Turning the tides in the Haringvliet

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An analysis of the ecological conditions required for a fish migration river

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Foreword

This ACT project has been a challenging, but nonetheless enjoyable experience for all of us. This was due to the pleasant team dynamics, but also because of many people outside of our team who have been able to support us in various ways. We would like to thank them here.

For imparting information and advice, we would like to thank Leo Nagelkerke for his sharp and critical feedback on our report. Also, thanks to Tinka Murk for her valuable input at the beginning of our project. Furthermore, we would like to thank Koen Workel from Rijkswaterstaat and Erik Bruins Slot from Provincie Fryslan for their time and input during our interview with them. Thanks to Huibert van Rossum of waterschap Hollandse Delta for some valuable insights during our conversation.

During this project we also worked on our communication skills and personal development. We would like to thank Auke Westerterp for his input on the team process during the Communication and Personal Development sessions. Special thanks to Bart Hermans for his patient, friendly and always helpful feedback, help and coaching during the entire process.

In our project we have had extensive contact with our commissioners Huub Lavooij, Leen Berke and Gijs Kok. We would like to thank them for the pleasant collaboration. We would also like to thank Jeroen Lokker and Bart van der Wolff of the Hogeschool van Rotterdam for their time, input and the sharing of their work so far.

Another special thanks is in place for our parallel ACT-group, whom we have also enjoyed a pleasant collaboration with in the beginning of the project.

Executive summary

The construction of the Haringvlietdam in 1970, as part of the Delta Works, changed the ecology and hydrology of the Haringvliet estuary by cutting it off from tidal influences of the North Sea. As a result, salt water cannot enter the Haringvliet, and the migratory routes of diadromous fish were obstructed. The Kierbesluit was introduced in 2018 as a solution to enhance fish migration, but only allows for migration when the sluices are opened which limits the migratory time window. Delta21 plans to make multiple changes in the Haringvliet and Voordelta by restoring the fish migratory route together with strenghtening coastal protection and realizing the production and storage of energy. This research was commissioned by Delta21 to investigate optimizing fish migration by means of a fish migration river (FMR). The emphasis of this paper lies on acquiring the ecological conditions required for creating a successful FMR in the Haringvliet. The Haringvliet FMR concept originates from the FMR that is to be constructed in the Afsluitdijk which will be the first of its kind. However, the FMR in the Haringvliet has different design requirements than the one of the Afsluitdijk due to location-specific conditions. Five target species were selected, three of which are anadromous (Atlantic salmon, twaite shad and European river lamprey) and two being catadromous (European eel and flounder). Migratory behavior, life cycle and seven environmental conditions (water temperature, critical water velocity, salinity, turbulence, turbidity, light and migratory environment) were examined for these target species. Conflicts between species exist for critical water velocity, turbulence, turbidity, and migratory environment, implying that for optimal migration conditions the FMR needs to be heterogeneous. We are convinced that an FMR in the Haringvliet can adhere to the ecological requirements of the five target species if the previously mentioned conflicts are addressed properly. Under those circumstances, the migration potential of these species would significantly expand.

Samenvatting

Als onderdeel van de Deltawerken werd in 1970 de Haringvlietdam gebouwd en veranderde daarmee de ecologie en hydrologie van het estuarium van het Haringvliet door deze af te sluiten van de getijdeninvloeden van de Noordzee. Hierdoor kon er geen zout water meer het Haringvliet instromen en werden de migratieroutes van diadrome vissen geblokkeerd. In 2018 werd het Kierbesluit geïntroduceerd als maatregel om de vismigratie te verbeteren. Het Kierbesluit laat echter alleen migratie toe bij open sluizen, wat de hoeveelheid migratietijd beperkt. Delta21 is van plan om in het Haringvliet en de Voordelta meerdere veranderingen door te voeren door de vismigratieroute te herstellen, de kustbescherming te versterken en de productie en opslag van energie te realiseren. In dit onderzoek in opdracht van Delta21 wordt gekeken naar het optimaliseren van vismigratie door middel van een vismigratierivier (FMR). De nadruk van dit rapport ligt op het verkrijgen van de ecologische voorwaarden die nodig zijn voor het realiseren van een succesvolle FMR in het Haringvliet. Het FMR-concept voor het Haringvliet komt voort uit de FMR die in de Afsluitdijk als eerste van zijn soort wordt gerealiseerd. De FMR in het Haringvliet heeft echter andere ontwerpeisen dan die van de Afsluitdijk vanwege locatiespecifieke omstandigheden. Daarom zijn er vijf doelsoorten geselecteerd, waarvan er drie anadroom zijn (Atlantische zalm, Fint en Europese rivierprik) en twee katadroom (Europese paling en bot). Voor deze soorten zijn het migratiegedrag, levenscyclus en zeven omgevingscondities (watertemperatuur, kritische watersnelheid, zoutgehalte, turbulentie, troebelheid, licht en migratie omgeving) onderzocht. Er zijn conflicten tussen de voorkeuren van doelsoorten voor de kritische watersnelheid, turbulentie, troebelheid en migratie omgeving. Dit suggereert dat voor optimale migratie deze omstandigheden binnen de FMR heterogeen moeten zijn. Wij zijn ervan overtuigd dat een FMR in het Haringvliet kan voldoen aan de ecologische voorwaarden van de vijf doelsoorten als de eerder genoemde conflicten goed worden verwerkt. Onder die omstandigheden is het migratiepotentieel van deze soorten aanzienlijk verbeterd.

Contents

1 Introduction

The Haringvliet is a former estuary of the North Sea located in the province of South-Holland in the Netherlands. It is an estuary that lies in the delta of the rivers Rhine and Meuse, which used to be open to the inflow of seawater (Ministerie van Infrastructuur en Waterstaat, 2020a).

In 1937 Rijkswaterstaat conducted a study for water safety, in which they found out that the Netherlands was prone to flooding if there were times of high river discharge and high sea water levels. Through this research the Deltaplan was initiated which was originally planned out to start in 1950. With the Deltaplan, the Dutch government wanted to gradually build several flood defences around the waterways of Zeeland for protection against flooding and better management of water. After construction started there was a big flood in 1953 which induced policy makers to not build the flood defences gradually, but as soon as possible (Ministerie van Infrastructuur en Waterstaat, 2020b).

One of these flood defences was the Haringvlietdam, which was finished in 1970. The delta area has undergone a series of water management constructions to protect the coast from high water levels. Most notably is the construction of several dams and sluices known as the Delta Works that started in 1954, which has been successful in preventing any flooding from storm surges over the years (Ministerie van Infrastructuur en Waterstaat, 2020b). Despite the protective function of this dam, it has caused previously existing estuarine conditions to disappear, as it cuts off the Haringvliet from the Voordelta (Staatsbosbeheer, 2021).

There are a variety of stakeholders with conflicting interests regarding the current situation. As the Haringvliet is currently a freshwater body, it has subsequently become an important freshwater supply for irrigation of agricultural fields and drinking water for surrounding municipalities. These stakeholders are, as such, benefiting from the current situation (Teunissen, 2019). This contrasts with many local environmental NGOs, who regard the disappeared estuarine conditions as detrimental to the natural value of the area (Eilanden-Nieuws, 2021). Additionally, there is increased attention from society to the effects of climate change (Sociaal en Cultureel Planbureau, 2020).

In order to deal with sea level rise and heavier river discharges that are likely to result from climate change, the national government has devised the Delta Programme, which aims to integrate freshwater provisioning and climate adaptation with coastal protection of the Dutch delta (Ministerie van Infrastructuur en Waterstaat, 2021). The Delta Programme recognizes that the Delta Works are embedded in a wide range of conflicting stakeholder views and societal challenges. As such challenges involve many layers of society and address various areas of expertise, the national Delta Programme of the Dutch government involves civil-society organisations, municipalities and water authorities (Ministerie van Infrastructuur en Waterstaat, 2021).

As a way of giving substance to the vision of a delta in which climate change, freshwater provisioning, and coastal protection are integratively addressed, Delta21 is an initiative devised in 2015 that aims for a wider functionality of the Delta Works in the Haringvliet. This initative covers the northern part of the Voordelta and the Haringvliet. The aim is to formulate an integral water management plan with three main pillars: coastal protection of the Dutch delta combined with the storage and production of sustainable energy, as well as nature restoration. As such, it can play a role in the mitigation of increased flood risk due to climate change, while additionally providing avenues for the sustainable energy transition and increasing the natural value of the Dutch delta (Delta21, 2019).

Flood safety is improved by the construction of a storage lake and a storm barrier (Figure 1). The storm barrier, which can keep seawater out and simultaneously reduce water levels in the tidal lake, will be opened nearly permanently. During exceptionally high sea levels, the storm barrier of the tidal lake can be closed. Excess water that accumulates from the Rhine and Meuse will spill over into the storage lake to prevent floods. This makes the continuation of dyke reinforcement by increasing the dyke height no longer necessary, leading to a significant financial benefit. At the same time, the storage lake can be utilized for the generation of sustainable energy (Delta21, 2021).

The energy storage lake is designed to have a generation capacity of 1860 MW. It is passively filled up during high river discharge or high seawater and generates electricity when emptied through the pumps. As a result, it can make a valuable contribution to the national energy transition (Delta21, 2020). In addition to the energy storage lake, a tidal lake will be constructed that will connect the river to the energy storage lake and is generally subject to inflow of saltwater from the sea (Figure 1).

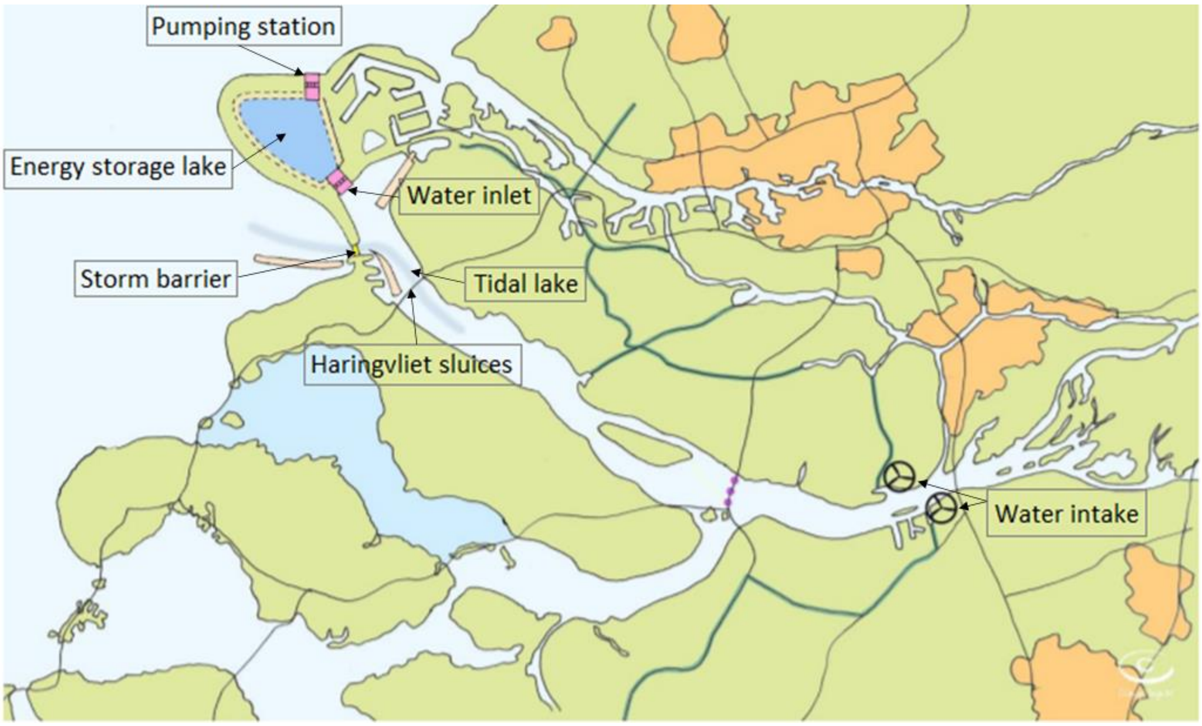


Figure 1: Overview of the proposed Delta21 project with most important constructions depicted on the map, Adapted from: (Delta21, 2019).

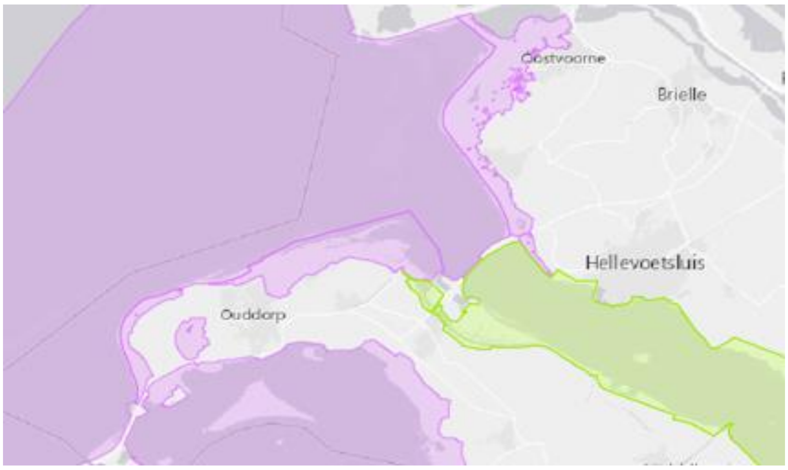


Figure 2: Overview of the current situation and N2000 designated areas. Purple and green indicate N2000 areas, green is the Haringvliet which falls under the birds directive and habitat directive (Ministerie van Landbouw, Natuur en Voedselkwaliteit a., n.d.)

The Delta21 plan, by means of the construction in the Voordelta, will have an impact on the natural value of that area. The proposed tidal lake overlaps with the Voordelta, which is a Natura2000 designated area (Figure 1 & 2). Natura2000 comprises a network designed to fulfill a nature conserving function under the EU habitat and birds directive (Figure 2; Ministerie van Landbouw, Natuur en Voedselkwaliteit, n.d.). As the project aims for nature restoration besides coastal protection and sustainable energy production, it is of vital importance for the project's net contribution to nature restoration to mitigate the ecological effects of construction in areas of such natural value. Hence, the initiators of Delta21 have come to an agreement with nature organizations that building in the Natura2000 area is acceptable as long as the project ensures a generous compensation to nature in another way (Delta21, 2019). As the Haringvliet used to be a major hotspot for estuarine and migratory fish, and this function has been impaired following the construction of the Delta Works, there is a potential to contribute to nature restoration in this regard (Waddenvereniging, n.d.).

1.1 Integrative project purpose

Permanently opening the sluices would be most beneficial for fish migration, but this is deemed impossible as water provisioning for the surrounding municipalities of the Haringvliet must be maintained (Delta21, 2020). Another initiative with a similar goal called the Kierbesluit has therefore been introduced in 2014 and was initiated in 2018. The Kierbesluit would facilitate fish migration by opening the sluices temporarily when the tide is rising, and water levels are low. However, the Kier only has a limited time window in which it can be opened. As monitoring is still in progress, there is not sufficient information available to determine whether this is sufficient for fish migration to occur effectively (K. Workel, personal communication, April 19, 2021).

Previous consultancy projects commissioned by Delta21 to investigate the possibilities for nature restoration, have identified the possibility of a fish migration river (FMR) to restore diadromous fish migration (Baas et al., 2020). Diadromous fish are fish species that migrate between fresh and saltwater to complete their life cycle (Reeze et al., 2017). For that reason, the focus of this report is to build on that advice by investigating the ecological conditions that need to be considered in the design of an FMR. Such a river has not been established anywhere in the world, although one is planned to be constructed in the Afsluitdijk (Van Calsteren & Stoop, 2015). As the members of our team are mainly ecologists by training, we have looked at the ecological conditions that have to be met within a fish migration river to allow for the most effective migration of diadromous species.

