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Restoring the migratory routes of yore

Constructing a fish future for the Dutch delta: How to facilitate migration of diadromous fish species in the Haringvliet

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Tide For Change

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ABSTRACT

ENGLISH

The Haringvliet was in open connection with the sea and provided a passage for migratory fish entering the Rhine for the purpose of reproduction. Since the Haringvliet sluices were constructed in 1970, migratory fish populations have declined greatly. In this paper we look at requirements needed to facilitate migration of catadromous and anadromous fish species in the Haringvliet. A selection is made that includes catadromous and anadromous fish species that use or have used the Haringvliet as a migratory route. Based on this selection, several fish characteristics are gathered that are deemed important to take into account in the construction of a fish migration system. Two of the most important characteristics are the swimming capacities of fish species and their ability to acclimatise to changes in salinity. These vary vastly between different species. Apart from accommodating these fish characteristics, the fish migration system also needs to fulfill several societal requirements. It should not interfere with the freshwater supply, water safety during high river discharge or high tide and with shipping in the Haringvliet. Some drawbacks that also need to be considered are changes in hydrology, fishery activities, a variable discharge of the Rhine and upstream obstacles. Several recommendations based on the findings from this report can aid in the design of a fish migration system in the Haringvliet, as well as focus on several points that should not be overlooked.

DUTCH

Het Haringvliet stond voorheen in open verbinding met de Noordzee en bood een doorgang voor trekvissen die de Rijn op wilden trekken voor paai doeleinden. Sinds de Haringvlietsluizen in 1970 zijn gebouwd, zijn de trekvispopulaties sterk afgenomen. In dit rapport wordt gekeken naar de vereisten die nodig zijn om migratie van katadrome en anadrome vissoorten in het Haringvliet te faciliteren. Er is een selectie gemaakt van katadrome en anadrome vissoorten die het Haringvliet als een migratieroute gebruiken of gebruikt hebben. Op basis van deze selectie worden verschillende eigenschappen verzameld die belangrijk worden geacht om in overweging te nemen bij de constructie van een vismigratiesysteem. Twee van de belangrijkste kenmerken zijn de zwemcapaciteit en het vermogen om te acclimatiseren aan veranderingen in het zoutgehalte. Deze variëren enorm tussen verschillende soorten. Naast het accommoderen van deze eigenschappen, moet het vismigratiesysteem ook aan verschillende maatschappelijke eisen voldoen. Het mag niet interfereren met de zoetwatervoorziening, waterveiligheid bij hoge rivierafvoer of hoogwater en met scheepvaart in het Haringvliet. Enkele nadelen die ook moeten worden overwogen zijn veranderingen in hydrologie, visserij, een variabele afvoer van de Rijn en stroomopwaartse obstakels. Verschillende aanbevelingen op basis van de bevindingen uit dit rapport kunnen helpen bij het ontwerp van een vismigratiesysteem in het Haringvliet, maar ook bij het focussen op verschillende punten die niet over het hoofd mogen worden gezien.

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Chapter One - Introduction

Over the last decades, over 1 million barriers were built in European rivers for purposes such as water safety, agriculture and power generation (AMBER, 2016). These barriers are introduced in the migration routes of diadromous fish species and are often mentioned as an important aspect in their population decline (Brooke, 1981; Morita et al., 2000; Quinn & Kwak, 2003). The Haringvliet dam is one of these barriers that hinders migratory fish species. Formally, the Haringvliet was in open connection with the sea, it was an estuarine system under influence of the tides. Diadromous fish could freely enter the Rhine and Meuse to spawn, up to Germany and France (Griffioen et al., 2017a; Breukelaar, 2018). However, after the North Sea flood in 1953, the Netherlands decided that this should never happen again. Thus began the construction of the 'Deltawerken', a huge project of dams and other structures, designed to protect the Dutch coastal area against future floods. The downside of this project was that the open connection between the sea vanished. This negatively impacted many ecosystems in the Dutch delta, including the Haringvliet.

After the Haringvliet was closed in 1970, most marine species disappeared and migration routes were obstructed, only a small number of smelt (*Osmerus eperlanus*) and flounder (*Platichthys flesus*) remained (Smit et al., 1997). The Haringvliet became a freshwater habitat, ruffe (*Gymnocephalus cernuus*) was one of the first colonizers, followed by common roach (*Rutilus rutilus*), perch (*Perca fluviatilis*) and bream (*Abramis brama*) (Smit et al., 1997). Zander (*Sander lucioperca*) arrived in 1976 and, being a predator species, became increasingly more important in over the years. Three decades later, in 2016, ATKB calculated the amount of fish in the Haringvliet, it resulted in 40.6kg/ha with 361 specimens/ha. The fish community consisted mainly out of common roach, bream, perch and zander (ATKB, 2016), which are common species in many waters in the Netherlands. With the dominance of common species, the lack of rarer species and a relatively low biomass per hectare compared to for example Lake Loosdrecht with 300 kg/ha and a similar species composition (van Liere & Gulati, 1992), the ecological value of the closed Haringvliet can be considered as fairly low.

