The potential influence of the Delta21 plan on the recovery of a tidal ecosystem and fish migration in the Haringvliet

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Illustration cover: Helmer, J. (2016). Unieke proef voor terugkeer verloren mosselbanken en oesterriffen voor ingang Haringvliet. Retrieved April 27, 2020, from https://haringvliet.nu/nieuws/unieke-proef-voor-terugkeer-verloren-mosselbanken-en-oesterriffen-voor-ingang-haringvliet.

Executive Summary

English

In the past the Haringvliet used to be an open estuary connecting the North Sea with the rivers Rhine and Meuse, functioning as an important passage for migratory fish. However, after the construction of the Haringvliet sluices in 1970, migratory fish populations declined significantly. A new plan, called Delta21, designed for ensuring water safety, is also expected to restore the fish migratory route by enabling permanent opening of the Haringvliet sluices. In this consultancy report we present the expected results of the Delta21 plan concerning the restoration of the former brackish ecotopes of the Haringvliet and its corridor function for migratory fish. Atlantic herring (*Clupea harengus*), Atlantic salmon (*Salmo salar*), European eel (*Anguilla anguilla*) and three-spined stickleback (*Gasterosteus aculeatus*) were used as indicator species for different groups of migratory fish. Out of several habitat characteristics on which fish rely during migration, the presence of seagrass is considered most essential. It is used for sheltering by a large array of fish, including juvenile herring and eel. Recovery of two species of seagrass native to the Netherlands, *Zostera marina* and *Zostera noltii*, would require between one and five years, depending on created habitat conditions and activities to kick-start recovery. With the return of tides, resulting from opening the Haringvliet sluices, intertidal and terrestrial brackish ecotopes are expected to complement the current freshwater system behind the Haringvliet sluices. An increase in abundance of diadromous and marine fish is expected in the Haringvliet. Increases in juvenile herring, eel and three-spined stickleback are expected, whereas more difficulties are expected for the return of salmon due to small contemporary population sizes. Recommendations to enhance the recovery of migratory fish populations are provided.

Dutch

In het verleden vormde het Haringvliet een open verbinding tussen de Noordzee en de rivieren Rijn en Maas. Dit estuarium fungeerde als belangrijke doorgang voor migrerende vissen. Echter, na de constructie van de Haringvlietsluizen in 1970 namen populaties van migrerende vissen sterk in omvang af. Een nieuw plan, genaamd Delta21, is op de eerste plaats ontworpen om de waterveiligheid te waarborgen. Tegelijkertijd biedt dit plan ook mogelijkheden voor het herstel van de migratieroute van vissen. In dit adviesrapport presenteren wij de verwachte resultaten van het Delta21 plan betreffende het herstel van het voormalige brakwater ecotoop en bijbehorende corridorfunctie van het Haringvliet voor migrerende vissen. Atlantische haring (*Clupea harengus*), Atlantische zalm (*Salmo salar*), paling (*Anguilla anguilla*) en driedoornige stekelbaars (*Gasterosteus aculeatus*) zijn gebruikt als indicatorsoorten voor verschillende groepen van migrerende vissoorten. De aanwezigheid van zeegras wordt gezien als de meest essentiële habitateigenschap waarvan migrerende vissoorten afhankelijk zijn. Het wordt voornamelijk gebruikt als beschutting door een grote diversiteit aan vissen, waaronder juveniele haring. Tijdsduur van het herstel van de twee inheemse soorten zeegras in Nederland, *Zostera marina* en *Zostera noltii*, varieert tussen één en vijf jaar, afhankelijk van habitatgeschiktheid. Met de terugkeer van de getijden als gevolg van het volledig openstellen van de Haringvlietsluizen wordt ontwikkeling van intergetijdengebieden en terrestrische, brakwater ecotopen verwacht. Deze zullen het huidige zoetwatersysteem achter de Haringvlietsluizen complementeren. Een toename in aantallen diadrome en mariene vissen wordt verwacht in het Haringvliet. Toenamen in juveniele haring, paling en driedoornige stekelbaars wordt verwacht. Terugkeer van zalm lijkt moeilijker te realiseren, aangezien huidige populatiegroottes klein zijn. Aanbevelingen om het herstel van populaties van migrerende vissen te bevorderen worden aangereikt.

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About Team Fish Migration

Figure 1 Our team. From left to right: Jeroen van Wijk, Hugo Beekelaar, Wouter van den Broek, Annamara de Wolf, Wolf van Lier en Wouter Vernooij.

We are a team of six master students from the Wageningen university (Figure 1 Our team. From left to right: Jeroen van Wijk, Hugo Beekelaar, Wouter van den Broek, Annamara de Wolf, Wolf van Lier en Wouter Vernooij.). The different masters that we are currently following are: Earth and Environment, Biology, Forest and Nature Conservation or Aquaculture and Marine Resource Management. Due to our varied field of study we could dive into the Delta21 with multiple perspectives. With our shared interest in ecology and migratory fish we examined the possibilities for the Haringvliet as migratory area and return of several fish species after permanently opening the Haringvliet sluices.

1 Introduction

The Dutch Haringvliet estuary used to be an open estuary connecting the North Sea with the rivers Rhine and Meuse frequented by several marine fish species (Jacobs, 2020) and functioned as an important passage for migratory fish (Quack, 2016) and spawning grounds for marine fish. The salt tide had a reach of about 50 km all the way to the Biesbosch area (Bol & Kraak, 1998a). Diadromous fish were able to freely enter or leave the Rhine and Meuse, with some species going as far upstream as Germany and France (Griffioen & Winter, 2017). Diadromous fish can be categorized as catadromous or anadromous. Catadromous fish are born in salt water, then migrate to and spend most of their life in fresh water and migrate back to salt water to reproduce, a well-known example is the eel. Anadromous fish are born in fresh water, then migrate to and spend most of their life in saltwater and migrate back to freshwater to reproduce, an important representative is the salmon. The situation in the Haringvliet changed after the construction of the Haringvlietdam in 1970 as part of the Dutch Delta Works project. The salt tide disappeared, and the previously brackish mixing zone turned into a freshwater area (Kraaijvanger, 2018). Simultaneously the Haringvliet sluices formed a barrier for fish migration (Smit et al., 1997). This resulted in diadromous fish being unable to migrate from the North Sea into the estuary or the other way around, causing the loss of many diadromous and brackish fish species previously present in the area (Quack, 2016).

In order to take a first step towards a restored fish migration route, in 2018 the decision was made to partly open the sluices in the Haringvliet (known as the Kierbesluit) (Delta21, 2018). The exact effects of this measure are still unclear, but as long as the sluices are still closed most of the time, the system will not be able to develop the characteristics of a tidal area (Griffioen & Winter, 2017). This means that the restoration of a brackish water zone with the corresponding flora and fauna will not take place. Therefore, it is expected to be mostly insufficient for restoring the fish migration, as fish require an area with gradual transition from salt to fresh water in order to successfully migrate (De Laak, 2007 & Hop, 2011). It is because of these reasons that many nature organisations, such as ARK Natuurontwikkeling, WWF and Natuurmonumenten, plead for a permanently open Haringvliet (Delta21, 2019).

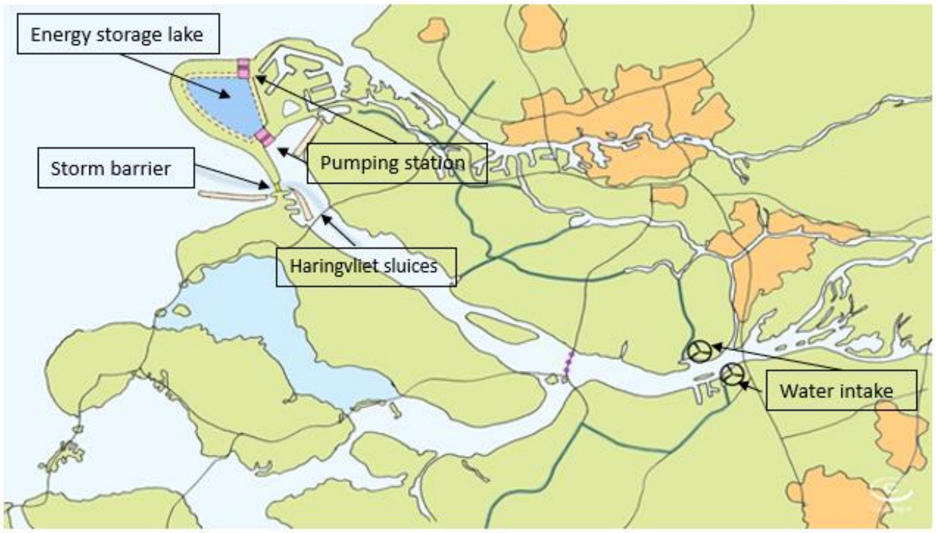

Figure 2 Overview of the Delta21 plan, the energy storage lake is located in sea, the pink squares around the lake are the spill-over and pumping station. In the Hollands Diep two freshwater intakes will be placed, which is shown as turbines in the picture (Delta21, 2019).

The Delta21 plan is a project with the main goal of guaranteeing the water safety in the Netherlands in times of rising water levels, and it includes the additional goals of constructing an energy storage lake and stimulating nature restoration (Delta21, 2019). With the energy storage lake, Delta21 is planning to fill and empty the lake to store surplus of energy (Figure 2). In order to achieve this nature restoration, the plan proposes to permanently open the Haringvliet sluices. This will allow the salt tide to return in the area, which should enable fish migration and brackish habitat restoration.

Several options for restoring the fish migration in the Haringvliet in combination with the Delta21 plan have already been studied (Delta21, 2018 & Van Zwieten et al., 2019). These approaches are based on a compartmentalisation of water systems near the island Tiengemeten to secure freshwater availability for the surrounding area. However, after meeting and discussing with various stakeholders, the original Delta21 plan was updated to a plan with a permanently connected waterflow between the North Sea and the rivers Rhine and Meuse (Delta21, 2019). It is expected that the inflow of saltwater will reach as far as the Biesbosch, causing changes in the physical and chemical characteristics of the waterflows, such as stream velocity and salinity (Delta21, 2019).

However, as fish migration depends on many different factors, it is still uncertain whether the Delta21 plan will have the desired outcome. Allowing fish to enter and leave the Haringvliet is one thing, but fish also require proper conditions to successfully survive and migrate further such as sheltering options, sufficient food sources, and a salinity gradient for physiological acclimatization (Hartgers et al., 2001). Furthermore, there may be species specific requirements for their use of the Haringvliet.

In this report the implications of opening the Haringvliet are reviewed and discussed. The objective is to evaluate how the conditions in the area will change and what the opportunities are for the fish migration, based on an analysis of the consequences for a selection of 'indicator species' with characteristic traits. An estimation will be made of the time it will take before the conditions are suitable, as well as what abundance of different fish species can be expected, with a focus on the indicator species.

2 Scenario description

2.1 Methods

In this report we will first analyse the expected hydro-morphological developments in the Haringvliet following two scenarios i.e. Kierbesluit and fully opening the Haringvliet. These two scenarios are the current and alternative situation in the Haringvliet following the Delta21 plan. Because seagrass is an extremely important parameter to support fish that return in the Haringvliet, extra attention is paid to opportunities for rehabilitation of seagrass fields. Lastly, the influence of the scenarios and the presence of seagrass on species diversity and abundancy is described. Because it would take too much time to consider every species that currently is or could in the future be present in the Haringvliet, a selection was made of four fish species (the indicator species) that are important to the Haringvliet and that are representative of other similar fish species. First an analysis on the characteristics of these species is given. The possibilities for migration and habitat use of these species are discussed based on these analyses. The assumption is made that if these species could successfully make use of the Haringvliet, other similar species that show similarities in their life history traits should be able to do so as well. The recovery of the selected species indicates that an environment has developed that fulfils the habitat requirements and corridor functions. The results were obtained by a literature study and conversations with experts i.e. Tinka Murk (researcher of the WUR, specialised in marine animal biology), Pieter Beeldman (Rijkswaterstaat, project manager of the Kierbesluit) and Reindert Nijland (researcher of the WUR, specialised in DNA analysis of marine systems).