To determine these conditions, we have investigated the current and historical ecological and hydrological situation in the Delta21 project area. This information was necessary to know to what extent the system is already conducive to the facilitation of fish migration. Secondly, the concept of an FMR was explored to provide an overview of how ecological conditions could be applied. Thirdly, a choice had to be made regarding the actual species that will be facilitated with a migration river. Once this choice had been made, the ecological conditions required for each species to migrate via a river had to be determined. Finally, these species' specific ecological conditions were compared to determine whether these could be combined to facilitate the migration of all target species in one river design. As such, the following questions were used to achieve our project goal:

1.2 Research questions

What are the ecological conditions required for creating a successful fish migration river to the Haringvliet?

Sub-questions:
- *What is the current ecological and hydrological situation in the Delta21 project area?*
- *How can the concept of a fish migration river be applied in the Haringvlietdam?*
- *What are the target species that should make use of a fish migration river?*
- *What ecological conditions must be met for successful migration of the identified target species?*

Within this report, we will limit our research to the ecological aspects of an FMR. The economic, technical, and social feasibility will therefore be excluded, aside from some general remarks in the discussion. Moreover, this project will focus on maximizing the potential of an FMR through identification of the ecological conditions for a select number of diadromous fish. These fish will be selected based on a variety of criteria, outlined in later chapters.

1.3 Methodology

The research questions have been answered by a combination of methods. Most aspects have been researched using a combination of literature research and personal interviews. The people interviewed, their specific area of expertise, and the information retrieved from each person can be found in Table 1. Literature review of species-specific research was the foundation for this report. Our contribution lies in combining the available knowledge and applying it to the concept of the FMR in the Haringvliet.

The interview with Koen Workel has primarily contributed to our knowledge of the current ecological situation in the Haringvliet. The interview with Erik Bruins Slot provided us with comparative information on required ecological conditions for migration. Additionally, multiple meetings with our academic advisor, Dr. Leo Nagelkerke, and a meeting with professor of marine animal ecology, Tinka Murk, have been held to provide additional input and feedback on the report.

Table 1: Overview of people interviewed for this report.

Koen Workel	Advisor Water and Ecology at Rijkswaterstaat - interviewed regarding state of fish migration following Kierbesluit
Erik Bruins Slot	Project leader fish migration river Afsluitdijk at Province of Friesland - interviewed regarding migration route Afsluitdijk

2 Historical and current situation of the Haringvliet as an estuary

Due to anthropogenic activities in the past century such as the construction of the Haringvlietdam, the ecological situation in the Haringvliet has changed drastically. This has had a major impact on diadromous fish that use the Haringvliet either as a passage or habitat. In this chapter we will discuss the current ecological state of the Haringvliet to later discuss its effects on the possible implementation of an FMR.

2.1 The Haringvliet as an estuary

Up until 1950, the Haringvliet was part of a transitional area between the North Sea and the major Dutch rivers where diadromous fish species were able to migrate up- and downstream without encountering any barriers. Every day, sea water could flow freely in and out of this estuary. An estuary is a system in which a partly enclosed body of water is characterized by mixing of salty ocean with fresh river water (Vilas et al., 2014). This results in a salinity profile with differing degrees and spatial distributions of freshwater, salt water, and brackish water. These salinity profiles are formed because of interactions of tidal working in combination with coastal morphology, freshwater inflow, and sediment type. The most important factors influencing estuarine ecology are salinity, sediment, dissolved oxygen content, and temperature (Kaiser et al., 2011; Attrill, 1998). Faunal and floral species distributions follow from different tolerances and preferences in response to these conditions as displayed in Figure 3 (Kaiser et al., 2011).

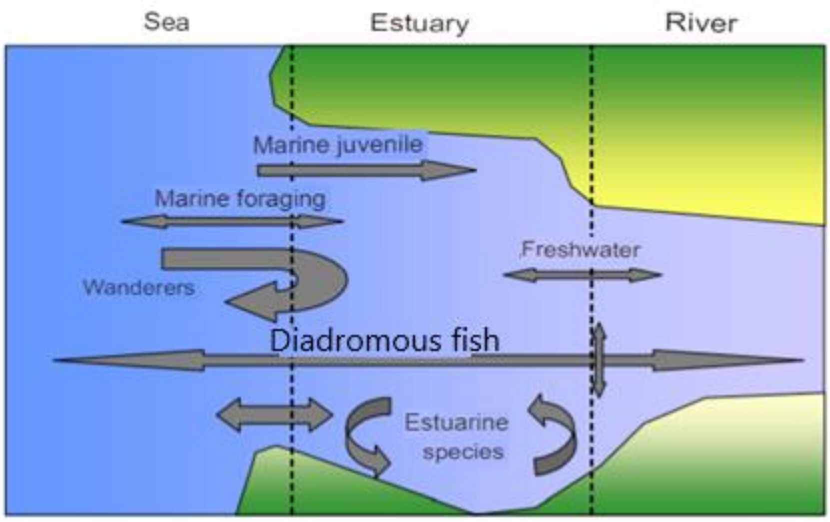


Figure 3: Use of estuary by different fish communities. The thickness of the arrows is an indication of the number of species in the group. Adapted from Ybema & Backx (2001)

2.2 Hydrological situation surrounding the Haringvlietdam

The current hydrological situation in the Haringvliet and Voordelta is governed by coastal influences. The salinity differences of the two water bodies as well as the difference in water level as a result of tidal dynamics have a large impact on the hydrology. In Figure 4 the frequency distribution of water level differences at high and low tide shows that water levels downstream are sometimes higher than the upstream levels due to the tides. Upstream river flow of saline seawater would occur if not for the closed sluices.

Furthermore, the Haringvlietdam forms a barrier between the sea and rivers. In the Haringvliet, the barrier changed the water composition from brackish to mainly fresh water. This removed the salinity profile normally associated with estuaries. Moreover, during low tides, excess river water is discharged through the Haringvlietsluices. On a yearly basis, 30 billion cubic metres of water (~950 m3/s) is released (Rijkswaterstaat, n.d.). The water is not released in a constant manner, but in periods when the water level of the Voordelta is low.

This creates a very periodic water discharge, which has led to unstable salinity levels in the Voordelta. This results in a rather brackish area in the east part of the Voordelta, especially right behind the sluices (K. Workel, personal communication, April 19, 2021; Figure 5).

Additionally, due to the Kierbesluit, saltwater occasionally enters the Haringvliet (Rijkswaterstaat, n.d.). Due to this intrusion of saltwater, the Haringvliet can become a bit more saline. The Kierbesluit states that the water upstream of the imaginary line Spui-Middelharnis (about 12km upstream) should not experience any increase of salinity to preserve its ability to extract freshwater for irrigation and drinking water purposes. In general, the maximum amount of chloride for irrigation and drinking water is stated as 150 mg/l (VROM, 1999). Careful management of the Kier is essential to prevent the intrusion of salt water from creating a Haringvliet that is too saline for the extraction of water.

Finally, due to the Haringvlietdam river water cannot always flow freely out to the North Sea and this results in the accumulation of polluted sediment in the Haringvliet. Because of this pollution the water quality in the Haringvliet has degraded throughout the years (Baan, 1987).

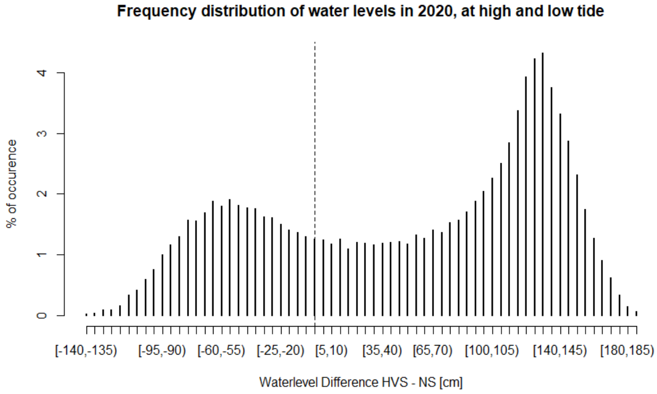


Figure 4: Frequency distributions of water level differences and high and low tide between Hellevoetsluis (HVS) and the North Sea (NS). Data retrieved from Rijkswaterstaat for 2020.

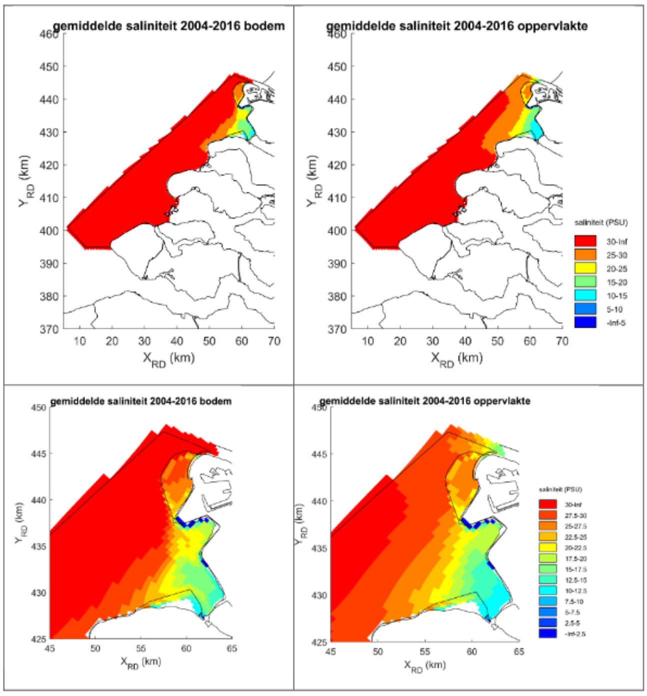


Figure 5: Bottom (left) and surface (right) salinity of the Voordelta, 2004-2016. Red indicates saline conditions, blue low salinity (Tulp et al., 2019)

2.3 Current Haringvliet ecology

Due to the aforementioned changes in the Haringvliet, the ecosystem has changed drastically. Many diadromous fish species have a difficult time fulfilling their life cycle. This is illustrated by the gathering of large amounts of fish in front of the sluices of the Haringvlietdam. It has been found that migration delay due to an unnatural situation can lead to higher mortality rates through predation (Dekker & van Willigen 1997; Dekker 2000).

Specific species that have been affected by the construction of the Haringvlietdam are the sturgeon, Atlantic salmon and the twaite shad. The sturgeon is dependent on the estuary to grow up and migrate up and down the river to fulfill its life-cycle. Due to the fact that this is no longer possible, the sturgeon completely disappeared from Dutch waterways (De Groot, 2002). The same problem is affecting the Atlantic salmon population which is to be considered an indicator species for the ecosystem (NOAA, n.d. a.). Currently, Atlantic salmon do not reside in the Haringvliet anymore and have a low chance of getting through the Haringvliet because of high fishing pressure (WWF, n.d.). Furthermore, species like the twaite shad who rely less on the migration function of the Haringvliet and more on the habitat and nursery function have a hard time (Maes et al., 2008; De Groot, 2002).

Not only did the Haringvlietdam affect fish populations, it also changed habitats and the vegetation of the Haringvliet. Brackish vegetation like marine eelgrass disappeared due to a set of factors including a higher mortality rate in freshwater (Nejrup & Pedersen, 2008). Marine eelgrass provides shelter for species like eels, flounder, mullets, crabs and shrimp. It also provides shore stability by retaining sediment and functions as food for different duck and swan species (Duarte, 2002; Spalding et al., 2003). Because of the change in water composition throughout the Haringvlietdam, the marine eelgrass with its ecological function disappeared. Also, due to sediment pollution, aquatic vegetation is under constant stress and struggles to survive (NSW, n.d.).

On a more positive note, it seems that the current Kierbesluit has increased fish passage opportunities. Now, the sluices are opened periodically, Rijkswaterstaat has found that there are 23 species migrating through the sluices (Ministerie van Infrastructuur en Waterstaat, n.d.). This appears to mainly happen on the southern side of the Haringvliet near the Zuiderdiep (E. Bruins Slot, K. Workel, personal communication, April 19, 2021). Typical diadromous fish were found, like the European eel, three-spined stickleback and the European smelt. Fish like salmon, sea trout and houting were not caught in the nets. They have a reputation of being able to evade nets better than other fish and thus are monitored in different ways (Ministerie van Infrastructuur en Waterstaat, n.d.). Furthermore, the expectation is that with the current Kierbesluit, the concentration of fish in front of the sluices will reduce because they are able to migrate more frequently. This will lead to a reduction in predation caused by gatherings in front of the sluices (Winter et al., 2020).

Nevertheless, it is unclear to what extent the Kierbesluit will restore diadromous fish migration from the North Sea to the Haringvliet. Therefore, other solutions that resemble the natural situation are being considered to improve fish migration in the area. The construction of an FMR through the Haringvlietdam is one of these proposed solutions. An FMR is a new concept that incorporates nature-like features, such as an estuary habitat, which facilitates both up- and downstream fish migration. The FMR differs from the Kierbesluit mainly because it creates estuarine type conditions. In the following chapter the concept of an FMR will be explained more in depth. Subsequently, in order for such an FMR to be successful, it is evident that it should satisfy certain ecological conditions that make fish migration through the Haringvlietdam possible. Henceforth, this report will focus on assessing what these conditions are and giving recommendations on implementing them.

3 FMR concept in the Haringvliet

In order to come up with certain ecological conditions for an FMR it is important to understand the concept. Moreover, the implementation of an FMR through the Haringvlietdam will be discussed. Finally, some remarks on monitoring fish migration through the FMR will be made.

3.1 FMR functionality

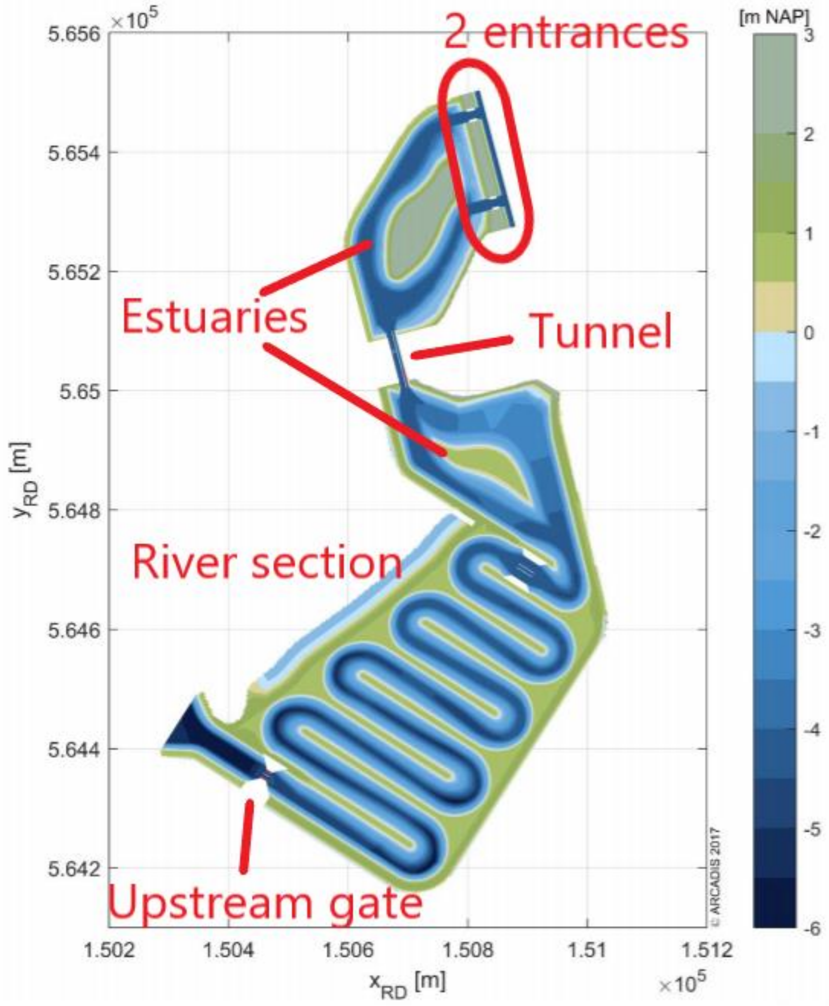


Figure 6: Schematic of the Afsluitdijk FMR. Adapted from Van Banning et al., (2018).