In an attempt to improve nature values in the Haringvliet and to open the migratory routes, the Dutch government implemented the 'Kierbesluit' policy in November 2018 (Ministerie van IenW, 2018). The effectiveness of this new policy cannot yet be evaluated due to the recent implementation. However, the sluices are actually still closed much of the times (Roels, 2018), it took until January the 16th for the first real action. At that day, one out of the seventeen sluices were opened for a morning due to the Kierbesluit policy (Ministerie IenW, 2019a). Almost a month later, on February the 12th, the next minor opening period due to the Kierbesluit happened (Ministerie IenW, 2019b). The irregular and infrequent operations of what this policy has led to and more drawbacks created doubts and resistance of many parties (Brom, 2018). Despite this, it can still be considered as a nice start towards a Haringvliet with a larger ecological value.

Besides this measure to increase nature values, other ideas and spatial plans are also being developed for marine and coastal areas, often related to sustainable energy production or water safety (TenneT, n.d.; Vattenfall, 2018). One of these plans is Delta21. The main objective of Delta21 is to create one overarching spatial solution that handles water safety, sustainable energy and nature restoration, while still maintaining the freshwater supply to

Rotterdam and the surrounding regions. The plan is to divide the Haringvliet into multiple areas. The 'Valmeer', tidal lake, Western Haringvliet and a brackish water basin (see Figure 1). The Valmeer and tidal lake mainly serve functions for the production of sustainable energy. These are, however, located in a Natura2000 area. In order to compensate for the loss of natural habitat in this area, the nature value of an area close by should be increased. The Western Haringvliet and brackish area are the chosen locations for this. The Western Haringvliet is proposed to fulfil estuary like roles by having a connection to the North Sea that is as open as possible. A completely open Haringvliet, like how it was historically, is not an option anymore due to societal demands for water safety and freshwater supply.

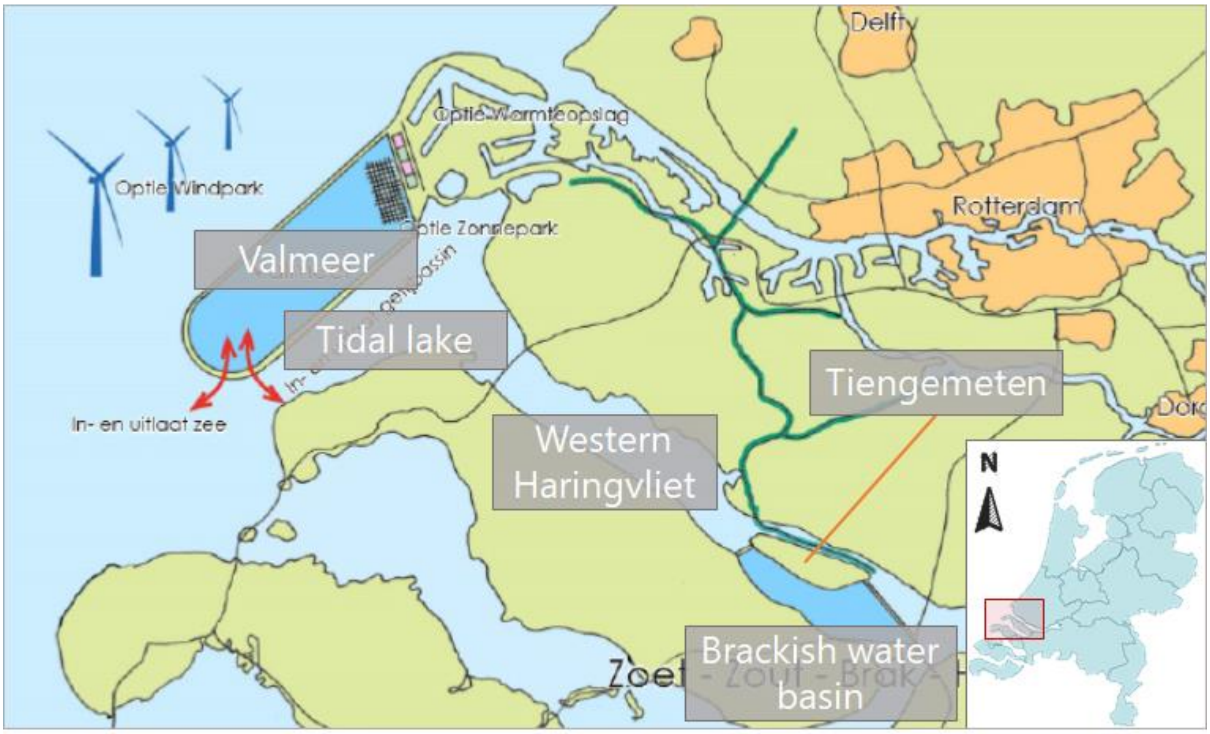

Figure 1: **A conceptual overview of the Delta21 plan**. This figure shows a first draft of what the Haringvliet might look like when Delta21 is implemented. The location of the spatial plan is near Rotterdam, The Netherlands. The water in the Valmeer, Tidal lake and Western Haringvliet is planned to be salt, the water basin below Tiengemeten is planned to be brackish (Delta21, n.d.).