2.2 Kierbesluit and Delta21 situation

The first situation that we will discuss is the Kierbesluit, which is the current situation in the Haringvliet. The main criterium for the current policy concerning the frequent closure of the Haringvliet sluices is that no salt water can reach the freshwater inlet of the Spui (Rijkswaterstaat, 2019). This policy was implemented in order to maintain freshwater availability for the surrounding civilization. The maximum amount of the chloride level is 300 mg Cl/l at the location indicated by the red dotted line in Figure 3. As a result of this standard, the Haringvliet sluices are only partly and temporarily opened resulting in a mostly freshwater environment (Rijkswaterstaat Waterinfo, n.d.).

Figure 3 The Haringvliet sluices are marked in orange to indicate that the sluices are partly and temporarily opened. The red dotted line indicates to where the 300 mg Cl/L border may reach before closing the sluices.

The second situation that was analysed is the Delta21 plan, which includes fully opening of the Haringvliet sluices for most of the time (Figure 4 Energy storage Lake and entrance of the Haringvliet A) The situation with a fully opened Haringvliet, the blue arrows indicate where the water can flow under influence of the tides. B) The situation where the storm barrier is closed (indicated in red). The blue arrows indicate how the water can be pumped from the Haringvliet to the energy lake and if necessary, to the sea. C) To prevent salt/brackish water from reaching too far inland during low river levels the Haringvliet sluices can be closed (marked in red). During these periods, water is still able to flow through the tidal lake (indicated with blue arrows). A). This means that the Haringvliet is exposed to inflow of salt/brackish water unless during extreme high tides the water safety is threatened and the storm barrier will be closed (Figure 4 Energy storage Lake and entrance of the Haringvliet A) The situation with a fully opened Haringvliet, the blue arrows indicate where the water can flow under influence of the tides. B) The situation where the storm barrier is closed (indicated in red). The blue arrows indicate how the water can be pumped from the Haringvliet to the energy lake and if necessary, to the sea. C) To prevent salt/brackish water from reaching too far inland during low river levels the Haringvliet sluices can be closed (marked in red). During these periods, water is still able to flow through the tidal lake (indicated with blue arrows). B). While the storm barriers are closed, fresh water will be pumped through the energy storage lake. Also, if Rhine discharge at Lobith drops below 1000 m3/s, as has happened in the dry summers of 2018 and 2019, the sluices will be closed as well (Figure 4 Energy storage Lake and entrance of the Haringvliet A) The situation with a fully opened Haringvliet, the blue arrows indicate where the water can flow under influence of the tides. B) The situation where the storm barrier is closed (indicated in red). The blue arrows indicate how the water can be pumped from the Haringvliet to the energy lake and if necessary, to the sea. C) To prevent salt/brackish water from reaching too far inland during low river levels the Haringvliet sluices can be closed (marked in red). During these periods, water is still able to flow through the tidal lake (indicated with blue arrows). C) to prevent saltwater to reach to far inland. As a result, the Haringvliet sluices could be closed for long periods when summers are extremely dry. This is based on the scenario "Stormvloedkering" from Wijsman et al. (2018) (see Appendix Figure 17).

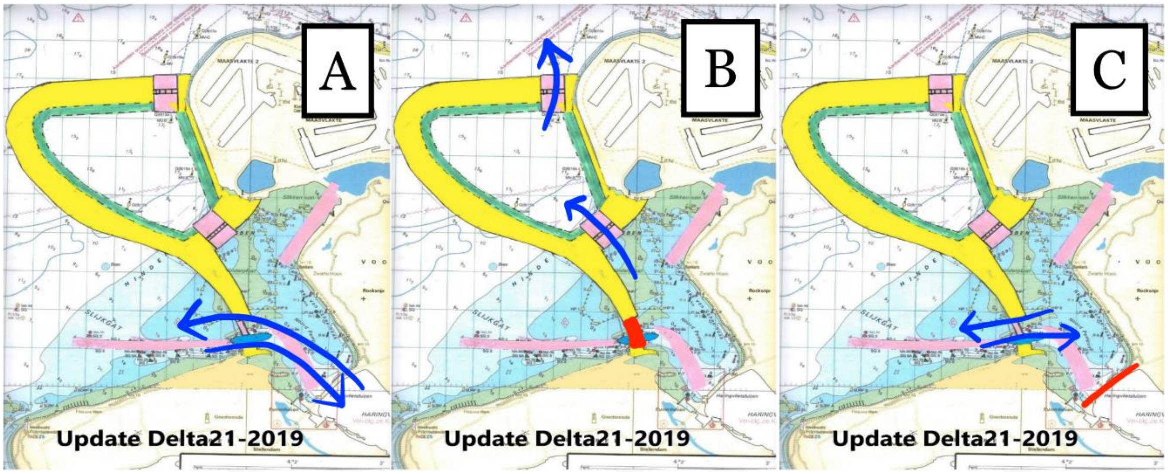

Figure 4 Energy storage Lake and entrance of the Haringvliet A) The situation with a fully opened Haringvliet, the blue arrows indicate where the water can flow under influence of the tides. B) The situation where the storm barrier is closed (indicated in red). The blue arrows indicate how the water can be pumped from the Haringvliet to the energy lake and if necessary, to the sea. C) To prevent salt/brackish water from reaching too far inland during low river levels the Haringvliet sluices can be closed (marked in red). During these periods, water is still able to flow through the tidal lake (indicated with blue arrows).

2.3 Selection of indicator species

The first indicator species that was analysed is the Atlantic herring (*Clupea harengus*) (Figure 5). This species was selected because of its historical importance to the Haringvliet, which was originally named after the Dutch word for herring (i.e. "haring"), and as a representative for fish species that occur as marine juveniles in the Haringvliet. Herring is a species that migrates between the estuary and the sea, as larvae migrate to a brackish estuary after hatching, and its presence is thus dependent on an open Haringvliet. Herring also used to be a keystone species in the Haringvliet, meaning that they were an essential part of the food chain and their presence could therefore be important to stimulate more biodiversity (Quack, 2016).

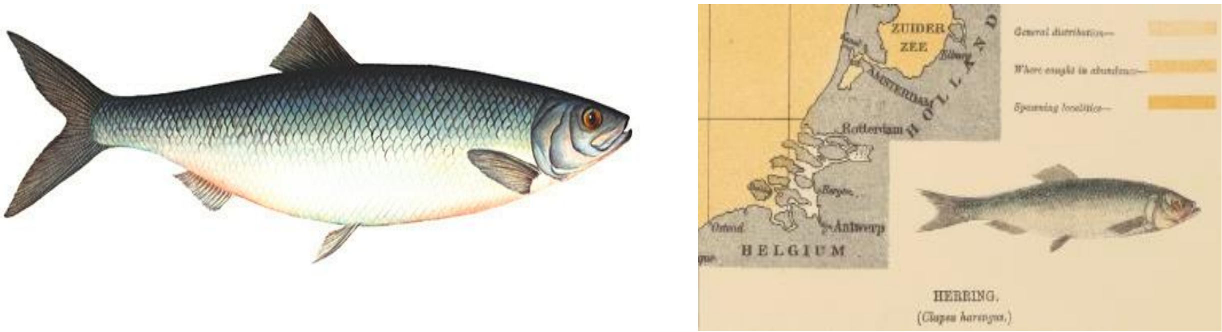

Figure 5 a) The Atlantic herring (Clupea harengus) retrieved from https://thisfish.info/fishery/species/atlantic-herring/ and b) its distribution and abundance around the Haringvliet in 1883 retrieved from http://bigthink.com/strange-maps/piscatorial-atlas.

The second indicator species that was analysed is the Atlantic salmon (*Salmo salar*) (Figure 6 The Atlantic salmon (Salmo salar), retrieved from https://favpng.com/png_view/fish-chinook-salmon-pink-salmon-sockeye-salmon-chum-salmon-png/w8qjsY7X). This species is an anadromous species with a long migration route and could therefore be representative for other species such as seatrout, which has an almost identical life cycle (Hop, 2011). What also distinguishes the salmon from our other indicator species is that they have a short duration time in the Haringvliet as they acclimate extremely quickly to the difference in salinity. It is also an extremely strong swimmer.

Figure 6 The Atlantic salmon (Salmo salar), retrieved from https://favpng.com/png_view/fish-chinook-salmon-pink-salmon-sockeye-salmon-chum-salmon-png/w8qjsY7X

The third indicator species that was analysed is the European eel (*Anguilla anguilla*) (Figure 7). This species can migrate over long distances, just as the Atlantic Salmon (Hop, 2011). European eel was selected as representative for catadromous fish species, i.e. fish species that spend most of their life in fresh water and migrate to the sea to spawn. European eels used to be common in the Netherlands and Haringvliet, but over the years stocks have declined by up to 95%. Nowadays, the species is categorised as critically endangered on the IUCN Red List (Jacoby & Gollock, 2014).

Figure 7 a) The European eel (Anguilla anguilla), retrieved from https://www.pngfuel.com/free-png/rozwx and b) its distribution and abundance around the Haringvliet in 1883, retrieved from http://www.vliz.be/wetenschatten/beeldbank.php?album=2397&pic=16500

The last indicator species that was analysed is the Three-spined stickleback (*Gasterosteus aculeatus*) (Figure 8). This species was selected because it represents stationary (i.e. non migratory) fish. If it turns out that the current stickleback population can still successfully survive once the Haringvliet opens, it can be assumed that other, already present stationary salt and brackish fish species are likely to remain as well. Furthermore, as adult three-spined sticklebacks are relatively weak swimmers (Van Emmerik, 2016), they also represent other slow-swimming species.

Figure 8 The Three-spined stickleback (Gasterosteus aculeatus) retrieved from http://jan.ucc.nau.edu/lrm22/macphee/stickleback/stickleback.htm

3 Analysis of Delta21 plan

3.1 Current conditions

According to the classifications by the Kaderrichtlijn Water (KRW), the water type of a closed Haringvliet is R8 (fresh tidal water with sand/clay). It is expected that the water type will change to O2 (estuary with mediocre tidal range) after the Kierbesluit (Noordhuis, 2017). Turbidity is expected to increase as a result of sediment resuspension and flocculation. In terms of flow velocities, no significant changes are expected. Around the sluices the flow velocities will reach a few meters per second, dependent on how much the sluices are opened (Noordhuis, 2017). Vegetation cover in the Haringvliet and Holland's Diep has recently been improved by planting fish forests. These should make the area more suitable for fish to spawn and find shelter (Rijkswaterstaat, 2019).

3.2 Altering environmental conditions

3.2.1 Morphological change

In a natural estuary there is a relationship between the tidal prism and the cross section of the inlet. When the tidal prism decreases, the cross section of the estuary tends to decrease as well. In 1969 O'Brien composed an empirical relationship between the tidal volume and the cross section of the inlet (O'Brien, 1969) (Equation 1).

Equation 1 The relationship between the tidal prism and the cross section of the inlet, where A is the cross section of the inlet and P is the spring tidal prism.

$$A = 4.69 * 10^{-4} * P^{0.85}$$

The construction of the sluices in the Haringvliet have caused a large decrease in tidal prism which is changing the estuarine morphodynamics. Since the sluices were built, the tidal volume almost disappeared and the gullies in the estuary tend to become shallower. The sand that fills up the gullies originates from the surrounding sandbanks and shores (Wijsman et al., 2018).

In an equilibrium the forces for sedimentation and erosion of sandbanks balance each other out. Erosion is mainly caused by waves that hit the sandbanks and shores and take some of the sediment away. Formation of these sandbanks mainly occurs by sedimentation due to tidal flow. In the current situation the forces for sedimentation are very small, whereas the forces to erode the shores are preserved. In addition, if the tidal range decreases, the wave energy that hits the shores will be concentrated on one spot, increasing the erosion (Figure 9, De Vet et al., 2017).