Fish passages are not a recent invention. All across the world various types of constructions have been built to accommodate the migration of different fish species and link together separated bodies of water (Larinier & Murmulla, 2004). These passages are often built to counteract the effects of water-controlling structures such as dams and weirs. In these passages, water is always flowing downstream. The FMR is a new concept to apply the principle of fish passages to flood-defense structures in coastal regions. One complication that requires consideration is that the water is no longer flowing solely downstream. The tides are much more prominent in the area downstream of the structure (generally, the sea) than in the upstream part (often a freshwater body separated from tidal influence). This difference in tidal influence can amount to inverted water levels, with higher water levels downstream of the passage, and therefore inverted water flow. To prevent salinization of the upstream freshwater it is essential to control the amount of water that moves upstream.

The only existing concept for an FMR is the structure planned near the Lorentzsluices of Kornwerderzand in the Afsluitdijk. The Dutch government and local waterboards designed an FMR to allow fish to cross the Afsluitdijk and traverse from the Wadden Sea to the IJsselmeer and vice versa. The current iteration of the design is depicted in Figure 6 (Van Banning et al., 2018). We will briefly discuss the components of the Afsluitdijk FMR and their purposes.

- **The seaside entrance** to the FMR consists of two separate openings. The openings are close to the active sluices, which contribute to the supply of freshwater that creates an attraction flow that guides the fish inwards.
- Moving southwards leads to a **seaside estuary**, creating a habitat that is as natural as possible.

- The **tunnel** through the dam is very rigid, as it needs to be able to be closed completely in the case of storms and extreme high water situations. In the tunnel, one main stream is created, along with a smaller one containing vertical slots passages. This is the only concrete section of the FMR.
- The **lakeside estuary** is located south of the tunnel. This is very similar to the estuary north of the tunnel, but will most likely end up with reduced saline conditions.
- A construction very akin to a **meandering river** continues from the estuary, with the purpose of leveling out the water level differences across the two waters over a longer distance. This reduces the water velocity in the FMR and therefore erosion of the structure.
- The FMR ends with a **gate** that allows for control of the amount of water entering the FMR. This is essential, as it prevents incidental saltwater intrusion into the lake. Yet, the water can also flow from the FMR into the IJsselmeer.

This concept of the FMR allows the regulators to control the amount of water that traverses the structure, and therefore prevent salt intrusion. In this report we will consider the FMR in the Haringvlietdam to consist of similar components.

3.2 Implementation FMR

Concrete details on the implementation of the FMR in the Haringvliet are a work in progress. One important aspect is the location of the FMR. The FMR could be placed in the center of the Haringvliet, but there are a few practical considerations which appear suboptimal to us. Among others, the construction is probably more difficult and the impact on the ecosystem will likely be large. The intuitive options are to construct the FMR in the water either on the southside, the coast of the island of Goeree-Overflakkee, or on the northside on the coast of Voorne-Putten. The current function of those areas should be taken into consideration; there is a harbour in the vicinity of the southern location and a beach with cafeteria on the northern side. On Goeree-Overflakkee, there is the lake of the Zuiderdiep, which runs parallel to the Haringvliet and flows past the Haringvlietdam. The Zuiderdiep currently has no defined goal state (Rijksoverheid SGBP 2022-2027, 2021). Therefore, it could be a possibility to include the Zuiderdiep into the concept of the Haringvliet FMR. Another aspect is the accessibility of the FMR for fish. In Figure 5 (Chapter 2), it appears that on the southern side a stronger brackish area has formed behind the sandbanks that are located to the north-west. These sandbanks could potentially contribute in containing released freshwater and thus maintaining relatively brackish conditions in the Voordelta.

On top of that, the brackish area in the Voordelta is important for another component of the FMR, which is the seaside estuary. It might be the case that the presence of the brackish area in the Voordelta reduces the importance of the estuarine parts of the FMR, because species that need brackish conditions might already be able to acclimate in the Voordelta. As a result, it could be considered to either reduce the length of the seaside estuarine part, or to leave it out of the design altogether. Reducing the size of the design of the FMR would mean both less intervention in the ecosystem as well as reduced costs. It should be noted that further research needs to be done to determine to which extent the current brackish conditions in the Voordelta accommodate acclimatization.

Strongly linked to the location and length of the FMR, is the placement of the seaside entrance of the FMR. The ability of the FMR to attract fish may be increased when the attraction flow created by the flushing sluices is aligned with the seaside entrance of the FMR. This would allow for easier navigation for the fish. It has been found that the freshwater attraction flow coming out of the FMR should be at least 3% percent of the total flow resulting from opening the Haringvlietsluices (van Banning et al., 2018). Together with the current Kierbesluit, it is expected that the implementation of an FMR will reduce the size of the gatherings of fish in front of the Haringvlietsluices. It is likely this will result in less predation pressure on fish in the Voordelta area in front of the sluices (Winter et al., 2020). Yet, it is possible that predation within the FMR will be high as it could serve as a funnel for all fish that make use of it (Agostinho et al., 2012).

3.3 Monitoring

After the construction of the FMR it is important that its effect on fish migration is monitored. Considering that an FMR is a relatively new solution for stimulating fish migration past structures, it will be useful to know whether the FMR functions as desired or adjustments need to be made to optimize its functionality. Therefore, quantifying the functionality and efficiency will be important. In order to analyze these features it is important to know the passage efficiency, attraction efficiency, habitat use and use of the acclimatization zone. Another useful insight is to assess the effect of the FMR on the population size of the diadromous fish species at both sides of the Haringvlietdam.

The passage efficiency can be defined as the percentage of fish that make it through the FMR of all fish motivated to start the migration up the Haringvliet (Griffioen & Winter, 2017). To visualize the effect of the FMR on the passage efficiency, the new situation should be compared with the old one. Hence, a reference is needed. The attraction efficiency can be defined as the percentage of fish that enters the FMR of all fish that approach the FMR at least once (Calles et al., 2014). The use of the habitat and acclimatization zone can be defined as the proportion of fish that have high residence time in the FMR (Calles et al., 2014).

The existence of monitoring techniques for observation of individuals and groups of fish are plentiful (Calles et al., 2014). Since the target species differ in size, behavior and ecological demands, multiple monitoring techniques need to be used. Calles et al. (2014) gives a detailed overview of the available monitoring techniques. More specifically, they elaborate on what techniques can be best applied on a certain species (Appendix A).

3.4 Maintenance

The client of the FMR in the Afsluitdijk demands low maintenance for the FMR (Banning et al., 2018). This has led to a design that is morphologically stable. For this to happen, their design required a maximum flow velocity in the sandy parts and hard materials were chosen for the steering elements (Banning et al., 2018). Although the design for the Haringvliet does not have these demands yet we can generally say that low maintenance is desirable because it provides a stable migration opportunity and decreases future costs. Therefore, morphological stability will supposedly be important. Factors that affect the morphological stability are at least waterflow, sedimentation and materials used (Banning et al., 2018).

4 Selecting target species

In order to determine what ecological requirements an FMR should have, it is important to state what ecological outcome is desired with the implementation of such a river. We decided to define such an outcome in terms of target species, because they have clear needs that can be used as a benchmark for designing a well-functioning FMR. Furthermore, species are often the goal within policy making and nature conservation organisations (Van Calsteren & Stoop, 2015). Lastly, looking at target species provides a useful metric to quantify how successful the FMR functions as a migration route.

4.1 Criteria

Since the goal is to facilitate fish migration between the North Sea and the Haringvliet, only diadromous fish species were considered as target species. Firstly, and contrary to other species, it is essential for diadromous fish to make use of a functional migration passage to complete their life cycle. Secondly, these species reflect a wide variety of physiological, behavioral and ecological traits which ensures that when an FMR is designed based on their ecological requirements, it will function for non-migratory, estuarine species as well (De Boer, 2001). Lastly, migratory fish species have gotten the most attention from nature organisations and policymakers, as their numbers have been declining due to river barriers such as the Haringvlietdam (De Boer, 2001).

The target species were chosen from the main sixteen migratory fish species (historically) found in the Voordelta and the Haringvliet (Table 2). The same sixteen species have been identified as target species by the Haringvliet Dream Fund Project and a study by Wageningen Marine Research (Reeze et al., 2017; Winter et al., 2020). Out of this list we selected our own target species based on a number of criteria similar to the strategy used to select the target species for the FMR in the Afsluitdijk (Van Calsteren & Stoop, 2015).

First, the status of the fish is determined by looking at the Dutch and EU policies described for each fish species. These policies have their own criteria (rate of decline, geographic distribution, ecological importance) to establish a conservation status and management plan for each species. By building on the information and choices presented by these nature policies, we can make a considered choice. The policies we used in our analysis are: Natura2000, EU Habitat Directive, Eel Management Plan, Wet natuurbescherming, Bern convention, IUCN Red List and the Nieuwe Rode Lijst as these are the most influential policies and in correspondence with the policy set used by van Calsteren & Stoop (2015). A second criterion used for the selection of our target species is their current distribution, between the years 2015 and 2021, based on the National Databank of Flora and Fauna (NDFF) Verspreidingsatlas (2021). If a species is no longer present in the Voordelta or the Haringvliet and has no viable population that can migrate to the area, it is unlikely it will make use of the FMR. Therefore, species with very low probability of migrating through an FMR were not selected. Lastly, to ensure that a wide range of ecological requirements would be taken into account, we aimed to choose 5 species and at least 2 anadromous and 2 catadromous fish species. Catadromous fish migrate to spawn in saltwater where anadromous species migrate to spawn in freshwater.

Table 2: Criteria used to select the target species
Columns from left to right: N2000 = Natura2000 guidelines, HD = European Union Habitat Directive, EMP = Eel Management Plan, WN = Wet Natuurbescherming (I = international significance, T = negative trend, Z = rarity), BC = Bern Convention, IUCN RL = IUCN Red List (LC = Least Concern, CR = Critical, EX = Extinct), DRL = Dutch Red List, Species included in the corresponding policy are displayed in red.

English name	Scientific name	N2000[1]	HD[2]	EMP[3]	WN[4]	BC[5]	IUCN RL[6]	DRL[7]	Presence[8]
Twaite shad	*Alosa fallax*				ITZ		LC		
Allis shad	*Alosa alosa*						LC		
Sturgeon	*Acipenser sturio*				TZ		CR		
Salmon	*Salmo salar*				I		LC		
Herring	*Clupea harengus*						LC		
Smelt	*Osmerus eperlanus*				IZ		LC		
Stickleback	*Gasterosteus aculeatus*						LC		
Houting	*Coregonus oxyrinchus*						EX		
Flounder	*Platichthys flesus*						LC		
Sea lamprey	*Petromyzon marinus*				I		LC		
River lamprey	*Lampetra fluviatilis*				I		LC		
Eel	*Anguilla anguilla*						CR		
Sea trout	*Salmo trutta trutta*						LC		
Sprat	*Sprattus sprattus*						LC		
Sea bass	*Dicentrarchus labrax*						LC		
Thinlip mullet	*Liza ramada*						LC		

catadromous
anadromous
seasonal guest
estuarine

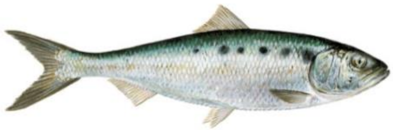
1 Ministerie van Landbouw, Natuur en Voedselkwaliteit a. (n.d.) Retrieved 28 April 2021
2 European Commission (n.d.) Retrieved 28 April 2021.
3 Ministerie van Landbouw, Natuur en Voedselkwaliteit (2009)
4 Ministerie van Landbouw, Natuur en Voedselkwaliteit e (n.d.) Retrieved 28 April 2021
5 Convention on the Conservation of European Wildlife and Natural Habitats.(1979)
6 IUCN (2021). The IUCN Red List of Threatened Species. Version 2021.
7 Spikmans & Kranenbarg, 2016
8 NDFF Verspreidingsatlas (2021)

4.2 Selected species

Based on Table 2, five species were selected to focus on for establishing the ecological conditions: Atlantic salmon, twaite shad, European eel, river lamprey and flounder (Table 2).

Except for the flounder, all these species were identified as a conservation priority by being a target species for at least three of the selected policies (Table 1). The flounder was chosen to meet our criterion of having at least two catadromous species. The eel only occurs in the Eel Management Plan, however this policy works on both the EU level and the national level of all member states, making it one of the most highly prioritized species (Van de Wolfshaar et al., 2018). Moreover, all these species showed high potential of making use of an FMR, either by being present in the Voordelta or showing incidental passage through the workings of the Kierbesluit (NDFF, 2021; Spikmans & Kranenbarg, 2016). These species will determine the ecological and hydrological conditions of the FMR. In the remainder of chapter 4, we will elaborate on the relevance and protection status of each target species and their associated migration habits during their life cycle. The latter will be used to identify the ecological requirements that have to be considered when designing an FMR.

Table 3: Target species that were selected from the criteria.

Common name	**Scientific name**	**Visual**
Atlantic salmon	*Salmo salar*	 Timothy Knepp (n.d.)
European eel	*Anguilla anguilla*	 EC (n.d.)
Twaite shad	*Alosa fallax*	 British Seafishing (n.d.)
River lamprey	*Lampetra fluviatilis*	 Noordzeeloket (n.d.)
European flounder	*Platichthys flesus*	 Fishingplanet (n.d.)

4.3 Atlantic salmon

The Atlantic salmon is an iconic species with a great economic and ecological value. The fish is popular for sport fishers and is increasing in numbers as a farmed species (Aas et al., 2010). The wild salmon, however, shows a great decline in population and has disappeared in most inland waters of Europe (Laak et al., 2007). As an anadromous fish, the species has a complex life cycle, making it sensitive to multiple threats. Migration barriers, like (hydroelectric) dams and weirs, prevent easy access to the river system and cause high mortality during migration. In addition, straightening of river stretches destroyed most of the flood areas used as spawning grounds by the salmon (Laak et al., 2007). Recovery of the salmon population in European riverlands has been mostly unsuccessful due to these modifications (Friedland et al., 2014). This alarming trend has listed them as a target species on both the EU habitat directive and Natura2000. The latter has stated in their evaluation that the Haringvlietdam poses a key migration bottleneck for salmon in the Netherlands (Ministerie van Landbouw, Natuur en Voedselkwaliteit., n.d.).

Migration during life cycle

The spawning takes place in upstream habitats where juvenile fish stay for several years before turning into smolts, which means that they become silvery and start to migrate downwards to sea between April and May (Van Emmerik, 2016). Unlike their Pacific cousins, Atlantic salmon do not die after first spawning, and are therefore able to repeat the cycle again (Aas et al., 2010). Atlantic salmon migration occurs during two life-stages: as smolts and adults. In this section, we will refer to smolts as juveniles.

Firstly, after spending 1-6 years in upstream habitats as young freshwater fish, the Atlantic salmon goes through a process known as smoltification, which involves a variety of changes in physiology in order to adapt to a future life in the sea (Aas et al., 2010). According to van Emmerik (2016), juvenile salmon prefer habitats that have a water velocity of 0.05 to 0.25 m/s. Furthermore, 14-18 degrees Celsius are optimal water temperatures for smolts (Van Emmerik, 2016). More importantly, salmon shows stress symptoms with temperatures exceeding 22 degrees Celsius (Armstrong et al., 2003). For juveniles, this can become lethal between 23 to 26 degrees Celsius (Van Emmerik, 2016). There is no need for juvenile salmon to acclimatize, as they are physiologically adapted to higher salinities through the smoltification process (Aas et al., 2010). Turbidity, in one study measured as total suspended sediment (TSS), was found to negatively affect oxygen uptake at low levels. The effect has been found to be more pronounced for juveniles, as dissolved oxygen requirements are higher (NOAA, n.d. b.). Juvenile salmon require small substrate types, like rocks and pebbles, as this allows them to hide from predators. Furthermore, additional habitat elements to serve this function include deep pools, overhanging boulders, vegetation, and other obstacles (Armstrong et al., 2003). Food requirements are small fish, shrimp and insects, and feeding usually takes place in pools (Van Emmerik, 2016; Aas et al., 2010).

