	aa (CS)	Attractant Repellent Repellent	FW FW SW	10^{-9} M 10^{-7} M 10^{-8} M	
β-alanine	aa (CS)	Attractant Attractant	FW SW	10^{-9} M 10^{-9} M	
l-asparagine	aa (CS)	Stimulant OE	–	10^{-9} M	Crnjar *et al.* (1992)
l-glutamine	aa (CS)	Stimulant OE	–	10^{-9} M	
Conspecific odour (*A. rostrata*)	Conspecific wash Conspecific wash	Attractant Attractant	FW Brackish	0.2 g of glass eels l^{-1} h^{-1} 6.3 g of elvers l^{-1} h^{-1}	Schmucker *et al.* (**2016**) Galbraith *et al.* (**2017**)
Glycocholate	Bile salts (CS)	Attractant Attractant	FW SW	10^{-11} M 10^{-10} M	Sola & Tosi (1993)
Taurodeoxycholate	Bile salts (CS)	Attractant Attractant	FW SW	10^{-11} M 10^{-10} M	
Taurocholate	Bile salts (CS)	Attractant*	FW	10^{-11} M	
Cholate	Bile salts (CS)	Attractant* Attractant*	FW SW	10^{-11} M 10^{-11} M	
Deoxycholate	Bile salts (CS)	Attractant* Attractant*	FW SW	10^{-14} M 10^{-10} M	
Glycochenodeoxycholate	Bile salts (CS)	Attractant* Attractant*	FW SW	10^{-12} M 10^{-11} M	
Taurochenodeoxycholate	Bile salts (CS)	Attractant* Attractant*	FW SW	10^{-14} M 10^{-12} M	
Taurine	Taurine (CS)	Attractant Attractant*	FW SW	10^{-12} M 10^{-9} M	