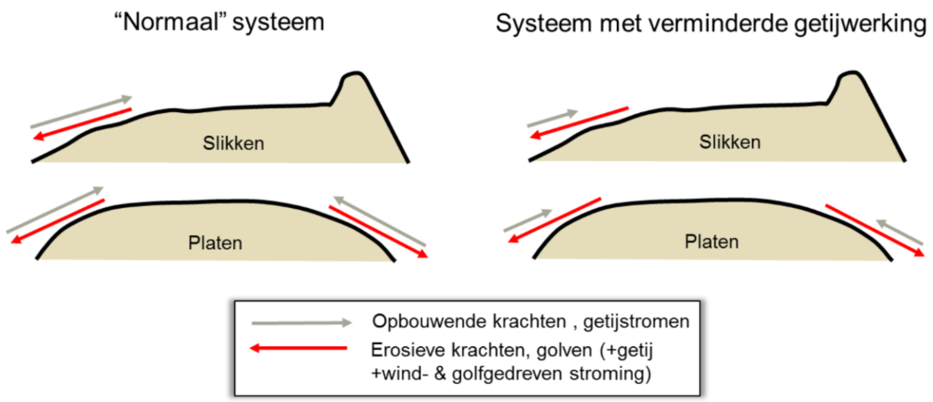

Figure 9 The two figures on the left display the erosive and formative forces of a natural situation which would occur when the Haringvliet sluices are fully opened. In the right two figures, a situation is displayed with a reduced tidal prism and formative forces (Wijsman et al., 2018).

Fully opening the Haringvliet sluices would shift the system closer to its natural tidal volume, which could result in decreased erosion of the sandbanks and shores. In case of fully opening the Haringvliet sluices, the tidal prism is expected to increase from 11,000 km^3 to 170,000 km^3 at the Haringvliet sluices (Baptist et al., 2007).

However, the tidal volume is still smaller than it was, and the equilibrium has not been fully reached (Wijsman et al., 2018). In the Delta21 plan the tidal prism will probably be even smaller since more constructions will be built in the inlet area.

3.2.2 Ecotopes

With the returning tide the morphology of the Haringvliet will be influenced again by tidal changes and higher and/or lower discharge. The sedimentation and erosion in the Haringvliet will change, which can cause new ecotopes to develop in the Haringvliet. An ecotope is an area or environment in which a community lives, this covers for example a zoobenthos community with fish and birds (De Jong, 1999). Ecotopes are dependent on a lot of abiotic parameters, e.g. water depth, flow velocity, salinity, soil composition etc. In the report by Wijsman et al. (2018) fourteen different ecotopes are defined (see Appendix Figure 18 Different ecotopes in the Haringvliet for different scenarios as mentioned in Wijsman et al. (2018)), from which a few are terrestrial ecotopes, a few are sublittoral and a few are intertidal areas. Birds and mammals can profit most from the terrestrial and intertidal areas. However, in this report the focus is on sublittoral and intertidal ecotopes in relation to fish species. Next to that the ecotopes are divided in fresh or brackish water, see

Table 1. The salt gradients are important for migrating fish species (Wijsman et al., 2018). With the current situation of the Kierbesluit, the salt gradient will be minimal, and a brackish water system will not be able to establish. Former salt gradients are shown in Figure 10 Isohalines of chlorinity in the south-western part of the Netherlands before the Delta Works in the period 1953-1963 from Peelen (1967).. In the scenario of the Delta21 plan (comparable to the Stormvloedkering scenario), the brackish water system will be able to establish which will be beneficial for migrating fish species, as will be explained in 3.3. The current situation is shown in Figure 11, here is shown that the brackish water cannot establish and that only close to the Haringvliet sluices the water can be brackish. For the future Delta 21 plan one needs to consider that in the Voordelta a tidal lake and an energy storage lake will be built and therefore ecotopes can develop differently.

Table 1 Division of salinities (Wijsman et al., 2018)

Zone	Salinity (ppt)	Salinity (g Cl/l)	Classes
Freshwater	< 0.5	< 0.3	Fresh
Oligohaline	0.5 – 5.4	0.3 – 3	Brackish
Mesohaline	5.4 – 18	3 – 10	Brackish
Polyhaline	18 – 30.6	10 – 17	Salt
Euryhaline	> 30.6	> 17	Salt

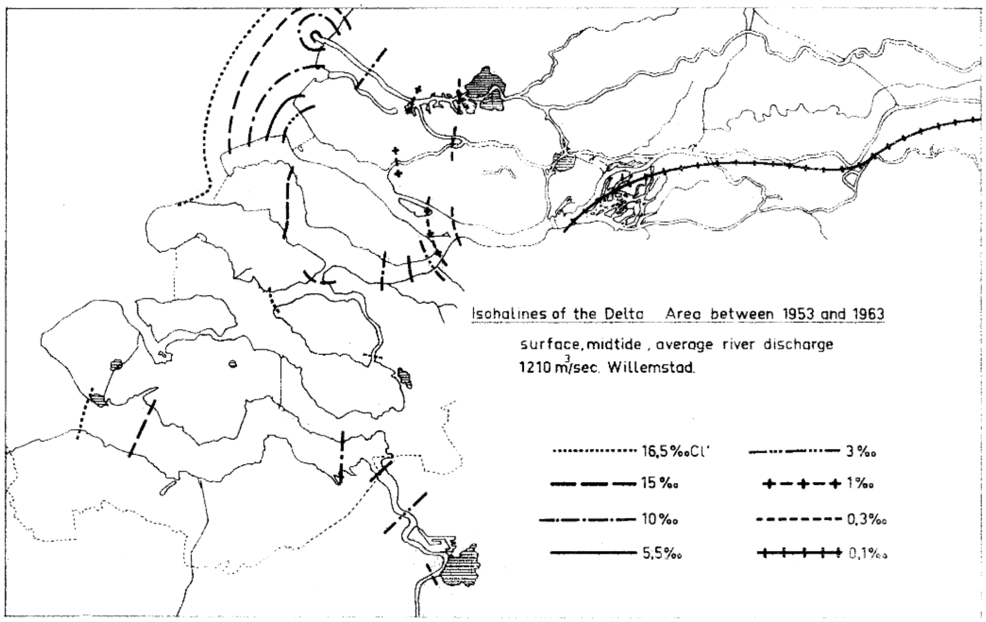

Figure 10 Isohalines of chlorinity in the south-western part of the Netherlands before the Delta Works in the period 1953-1963 from Peelen (1967).

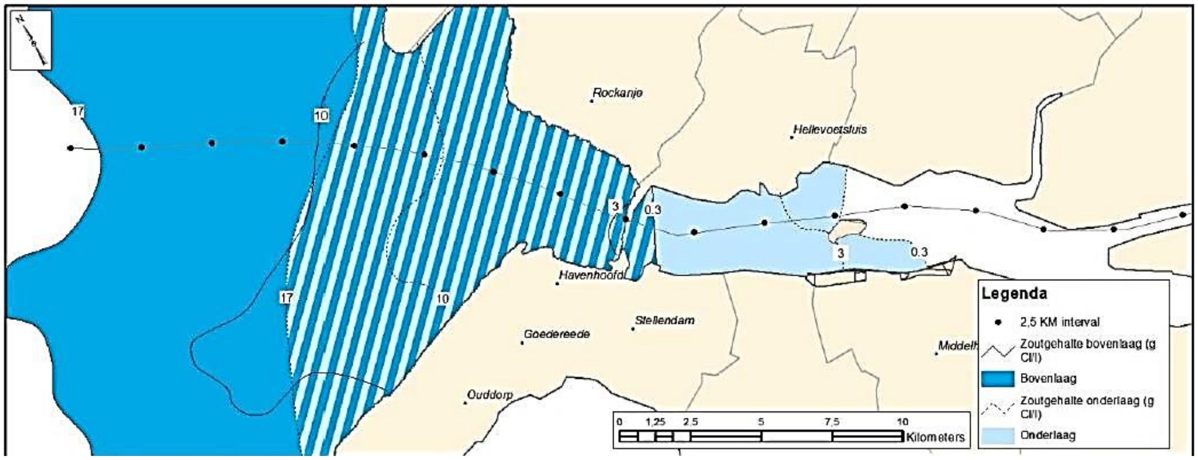

Figure 11 Salinity in the current situation, light blue is the salinity at the bottom layer, dark blue is salinity at the upper layer. In the Haringvliet the salinity is 0.3 g Cl/l and at sea the salinity lies between 3 g Cl/l and 17 g Cl/l, based on Bol and Kraak (1998).

The tide will create intertidal areas in the Haringvliet, during low tide areas in the Haringvliet will be exposed and will be dry, during high tide these areas are wet or flooded. These areas are dependent on the seasonal variation of the river discharge. Therefore, a division is made between summer and winter intertidal areas. Intertidal areas are a possible area for foraging birds, the (brackish) benthic fauna will be exposed and therefore birds can predate on them (Wijsman et al., 2018). This is another benefit for a restored estuary. To specify which areas in the Haringvliet will be influenced by the tide, the small islands "Slijkplaat" and "Ventejagersplaten" will be influenced most by sedimentation and erosion. These two sandbanks will become larger due to the tidal amplitude, so with the Kierbesluit no effect will be measured on these islands. However, with the Delta21 scenario the tide can cause these areas to enlarge, which will increase the terrestrial ecotopes, continuous sedimentation by the tide causes the enlargement of the islands. Next to that, with the scenario "Stormvloedkering" the potential intertidal areas can increase with almost 2000 hectare compared to the scenario Kierbesluit, respectively 8,354 ha compared to 6,513 ha (Wijsman et al., 2018). So, with the Delta21 scenario almost the equal amount of possible intertidal area can be reached as situated in the Stormvloedkering. However, the tidal lake included in the Delta21 plan will probably influence the flow dynamics and the tidal dynamics, but this is a first estimation.

The brackish water ecotopes which will develop, will firstly cause freshwater flora and fauna to decrease or even disappear due to the increased salinity. Instead of these freshwater species, brackish water species will return. The species richness of brackish ecosystems is usually lower (Figure 12 Relative number of species versus the salinity. The left figure shows the cumulative amount of species and the right figure the specific species per salinity. The dotted vertical line gives the fifty percent saltwater and fifty percent freshwater (from Wijsman et al., 2018).), but the density of these species can be larger (Wijsman et al., 2018). Another point which affects the benthic fauna are the deeper holes in the Haringvliet. These holes are probably stratified and can be anaerobic which can cause impoverishment of benthic fauna in these areas (Wijsman et al., 2018). This could have a negative effect on the foraging fishes in these areas and even on the habitat of specific species.