In comparison to juvelines, adult salmon have a physiological advantage and can tolerate habitats with water velocities up to 2 m/s (Van Emmerik, 2016). During their upward migration, adult salmon use pools as holding stations to rest (Aas et al., 2010). Sufficient depth of such pools is important to provide adequate habitat, with preferred depth ranges up to 5 meters (Aas et al., 2010, p. 173; Van Emmerik, 2016). Optimal temperatures for adult salmon are 18 to 22 degrees Celsius with a lethal upper limit of 28 degrees Celsius. This optimal temperature also explains that peak numbers of upward migrating salmon are seen between June and August (Van Emmerik, 2016). There appear to be no specific substrate requirements for adults (Van Emmerik, 2016). However, deep columns can still be utilized as resting places. Feeding generally does not take place during upwards migration. (Aas et al., 2010). Moreover, as they migrate from the sea, there are no relevant salinity constraints for adult salmon (Aas et al., 2010). Turbidity plays a significant role for adult salmon, as they require turbid conditions to hide from predators, which are mainly otters and birds of prey (Aas et al., 2010, p.15). There is, however, uncertainty to what extent predation has an influence on adult salmon during upstream migration (Thorstad et al., 2007). Excessive turbidity is not desirable, as it makes finding passages more difficult.

4.4 European eel

The European eel is a commercially interesting species as they are subject to fishing in all stages of their life cycle (Solomon & Ahmed, 2016). Furthermore, the species is listed as critically endangered and decreasing by the IUCN. The decline can be attributed to a range of factors including pollution, overfishing and the limited access to freshwater habitat (Laffaille et al., 2005). Through these factors, the entry of glass eel (juvenile stage) into European rivers has been reduced to 1% of its original level (Dekker et al., 2008). In reaction to this decline, the European Union declared that every member state had to establish an Eel Management Plan in 2007 (EC, 2007). In the Netherlands this led to multiple conservation measures, including a fishing ban in the Haringvliet and the upstream rivers. Another aim is to minimize the fish migration barriers by creating fish passages for this catadromous species (CBS, 2013).

MIGRATION DURING LIFE CYCLE

The life cycle of the European eel commences in the Sargasso Sea where it spawns. It is assumed that by means of the Gulf Stream's current the larval fish are transported across the Atlantic. During this journey, the larvae undergo a metamorphosis into the glass eel stage. The first glass eels arrive at the Dutch shores during September (Solomon & Beach, 2004). However, the start of their upstream migration is not instigated by date but by a rise in water temperature. Because of this, migration of glass eels takes place mainly between February and June (Solomon & Beach, 2004). Upstream migration will start when water temperatures reach 9 degrees Celsius (Deelder, 1984), and time of day is not important (Solomon & Beach, 2004). Average sized glass eels are able to swim through currents of 0.4 m/s (Solomon & Beach, 2004 from Sorenson 1951). Yet, glass eels will not actively swim upriver, instead they will use selective tide transport to move up the river using the incoming tide. This means tidal movement is of the essence for successful migration in the FMR of the European eel (Dekker et al., 2008). Here, it is useful to note that the transition from salt to fresh waters is not harmful for the European eel, thus no acclimatization period is needed (Wilson et al., 2004). Furthermore, it is important to stress that the construction of manmade channels containing natural features such as roots and rocks improve the pass efficiency for eels (Solomon & Beach, 2004). These features are typical hiding places for eels against predators such as birds and predatory fish. Additionally, it is recommended to include other resting places that reduce the flow velocity of the river such as pools and tanks (Solomon & Beach, 2004). The European eel occurs in a wide variety of freshwater types including, slow flowing and fast flowing rivers, lakes, and ditches (Solomon & Beach, 2004).

The European eel grows up in the river and is called a "yellow eel". In this stage the eel leads a hidden existence where it digs itself into the soft muddy or sandy soils, where it can withstand low dissolved oxygen levels (Solomon & Beach, 2004). Maes et al. (2007) found that the European eel can survive in waters low on dissolved oxygen content and hides between water plants and rocks. This stage lasts around 11 years for females and 8 years for male specimens, after which they will undergo a second metamorphosis during which they mature, and the 'silver eel' stage commences. During this stage, the European eel will remigrate seawards and return to the Sargasso Sea to spawn (Deelder, 1984). This migration takes place at night starting in September, and lasting up until November (Van Emmerik, 2016). Most eels migrate when temperatures reach about 9 to 11 degrees Celsius. During this downstream migration, the European eel will not feed anymore (Solomon & Beach, 2004).

4.5 Twaite shad

The twaite shad was already identified as a protected species at the Bern Convention in 1979 and the EU Habitat Directive in 2007 to ensure designated areas would be protected for its survival. Despite these efforts, the species has recently been placed on the Dutch Red List as no sustainable reproduction is possible due to the lack of accessible freshwater spawning areas (Spikmans & Kranenbarg, 2016). The species previously spawned upstream of the Biesbosch but with the establishment of the Haringvlietdam this migration was impeded. Now, spawning has only been observed incidentally in the area downstream of the Haringvliet (Spikmans & Kranenbarg, 2016). To keep the population at a sustainable level it is of high importance that the migration route to their original spawning area is recovered (Spikmans & Kranenbarg, 2016).

MIGRATION DURING LIFE CYCLE

Twaite shad live in the water column along the coast from Norway to Morocco. They spawn up to 190 km upstream, where tidal differences are not perceptible anymore and there is a flow velocity of 0.2 m/s to 0.5 m/s (Maitland & Hatton-Ellis, 2003). Twaite shad makes use of selective tidal transport when migrating, requiring less effort to travel (Maitland & Hatton-Ellis, 2003). Turbulence can cause the fish to shift places in the vertical water column where they experience a higher current against the swimming direction. For this reason, twaite shad prefers smooth laminar flow. Migration is triggered and positively correlated by temperature and the amount of dissolved oxygen, while high flow rate delays the start of the upstream migration (Maes et al., 2008). When water temperature is 10 – 12 °C the spawning migration starts. During upstream migration the fish swim close to the bottom where the flow velocity is lowest. Migration happens in groups and takes place during the daytime (Aprahamian et al., 2003; Maitland & Hatton-Ellis, 2003). Spawning happens above gravel or coarse sand. Immediately after spawning, the adult twaite shad migrate back to the sea in the upper water layers using the higher water flow as an advantage (Aprahamian et al., 2003; Doherty et al., 2004). The eggs are deposited at the surface area whereafter they take up water and sink to the bottom. After hatching, the larvae feed on fine plankton and during summer move slowly towards the estuary. Downstream migration starts when the river water temperature is below 19 degrees Celsius and they reach the estuary at the end of summer to beginning of autumn (Maitland & Hatton-Ellis, 2003). The juveniles need a salinity gradient to acclimatize to the salt water (Maitland & Hatton-Ellis, 2003). In July-November, when the twaite shad have grown to be 10-12 cm, they swim out to sea. In addition to plankton, they also feed on fish at this life stage. After two to three years, the twaite shad are about 30-40 cm in length and migrate upriver to spawn, completing their life cycle (Doherty et al., 2004).

4.6 River lamprey

The river lamprey is an anadromous species. In the Netherlands it travels inland from the saline coastal areas through the Meuse and Rhine rivers to its spawning grounds in the Netherlands and Germany. Although data on their reproduction is limited, it is expected that the Dutch Meuse and Rhine rivers make a valuable contribution to the global population of river lamprey as some of the spawning grounds are within these river systems (Emmerik & de Nie, 2006). Recently the river lamprey has been added on the Dutch Red List because their numbers are declining (Creemers & Kranenbarg, 2016). Similar to the Atlantic salmon, river lamprey are sensitive to migration barriers and the straightening of rivers and streams that make spawning grounds disappear (Nunn & Cowx, 2012; Russon & Kemp, 2011).

MIGRATION DURING LIFE CYCLE

The life cycle of the river lamprey starts upriver where this fish species spawns. When hatched, the larvae (ammocoetes) will move out of their spawning nest and scatter by floating downstream and burrow themselves in silt beds (Docker, 2015). The ammocoetes' ability to burrow itself results from the fact that they have the capacity to sustain low oxygen levels (Potter et al., 1970). The ammocoetes will stay in these silt beds for 3 to 6 years after which they become juvenile larvae and obtain their eyes, teeth and genitalia (Ministerie van Landbouw, Natuur en Voedselkwaliteit b., n.d.; Docker, 2015). Hereafter, the juveniles migrate to the sea where they will experience a growing phase of two to three years before migrating upstream again (Docker, 2015). Manzon et al. (2015) found that water temperature is not the main determinant in instigating seawards migration. In Dutch waters, this migration will take place from March to June during dark nights (Deelder 1984; Maitland 1980). Moreover, during this downstream migration the river lamprey presumably does not feed (Docker, 2015). Swim capacity of small river lampreys, which is estimated between 0.01 and 0.5 m/s (De Boer, 2001), cannot be compared to strong swimmers like salmonids. To overcome situations with stronger currents they attach themselves by sucking to stones and rocks and using small bursts to move ahead and thereafter attaching to objects again. This “burst-attach-rest” tactic requires waters with heterogeneous flow velocity and flows that are not too turbulent. Furthermore, they need resting places such as rocks and stones to attach to, and not too much turbidity in order to locate places where they can reattach themselves (Sportvisserij Nederland; Foulds & Lucas, 2013). The burst speed of river lamprey through a fish passage similar to the FMR is estimated at 2.6 and 3.4 m/s (De Boer, 2001). The need for acclimatization to North Sea salinity levels for river lamprey is not found in literature, however it is assumed not to be of great importance by Winter et al (2014).

After their growing phase in the sea, in which they have been parasitizing and feeding on other fish, the adult river lamprey will migrate upriver (Docker et al., 2015). This upward migration will take place between September and November, when optimal water temperatures are between 15 and 19 degrees (Pereira et al., 2019). In order to find the rivers, it is important for river lamprey that there is sufficient attraction flow. However, the impact of the attraction flow that is created by opening the Haringvlietsluices on diadromous fish has not been documented yet (Winter et al., 2020). The life cycle is completed when male lamprey prepare a nest for the incoming females, which arrive a few weeks later to the spawning grounds to lay their eggs in (Docker, 2015).

4.7 Flounder

The flounder is a common species in the Netherlands and subject to both commercial fishing and recreational angling. The catch amount is however below the maximum sustainable level and no significant pressures to flounder populations have been identified (Van Emmerik & de Nie, 2006). Nonetheless, the species is included as a target species because of its catadromous nature as it is the only catadromous species in the initial list besides the European eel.

Migration during life cycle

Flounder is a catadromous flatfish that lives at the bottom of the shallow parts of the European seas. The diet of flounder consists of worms, small crustaceans and small molluscs. Bigger flounders also predate on other fish. From February until May, the flounder migrates relatively far out into the North Sea (50 to 100km) at depths of 20 to 50 meters in order to spawn (Van Emmerik & De Nie, 2006). Spawning migration is not triggered by water temperature and takes place mostly during the day (Skerrit, 2010; Van Emmerik & De Nie, 2006).

Eggs and larvae use selective tidal transport to migrate to the coast (Muus et al., 1999; Jager, 1999b). During upcoming tide, they are in the upper layers of the water flowing toward the estuaries and rivers. During outgoing tide they are at the bottom where the flow speed is lower. Turbulent water can move the fish and eggs into other waterlayers, making for less efficient transport (Jager, 1999a).

Juveniles live in salt, brackish or freshwater. Migration to fresh and brackish water for survival is preferred during the juvenile life stage, but not a necessity (Jager, 1999a). In the past, flounder larvae were found up to 1000 km inland. During upstream migration it is important that there is a gradual decrease in salinity (Vethaak, 2013). In winter, juveniles move to deeper water (5-10m) and return to the shallow water in spring (Muus et al., 1999; Jager, 1999a). Juveniles do not seem to be bothered by turbidity as they forage in turbid estuarine waters at dawn, dusk, and night (Bregnballe, 1961; Muus, 1967; Pihl, 1982; cited in Vinagre et al., 2008). Moreover, it has been found that flounder abundance is positively correlated to turbidity (Blaber & Blaber, 1980; cited in Zucchetta et al., 2010). Turbidity even reduces the inter -and intraspecific predation risk for juveniles (Blaber & Blaber, 1980; cited in Zucchetta et al., 2010). According to Le Pichon et al. (2014) juveniles have a preference for shaded areas, suggesting that they search for food and shelter from predators. After two to four years the juveniles are sexually mature and will migrate to the open sea to spawn. The flounders that grew up in fresh water do not return after spawning (Schmidt-Luchs, 1977).

Adult flounder does not have very specific habitat criteria. Since flounder is a benthic flatfish, it prefers a flat bottom surface of either sand, clay or silt and does not need vegetation (Schmidt-Luchs, 1977).

5 Determining the ecological conditions for a fish migration river

After looking at the migration habits and needs of each target species, we identified eight different ecological conditions that had varying effects on the migration of all target species. The following conditions were investigated: water temperature, critical water velocity, salinity, turbulence, turbidity, light and migratory environment. This information was compiled and used to determine the similarities and difference between the species (Appendix B). We also took the migration window for each species into consideration.

Next, we determined what we consider to be the best choice for each condition. Some species have more demanding needs than others. If possible, we suggest choosing the values or circumstances in which migration of all five target species is possible.

For four out of seven conditions, we identified conflicting preferences between target species. In our recommendations we provide several solutions and recommendations for the creation of an FMR in which different conditions can co-exist. In the next part, we will further elaborate on the outcome of our analysis and resolutions for conflicting requirements for each ecological condition.

5.1 Water temperature

The temperature of the water can both be a physiological requirement and a behavioral trigger for migration. The target species have various preferred water temperatures in which they migrate. For the Atlantic salmon, European eel and twaite shad, temperature is very important for initiating migration (Aas et al., 2010; Deelder, 1984; Maitland & Hatton-Ellis, 2003). In contrast, for juvenile river lamprey and flounder, other factors are more important in determining the migration window (Skerrit, 2010). If one considers the upper and lower limits for migration of our five target species, there does not seem to be any conflict regarding required water temperatures. Moreover, as temperature is mostly determined by climatic factors, the different species can migrate through their preferred water temperature depending on the time of year. Most notably are the optimal temperatures of the juvenile European eel and the adult Atlantic salmon, which occur in the Dutch winter and summer respectively, in the time of their migration (Table 4). Therefore, this requirement does not have any implications for the design of an FMR, besides that the passage needs to remain open over the entire year. This would allow all target species to migrate during the most suitable time and temperature frame.

Table 4: Target species' preferred water temperature during migration. Optimal temperatures depicted in green and upper/lower limits depicted in yellow for all target species in their juvenile and adult stage. Red indicates that no migration takes place.

		Water Temperature (°C)	Source
Atlantic salmon	*juvenile*	*14* *18* *26*	Van Emmerik, 2016
S. salar	*adult*	*18* *22* *28*	Van Emmerik, 2016
European eel	*juvenile*	*4* *9* *11* *18*	Solomon and Beach, 2004
A. anguilla	*adult*	*9* *20*	Deelder, 1984
Twait shad	*juvenile*	*Most migration occurs below 19 °C* *19*	Maitland and Hatton Ellis, 2003
A. fallax	*adult*	*10* *14*	Aprahamian, 1984
River lamprey	*juvenile*	*Temperature not main determinant*	Docker, 2005
L. fluviatilis	*adult*	*15* *19* *28*	Pereira et al, 2019; Potter, 1980
Flounder	*juvenile*	*Temperature not main determinant*	Skerrit, 2010
P. flesus	*adult*	*Temperature not main determinant*	Skerrit, 2010

Optimal | Lower/upper limit | No migration

5.2 Critical water velocity

Table 5 shows the swimming capacity for the fish species in their active swimming stage. In the juvenile stage for anadromous fish and the adult stage for catadromous fish, the target species make use of tidal transport. During high tides, most migrating species use selective tidal transport and let themselves get carried along with the incoming salt water. During low tide, the water velocity at the sea-side entrance of the FMR is highest and should be bound to a certain limit, based on the swimming capacity of the active swimmers. This limit, called the critical water velocity, is the value below which the target species (active migrants) can still enter and move up the river (Table 5). Based on the lowest critical water velocity found for the target species (for the European eel), a critical water velocity of 0.4 m/s should be maintained at the entrance of the river, to ensure all active swimming species can enter the FMR.