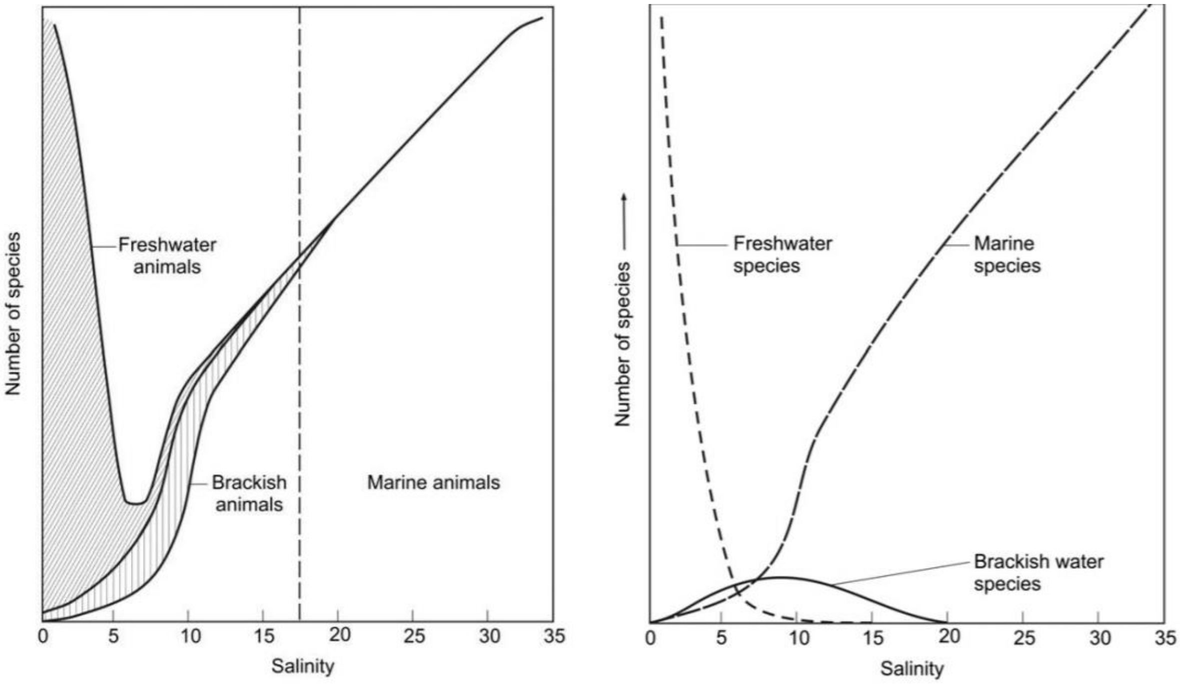

Figure 12 Relative number of species versus the salinity. The left figure shows the cumulative amount of species and the right figure the specific species per salinity. The dotted vertical line gives the fifty percent saltwater and fifty percent freshwater (from Wijsman et al., 2018).

3.2.3 Salt water

In the scenario of fully opening the Haringvliet sluices, tides will come back, and this will possibly drastically influence the morphology. Moreover, when the tide returns to the Haringvliet, mixing of salt and fresh water will take place. Salt water is heavier than fresh water and fresh water tends to float on the salt water. The Estuarine Richardson number is commonly used to indicate if an estuary is well-mixed or stratified in means of mixing of fresh water and salt water. An Estuarine Richardson number smaller than 0.08 indicates a well-mixed system, a value higher than 0.8 indicates a stratified system (I.e. a "zoutwatertong") (List, 1979 & Baptist et al., 2007). The Estuarine Richardson number will be 0.39 (Table 2 Numbers for average discharge and tides in the Haringvliet with the scenario of the Kierbesluit and of open Haringvliet sluices (Baptist et al., 2007).) when the Haringvliet sluices are fully opened, which is most time the case with the Delta21 plan. For the scenario with the Kierbesluit the value of the Estuarine Richardson number is 14.4 (Table 2 Numbers for average discharge and tides in the Haringvliet with the scenario of the Kierbesluit and of open Haringvliet sluices (Baptist et al., 2007).), which indicates stratification (Baptist et al., 2007). Deep holes are present in the bottom of the Haringvliet, which will be filled with salt water. On top of these filled holes fresh water will float. So, with the Kierbesluit one will get saltwater patches instead of a mixed (i.e. brackish water) system (Baptist et al., 2007).

Table 2 Numbers for average discharge and tides in the Haringvliet with the scenario of the Kierbesluit and of open Haringvliet sluices (Baptist et al., 2007).

	Kierbesluit	Situation Stormvloedkering (i.e. open Haringvliet)
Cross section A_0 *(m2)*	1250	6000
Tidal prism P_t (Mm3)	11	170
Average river discharge Q_f (m3/s)	877	877
Average depth h (m)	6.3	6.3
Maximum tidal velocity v_0 (m/s)	0.62	0.96
Tidal mixing zone (km)	8.8	13.6
Estuarine Richardson number N_R (-)	14.4	0.39

3.2.4 Turbidity

In estuaries turbidity plays an important role in ecological terms, due to that the sludge will cause turbid waters when the fresh river water and the saltwater meet. These high turbidity zones are called turbidity maxima. Turbidity maxima are phenomena in estuary which are zones in an estuary with a higher turbidity due to physical or chemical processes (Baptist et al., 2007). In a stratified layer with the fresh- and saltwater, one turbidity maximum is found. Such a situation can occur when the Haringvliet sluices remain open. Such a turbidity maximum is caused by the sludge which is trapped between the two different layers of water (Baptist et al., 2007). This can have large effects on the benthic fauna due to that sedimentation takes place in these stratified layer (Paalvast, 2016). In addition, the freshwater plankton and saltwater plankton which are taken with the current will die in the stratified layer due to changing salinities, this causes a large amount of detritus. However, this can lead to a higher production of zooplankton which is beneficial for fish larvae who feed on the zooplankton (Paalvast, 2016). This situation will thus take place in a stratified estuary.

In most estuaries the water is mixed and in that situation two turbidity maxima are observed due to the tidal influence i.e. at low tide and at high tide (Baptist et al., 2007). The sludge is trapped between the currents, it cannot move forward or backward and therefore two turbidity maxima are observed in a mixed estuary. In those turbidity maxima lower oxygen levels are measured, which is caused by the high amount of organic matter which is decomposing. The lower oxygen levels can have a negative effect on fish, but fish can swim away from hypoxia zones (Marchand, 1993). However, turbidity can also have a positive effect on juvenile fish, as mentioned earlier with high production of zooplankton, and the lower visibility can prevent juvenile fish from being predated by birds or fish (Marchand, 1993 & Paalvast, 2016).

Environmental condition	Kierbesluit	Delta21
Salinity (i.e. brackish or fresh water)	No brackish water gradient can establish due to low frequency of opening the sluices.	Brackish water gradient can establish due to the returning of the tide, mixing will take place
Turbidity	Low, due to lack of tide	Two turbidity maxima due to tide
Ecotopes	Same amount of ecotopes, but some are underrepresented (see Appendix Figure 18)	Ecotopes are more equally distributed in the Haringvliet, so more potential habitat development.
Sandbank Erosion	Sedimentation forces are very low compared to erosive forces	Increased sedimentation forces result in a situation closer to the equilibrium, but erosive forces are still higher.

3.3 Required Conditions for seagrass and fish species

3.3.1 Seagrass recovery as important parameter for fish return

In the Netherlands two species of seagrass are known to exist. The species *Zostera marina* (eelgrass) growing to a size up to 60 centimetres, is found at depths variating from 10 to 15 meters and *Zostera noltii* (dwarf eelgrass) growing up to 20 centimetres, is found in shallower waters. Both species have a salinity range from a few to 30 ppt (Van Katwijk, 2003 & Borum, 2004). When the Haringvliet will be fully opened and fish will return, a suitable habitat is needed for more fish species. The presence of seagrass is an important habitat requirement for many fish species since it provides shelter for a lot of fish, like juvenile herring, as well as for crustaceans. Additively, for species like the three-spined stickleback it provides a nursery ground (Bertelli & Unsworth, 2014).

In both scenarios (Kierbesluit & Delta21 plan) the salinity will be sufficient for both seagrass species (a few ppt to 30 ppt). However, seagrass is vulnerable to stream velocities and it does not grow in areas with a stream velocity higher than or equal to 1.5 m/sec (Borum, 2004). When the Delta21 is applied, the tidal lake is formed which features lower stream velocities than the Voordelta in the Kierbesluit scenario. Therefore, it is more likely that seagrass is able to successfully return when the Delta21 plan is implemented.

The *Zostera* species have a so called hydrophilous pollination. Fertilization occurs after pollen are set free to the water column. For successful fertilization, the pollen needs to reach the female flowers of the eelgrass. A large amount of pollen produced by the seagrass does not survive. Therefore, the production of seed is high, which increases the survival chance. For the *Zostera* species the production can reach up to thousand seeds per square metre (Borum, 2004).

Flowering of *Zostera noltii* mostly occurs in the period March to November. However, the flowering period differs between locations and is easily influenced by changes in water temperature and tidal flows, all linked to light availability. Light is the most important factor for photosynthesis (Borum, 2004). Light availability can be decreased by an increase in water turbidity resulting from increasing temperatures or sediments floating in the water as a result of water dynamics. The rate in which turbidity contributes to the variance in irradiance can be up to 95% when the depth increases (Anthony et al., 2004).

Borum (2004) conducted a study on the recolonization rate of *Zostera noltii* in Portugal. It was found that recovery of this species often happens on places that had undergone disturbances. For example, gaps created by digging bivalves were inhabited by *Zostera noltii*. This type of recovery was visible after a few months. In order to recover quickly after such a disturbance, *Zostera noltii* produced more seed. Another favourable disturbance was the migration of sand banks, which was shown to have impacts on larger scales (hectares). The recovery rate after such a disturbance can take up to five years. Overall, the species *Zostera noltii* showed a rapid growth and when new areas are formed as a suitable habitat, this eelgrass species is able to recover and form a new meadow in a period of one to a few years (Borum, 2004).

Worldwide many attempts to restore seagrass fields have been made. One condition is that the environmental conditions in terms of turbidity, type of sediment, light availability, depth, predation pressure etcetera, have to be optimal in order to form large seagrass meadows (Borum, 2004). Transplantation of shoots as well as seagrass seeds can be considered. However, seed banks are not known to be the most successful method for seagrass recovery. Therefore, transplanting methods might be required to stimulate seagrass recovery. Three different transplanting methods are seen in seagrass recovery projects: "plug methods", "staple methods" and "peat pot methods" (Borum, 2004):

- For the "Plug method", sediment with the attached seagrass is taken out of a consisting seagrass meadow. The sediment is removed from the seagrass before it is transported in a tube. At the future seagrass bed, a hole must be created to insert the tube with the seagrass plant (the plug) into the sediment.
- Shovels are used to extract sea grass plant out of the sediment by the "Staple method". Roots and rhizomes of the seagrass are clean from sediment and are bound together and stapled on a small metal tie. The staples with the attached roots and rhizomes are stuck in the sediment in such a way that it is covered with sediment.
- The "Peat Pot Method" consist of blocks of sediment with seagrass plants which are taken out of an existing seagrass meadow. The blocks are transferred into biodegradable pots. The pots are "planted" in the sediment where they are taken in by the sediment and ripped apart when roots and rhizomes of the seagrass are formed.

When the seeds that survived all environmental challenges, like predation by crabs, finally reach the sediment to settle, it can still take a few months before the seeds start to sprout. Records are mentioned for *Zostera marina* that showed germination after a period of dormancy about half a year (Borum, 2004).

In the 1930s *Zostera marina* underwent a large decrease in abundance due to a disease. Monitoring the areas in the years after the disease showed that the recolonization took up to two to three decades. Although, the amount of eelgrass after the disease never totally reached the same amount as before the disease recovery was happening. The reason for this is that the eelgrass was subjected to disturbances caused by humans, like mussel collection and the use of bottom trawls, limiting the recovery of the eelgrass (Borum, 2004).

A recovery project in America added seeds to several plots instead of adult plants in an area where eelgrass had completely disappeared for at least 70 years. Monitoring of 11 years showed yearly recovery of *Zostera marina.* Although, the rate of recovery differed per year and per area. It is important to keep in mind that depths in these areas varied between 0.9 and 1.6 meter at low tide (Orth et al., 2012). In the Haringvliet water depths are much greater.

To accelerate the recovery of seagrass, the presence of bivalves can have an influence. Bivalves like mussels and oysters are known to filter algae and sludge out of the water, which can be beneficial for seagrass growth by decreasing turbidity and allowing more light radiation through the water (Peterson & Heck, 2001). Not only for bivalves can the presence of oyster riffs be beneficial. It has a positive effect on the establishment of multiple species. This contributes to the goals of the KRW and Natura2000 (Witteveen et al., n.d.). Therefore, it is suggested to create oyster riffs in the Haringvliet area and tidal lake in order to stimulate seagrass growth and thereby fish habitats. According to Witteveen et al. (n.d.) comparable constructions of oyster riffs in the Eastern Scheldt and near the Oyster dam have costed approximately €30/m2 and €72/m2. Difference in cost is here mainly due to the different distances to the mainland and place of oyster origin. In total, reefs of approximately 1600 and 2600 m^2 have been created (Witteveen et al., n.d.).