Table 5: Target species' swim capacity in their active swimming life stage with the associated cruising speed, sprinting speed and critical water velocity. Sources: 1. Videler, 1993; cited in De Boer, 2001 2. Van Emmerik, 2016 3. Sorenson 1951; cited in Solomon & Beach, 2004. 4. Peake, 2008; cited in Van Banning et. al., 2018

		Life stage	Cruising speed (m/s)	Sprinting speed (m/s)	Critical water velocity (m/s)
Atlantic salmon	*anadromous*	*adult*	1.35 - 2.55 [1]	4.10 - 7.80 [1]	2.0 [2]
European eel	*catadromous*	*juvenile*	0.29 - 0.37 [1]	0.84 - 1.07 [1]	0.4 [3]
Twait shad	*anadromous*	*adult*	0.75 - 135 [1]	2.25 - 4.1 [1]	0.5 [4]
River lamprey	*anadromous*	*adult*	0.87 - 1.11 [1]	2.62 - 3.36 [1]	Unknown
Flounder	*catadromous*	*juvenile*	0.17 - 0.27 [1]	0.47 - 0.77 [1]	Unknown

Besides the entrance, the water velocity over the entire FMR should be adjusted to the migratory behavior and swimming capacity of the target species. Based on their sprinting and cruising speed, the Atlantic salmon and the flounder are the strongest and weakest swimmers respectively. For the most effective passage, the water velocity of the river should not exceed the cruising speed of the weakest swimmer. Therefore, the maximum water velocity over the entire FMR should not exceed the cruising speed of the flounder (0.17 – 0.27 m/s) to ensure migration possibilities for each species. In case this is not feasible, spatial heterogeneity of flow conditions in the FMR can support effective migration for the weaker swimmers.

For instance, the FMR could be subdivided into different channels or have slopes of various depths along the banks where the flow rate is lower (Figure 7). Constructing one fast-flowing and one slow-flowing channel gives both weak and strong swimmers the opportunity to migrate. In addition, the FMR should have zones with lower flow velocities that can serve as places where fish can temporarily settle and wait during the ebb tide when high flow velocities occur (van Banning et. al., 2018). These areas could also be used by fish to rest, when moving through fast flowing areas exerted their energy.

It should be noted that although a critical water velocity for the entrance and the entire river has been identified, these maximum velocity rates only occur for a short period. During the vast majority of the tide the water velocity is lower, or the flow direction is reversed (Van Banning et. al., 2018). The maximum rates are therefore recommended when effective migration for all species is required throughout the entire year and tidal periods. Otherwise, if the maximum critical velocity is not met, weaker swimmers could still migrate but are limited to a smaller migration window, mainly when the incoming tide causes the countercurrent to diminish and velocities rates are lower.

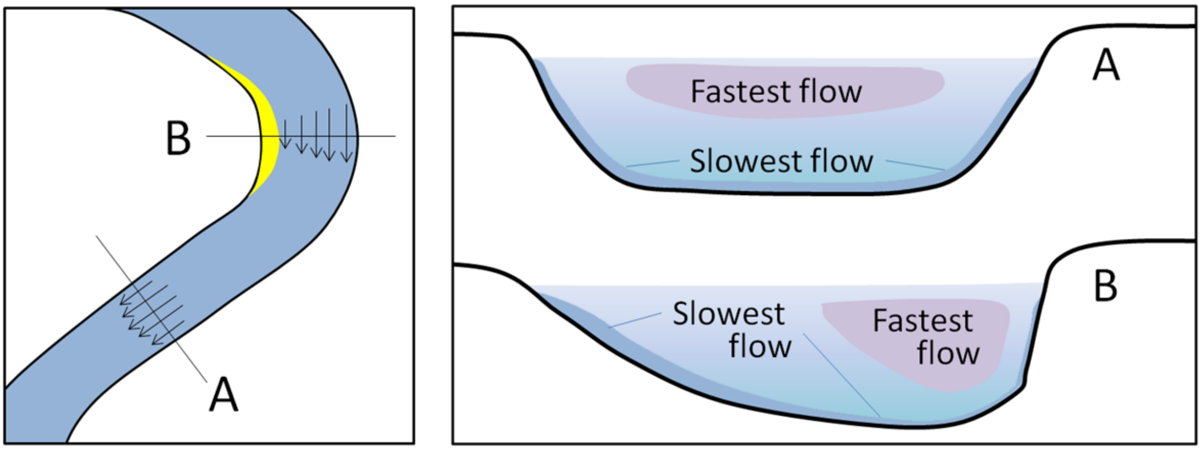


Figure 7: River with flow differentiation along its profile (source: Lumen Learning (n.d.))

5.3 Salinity

When migrating from fresh to saline waters and vice versa, some species need an acclimatization period to get used to different salinity levels (Table 6). When this period is absent, too rapid salinity changes can have a negative impact on fish health (Wong et al., 2017). From our target species, juvenile twaite shad and the flounder require an acclimatization period when migrating along different salinity levels (Vethaak, 2013; Griffioen & Winter, 2014). In order to facilitate migration for these species a gradual change from saline to freshwaters should be created from one end to the other within the FMR. As mentioned before, the flushing of superfluous river discharge water already aids in this task because it creates brackish conditions in the Voordelta.

Creating a salinity gradient does not cause any conflicts between the needs of our target species; species that do not require acclimatization experience no problems when migrating in waters that gradually change in salinity levels.

Table 6: Target species' salinity tolerance

		Salinity requirements	Source
Atlantic salmon	*juvenile*	none	Hoar, 1988; De Laak, 2007
S. salar	*adult*		
European eel	*juvenile*	none	Wilson et al., 2004
A. anguilla	*adult*		
Twaite shad	*juvenile*	acclimatization	Griffioen & Winter, 2014
A. fallax	*adult*		
River lamprey	*juvenile*	Unknown, assumed low importance	Winter et al., 2013
L. fluviatilis	*adult*		
Flounder	*juvenile*	acclimatization	Vethaak, 2013
P. flesus	*adult*		

5.4 Turbulence

Turbulence can have different effects on migrating fish. High levels of turbulence may be injurious to fish, while unexpected changes in turbulence can lead to disorientation and slow down migration (Neitzel et al., 2000; Odeh et al., 2002). As can be seen in Table 7, twaite shad and juvenile salmon prefer low levels of turbulence (Enders et al., 2009; Jager 1999a; Maitland & Hatton-Ellis, 2003). Likewise, the river lamprey prefers lower levels of turbulence, because turbulence increases water turbidity, which makes it more difficult to find attachment places and have a rest during migration (Foulds & Lucas, 2013). In contrast to the other species, Russon & Kemp. (2011) state that the European eel mostly moves along routes where turbulence intensity is high.

It is expected that mildly turbulent, smooth flowing conditions are easy to create, since delta systems are generally slow flowing and have low elevation differences. In addition, we recommend creating high turbulent migration routes for the European eel.

Table 7: Target species' tolerance to water turbulence

		Tolerance to turbulence	Source
Atlantic salmon	*juvenile*	Parr salmon tend to prefer less turbulent areas; During sluice passage irrelevant because uses tides to migrate	Enders et al, 2009
S. salar	*adult*	No literature available	-
European eel	*juvenile*	Irrelevant; Tidal change is important to migrate	Solomon and Beach, 2004
A. anguilla	*adult*	High	Russon et al, 2010
Twaite shad	*juvenile*	Prefers laminar smooth flows; During sluice passage irrelevant because uses tides to migrate	Aprahamian, 2003
A. fallax	*adult*	Prefers laminar smooth flows	
River lamprey	*juvenile*	Low, in order to attach to rocks and pebbles	Foulds & Lucas, 2013
L. fluviatilis	*adult*		
Flounder	*juvenile*	Irrelevant; Tidal change is important to migrate	Muus et al., 1999; Jager 1999
P. flesus	*adult*		

5.5 Turbidity

Turbidity is the degree to which water transparency is reduced through the presence of suspended solids. While quantification of the turbidity requirements of the target species has proven to be difficult, there are clear contradicting preferences. High turbidity is preferred by the European eel because it prolongs the darker circumstances that stimulate its migration. For the Atlantic salmon and flounder, a reduced sight means the risk of predation is lower. However, the Atlantic salmon also needs less turbid conditions for efficient route finding. The same applies to the river lamprey, who needs clear water to find rocks to rest on. Lastly, the twaite shad strongly prefers low turbid conditions and will halt its upstream migration if the water is too turbid. An overview is given in Table 8, with corresponding references.

An FMR with both turbid and less turbid water could be created by constructing extensive banks, where more turbid conditions can prevail. Designing an FMR with multiple streams could also be an outcome. It is however essential that there is at least one non-turbid route if one aims to facilitate the migration of twaite shad.

Table 8: Turbidity requirements for target species. Requirements are the same for both adult and juvenile life stages for Atlantic salmon, river lamprey and flounder. No information was found on the turbidity requirements for juvenile European eel and juvenile twaite shad.

		Turbidity	Source
Atlantic salmon	*juvenile*	+ Predator hiding - Reduces ease of route finding; - Reduce oxygen uptake (more sign. for juveniles)	Thorstad et al., 2007; NOAA, n.d.
S. salar	*adult*		
European eel		+ Increases migration window by reducing light; + Tends to follow turbulent and turbid routes	Solomon & Beach 2004; Russon et al., 2010
A. anguilla	*adult*		
Twaite shad		- With reduced clarity, turns around	Maitland & Hatton-Ellis, 2003
A. fallax	*adult*		
River lamprey	*juvenile*	- Reduces ease of finding surfaces to stick and rest	Foulds & Lucas, 2013
L. fluviatilis	*adult*		
Flounder	*juvenile*	+ Increases prevalence of food sources (esp. for juveniles) + Reduces inter- and intraspecific predation	Blaber & Blaber, 1980
P. flesus	*adult*		

5.6 Light

As shown in Table 9, there are differences in the time of day during which our target species migrate. When creating conditions for the FMR it is useful to be aware of these differences, especially for nocturnal migrating species. The European eel, for example, relies on dark conditions to migrate whereas bright conditions induced by artificial light have been found to halter its migration (Solomon & Beach, 2004). To mitigate this concern, light proof covers have often been installed by manmade structures such as dams and power installations (Solomon & Beach, 2004). In order to facilitate migration of nocturnal migrating species it would be recommended to reduce bright conditions as much as possible during the night. This could be done by turning off the street lighting associated with the road on top of the dam in certain migration periods during the year. Besides implementing these measures, it should be emphasized that the FMR remains open throughout different periods of the day and night, in order to facilitate all target species according to their preferred migration time.

Table 9: Time of day during migration of target species

		Time of day during migration	Source
Atlantic salmon	*juvenile*	Night	Aas et al, 2010
S. salar	*adult*	Mainly night	
European eel	*juvenile*	Unclear, suggests night	Solomon and Beach, 2004
A. anguilla	*adult*	Night	
Twaite shad	*juvenile*	Daytime	Winter et al, 2014
A. fallax	*adult*		
River lamprey	*juvenile*	Night	Maitland, 1980; Kelly and King, 2001
L. fluviatilis	*adult*		
Flounder	*juvenile*	Mainly daytime	Trancart et al, 2012
P. flesus	*adult*		

5.7 Migratory environment

Creating the right environment in the FMR is an important step in making migration an attractive option for migratory fish. This is also an aspect where the target species vary widely in their needs. We obtained the habitat needs of the target species for migration and specifically looked for characteristics of their preferred resting and hiding habitat. Resting possibilities can increase the probability of fish swimming through the FMR when the water velocity is high and swimming is energetically costly (De Boer, 2001). Similarly, the availability of hiding spots can make species less vulnerable to predation during their migration (Gilinsky, 1984; Savino & Stein, 1982; Heck & Crowder, 1991).

5.7.1 Resting and hiding

Most of the target species, namely the river lamprey, Atlantic salmon and the European eel, need rocks (and other hard structured loose components) and vegetation to rest and hide. The river lamprey uses wood or rocks as attachment sites for resting in between sprints, which is seen as an essential condition for migration (Foulds & Lucas, 2013). Adult Atlantic salmon rest in deep pools with overhanging boulders, as do juveniles, who also rest between plants and take shelter in crevices and between rocks (Aas et al., 2010). Lastly, the European eel also needs vegetation and rocks for hiding spots, which are very important for this species (Deelder, 1984; van Emmerik & De Nie, 2006). However, unlike the river lamprey and Atlantic salmon, they prefer to dig in muddy and sandy soils to rest and hide beneath the vegetation and rocks, instead of between them (Deelder, 1984). This matches with the needs of the flounder, who prefers a soft riverbed made of sand, silt or clay (Schmidt-Luchs, 1977; cited in Kroon, 2009). Finally, the resting and hiding conditions of the twaite shad are still unknown. Because of this and the differences in preferences of the other species, we suggest creating a spatially diverse migratory environment. The FMR should have sufficient areas that are strewn with rocks and areas where there is a flat and bare surface. In addition, there should be different types of vegetation growing and the FMR should have a soft soil in general.

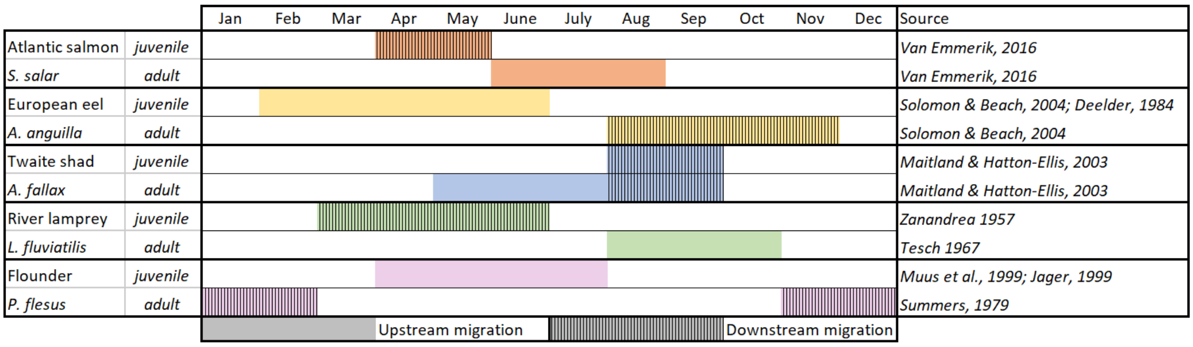
5.7.2 Feeding

In addition to resting and hiding conditions, we also reviewed the feeding behavior of all target species during migration. Juvenile Atlantic salmon feed mainly in pools, on small fish, shrimp and insects (Van Emmerik, 2016). Juvenile European eel are omnivore and feed mostly on bottom-dwelling organisms (Klein Breteler, 2005). Juvenile twaite shad mainly feeds on fine plankton and sometimes small fish (Aprahamian et al., 2003). All three species do not feed as an adult during their migration. According to Docker (2015), river lamprey does not feed during migration at any life stage. In contrast, flounder feeds in both life stages during migration, mostly on insects, crustaceans, and mollusks (Beaumont & Mann, 1984). Even though our target species (and possibly other migratory species) might not reside long within the FMR, it could still be worthwhile to compare and consider their feeding habits. All mentioned groups of feeding organisms can occur together in a brackish water system. However, the specific species and their population numbers will depend in part on their own habitat requirements, which are out of the scope of this report. Nonetheless, finding this information and applying it to the design of the FMR is advised, since it will increase the attraction of migration for the target species.

5.8 Migration windows

As discussed in the previous chapter, the five target species have different life cycles with different migration periods (Table 10). For most species, upstream migration occurs during the summer months. The downstream migration window is less universal, with different species traversing the structure every month of the year. As a result, they require passage around the Haringvlietdam at different moments. This should be considered during the design of the FMR, as it could present possibilities by changing the ecological conditions based on the preferred migration of different species. To do this most efficiently, different simulations have to be made on the target species' migration patterns.