Table 3 Comparison of potential seagrass development between Kierbesluit and Delta21 scenarios.

	Kierbesluit	**Delta21**
Seagrass potential	Stream velocity expected to be high, especially in the Voordelta	Stream velocity lower/sufficient for seagrass growth in the new formed tidal lake

3.3.2 European eel (*Anguilla anguilla*)

The European Eel (*Anguilla anguilla*) is a catadromous species and can thus be found in both fresh water and salt, coastal waters in Europe. It is also categorized as a critically endangered species in the IUCN Red List (Jacoby & Gollock, 2014).

European eel eggs hatch in the Sargasso Sea and larvae drift towards the European coast by using the Gulf Stream. Subsequently, when water temperature is around 10°C, inland migration starts, especially during high tide (Klein Breteler, 2005). In the Netherlands the peak in this migration of so-called glass eels occurs from February to April (Bruijs & Durif, 2009). European eel was found to acclimatise well to new salinity levels in a relatively short period (Rankin, 2009), hence this acclimatisation is not considered as very important for the species (Wilson et al., 2004). Once the freshwater systems are reached eels will grow to maturity before migrating back to sea (Klein Breteler, 2005 & Friedland et al., 2007). The duration of this maturation phase, in which the eels are called yellow eels, varies between 5 to 14 years for males, and 7 to 18 years for females (Svedaung et al., 1996; Klein Breteler, 2005). During this phase eels have a very broad diet, containing e.g. fish, molluscs, crustaceans, insects and plant material (Klein Breteler, 2005). Once the mature stage of silver eel is reached, eels will stop foraging and migration back towards the oceanic spawning areas will start. In the Netherlands, this event typically occurs at the end of summer and beginning of autumn, reaching its peak in August (Bruijs & Durif, 2009; Klein Breteler, 2005).

Migration of eels depends on several factors. In order to find a suitable migratory route, flow attraction plays an important role. Upstream migrating eels are known to strongly rely on water currents, of which flow rate and flow orientation provide them with important migratory cues (Piper et al., 2012). Critical stream velocity for European eel is specified to be 0.2 m/s, but an average sprint speed of 0.4 m/s was found by Van Emmerik (2016). Downstream migrating eels prefer to follow strongest currents of main streams of rivers, in which they mostly float in the lower and middle water layers (Klein Breteler, 2005).

As eels are negatively phototactic (moving away from light), they mostly migrate during the night. During daytime, they hide in the bottom or banks (Klein Breteler, 2005 & Bruijs & Durif, 2009). For this a soft muddy or sandy substrate in which they can dig is preferred. Alternatively, pebbles, large rocks, existing holes, roots and vegetation can facilitate hiding as well (Klein Breteler, 2005, Van Emmerik, 2016). Depending on eel density, vegetation cover between 20% and 80% of the bottom surface is optimal. Higher covers limit the ability of eels to forage (Klein Breteler, 2005). Furthermore, optimal foraging behaviour requires a minimum oxygen concentration of water of 5 mg/l. In general, eels do not seem to be very sensitive to water pollution, as their presence is reported in virtually all water types. However, because of their bottom-bound lifestyle and high fat content, eels might potentially be highly sensitive to bioaccumulation of PCBs. Although this is not likely to cause immediate mortality, it is suggested to limit the quality of eggs and thereby reproduction of eels (Klein Breteler, 2005).

Low water levels usually do not limit habitat suitability of European eels (Klein Breteler, 2005). However, as downstream migration increasingly coincides with low water levels in the main streams of rivers, mortality in eels is likely increased as a result of ships using the more shallow and narrower streams and thereby killing eels with propellers (RTL nieuws, 2019). Furthermore, obstacles such as dams, sluices and power stations are known to inhibit migration or cause high mortality in eels (Dufour & Thillart, 2009 & Klein Breteler, 2005 & Winter et al., 2013).

Table 4 Comparison of habitat and migration requirements of European eel between the current situation (Kierbesluit) and the Delta21 plan.

Habitat/migration requirement	**Kierbesluit**	**Delta21**
Substrate	Sufficient	Sufficient, no changes expected
Vegetation	Sufficient (Rijkswaterstaat, 2019)	Sufficient, increase in sheltering possibilities due to sea-grass development (Rijkswaterstaat, 2019)
Open estuary access	Mostly limited by closed Haringvliet sluices	Sufficient in scenario A, limited in scenarios B and C

5.3.3 Atlantic herring (*Clupea harengus*)

The Atlantic herring (*Clupea harengus*) belongs to the family *Clupeidae,* which consists of some of the most common fish species in the world (Brevé, 2007). Reproduction of herring takes place at sea with eggs being deposited on coarse gravel, sand, shells, small stones, red algae and sea grass (Brevé, 2007 & Van Emmerik, 2016). According to Reid (1999), the preferred substrate is gravel, and spawning takes place in well-mixed waters. Reid also states that normal egg development and hatching occurs between temperatures of 10-15°C.

After hatching, juveniles migrate to estuaries between January and June and some adults join this migration between March and June (Quak, 2016). During this migration juveniles reach a maximum speed of 0.5 m/s, and adults swim with a constant speed of 1.5 m/s (Turpenny, 1982 & Brevé, 2007). Once these fish arrive at the estuary, adults stay close to the sea while juveniles migrate further upstream, based on salinity tolerance (Quak, 2016). Moreover, larvae stay upstream for approximately one year. One-year old juveniles have adapted enough to resist higher salinity levels in the estuary. The capability of herring adjusting well to salinity levels can also be seen in their reproduction areas, where salinities differ between 2% and 35% (Brevé, 2007). Currently, only little migration of herring into the Haringvliet takes place (Ploegaert et al., 2019).

Herring diet differs between the different life stages. In general, larvae (< 45 mm) eat micro zooplankton, juveniles (< 3 cm) eat individual zooplankton, krill, copepod spp., etc., and adults (> 20 cm) eat small fish, copepod spp., eggs, worms etc. Herring perform schooling behaviour which is important for feeding in all life stages. Schooling herring are also an important food source for other predators i.e. tuna, mackerel, bass, pike and multiple fish-consuming bird species (Brevé, 2007). It is therefore important for herring to have enough sheltering options (which can be provided by e.g. seagrass or increased turbidity), so that the population does not suffer from too much predation.

Utne-Palm (2004) found that younger larvae had a higher tolerance to increased turbidity than older larvae due to lower predation risk, but they also required higher light levels to feed. Boehlert & Morgan (1985) presented similar findings for Pacific herring, with higher feeding rates under intermediate turbidity levels. An explanation for this could be that turbidity increases the contrast between the prey and its background, and that a lowered predation risk at higher turbidity levels leads to increased feeding motivation (Gregory & Northcote, 1993). Other important habitat requirements are strong tidal currents, sufficient oxygen levels (for juveniles: between 2-5 µl O2 per mg dry mass) and a sufficient water quality (especially oil, in concentrations of 20 ml/l water for 3-5 days will cause very high juvenile mortality) (Brevé, 2007). However, herring is also known to have a well-developed acoustic-lateral hearing system and is therefore considered to be sensitive for noise disturbance (Brevé, 2007).

Table 5 Comparison of habitat and migration requirements of Atlantic herring between the current situation (Kierbesluit) and the Delta21 plan.

Habitat/migration requirement	**Kierbesluit**	**Delta21**
Vegetation	Sufficient (Rijkswaterstaat, 2019)	Sufficient (Rijkswaterstaat, 2019)
Open estuary access	Mostly limited by closed Haringvliet sluices	Sufficient in scenario A, limited in scenarios B and C
Turbidity	Sufficient	Mostly sufficient, possibly limited during tides (I.e. turbidity maxima)
Low noise pollution	Unknown	Further investigation needed

3.3.3 Atlantic Salmon (*Salmo salar*)

Atlantic Salmon (*Salmo salar*) is an indigenous species to the Netherlands and has a protected status in Europe (De Laak, 2007). It is an anadromous species, spending a part of its life at sea, and migrating upstream to spawn. As salmon barely had spawning and maturing grounds in the Netherlands (Semmekrot, 1992), the Dutch rivers were only used for the upstream migration of adult fish, and in addition for downstream (seaward) migration of juveniles (smolts) (De Laak, 2007). Adult migration only lasts for a short period but can occur throughout the year (mainly between May and August). Juvenile migration starts in February but reaches its peak in April and May (Van Emmerik, 2016).

Salmon migration depends on multiple factors. In general, smolts require stream velocities between 0.05 to 0.25 m/s. Adults can handle stream velocities up to 2 m/s (Van Emmerik, 2016). In rivers in north-west England, Cragg-Hine (1985) established that at a minimum flow of 7250 m3/d per meter width was required to commence upstream migration. The migration peaked at a mean flow of 17300 m3/d/m and it reduced again at higher flow velocities than this. When migrating downstream or upstream, salmon are hindered by obstacles such as weirs, hydropower plants, and dams like the Haringvlietdam (De Laak, 2007). When there are too many obstacles, upstream migrating salmon might not be able to reach the spawning areas on time.

Smolts consume insects and fish, like young herring and shrimps. In order to facilitate successful downstream migration of smolts, these food sources should thus be available. Adult salmon do not consume any food during their upstream migration towards the spawning area (Van Emmerik, 2016).

The salinity gradient is important for salmonids at the transition from fresh- to saltwater and the reverse (De Laak, 2007). The tolerance of salmonids to salinity increases with age and especially with size (Parry, 1960). Smolts require some time to adapt to the changes in salinity when they migrate towards to the sea. If the adaptation is poor, fish become more vulnerable to e.g. predation, and smolts are thought to suffer from permanently reduced eyesight due to a phenomenon known as cataract which occurs as a result of problems with osmosis. This mainly occurs if the smolts enter the saltwater too late. Adult salmon also have to adapt when they leave the sea to enter the rivers, but they are known to be able to do this within one hour. There are currently no sufficient known values of the exact salinity required for migration by both smolts and adults (De Laak, 2007).

Water pollution can affect all life stages of salmonids. Relatively low values of copper (5 µg/l) can already have negative effects on the amount of smolts that migrates downstream (De Laak, 2007). Van Brummelen (1990) stated that there are substances that exceed the established threshold values in the river Rhine, especially in industrial areas. He also states that this can disturb the migration of spawning fish. Thermo pollution can also be a problem, because migration can be postponed or disturbed by high water temperatures (De Laak, 2007). In general, a water temperature of 15°C in winter is the lower limit for salmonids and a water temperature of 23°C in summer is the upper limit (De Laak, 2007).

According to Crisp (1993), oxygen concentrations for salmonids should be at least 4 mg/l. As salmon only used Dutch rivers for migration, factors such as pH, turbidity, light, the substrate, and the presence of vegetation are not considered to significantly impact habitat suitability for salmon in the Netherlands.

(De Laak, 2007). Water depth only seems to be a limiting factor for salmon migration when parts of the migration routes run dry (De Laak, 2007).

Table 6 Comparison of habitat and migration requirements of Atlantic salmon between the current situation (Kierbesluit) and the Delta21 plan.

Habitat/migration requirement	**Kierbesluit**	**Delta21**
Open estuary access	Mostly limited by closed Haringvliet sluices	Sufficient in scenario A, limited in scenarios B and C
Salinity gradient	Not present	Sufficient in scenario A, decreases and eventually disappears in scenarios B and C

3.3.4 Three-spined stickleback (*Gasterosteus aculeatus*)

The three-spined stickleback (*Gasterosteus aculeatus*) is among the most common fish species in the Netherlands. Three different types of three-spined stickleback are distinguished. The first type permanently resides in a freshwater habitat (Leiurus form). The second type matures in salt or brackish water and only migrates to spawn in freshwater (Semiarmatus form). The third type permanently resides in the sea (Trachurus form). Migratory sticklebacks form an important source of food for other migratory fish species, such as salmonids (Münzing, 1963 & Ravon, n.d. & Reeze et al., 2017).

Spawning of the Leiurus and Semiarmatus forms takes place in freshwater in the downstream stretch of the rivers in the period between March and July. The juvenile period lasts for about six months. After this period the sticklebacks either stay in the downstream stretch of the river, or they migrate towards the sea during the period from July to September. The latter then continues to live in estuaries and coastal areas. In February/April to May the Semiarmatus form migrates upstream again from the sea to rivers for spawning (Reeze, et al., 2017). However, this migrating anadromous form of stickleback has become much less abundant due to the current barriers between the fresh- and saltwater (Griffioen & Winter, 2014).

Three-spined sticklebacks have a critical stream velocity of 0.2 m/s (Van Emmerik, 2016). Larvae and juveniles generally feed on water fleas, while adults feed on small invertebrates and spawn or larvae of other fish species (Ravon, n.d. & Van Emmerik, 2016). According to Ajemian et al. (2015), sticklebacks prefer vegetated, sheltered habitats over open habitats. In natural environments they are generally encountered over seagrass or rock weed. Increased turbidity has been shown to be harmful to prey fish as a result of a reduced reaction distance relative to their predator (Ajemian et al., 2015). This includes three-spined sticklebacks which are prone to greater predation risk at higher turbidity levels. In such conditions, they benefit from vegetation functioning as shelters. Salinity tolerance depends on the origin of the stickleback. De Faveri & Merilä found that the survival probability and body size of three-spined sticklebacks originating from low salinity regions had reduced when they were reared under high salinity conditions. On the other hand, the capacity to survive and grow in low salinity was retained in populations originating from marine environments.

Table 7 Comparison of habitat and migration requirements of three-spined stickleback between the current situation (Kierbesluit) and the Delta21 plan.

Habitat/migration requirement	**Kierbesluit**	**Delta21**
Open estuary access	Mostly limited by closed Haringvliet sluices	Sufficient in scenario A, limited for Semiarmatus form in scenarios B and C
Vegetation	Sufficient (Rijkswaterstaat, 2019)	Sufficient (Rijkswaterstaat, 2019)

3.4 Historical abundance and potential for restoration

3.4.1 Historic catches

The Haringvliet contained a brackish water habitat before the sluices closed in 1970. In this habitat maximum tidal flow rate was approximately 0.85 m/sec with chloride levels reaching approximately 50 kilometres upstream i.e. 3.001 mg/l till Den Bommel and 2.092 mg/l till Nieuwendijk (Van der Spek & Elias, n.d.; Peelen, 1970; Tönis et al., 2002). However, species diversity and species abundance were calculated according to the fisheries data of Vaas (1968), revised by Hop et al. (2011): in Quak (2016) (Table 8). This report shows that there were approximately 21 species in front of the Haringvliet, which included marine (16 spec.) and diadromous (5 spec.) fish. Specifically, abundancy of indicator species was: herring (3 ind.), eel (67 ind.), three-spined sticklebacks (3 ind.) and salmon (n.d.). However, further upstream i.e. Haringvliet and Hollands Diep, 33 species were caught, which included marine (19 spec.), diadromous (5 spec.) and freshwater fishes (9 spec.). In specific, abundancy for indicator species was: herring (2 ind.), eel (312 ind.), three-spined sticklebacks (17 ind.) and salmon (n.d.). An important thing to note is that sampling efforts were limited i.e. 575 minutes in total. Therefore, it is likely that species that enter the Haringvliet more incidentally (mainly pelagic species) were not caught, which could explain why no salmon catches were recorded. Research of Quak (2016) shows that the influx of adult salmon was high during May-August and low during October-December. Also, juvenile salmon were much abundant which isn't shown in the catches of Vaas (1968) but is mentioned in Quak (2016). Moreover, they can be found throughout the year in the Haringvliet were they form a key food source (Quack, 2016).

3.4.2 Fish numbers during Kierbesluit

After a new policy was implemented in the Haringvliet delta i.e. the Kierbesluit, a baseline measurement was executed by Ploegaert et al. (2019). This baseline measurement included the effect of the Kierbesluit on species diversity, species abundance and quality of the habitat in the Haringvliet (Table 8). The percentage of freshwater, diadromous, estuary resident, marine juveniles, marine seasonal and marine vagrant fish species are shown in Figure 13. However, because the Haringvliet sluices opened only a few times in the year of monitoring (whole year of 2018), the freshwater ecosystem was maintained. In this system, maximum accepted tidal flow rate was approximately 0.62 m/sec with chloride levels of 300 mg/l until Middelharnis and <300 mg/l further up the river (Wijsman et al., 2018). In this system i.e. Haringvliet and Hollands Diep there was a total catch of 25 species, which included marine (2 spec.), diadromous (5 spec.) and fresh water (18 spec.) fish. However, the total amount of fish species caught was quite season dependent. Highest abundancy was caught in spring i.e. freshwater 26,625, diadromous 98 (eel= 59, three-spined stickleback= 10). The second highest abundance was caught in summer i.e. freshwater 18,595, diadromous 193 (eel= 48, three-spined stickleback= 49). Lowest abundance was in autumn i.e. freshwater 247, diadromous 220. The marine species i.e. herring (1 ind.) brackish goby (67 ind.) have most likely occurred due to the salt leak between February and July. Specifically, the abundance of the indicator species was: herring (1 ind.), eel (233 ind.), three-spined sticklebacks (121 ind.) and salmon (n.d.). However, the amount of species currently present in front of the Haringvliet is equal to 25. This consists of 7 diadromous, 4 estuarine, 4 marine, 4 marine vagrant, 2 marine seasonal, and 6 freshwater species. The total amount of individuals caught was quite season dependent. In spring, when large amounts of freshwater fish washed out from the Haringvliet, the total amount of each type of fish caught was approximately 13,126 freshwater, 325 diadromous, 27,421 marine juveniles (almost completely consisting of herring), and only 24 estuarine residents, 1 marine seasonal, and 1 marine vagrant. In summer, when the sluices were closed, the amounts of fish caught were approximately 166 freshwater, 302 diadromous, 1,057 estuarine residents, 5,161 juveniles (still mainly consisting of herring), 119 marine seasonal and 70 marine vagrants. In autumn the sluices were still closed because of the big drought, and the amounts caught were approximately 0 freshwater fish, 316 diadromous fish, ~1066 estuarine residents, ~27 marine juveniles, ~21 marine seasonal and 0 marine vagrants. Specifically, the abundance of the indicator species in the Voordelta was approximately 8286 herring, 1 eel, and 2 three-spined sticklebacks. Salmon catches were not recorded. Research of Van Beek & Meijer (1997) shows that in the past years, salmon have been rarely found. Therefore, reintroduction programmes have started to boost the populations of salmon again. However, fish abundancy monitoring of WMR Open Data (2018) showed only one individual within that year of monitoring. It is expected that once the Delta21 plan is implemented, fish population numbers will start to approach historical numbers.

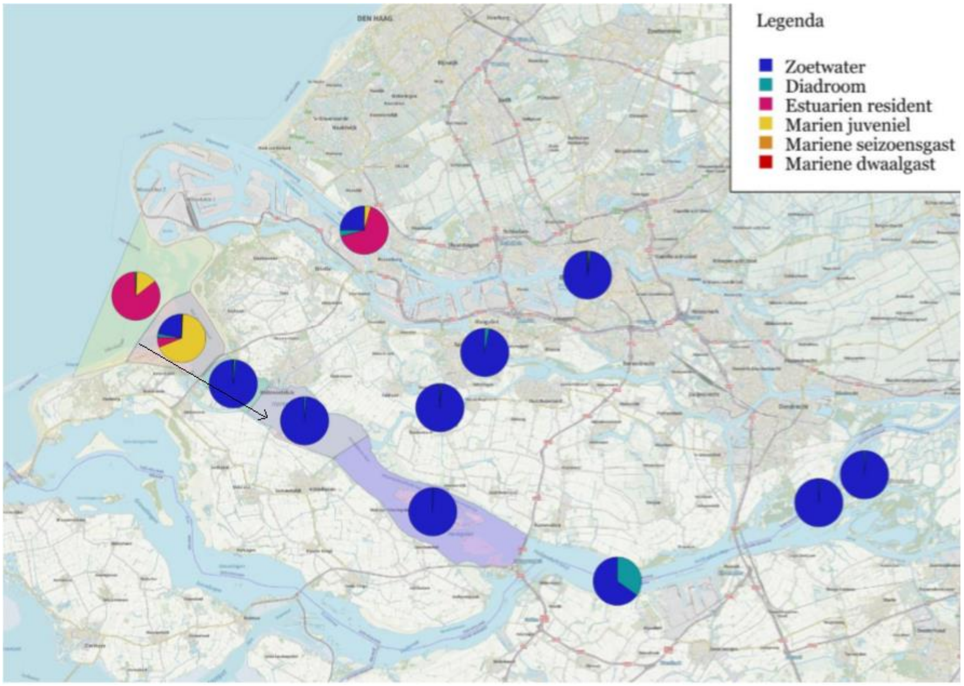

Figure 13 The percentage of freshwater, diadromous, estuarine residents, marine juveniles, marine seasonal and marine vagrant fish species caught during the Kierbesluit in 2018. The arrow indicates the shift of these fish species when the Haringvliet will fully open (Ploegaert et al., 2019).

3.4.3 Expectations

When the Haringvliet will fully open, at low river discharge and high tide a salinity of 300 mg Cl/l is expected at Moerdijk. With average river discharge and high tide this salinity of 300 mg Cl/l is expected at Volkerak instead. The main importance for fish migration is the presence of a salinity gradient so that fish can acclimate to different salinities. For this reason, it is expected that the indicator species will change in abundancy. These different abundancies of the indicator species are indicated with the arrow in figure 3. It is expected that marine juveniles (juvenile herring and glass eel) and Marine residents (marine three-spined sticklebacks) will be most abundant in the Haringvliet. The species that are expected to occur in low numbers only use the Haringvliet as corridor (adult salmon, adult eels) (Table 8). Nevertheless, eel populations used to be dominant in front of the Haringvliet. However, after the Haringvliet sluices closed this changed to a Herring dominate state. In the case of an open Haringvliet eels migrate towards the Voordelta to spawn in the sea and consequently the abundance of glass eels in the North Sea and the Voordelta is expected to increase. Because eels can tolerate a wide range of salinity levels, they are also expected in the Haringvliet throughout the year in low numbers. Herring on the other hand mainly reside in marine waters, but are also tolerant to a wide range of salinity levels. In the case of an open Haringvliet herring migrate land inwards towards the salt or brackish estuary to spawn and are therefore expected to lower in abundance in the Voordelta. However, it is expected that herring will be highly abundant in the Haringvliet throughout the year (most abundant in spring). For the three-spined sticklebacks (*Semiarmatus form),* opening the Haringvliet will allow migration between the sea and the Haringvliet again, and thus their population will also increase in the Voordelta. However, the currently present population only resides in fresh water. Their abundancy is expected to decrease, while abundance of sticklebacks tolerant to higher salinities is expected to increase. For salmon, populations only migrate through the Haringvliet and the Voordelta (without long duration time) and populations are extremely low in abundancy. It is therefore expected that abundancy of salmon in the Haringvliet will be extremely low. However, if re-introduction programmes improve it is expected that these salmon can use the Haringvliet as corridor. Salmon are very tolerant to high salinities, but they do require a transition area, especially smolts that migrate towards the sea.