Table 10: Target species' migration windows



6 Conclusion

The aim of this report was to outline the ecological conditions for an FMR that would optimize fish migration to the Haringvliet for diadromous species. To answer the posed research questions, we have conducted an extensive literature study and interviews with experts.

The Haringvlietdam has resulted in a strict division of a saline water body in the Voordelta and a freshwater body in the Haringvliet. Due to the Kierbesluit, there is limited salt intrusion into the Haringvliet. Furthermore, periodic flushing of freshwater into the Voordelta leads to brackish conditions directly behind the dam. These hydrological changes have caused a change in ecological conditions, such as the disappearance of brackish vegetation in the Haringvliet, which previously served as a sediment stabilizer and as shelter for many species.

The Kierbesluit has increased migration opportunities for diadromous fish, but the extent to which it is effective is still uncertain. This is because the sluices are not permanently open, and there is no conclusive data available which demonstrates that migration is effectively restored. The FMR could play an added role as it provides favourable species-specific habitat conditions which are likely to increase fish passage through the Haringvlietdam.

The considerations for an FMR in the Haringvliet are based on the design components of the FMR that is to be constructed in the Afsluitdijk. This FMR has a seaside entrance with an estuarine zone, followed by a tunnel and another estuarine zone on the freshwater side which leads into a meandering section that flows out through a gate into the freshwater body. An FMR in the Haringvliet will have different design requirements due to location-specific conditions. This is because the somewhat brackish conditions in the eastern Voordelta may reduce the need for an estuarine zone and thus could shorten the length of the FMR. Furthermore, the seaside entrance could be placed in such a manner that the attraction flow created by the sluices aligns with the entrance of the FMR.

In order to define what the ecological conditions should be for an FMR, a certain benchmark needed to be set. We have chosen five diadromous fish species to serve as target species to set this benchmark, namely: the Atlantic Salmon, European eel, twaite shad, river lamprey and flounder. They were selected on the basis of their status in Dutch and EU policy, current distribution and our criterion of wanting to include at least two catadromous and two anadromous species in a total of five diadromous fish species.

For our target species we have identified seven different ecological conditions that should be satisfied in order to maximize fish migration to the Haringvliet. These are: water temperature, critical water velocity, salinity, turbulence, turbidity, migratory environment and migration window. Based on our research, we are convinced that an effective FMR that satisfies all these conditions for all target species can be realised. For those conditions with conflicting differences in the needs of the target species (turbulence, turbidity, and migratory environment) solutions can be found by making use of spatial heterogeneous elements. The use of multiple streams with different dimensions, flow velocities, substrate materials and environmental elements will be elaborated on in the recommendations.

As the target species have a historical presence in the Haringvliet, and are considered a priority by several conservation management plans, creating an FMR based on their respective ecological requirements has the potential to contribute to effective nature restoration within the Delta21 project.

7 Consult

As mentioned in the conclusion, we are convinced that an FMR can facilitate the migration of all five target species to the Haringvliet. However, this is only possible if several aspects are carefully considered and implemented. In the following section we will present our recommendations to the commissioners of Delta21.

7.1 Ecological recommendations

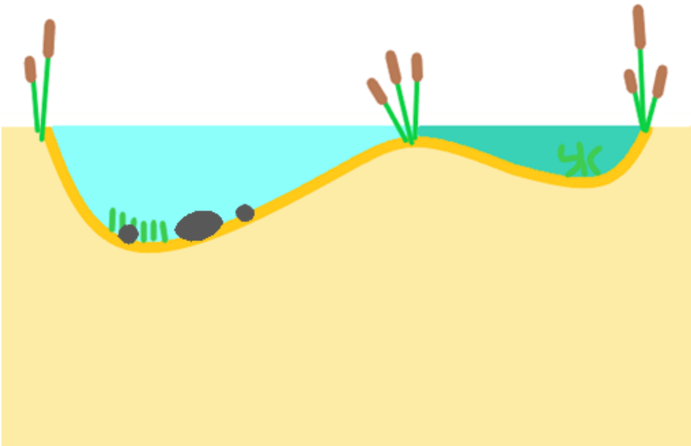
Based on the needs of all five target species, we have made recommendations for the optimization of the ecological conditions of the FMR. A summary of our recommendations can be found in Table 11.

Table 11: Summary of our recommendations for the ecological conditions, based on the needs of the target species. In the case of conflicting requirements between species, this is indicated by a "yes" in the second column. An extensive version of the table can be found in Appendix B.

	Conflict?	Recommendation
Water temperature	*no*	Keep the FMR open throughout the year, to allow all fish to migrate in water within their optimal temperature range.
Critical water velocity	*no*	Keep the critical water velocity below 0.4 m/s at the entrance of the river to ensure active swimmers can enter. Maintain a preferred maximum flow velocity of 0.2 m/s in the entire river, to ensure flounder can migrate.
Salinity	*no*	Create a salinity transition that is as gradual as possible to let species acclimatize.
Turbulence	*yes*	Include differently sized or shaped gullies with different turbulence and flow velocities. Be wary of turbulence near sudden changes in river cross-section (tunnel through dam, gates at beginning/end FMR).
Turbidity	*yes*	Design a river with extensive banks or multiple streams, where low and high turbid conditions can prevail. Create at least one non-turbid route to facilitate flounder migration.
Light	*no*	Prevent significant light pollution at night by traffic lights and other sources of artificial light. Keep the FMR open throughout the day.
Migratory environment	*yes*	Create resting and hiding spaces in a spatially heterogeneous environment, with a.o. different sized rocks, vegetation, and flat areas with sandy or muddy soils.

For four of the studied ecological conditions, there is a clear direction to take in the planning of the FMR. To ensure fish can migrate when the water temperature and light conditions are as they prefer, the FMR should remain open at all times. Light pollution at night should be minimized and a transition from fresh to salt conditions should be kept as gradual as possible. The critical water velocity at the entrance of the river during maximum ebb flows should stay below 0.4 m/s, while the maximum flow velocity in other parts of the river is recommended to stay below 0.2 m/s. The velocity at the entrance is allowed to be slightly higher due to the inevitable funnel effect that will occur at that location.

Regarding turbulence, turbidity and migratory environment, there were some opposing needs between target species. To avoid making hard choices that prevent species from using the FMR, we recommend designing an FMR with spatially heterogeneous conditions. One option for this is to create multiple streams: one turbulent stream with a high flow velocity and one stream with smooth, slow moving water. These streams could follow their own course entirely or intersect at a number of places. Another option is to create one stream that is subdivided into channels with different depths (Figure 8). These parallel running channels can overflow and be connected to each other by a greater or lesser extent. Regardless of the specifics mentioned above, we suggest creating a river where a non-uniform flow occurs, meaning different flow velocities at different locations in the river. To accommodate species that prefer turbid conditions, we recommend including river parts that have little stabilizing vegetation and a riverbed consisting of loose sediment. Finally, variation in the depth of the channels is also recommended, since this will offer differences in light conditions and associated plant and algae species.



Finally, we suggest an FMR with spatially diverse habitat conditions. Parts of the FMR should have rocks, overhanging boulders, roots, crevices etc. that can function as hiding spots. In addition, there should be different types of vegetation growing, in a soft soil where the European eel can burrow in. At fast flowing areas, attachment sites (like rocks) are recommended, to meet the needs of the river lamprey. Other areas should have a flat and bare surface to accommodate for the flounder's needs.

7.2 Location specific recommendations

Further research into the role of the Voordelta brackish water area is strongly advised. This would clarify the extent to which habitat creation through estuarine sections in the FMR is a necessity and how long the FMR should be to bridge the complete salt transition. Extensive flow simulation should conclude whether the FMR in the Haringvliet could indeed be reduced in length when compared to the Afsluitdijk example.

The entrance of the FMR should also be placed in such a manner that fish are able to locate it as easily as possible. It is recommended to place the entrance close to the sluices, as the combined release of freshwater could create one large attraction flow. This would improve the locatability of the seaside entrance. Preferably, the discharge through the FMR should be as large as possible to create an attraction flow which maximizes the number of attracted diadromous fish species.

Location wise we recommend that further investigation towards the possibility of constructing an FMR through the Zuiderdiep is carried out. Besides the Zuiderdiep, the southern shore has an extended sandbank that shelters a brackish water zone behind it. The southern side of the Haringvliet therefore seems promising as a location for the FMR due to its current topology.

7.3 Recommendations for monitoring and maintenance

Since the FMR will be situated in a greatly dynamic environment a maintenance plan needs to be made in order for the FMR to keep its desired function in the future. In terms of maintenance we advise to make the FMR design as low maintenance as possible. Aspects that need to be considered in the maintenance plan in any case are the waterflow, sedimentation and materials used (Banning et al., 2018).

We suggest monitoring the passage efficiency, attraction efficiency, habitat use and use of the acclimatization zone for transition from and to freshwater within the FMR. With these data the effects of the FMR can be made clear and need for adjustment can be made apparent.

8 Discussion

Our report findings have shown that an FMR has great potential to facilitate fish migration for the selected target species when all ecological conditions are met. It should however be noted that as an FMR is a relatively new concept, with the first FMR being realized at the Afsluitdijk in a few years (De Afsluitdijk, n.d.), the knowledge available on the exact effects an FMR has on fish migration is limited to theory. Moreover, the concept of an FMR lies within a broader societal context, which should be considered seriously before the idea is brought to the implementation stage. In this section we will elaborate on these considerations and give advice on further research.

During the examination of the current ecological situation in the Delta21 project area, limited sources were available on the presence of fish species. Data from the NDFF (2021) was used to assess the presence of fish populations in the Haringvliet. However, the most recent monitoring of the effect of the Kierbesluit on fish populations and migration are not published yet and are therefore not included in this research. This made it difficult to evaluate what impact the Kierbesluit has had on fish migration and populations. Adding to this argument, more elaborate information on the limitations of the current Kierbesluit would be very valuable as the FMR might be able to overcome these shortcomings.

Furthermore, at the time of writing, information is incomplete for some life stages of several target species. Important missing information is the salinity requirements for the river lamprey, the tolerance to turbulence for adult salmon and the critical water velocity for the river lamprey and flounder. If this data is acquired it would be a useful addition to our findings and give a more elaborate overview of the ecological conditions that have to be met to facilitate fish migration.

Due to the project time-frame we limited our target species to identify the ecological conditions to only five species based on the predefined criteria. However, to ensure that all desired species would be able to pass the FMR it would be wise to extend the list of target species to incorporate additional diadromous species when more extensive assessments will be executed in the future.

Because the FMR will have an impact in an area where many stakeholders are involved, it would be useful to further examine the viewpoints of these stakeholders with regards to an FMR through the Haringvlietdam. For example, concerns were raised during the expert interview about the effect of the construction of the FMR on the current ecological situation in the Delta21 area (K. Workel, personal communication, April 19, 2021). Additionally, it would be good to identify the potential impact on the surrounding Natura2000 areas, drinking water provisioning for surrounding municipalities and freshwater security for the agricultural sector by involving the associated stakeholders. This way, a design that is most desirable for all parties can be devised.

Although the actual design of the FMR does not fall within the scope of this report, a few considerations should be noted when the project gets to the design stage. To determine the size and outlook of the different components of the FMR, it would be useful to use simulations based on the fish species' characteristics regarding features like water velocity, salinity gradient, attraction flow and the size of the river. Similar simulations have been performed to determine these features for the FMR through the Afsluitdijk (van Banning, 2018). Moreover, further research should be conducted in order to determine to what extent the current unstable brackish conditions in the Voordelta accommodate salinity acclimatization. From this, a decision could be made on the inclusion of a seaside estuary.

The construction of an FMR is a possible solution for the aim of Delta21 of restoring fish migration to the Haringvliet. However, it would only provide a passage between the North sea and the Haringvliet, and does not guarantee any successful survival once the fish have migrated. Examining the ecological suitability of the hinterland of the Haringvliet is very important when the aim is to actually restore the populations of these migratory species. When the entire area used by the target species in their life cycle is accounted for, the FMR could provide a contribution in connecting different locations and thereby making a valuable contribution to restoring fish stocks of our target species.

9 References

Aas, Ø., Klemetsen, A., Einum, S., & Skurdal, J. (2010). *Atlantic Salmon Ecology*. Wiley.

Agostinho, A. A., Agostinho, C. S., Pelicice, F. M., & Marques, E. E. (2012). Fish ladders: safe fish passage or hotspot for predation?. *Neotropical Ichthyology*, *10*(4), 687-696.

Aprahamian, M. W. (1985). The effect of the migration of Alosa fallax fallax (Laécpède) into fresh water, on branchial and gut parasites. *Journal of Fish Biology*, *27*(5), 521-532.

Aprahamian, M.W., C.D. Aprahamian, J.L. Baglini.re, M.R. Sabati., P. Alexandrino (2003). Alosa alosa and Alosa fallax spp. Literature review and Bibliography. Environment Agency R&D Technical report W1- 014/TR

Armstrong JD, Kemp PS, Kennedy GJA, Ladle M, Milner NJ. (2003). Habitat requirements of Atlantic salmon and brown trout in rivers and streams. Fish Res. 62(2):143–170

Arneth, A., Shin, Y. J., Leadley, P., Rondinini, C., Bukvareva, E., Kolb, M., ... & Saito, O. (2020). Post-2020 biodiversity targets need to embrace climate change. *Proceedings of the National Academy of Sciences*, *117*(49), 30882-30891.).

Attrill, M. J. (Ed.). (1998). *A rehabilitated estuarine ecosystem: The environment and ecology of the Thames estuary*. Springer Science & Business Media.

Baan, P. J. A. (1987). Research on Polluted Sediment. In *Environmental Technology* (pp. 568-576). Springer, Dordrecht.

Baas, V., Clabbers, N., Moens, J., Schuurke, E., Spierings, J., Termaat, E., & Wolma, A. (2020). *Opening of the Haringvliet, a stream of possibilities*. https://www.delta21.nl/wp-content/uploads/2020/12/GWF-Final-Consultancy-Report.pdf

Beaumont, W. R. C., & Mann, R. H. K. (1984). The age, growth and diet of a freshwater population of the flounder, Platichthys flesus (L.), in southern England. *Journal of Fish Biology*, *25*(5), 607–616. https://doi.org/10.1111/j.1095-8649.1984.tb04907.x

Blaber, S. J. M., & Blaber, T. G. (1980). Factors affecting the distribution of juvenile estuarine and inshore fish. *Journal of fish biology*, *17*(2), 143-162.

Bregnballe, F. (1961). Plaice and flounder as consumers of the microscopic bottom fauna. CA Reitzels Forlag.

British seafishing (n.d.) Allis and Twaite Shad. Retrieved 2021. From https://britishseafishing.co.uk/shad

Bruijs, M. C. M., & Durif, C. M. F. (2009). Silver Eel Migration and Behaviour. *Spawning Migration of the European Eel*, 65–95. https://doi.org/10.1007/978-1-4020-9095-0_4

Calles, O., Griffioen, B., Winter, E., Watz, J., Nyqvist, D., Hagelin, A., ... & Bergman, E. (2014). Fish Migration River Monitoring Plan.

Castro, J. (1995). *Effects of sediment on the aquatic environment: potential NRCS actions to improve aquatic habitat* (No. 6). US Department of Agriculture, Soil Conservation Service.

CBS, PBL, RIVM, WUR (2013). Achteruitgang paling (glasaal) (indicator 1227, versie 05 , 6 februari 2013). www.clo.nl. Centraal Bureau voor de Statistiek (CBS), Den Haag; PBL Planbureau voor de Leefomgeving, Den Haag; RIVM Rijksinstituut voor Volksgezondheid en Milieu, Bilthoven; en Wageningen University and Research, Wageningen.

EC. (2007). No. 1100/2007 of 18 September 2007 establishing measures for the recovery of the stock of European eel. *Official Journal of the European Union L*, *248*(22.29).