Before the Haringvliet sluices closed, a total of 53 fish species was present in the estuary (Quak, 2016). In this system, presence of juvenile herring was a highly important parameter (food source) for species diversity and abundancy. It is expected that when the Haringvliet sluices open the old habitat will partially be restored. An important parameter for this is seagrass, which could grow back within one to a few years if the conditions are suitable (see 3.2.1.). Herring can, as a result, return in high abundance to the Haringvliet. However, it is not expected that the amount of fish species will increase till 53 species again due to declining populations and more anthropogenic influences. Examples of these influences are sound, constructions, water pollution, fisheries, and soil pollution. Moreover, the opening of the Haringvliet will lead to a large increase in abundance of marine species and diadromous species in the Voordelta and the Haringvliet. More species with the comparable characteristics as the indicator species like *Thinlip Grey Mullet, Sprattus sprattus, Dicentrarchus labrax, Coregonus oxyrinchus, Osmerus eperlanus, Dermatobia hominis* and *Salmo trutta trutta* are expected to be most dominant in this habitat. Species that have higher requirements of their habitat like *Acipenser sturio, Petromyzon marinus, Lampetra fluviatilis, Dorosoma cepedianum* and *Alosa fallax* are not expected to return to the Haringvliet (or in extremely low numbers). Fresh water species are expected to swim further upstream i.e. Hollands Diep. It is expected that only a few freshwater species will stay within the Haringvliet and the Voordelta.

4 Discussion

As soon as the Haringvliet sluices open, fish are expected to migrate through the Haringvliet. The area could then function both as a habitat and as a corridor for fish to migrate through. Each function has different requirements. For the corridor function the main importance is that a gradual transition from salt to fresh water is present. While some species such as European eels can quickly acclimate to salinity changes (Rankin, 2009), others such as Atlantic salmon require sufficient time to acclimate to different salinities (De Laak, 2007).

For species that mainly use the area as a habitat for extended periods of time, such as herring, European eel, and three-spined stickleback, other conditions are important. Options for shelter, such as seagrass, are important to prevent too much predation. Higher turbidity levels can also lower predation risk (Boehlert & Morgan, 1985 & Utne-Palm, 2004), but might also reduce growth of e.g. seagrass (Borum, 2004), and can thereby reduce sheltering options and increase predation risk. Salinity is also of high influence, but salinity preference and tolerance obviously differ for different fish species. Since opening the Haringvliet will result in salinization of the area in and behind the Haringvliet, most if not all species that only reside in fresh water are expected to disappear, while abundances of brackish or saltwater species are expected to increase (Quak, 2016). Species that can survive in both fresh and brackish or salt water, such as three-spined stickleback, are not expected to be directly affected by salinity changes.

Nevertheless, expectations about the fish abundancy in the Haringvliet after fully opening has been made by compare the fishing data of Vaas (1968) and monitoring data of Ploegaert et al. (2019). Good to note is that the amount of activities related to fish catches was much different. Vaas (1968) caught fishes in front of the Haringvliet, in the Haringvliet and in the Hollands Diep within 575 minutes. However, Ploegaert et al. (2019) caught fish in front of the delta in the spring (9 days), summer (23 days) and autumn (7 days). Moreover, in the Haringvliet and Hollands Diep fish was caught in spring (10 days), summer (51 days) and autumn (13). However, as is shown in multiple studies (e.g. Hartgers et al., 2001 & Griffioen & Winter, 2017) species abundancy can be analysed with differences in fishing methods and activities. They show that this can only be done when additional information is given, which is the case in Vaas (1968) and Ploegaert (2019). The additional literature is used to make the expectations for fish abundance in the Haringvliet, while the real catch data is used to show abundancy and diversity at that time and the ratio of fresh, diadromous and marine fish species.

An important factor that could hold back fish migration is gill net fishing. Evidence has shown that the use of gillnets has caused worldwide declines of fish populations (Syrjänen & Valkeajärvi, 2010). Besides this, using catch and release angling can negatively affect health or reproductive behaviour of for example Atlantic salmon when they get entangled in gill nets (Mäkinen, 2000). Currently gill net fishing is extensively used close to the Haringvlietdam at the zone where fish acclimate between the salt water and fresh water, and this leads to the fish getting blocked or caught in the nets (van Burg, 2020 & Berkelder, 2020). This means that even if the conditions in the Haringvliet are sufficient, gill net fishing at the boarder of the Haringvliet will negatively affect or even prevent fish migration from taking place.

The scenario of the "Stormvloedkering" which is described in Wijsman et al. (2018) can cause more erosion of the sludge layer. After complete closure of the Haringvliet in 1971, polluted sediment has been deposited in the Haringvliet (Verwaart, 1989) and with the "Stormvloedkering" scenario, which is comparable with the Delta21 plan, the polluted sludge can erode again and cause pollution in the Haringvliet. So, this is something which must be considered in the Delta21 plan. Bivalve reefs could potentially be used to reduce excessive turbidity.

It needs to be considered that Delta21 plan is compared with the situation "Stormvloedkering" as mentioned in Wijsman et al. (2018). The Delta21 plan is not the same as the situation "Stormvloedkering". The Delta21 plan has an energy storage lake and a new barrier which still needs to be realised, therefore we made some assumptions and comparisons, but these can of course not be validated. The morphology of the Haringvliet will change with the Delta21 plan, this is unknown until so far. However, we based our assumptions thus on the situation of the "Stormvloedkering" as this is most comparable with the Delta21 plan.

Fish can experience stress as a result of noise pollution. It may for example disrupt their ability to avoid predators or to locate food, and intense noise can cause acoustic trauma or even death (Crane & Ferrari, 2018). The risk of noise disturbance on population level is dependent the total amount of fish in the population as well as on the thresholds of the responses in behaviour. For example, to what extent the reproductive, foraging or migrating abilities of the fish are resistant to noise disturbance differs per period. In periods of fish migrating to the sea, the effect will be much smaller than in a period where the fish stay in the Haringvliet in order to search food or building nests in case of the three-spined stickleback (Sivle et al., 2015). For the Haringvliet, the expected noise disturbance will be a result of the pumps of the energy storage lake and the turbines in the energy storage lake. Beside the effect of noise pollution, turbines used in the energy storage lake and the tidal lake might potentially harm passing fish (Bruijs, 2010; Griffioen et al., 2015). It is assumed that especially strongest swimming species, like salmonids, will be affected by during upstream migration, as weaker swimmers will not be able to swim against the currents. During downstream migration of fish, turbines might form a risk for all species, as all species will use downstream currents to float and thus reduce energy expenditure (Bruijs, 2010 & Griffioen et al., 2015). Mortality can result from fish colliding with blades and structures, differences in pressure, cavitation, turbulence or shear stress (Griffioen et al., 2015). However, hardly any studies are currently conducted on the effects of turbines on fish in the field (Bruijs, 2010 & Griffioen et al., 2015). Yet, Rijkswaterstaat (2019) applies a standard in which a maximum fish mortality of 10% is allowed, which is based on 'best professional judgement' (Bruijs, 2010). It is assumed that populations of prioritised fish species will not significantly negatively be impacted by 10% mortality. Laboratory studies have shown that use of (Kaplan) turbines with adapted blades and a vertical axis can lead to a yield survival efficiency up to 90% (Bruijs, 2010).

In the most recent update of the Delta21 plan, a proposition was done to close the Haringvliet sluices when the Rhine discharge at Lobith would drop below 1000 m^3/s. According to Delta21, this means in an average year a closure of the sluices for 10 days a year (Delta21, 2019). In the W_L and W_H climate scenarios with an increased mean air temperature of 2°C the Rhine Discharge in September is expected to decrease by 5% to 27% (Deltares, 2015). Longer periods of low discharge would result in longer periods of closure of the Haringvliet sluices. Figure 14 River Discharge at Lobith during the whole year of 2018. The Discharge is indicated in blue. The critical Discharge for closing the Haringvliet sluices is indicated by the red horizontal line (Based on data retrieved from Rijkswaterstaat). shows that in 2018 during more than 100 days the river discharge was below 1000 m^3/s during an almost continuous period. Closing the Haringvliet sluices for such long periods would be devastating for brackish water habitats and residing flora and fauna that cannot survive such long periods of exposure to fresh water (Griffioen & Winter, 2017).

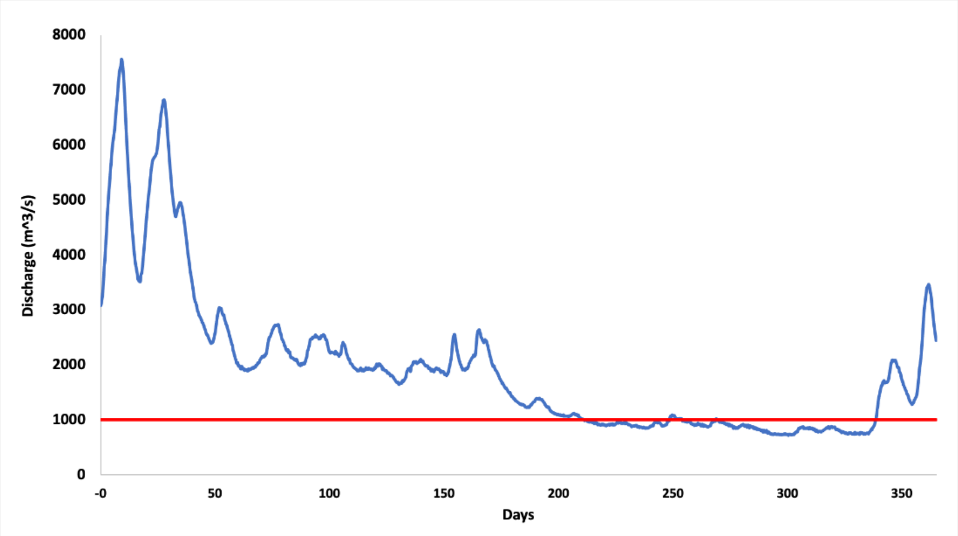

Figure 14 River Discharge at Lobith during the whole year of 2018. The Discharge is indicated in blue. The critical Discharge for closing the Haringvliet sluices is indicated by the red horizontal line (Based on data retrieved from Rijkswaterstaat).

The tidal lake which will be made when the Delta21 plan will be realised, has according to us a high potential in nature value. Due to the shallow areas in the tidal lake, seagrass can grow and provide habitats and residence for fish species. We recommend to plant seagrass patches, in combination with bivalve reefs for reducing water turbidity by water filtering, in the tidal lake. Because we expect that this part of the Delta21 plan will contribute most to recovering the fish migration. Of course, in the Haringvliet those seagrass patches can be planted as well, but we think that in the tidal lake the seagrass will grow the best. The reason behind that is that the tidal lake is less exposed to stream velocities higher than 1.5 m/sec compared to the Haringvliet. However, the shallow waters of the Haringvliet close to the edges might be suitable for *Zostera noltii* to, if the stream velocity is not higher than 1.5 m/sec here. Nevertheless, no larger meadows can form due to lack of space which is no problem in the tidal lake area.

In addition, fish that are adapted to brackish water, herring for example, can experience problems with a sudden change to fresh water. Species that acclimate well to salinity changes, such as the European eel (Rankin, 2009), are not expected to experience many issues in case of desalinization as a result of the closing of the sluices.

Most droughts occur during the summer months. Especially Atlantic salmon could experience problems in these dry periods. Upstream migration of adult salmon to their spawning areas primarily takes place between May and August (Van Emmerik, 2016). If the sluices close during the summer, salmon migration could be inhibited because they are unable to enter the Haringvliet. The salmon could also experience problems due to the absence of a salinity gradient which they need for acclimatization (De Laak, 2007). However, this is primarily necessary for smolts which migrate upstream mainly in April and May (Van Emmerik, 2016). Due to the changing climate, dry summers are expected to occur more often. Depending on how often such droughts will occur in the future, the extent of disturbance can be estimated. Also, abundance of fish species can also be dependent on the substrate of their habitat. Some species, like the European eel, require soft muddy or sandy substrate or other objects in their habitat in which they can hide (Bruijs & Durif, 2009; Klein Breteler, 2005). Nevertheless, since the downstream migration period of matured silver eels peaks in August (Bruijs & Durif, 2009 & Klein Breteler, 2005), closed sluices could strongly disturb the migration of eels to their spawning areas. At the same time, eel mortality could increase during droughts as a result of ships making use of shallower and narrower streams (RTLnieuws, 2019). One variant of three-spined stickleback can also migrate downstream during summer in the period from July to September. These could therefore experience the same issues as downstream migrating eels.

5 Recommendations

5.1 Seagrass recommendations

Experiments of seagrass (*Zostera marina*) transplantation were conducted in former seagrass areas in America. Those experiments showed a higher successful survival rate for the transplanted seagrass plants (42%) than the transplantation of seagrass seeds (<10%) (Borum, 2004). Therefore, it is suggested to choose and focus on the recovery of seagrass by making use of seagrass plant transplantations instead of spreading seeds in the Haringvliet.

To increase the recovery rate of *Zostera marina* it is important to know that this eelgrass species recovers better when many small patches are created instead of a few large patches after reintroduction (Borum, 2004). Olesen & Sand-Jensen (1994) suggested 1000 patches per hectare per year for *Zostera marina.* The recommended number of patches per hectare is not yet determined for *Zostera noltii*. However, due to high horizontal expansion of roots (Figure 15 Sketch of the seagrass species Zostera marina (left) and Zostera noltii (right) where you can see a clear difference in root formation. Zostera noltii shows more horizontal distribution (Borum, 2004).) it is expected that this species will form patches easily (Borum, 2004).

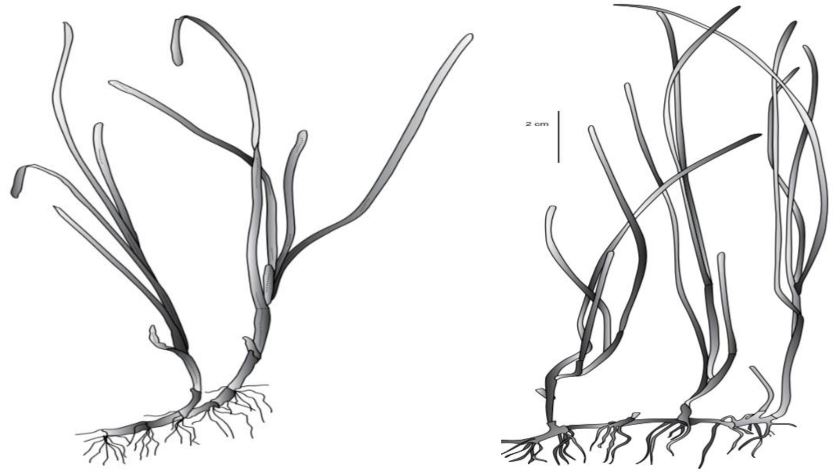

Figure 15 Sketch of the seagrass species Zostera marina (left) and Zostera noltii (right) where you can see a clear difference in root formation. Zostera noltii shows more horizontal distribution (Borum, 2004).

A situation like in the picture below (Figure 16) shows a possible situation with can be created in the Haringvliet. *Zostera noltii* in shallower depths because it is more resistant to water dynamics than *Zostera marina* which is planted in deeper areas with less severe water velocities and where it still can receive enough sunlight and a bivalve bed for water filtration. In such a way the species can protect each other against water velocities. (Peterson & Heck, 2001).

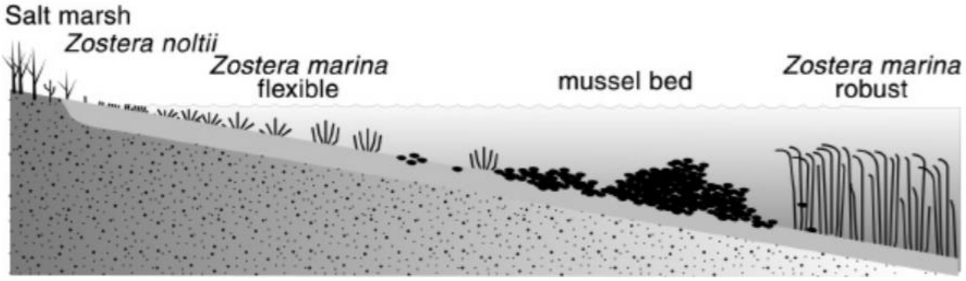

Figure 16 Example of a bivalve seagrass habitat (Van Katwijk, 2003).

The tidal lake which will be made when the Delta21 plan will be realised, has according to us a high potential in nature value. Due to the shallow areas in the tidal lake and the lower stream velocities compared to the Voordelta, seagrass can grow and provide habitats and residence for fish species. We recommend to plant seagrass patches in the tidal lake, because we expect that the use of this tidal lake is a promising part of the Delta21 plan for the recovery of the fish migration. Of course, in the Haringvliet those seagrass patches can be planted as well, but we think that in the tidal lake the seagrass will grow the best. The reason behind that is that the tidal lake is more influenced by the tide and thus salt water, which is needed for the seagrass to grow.

5.2 Delta21 plan during Low Rhine discharge

In periods of low Rhine discharge (<1000 m^3/s) the Haringvliet sluices will close to prevent saline water to intrude into the Haringvliet and Hollands Diep according to the current Delta21 proposition. The resulting barrier in the fish migration route and no salt-fresh water gradient could be limiting the fish migration. As a solution, the Haringvliet sluices could partly be opened to maintain fish migration, such as in the current Kierbesluit, while simultaneously preventing saline water from reaching too far inland. In this way, the Haringvliet sluices will function in a similar way as the current Kierbesluit. We recommend further investigation on this alternative to tell whether it would be a feasible solution to safeguard the fresh water supply.

5.3 Habitat requirements

A diverse habitat is key for fish species return. We recommend a vegetation/bivalve reef cover between 20% and 80% of the bottom surface. Higher cover would limit foraging possibilities for bottom-bound species such as eel, and lower cover would provide insufficient sheltering options for e.g. juvenile herring and three-spined sticklebacks. Also, some areas with muddy substratum is recommended, because some species e.g. eels use this for sheltering during the day. However, this muddy substrate can increase turbidity by the influence of tide. Some species profit from this increase as they can easily hide from predators. However, an enlarged turbidity mostly causes problems for foraging and migration behaviour, therefore, we advise to regulate turbidity but also water quality by implement oyster reefs (Peterson & Heck, 2001). Nevertheless, other sheltering options which are recommended are fish hotels and seagrass beds. These sheltering areas are important to hide for predators and to prevent outflowing fish i.e. mainly juveniles. Other hard substratum like large rocks should be implemented as well in order to create brackish gradients. This is highly essential for fish acclimatization while migrating.

5.4 Mitigating anthropogenic threats

In general, barriers will always reduce the migratory success of fish. By opening the sluices of the Haringvliet dam, a major barrier in this area will already be removed. However, gill net fishery can also have a significant negative impact on migrating fish populations. We therefore recommend extending the length of the fishing-free zone around the Haringvliet, which currently encompasses an area of 500 meters. This is also insisted on by several parties, such as nature organisations and the Dutch House of Representatives (Bouma, 2020 & Haringvliet.nu, 2020).

6 Conclusion

Opening the Haringvliet as proposed in the Delta21 plan can contribute to the restoration of migratory fish routes. By fully opening the Haringvliet sluices salt tides and brackish water can return to the Haringvliet. For species that use the Haringvliet mainly for its corridor function i.e. salmon, this is sufficient. For fish species that need a brackish habitat to spawn, restoration of a brackish water ecosystem is required. Seagrass development will be an essential component in this ecosystem since it can function as a shelter and a spawning place. We presume that the chances for a stable brackish ecosystem to develop will increase substantially by the implementation of the Delta21 plan compared to the current Kierbesluit situation.

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9 Appendix

Figure 17 By modelling, the salt intrusion is determined in the Haringvliet during the scenario Stormvloedkering. The purple area indicates the salt intrusion during normal discharge and high tide, the red area indicates the salt intrusion during low discharge and high tide. The lines give the upper boundary of freshwater of 300 mg Cl per liter (salinity of 0.5 ppt) which will be the most likely, the purple and red area give the high uncertainties (Wijsman et al., 2018).

Table 8 The amount of species, which was caught before the Haringvliet sluices closed (Vaas, 1968, revised by Hop et al. (2011) in Quak (2016) and with the Kierbesluit (Ploegaert et al., 2019). Also, an indication about species abundancy is given when the Haringvliet sluices would fully open. High means high abundancy, low means low abundancy.

Time	Area	Total amount of species	Freshwater	Marine	Diadromous	Three spined stickelbacks	Herring	Eel	Salmon
Before the Haringvliet dam	Voordelta	21	0	16	5	3	3	67	High, short stay
	Haringvliet and Hollands Diep	33	9	19	5	17	2	312	High, short stay
During Kierbesluit	Voordelta	25	4	14	7	2	8286	1	Low, short stay
	Haringvliet and Hollands Diep	25	18	2	5	121	1	233	Low, short stay
Expected	Voordelta		Low	High	High	High	Low	High	Low
	Haringvliet and Hollands Diep		High, Holland Diep; Low, Haringvliet	High, Haringvliet; Low Hollands Diep	High	High	High	Low	Low

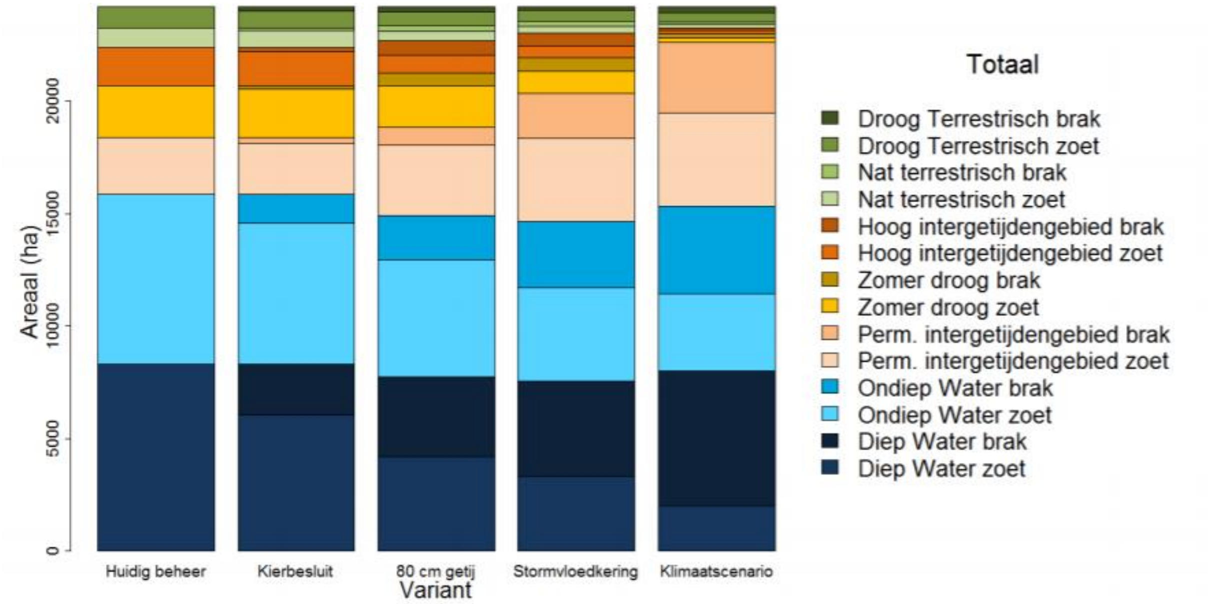

Figure 18 Different ecotopes in the Haringvliet for different scenarios as mentioned in Wijsman et al. (2018).