De Afsluitdijk (n.d.) Vismigratierivier officieel van start | de afsluitdijk. Retrieved 2021, From https://deafsluitdijk.nl/nieuws/officiele-start-vismigratierivier/

De Boer, W. F. (2001). *Verbetering van vismigratie door de Afsluitdijk; wat wil de vis?*. Unknown Publisher.

De Groot, S. J. (2002). A review of the past and present status of anadromous fish species in the Netherlands: is restocking the Rhine feasible?. *Ecological Restoration of Aquatic and Semi-Aquatic Ecosystems in the Netherlands (NW Europe)*, 205-218.

Deelder, C.L. (1984). Synopsis of biological data on the eel Anguilla anguilla (Linnaeus, 1758). Food and Agriculture Organization of the United Nations, Fisheries Synopsis No. 80, Revision 1.

Dekker, W. en J. van Willigen (1997). Hoeveel glasaal trekt het IJsselmeer in? - verslag van een merkproef met glasaal te Den Oever in 1997 - RIVO rapport nr C062/97.

Dekker, W. J. A. v. W. (2000). De glasaal heeft het tij niet meer mee. RIVO-Nederlands Instituut voor Visserijonderzoek, IJmuiden. RIVO Rapport C055/00., rapport.

Dekker, W., C. Deerenberg, H. Jansen (2008) Duurzaam beheer van de aal in Nederland: onderbouwing van een beheersplan. Wageningen Imares, Rapport C041/08

Delta21, Wageningen University, Brühl, C., Helsen, G., van Kempen, G., Kivits, D., & van Toorn, M. (2020). Connecting Delta21 to its stakeholders: The Haringvliet case (L. Berke & H. Lavooij, Reds.)

Delta21. (2019). DELTA21: Een actualisering van het plan. Retrieved April 20, 2021, From https://www.delta21.nl/wp-content/uploads/2019/09/UPDATE-DELTA21-29-7-2019.pdf.

Delta21. (2021). *Kennisprogramma Zeespiegelstijging*. https://www.delta21.nl/wp-content/uploads/2020/11/01-Kennisp.ZSR-DELTA21.pdf

Docker (editor). (2015). Lampreys: biology, conservation and control. Springer Fish & Fisheries, serie 37, volume 1.

Doherty, D., N. O'Maoil.idigh and T.K. McCarthy. (2004). The biology, ecology and future conservation of twaite shad (Alosa fallax Lac.p.de), allis shad (Alosa alosa L.) and killarney shad (Alosa fallax killarnensis Tate Regan) in Ireland. Biology and environment: Proceedings of the Royal Irish Academy, vol. 104b, no. 3, 93-102 (2004).

Duarte, C. M. (2002). The future of seagrass meadows. *Environmental conservation*, 192-206.

Creemers, R. & Kranenbarg, J (2016) Nieuwe Rode Lijst Vissen laat lichte verbetering voor zoetwatervissen zien. Naturetoday.

Eilanden-Nieuws. (2021, January 25). *Natuurorganisaties gematigd positief over openen Haringvlietsluizen*. https://www.eilandennieuws.nl/nieuws/algemeen/10673/natuurorganisaties-gematigd-positief-over-openen-haringvlietslu

Enders, E. C., Roy, M. L., Ovidio, M., Hallot, É. J., Boyer, C., Petit, F., & Roy, A. G. (2009). Habitat choice by Atlantic salmon parr in relation to turbulence at a reach scale. *North American Journal of Fisheries Management*, *29*(6), 1819-1830.

European commission (n.d.) Oceans and Fisheries. Retrieved 2021. From https://ec.europa.eu/oceans-and-fisheries/index_en

Fishingplanet (n.d.) European Flounder. Retrieved 2021. From https://wiki.fishingplanet.com/European_Flounder

Foulds, W. L., & Lucas, M. C. (2013). Extreme inefficiency of two conventional, technical fishways used by European river lamprey (Lampetra fluviatilis). *Ecological Engineering*, *58*, 423-433.

Friedland, K. D., Shank, B. V., Todd, C. D., McGinnity, P., & Nye, J. A. (2014). Differential response of continental stock complexes of Atlantic salmon (Salmo salar) to the Atlantic Multidecadal Oscillation. *Journal of Marine Systems*, 133, 77–87. https://doi.org/10.1016/j.jmarsys.2013.03.003

Griffioen, A. B., & Winter, H. V. (2017). *Fish migration river monitoring plan: Monitoring program on the effectiveness of the FMR at Kornwerderzand* (No. C012/17A). Wageningen Marine Research.

Griffioen, A. B., H. V. Winter, O. A. van Keeken, C. Chen, B. van Os-Koomen, S. Schönlau en T. Zawadowski (2014). Verspreidingsdynamiek, gedrag en voorkomen van diadrome vis bij Kornwerderzand t.b.v. de VismigratieRivier. IMARES Rapport C083/14, rapport

Gilinsky, E. (1984). The role of fish predation and spatial heterogeneity in determining benthic community structure. *Ecology*, *65*(2), 455-468.

Heck, K.L., and Crowder, L.B. (1991). Habitat structure and predator–prey interactions in vegetated aquatic systems. In Habitat structure: the physical arrangement of objects in space. Edited by S.S. Bell, E.D. McCoy, and H.R. Mushinsky. Chapman and Hall, New York. pp. 282–299

Hoar, W. S. (1988). 4 The physiology of smolting Salmonids. In *Fish physiology* (Vol. 11, pp. 275-343). Academic Press.

IUCN (2021). The IUCN Red list of threatened species. Version 2021.

Jager, Z. (1999a). *Processes of tidal transport and accumulation of larval flounder (Platichthys flesus L.) in the Ems-Dollard nursery* (Doctoral dissertation, Dissertation ISBN 90-9012525-6).

Jager, Z. (1999b). Selective tidal stream transport of flounder larvae (Platichthys flesusL.) in the Dollard (Ems Estuary). *Estuarine, Coastal and Shelf Science*, *49*(3), 347-362.

Kaiser, M. J., Attrill, M. J., Jennings, S., Thomas, D. N., & Barnes, D. K. (2011). *Marine ecology: processes, systems, and impacts*. Oxford University Press.

Kelly, F. L., & King, J. J. (2001). A review of the ecology and distribution of three lamprey species, Lampetra fluviatilis (L.), Lampetra planeri (Bloch) and Petromyzon marinus (L.): a context for conservation and biodiversity considerations in Ireland. In *Biology and environment: proceedings of the royal Irish academy* (pp. 165-185). Royal Irish Academy.

Klein Breteler, J. G. P. (2005). Kennisdocument Europese aal of paling, Anguilla anguilla (Linnaeus, 1758).

Kroon, J. W. (2009). Kennisdocument bot Platichthys flesus (Linnaeus, 1758). Sportvisserij Nederland.

Laak, G. D., Emmerik, W. V., & Moquette, F. D. (2007). *Kennisdocument Atlantische zalm Salmo salar (Linnaeus 1758)* (Vol. 6). Kennisdocument.

Laffaille P, Acou A, Guillouet J, Legault A. Temporal changes in European eel, Anguilla anguilla, stocks in a small catchment after installation of fish passes. Fisheries Management and Ecology. (2005) ;12(2):123-129. ISSN 1365-2400.

Larinier, M., & Marmulla, G. (2004). Fish passes: types, principles and geographical distribution-an overview. In *Proceedings of the second international symposium on the management of large rivers for fisheries* (Vol. 2, pp. 183-206). RAP publication.

Le Pichon, C., Trancart, T., Lambert, P., Daverat, F., & Rochard, E. (2014). Summer habitat use and movements of late juvenile European flounder (Platichthys flesus) in tidal freshwaters: results From an acoustic telemetry study. *Journal of experimental marine biology and ecology*, *461*, 441-448.

Leprieur, F., Olden, J. D., Lek, S., & Brosse, S. (2009). Contrasting patterns and mechanisms of spatial turnover for native and exotic freshwater fish in Europe. *Journal of Biogeography*, *36*(10), 1899-1912.

Leuven, R. S. E. W., Hendriks, A. J., Huijbregts, M. A. J., Lenders, H. J. R., Matthews, J., & Velde, G. V. D. (2011) Differences in sensitivity of native and exotic fish species to changes in river temperature. *Current Zoology*, *57*(6), 852-862.)

Lumen Learning (n.d.). Retrieved 2021. From https://courses.lumenlearning.com/physicalgeology/chapter/13-3-stream-erosion-and-deposition/

Maes, J., Stevens, M., & Breine, J. (2007). Modelling the migration opportunities of diadromous fish species along a gradient of dissolved oxygen concentration in a European tidal watershed. *Estuarine, Coastal and Shelf Science*, *75*(1-2), 151-162.

Maes, J.; Stevens, M.; Breine, J., 2008. Poor water quality constrains the distribution and movements of twaite shad Alosa fallax fallax (Lacépède, 1803) in the watershed of river Scheldt. Hydrobiologia 602(1): 129-143

Maitland, P. S. (1980). Review of the ecology of lampreys in northern europe. *Canadian Journal of Fisheries and Aquatic Sciences*, *37*(11), 1944–1952. https://doi.org/10.1139/f80-234

Maitland, P.S. & T.W. Hatton-Ellis, 2003. Ecology of the Allis and Twaite Shad. Conserving Natura 2000 Rivers Ecology Series No.3. English Nature, Peterborough.

Manzon, R. G., Youson, J. H., & Holmes, J. A. (2015). Lamprey metamorphosis. *Lampreys: Biology, conservation and control*, 139-214.

Ministerie van Landbouw, Natuur en Voedselkwaliteit a. (n.d.). Haringvliet | natura 2000. Natura2000. Retrieved 22 April 2021, From https://www.natura2000.nl/gebieden/zuid-holland/haringvliet

Ministerie van Landbouw, Natuur en Voedselkwaliteit b. (n.d.) Profielendocument Rivier prik H1099 | Natura 2000.

Natura 2000 (n.d.) Retrieved 26 April 2021, From https://www.natura2000.nl/profielen/h1099-rivierprik

Noordzeeloket (n.d.) Rivierprik. Retrieved 2021. From https://www.noordzeeloket.nl/beleid/noordzee-natura-2000/gebieden/vlakte-raan/vlakte-raan/beschermde-soorten/vissen/rivierprik/

Nyman, L. (1991). Conservation of freshwater fish. Protection of biodiversity and genetic variability in aquatic ecosystems. Fisheries Development Series (Sweden).

Ministerie van Landbouw, Natuur en Voedselkwaliteit c. (n.d.) Voornes Duin | Natura 2000 Natura 2000. Retrieved 2021, From https://www.natura2000.nl/gebieden/zuid-holland/voornes-duin

Ministerie van Landbouw, Natuur en Voedselkwaliteit d. (n.d.). Profielendocument Zalm | Natura 2000. Retrieved 2021, From https://www.natura2000.nl/profielen/h1106-zalm

Ministerie van Landbouw, Natuur en Voedselkwaliteit e. (n.d.). Beschermde Natuur in Nederland: soorten en gebieden in wetgeving en beleid. Retrieved 28 April 2021, From https://minlnv.nederlandsesoorten.nl/soorten

Ministerie van Landbouw, Natuur en Voedselkwaliteit (15 juli 2009): Aalbeheerplan.

Ministerie van Infrastructuur en Waterstaat, (2021). National Deltaprogramme 2021: staying on track in climate-proofing the Netherlands.

Ministerie van Infrastructuur en Waterstaat. (2020a, July 28). *Haringvliet - informatie en waterdata*. Rijkswaterstaat. https://www.rijkswaterstaat.nl/water/vaarwegenoverzicht/haringvliet

Ministerie van Infrastructuur en Waterstaat. (2020b, December 21). *De Deltawerken*. Rijkswaterstaat. https://www.rijkswaterstaat.nl/water/waterbeheer/bescherming-tegen-het-water/waterkeringen/deltawerken#aandacht-voor-ecologisch-herstel-en-waterkwaliteit

Ministerie van Infrastructuur en Waterstaat (n.d.) Trekvissen weten kieropening bij Haringvlietsluizen massaal te vinden | Rijkswaterstaat. Retrieved 2021, From https://www.rijkswaterstaat.nl/nieuws/archief/2020/10/trekvissen-weten-kieropening-bij-haringvlietsluizen-massaal-te-vinden

Muus, B. J. (1967). The fauna of Danish estuaries and lagoons: distribution and ecology of dominating species in the shallow reaches of the mesohaline zone. Høst.

NDFF (2021). NDFF Verspreidingsatlas. 20 november 2015, http://verspreidingsatlas.nl.FLORON (2021).

Neitzel, D. A., Richmond, M. C., Dauble, D. D., Mueller, R. P., Moursund, R. A., Abernethy, C. S., & Guensch, G. R. (2000). *Laboratory studies on the effects of shear on fish* (No. PNNL-13323). Pacific Northwest National Lab.(PNNL), Richland, WA (United States).

NOAA (n.d. a.) Atlantic salmon (protected). Retrieved 2021, From https://www.fisheries.noaa.gov/species/atlantic-salmon-protected

NOAA (n.d. b.). *Section 7 Effect Analysis: Turbidity in the Greater Atlantic Region*. Retrieved 2020, From https://www.fisheries.noaa.gov/new-england-mid-atlantic/consultations/section-7-effect-analysis-turbidity-greater-atlantic-region

NSW (n.d.) Threats to estuaries | NSW Government. Retrieved 2021, From https://www.environment.nsw.gov.au/topics/water/estuaries/about-estuaries/threats-to-estuaries

Nunn, A. D., & Cowx, I. G. (2012). Restoring river connectivity: prioritizing passage improvements for diadromous fishes and lampreys. *Ambio*, *41*(4), 402-409.

Odeh, M., Noreika, J. F., Haro, A., Maynard, A., Castro-Santos, T., & Cada, G. F. (2002). Evaluation of the effects of turbulence on the behavior of migratory fish. *Final Report to the Bonneville Power Administration, Contract*, *22*.

Osenberg, C., Mittelbach, G., Polis, G. A., & Winemiller, K. (1996). Integration of patterns and dynamics.)

Peake, S. (2008). Swimming performance and behaviour of fish species endemic to Newfoundland and Labrador: A literature review for the purpose of establishing design and water velocity criteria for fishways and culverts. In Canadian Manuscript Report of Fisheries and Aquatic.St. John's.

Pereira, E., Cardoso, G. R., Quintella, B. R., Mateus, C. S., Alexandre, C. M., Oliveira, R. L., ... & Almeida, P. R. (2019). Proposals for optimizing sea lamprey passage through a vertical-slot fishway. *Ecohydrology*, *12*(4), e2087.

Pihl, L., (1982): Food intake of young cod and flounder in a shallow bay on the Swedish west coast. Neth. J. Sea Res. 15, 419–432.

Potter, I. C., Hill, B. J., & Gentleman, S. U. S. A. N. (1970). Survival and behaviour of ammocoetes at low oxygen tensions. *Journal of Experimental Biology*, *53*, 59-73.

Quak, J., (2011). Portret van een bizarre vis: Mysterie aal bijna ontrafeld, Visionair 21: 4 – 9.

Reeze, B., Kroes, M., van Emmerik, W. (2017) *Fish flows*: *migratory fish and migration calendar for the Haringvliet and the Voordelta.* Haringvliet Dream Fund Project.

Rijksoverheid *SGBP 2022-2027 (2021) Factsheet KRW - Stroomgebiedbeheerplan.* https://www.waterkwaliteitsportaal.nl/WKP.WebApplication/Beheer/Data/Publiek?viewName=Factsheets&year=2020&month=December

Rijkswaterstaat (n.d.). *Kier Haringvlietsluizen.* Rijkswaterstaat. Retrieved 2021, From https://www.rijkswaterstaat.nl/water/waterbeheer/waterkwaliteit/maatregelen-waterkwaliteit/ruim-baan-voor-vis/kier-haringvlietsluizen.

Rolls, R. J., & Bond, N. R. (2017). Environmental and ecological effects of flow alteration in surface water ecosystems. In Water for the Environment (pp. 65-82). Academic Press.

Russon, I. J., & Kemp, P. S. (2011). Experimental quantification of the swimming performance and behaviour of spawning run river lamprey Lampetra fluviatilis and European eel Anguilla anguilla. *Journal of Fish Biology*, *78*(7), 1965-1975.

Savino, J.F., and Stein, R.A. (1982). Predator–prey interaction between largemouth bass and bluegills as influenced by simulated, submerged vegetation. Trans. Am. Fish. Soc. 111: 255–266.

Schmidt-Luchs C.W. (1977) Visplatenalbum deel 1; Zeevissen. Uitgeverij Beet, Utrecht. spISBN 90-70206-01-3.

Skerritt, D. J. (2010). A review of the European flounder Platichthys flesus–biology, life history and trends in population. Eastern Sea Fisheries Joint Committee Report. Newcastle University.

Sociaal en Cultureel Planbureau. (2020). *Klimaatbeleid en de samenleving*. https://www.scp.nl/binaries/scp/documenten/publicaties/2020/10/12/klimaatbeleid-en-de-samenleving/Klimaatbeleid+en+de+samenleving.pdf

Solomon, D. J., & Beach, M. H. (2004). Fish pass design for eel and elver (Anguilla anguilla). *Environment Agency, Technical Report W2–070/TR1, Bristol, UK*.

Solomon, O. O., & Ahmed, O. O. (2016). European eel: ecology, threats and conservation status. *Journal of Scientific Research and Reports*, 1-13.

Sörensen I (1951) An investigation of some factors affecting the upstream migration of the eel. Inst. Freshwat. Res., Drottningholm, Rep 32, 126-132.

Spalding M, Taylor M, Ravilious C, Short FT, Green F. (2003).Global overview: the distribution and status of seagrasses. InWorld Atlas of Seagrasses, Green EP, Short FT (eds). UNEPWorld Conservation Monitoring Centre, University ofCalifornia Press: Berkeley *Special edition in Croatian: Chapter 04 Volume 005 P. 183 – 189*

Spikmans, F., & Kranenbarg, J. (2016). Nieuwe Rode Lijst vissen Nederland. *RAVON*, *18*(1), 9-12.

Staatsbosbeheer. (2021). *Haringvliet*. https://www.staatsbosbeheer.nl/natuurgebieden/haringvliet

Summers, R. W. (1979). Life cycle and population ecology of the flounder Platichthys flesus (L.) in the Ythan estuary, Scotland. *Journal of Natural History*, *13*(6), 703-723.

Tesch, F. W. (1967). Homing of eels (Anguilla anguilla) in the southern North Sea. *Marine Biology*, *1*(1), 2-9.

Teunissen, H. (2019). *Gebiedsdossier oppervlaktewaterwinning Haringvliet*. https://puc.overheid.nl/PUC/Handlers/DownloadDocument.ashx?identifier=PUC_165557_31&versienummer=1

The Habitats Directive (n.d.) The habitats Directive | European commission. Retrieved 2021, 28 April. From https://ec.europa.eu/environment/nature/legislation/habitatsdirective/index_en.htm

Thorstad, E. B., Økland, F., Aarestrup, K., & Heggberget, T. G. (2007). Factors affecting the within-river spawning migration of Atlantic salmon, with emphasis on human impacts. *Reviews in Fish Biology and Fisheries*, *18*(4), 345–371. https://doi.org/10.1007/s11160-007-9076-4

Knepp, Timothy (n.d.). Atlantic salmon fish. National Digital Library of the United States Fish and Wildlife Service. Retrieved 2021. From https://commons.wikimedia.org/wiki/File:Atlantic_salmon_fish.jpg

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*, 191-198.

Van Banning, G., Van der Baan, J., De Bruijne, W (2018) Vismigratierivier afsluitdijk, Hydraulische en ecologische toetsing van het ontwerp. ARCADIS rapport C03141.000015

Van Calsteren & Stoop (2015). Milieueffectenrapportage Vismigratierivier Afsluitdijk

Van de Wolfshaar, K. E., Griffioen, A. B., Winter, H. V., Tien, N. S. H., Gerla, D., van Keeken, O., & van der Hammen, T. (2018). *Evaluation of the Dutch Eel Management Plan 2018: Status of the eel population in 2005-2016* (No. 18.009). Stichting Wageningen Research, Centrum voor Visserijonderzoek (CVO).

Van Emmerik, W. A. M. (2016). *Biologische factsheets trekvissen Haringvliet en Voordelta*. https://edepot.wur.nl/412453

Van Emmerik, W.A.M. & de Nie, H.W. (2006). De zoetwatervissen van Nederland. Ecologisch bekeken. Sportvisserij Nederland, Bilthoven

Velasco, J., Gutiérrez-Cánovas, C., Botella-Cruz, M., Sánchez-Fernández, D., Arribas, P., Carbonell, J. A., ... & Pallarés, S. (2019). Effects of salinity changes on aquatic organisms in a multiple stressor context. *Philosophical Transactions of the Royal Society B*, *374*(1764), 20180011.

Vethaak, A. D. (2013). Disease prevalence in flounder (Platichthys flesus) From the Dutch Wadden Sea as indicator of environmental quality: a summary of 1988–2005 surveys. *Journal of Sea research*, *82*, 142-152.

Videler, J.J, (1993) Fish Swimming. Chapman en Hall, London, p. 260

Vilas F., Rubio B., Rey D., Bernabeu A.M. (2014) Estuary. In: Encyclopedia of Planetary Landforms. Springer, New York, NY.

VROM (1999). *Stoffen en normen 1999 – Overzicht van belangrijke stoffen en normen in het Milieubeleid.* Alphen aan de Rijn, The Netherlands: Samson, ISBN 90 6092 802 4.

Vinagre, C., Cabral, H., & Costa, M. J. (2008). Prey selection by flounder, Platichthys flesus, in the Douro estuary, Portugal. *Journal of Applied Ichthyology*, *24*(3), 238-243.

Waddenvereniging (n.d.) What does the fish migration river Afsluitdijk stand for? Retrieved 2021, From https://www.waddenvereniging.nl/happyfish/operation

Wilson, J. M., Antunes, J. C., Bouça, P. D., & Coimbra, J. (2004). Osmoregulatory plasticity of the glass eel of Anguilla anguilla: freshwater entry and changes in branchial ion-transport protein expression. *Canadian Journal of Fisheries and Aquatic Sciences*, *61*(3), 432-442.

Winter, H. V., Griffioen, A. B., & Van Keeken, O. A. (2014). *De Vismigratierivier: Bronnenonderzoek naar gedrag van vis rond zoet-zout overgangen* (No. C035/14). IMARES.

Winter, H. V., Mulder, I. M., Griffioen, A. B., van Rijssel, J. C., de Leeuw, J. J., & Tulp, I. Y. M. (2020). *Herstel van vismigratie in het Haringvliet: kennisvragen, monitoring en wetenschappelijk onderzoek* (No. C061/20). Wageningen Marine Research.

Wong, M. K. S., Tsukada, T., Ogawa, N., Pipil, S., Ozaki, H., Suzuki, Y., ... & Takei, Y. (2017). A sodium binding system alleviates acute salt stress during seawater acclimation in eels. *Zoological letters*, *3*(1), 1-20.

WWF (n.d.) Dutch Government must set-up a no-fishing zone in the Haringvliet | WWF Retrieved 2021, From https://wwf.panda.org/wwf_news/?359794/Dutch-Government-must-set-up-a-no-fishing-zone-in-the-Haringvliet

Zanandrea, G. (1957). Neoteny in a lamprey. *Nature*, *179*(4566), 925-926.

Zucchetta, M., Franco, A., Torricelli, P., & Franzoi, P. (2010). Habitat distribution model for European flounder juveniles in the Venice lagoon. *Journal of Sea Research*, *64*(1-2), 133-144.

Ybema, M.S. & J.J.G.M. Backx, (2001). Kansen voor estuariene vissen in het Haringvliet door gewijzigd sluisbeheer : een onderzoek naar de estuariene visstand van het toekomstig Haringvliet door gewijzigd sluisbeheer. Ministerie van Verkeer en Waterstaat, Rijkswaterstaat, Rijksinstituut voor Integraal Zoetwaterbeheer en Afvalwaterbehandeling (RWS, RIZA).

10 Appendix

10.1 Appendix A

Table by Calles et al., 2014 with our target fish species and monitoring techniques that can be used for the evaluation of the FMR. Techniques are rated on suitability for each species and are referred in the table as visual counters (VIS), color marking (COL), external tagging ID-tags (EXT), radio frequency identification (RFId), NEDAP TRAIL System ™ (NEDAP) and hydroacoustic telemetry (AT).

Species	VIS	COL	EXT	RFId	NEDAP	AT
European eel	+	++	++	++	++	++
Juvenile eel		++				
Flounder		++	++	++		+
Flounder larvae		+				
Twaite shad	++	++	+	+	+	+
River lamprey	+	++	++	++	++	++
Atlantic salmon	++	++	++	++	++	++

10.2 Appendix B

Overview of the preferences and needs of the target species (both juvenile and adult stages) for all seven conditions: water temperature, critical water velocity, salinity, turbulence, turbidity, light and migratory environment. Colours have no meaning, other than indicating differences in the needs of target species per ecological condition.

Sources: 1. Van Emmerik, 2016 2. Solomon & Beach, 2004 3. Deelder, 1984 4. Maitland & Hatton-Ellis, 2003 5. Zanandrea, 1957 6. Tesch, 1967 7. Muus et al., 1999 8. Jager, 1999 9. Summers, 1979 10. Aas et al., 2010 11. Winter et al., 2014 12. Maitland, 1980 13. Kelly and King, 2001 14. Trancart et al., 2012 15. Aprahamian, 1985 16. Docker, 2015 17. Pereira et al, 2019 18. Potter, 1970 19. Skerrit, 2010 20. Hoar, 1988 21. Laak et al., 2007 22. Wilson et al., 2004 23. Griffioen & Winter, 2014 24. Winter et al., 2013 25. Vethaak, 2013 26. Enders et al., 2009 27. Russon & Kemp., 2011 28. Aprahamian, 2003 29. Maes et al., 2008 30. Foulds & Lucas, 2013 31. Thorstad et al., 2007 32. NOAA, n.d. 33. Blaber & Blaber, 1980 34. Bruijs & Durif, 2009 35. Schmidt-Luchs, 1977; cited in Kroon, 2009 36. Klein Breteler, 2005 37. Beaumont & Mann, 1984 38. Videler, 1993; cited in De Boer, 2001 39. Peake, 2008; cited in Van Banning et. al., 2018 40. Sorenson 1951; cited in Solomon & Beach, 2004

		Water temperature	Salinity	Turbulence	Turbidity
Atlantic salmon	*juvenile*	Optimal: 14-18; Upper limit between 23 and 26[1]	None[20,21]	Parr salmon tend to prefer less turbulent areas[26]	+ Predator hiding - Reduces ease of route finding; - Reduce oxygen uptake (more sign. for juveniles)[31,32]
S. salar	*adult*	Optimal 18-22; Upper limit; 28[1]		Unknown	
European eel	*juvenile*	Lower limit: 4; Upper limit:18; Optimal 9-11[2]	None[22]	Irrelevant[2]	+ Increases migration window by reducing light[2] + Tends to follow turbulent and turbid routes[27]
A. anguilla	*adult*	Lower limit:9; Optimal 20[3]		Tolerates high turbulence[27]	
Twaite shad	*juvenile*	Most migration when temperature drops below 19[4]	Acclimatization[4]	Prefers laminar smooth flows[28,29]	- With reduced clarity, turns around[4]
A. fallax	*adult*	Optimal; 10-14[15]	Unknown, assumed of low importance	Prefers laminar smooth flows[28]	
River lamprey	*juvenile*	Temperature not main determinant[16]	Unknown, assumed of low importance[24]	Requires low turbulence, in order to attach to rocks and pebbles[30]	- Reduces ease of finding surfaces to stick and rest[30]
L. fluviatilis	*adult*	Optimal 15-19; Upper limit: 28[17,18]			
Flounder	*juvenile*	Temperature not main determinant[19]	Acclimatization[25]	Irrelevant[7,8]	+ Increases prevalence of food sources (esp. for juveniles) + Reduces inter- and intraspecific predation[33]
P. flesus	*adult*				

Recommended choice per ecological condition	No implications for the design of an FMR, besides that the passage needs to remain open over the entire year. This would allow all target species to migrate during the most suitable time and temperature frame.	To allow for successful migration of juvenile twaite shad and flounder, the shift from saline to freshwater should be as gradual as possible.	Different sized and/or shaped gullies and pools where turbulence and flow velocities differ.	FMR with extensive banks or multiple streams, where different turbid conditions can prevail. At least one non-turbid route to facilitate flounder migration.

		Cruising speed (m/s)	Sprinting speed (m/s)	Critical water velocity	Time of day migration (light)
Atlantic salmon	*juvenile*	No upward migration	No upward migration	No upward migration	Night [10]
S. salar	*adult*	1.35 - 2.55 [38]	4.10 - 7.80 [38]	2.0 [1]	Mainly night [10]
European eel	*juvenile*	0.29 - 0.37 [38]	0.84 - 1.07 [38]	0.4 [40]	Unclear, suggests night [2]
A. anguilla	*adult*	No upward migration	No upward migration	No upward migration	Night [2]
Twaite shad	*juvenile*	No upward migration	No upward migration	No upward migration	Daytime [11]
A. fallax	*adult*	0.75 - 1.35 [38]	2.25 - 4.1 [38]	0.5 [39]	
River lamprey	*juvenile*	No upward migration	No upward migration	No upward migration	Night [12]
L. fluviatilis	*adult*	0.87 - 1.11 [38]	2.62 - 3.36 [38]	Unknown	Night [13]
Flounder	*juvenile*	0.17 - 0.27 [38]	0.47 - 0.77 [38]	Unknown	Mainly daytime [14]
P. flesus	*adult*	No upward migration	No upward migration	No upward migration	
Recommended choice per ecological condition		-	-	To ensure all active swimming species can enter the FMR, a maximum water velocity of 0.4 m/s should be maintained at the entrance of the river.	Prevent significant light pollution at night by traffic lights and other sources of artificial light. Keep the FMR open throughout the day.

		Resting conditions	Hiding conditions	Feeding during migration	Migration window
Atlantic salmon	*juvenile*	Deep pools and overhanging boulders; small sediment and vegetation [10]	Crevices in sediment and rocks [10]	Small fish, shrimp and insects; feeding usually takes place in pools [1,10]	Apr-May [down] [1]
S. salar	*adult*	Deep pools and overhanging boulders [10]	Irrelevant [10]	No feeding [10]	All year, mainly June-Aug [up] [1]
European eel	*juvenile*	Soft muddy and sandy soils, water plants and rocks and areas with low water velocity, like pools [2,3]	Soft muddy and sandy soils, water plants, roots and rocks [2,3]	Omnivore, but they feed mostly on bottom-dwelling organisms [36]	Feb-June [up] [2,3]
A . anguilla	*adult*	Unknown	Soft sediment at daytime [34]	No feeding [2]	Aug-Nov [down] [2]
Twaite shad	*juvenile*	Unknown	Unknown	Fine plankton [4]	Aug-Sep [down] [4]
A. fallax	*adult*			No feeding [28]	May-July [up]; Aug-Sep [down] [4]
River lamprey	*juvenile*	Low velocity areas and attachment sites [30]	Unknown	No feeding [16]	Mar-June [down] [5]
L. fluviatilis	*adult*			No feeding [1]	Aug-Oct [up] [6]
Flounder	*juvenile*	Not necessary (use selective tidal transport) [8]	Flat soft benthic surface (sand, clay or silt) [35]	Mainly insects, crustaceans and molluscs [37]	Apr-July [up] [7,8]
P. flesus	*adult*				Nov-Feb [down] [9]
Recommended choice per ecological condition		A spatially diverse migration environment with sufficient areas that are strewn with rocks and areas where there is a flat and bare surface. In addition, there should be different types of vegetation growing and the FMR should have a soft soil in general.		All mentioned groups of feeding organisms can occur together in a brackish water system.	-