Further opening up the Haringvliet will bring back the influence of the tides and the old freshwater system will be lost. By changing the freshwater system to a system with many similarities to an estuary, habitat is created that is becoming rarer and rarer worldwide (Lotze et al., 2006). Many studies have emphasized the ecological importance of estuaries for a wide variety of organisms on different trophic levels (Barbier et al., 2011; Day et al., 1989; Sheaves et al., 2015). Reopening the haringvliet can also be considered as an essential first step for the recovery of catadromous and anadromous species in the Netherlands, as well as Germany and France (Griffioen et al., 2017a; Breukelaar, 2018). Therefore, when the Haringvliet fulfils the functions of an estuary, it is expected to have a much higher ecological value than in its closed status.

The open connection and salty tides will also affect flora and fauna, among which fish. For this reason the brackish area is proposed, here diadromous fish should be able to acclimate to the change in salinity during their journey. Delta21 has asked us to help them with the question of how to facilitate the migration of diadromous fish in the Haringvliet. Delta21 emphasizes that the spatial plan is not definite yet and adaptations to improve it are appreciated. To help Delta21 with this question, this report will cover questions related to requirements of fish during their migration as well as requirements of fish migration systems.

1.1 Scope and objective of this report

This report focuses on the area where the brackish water basin is planned (see figure 1). The objective is to give requirements for the facilitation of fish migration of catadromous and anadromous fish in this area. We take physical and chemical requirements of fish, requirements for fish passage systems and societal requirements into account. These requirements can be used to optimise or perhaps change the brackish water basin idea. Amphidromous fish that use the estuary, but are not dependent on a migratory route between fresh- and saltwater, are considered beyond the scope of this project. The technical specifications on how to realise these requirements are also beyond the scope of this project. Finally, we assume that potential obstacles to migration implemented by Delta21, such as fish friendly turbines, do not impair fish migration.

1.2 Research questions

Main research question:

> *What are the most important requirements for a fish migration system in the Haringvliet that enables the migration of anadromous and catadromous fish between the North Sea and the Rhine and Meuse?*

Sub-questions:

- *Which catadromous and anadromous fish species will presumably make use of a future system facilitating fish migration in the Haringvliet?*
- *Which physical and chemical conditions are most important for catadromous and anadromous fish species during their migration between fresh- and saltwater?*
- *Which requirements are essential in a system that has to facilitate fish migration between fresh- and saltwater?*

1.3 Methodology

This report is primarily based on literature research, including available monitoring data. We tried to fill potential gaps in available information through the consultation of experts. The experts from whom we received information were Jasper Fiselier from Royal Haskoning, and Erwin Winter from Wageningen Marine Research. The consultation of experts was also used to broaden our view and attain different perspectives regarding the subject.

1.4 Reading guide

Chapter 2 focuses on different fish species that might make use of the Haringvliet for their migration when the migration route is restored. Information regarding dispersal and population status as well as swimming capacity and migration period are covered here. At the end of Chapter 2, in the compendium, a comprehensive overview of the most relevant information of every species is given. Chapter 3 covers the requirements that are important for a fish migration system for diadromous fish. These requirements are derived from our findings in Chapter 2 as well as literature regarding similar systems and societal concerns. Chapter 4 highlights possible drawbacks that should be closely considered when creating a fish migration system based on the formulated requirements. In Chapter 5, the conclusion of this paper is given. Following this conclusion, Chapter 6 ends this report with several recommendations with advice for the fish migration system and suggestions for future research. To finish the references are given as well as a glossary in which complex (biological) terms are explained.

Chapter Two - Selection of Fish Species

The selected fish species are either catadromous or anadromous since these will have to use a system between fresh- and saltwater. Catadromous and anadromous fish species are both defined by a migration between freshwater and saltwater in the spawning season. These behaviours are summarised in the term diadromous. It applies for both kinds that the primary biome where they spend the majority of their life, is different from their spawning biome.

The life cycle of catadromous fish (Figure 2) starts in the sea, where they are born. The young larvae migrate towards the coast where they search for estuaries that allow entrance to freshwater. Catadromous fish will feed and grow to mature size in freshwater. When fully grown, the adults migrate back towards the spawning grounds at sea to complete the life cycle (Cooney, 2013).

For anadromous fish it is the other way around, these fish start the life cycle (Figure 2) in freshwater. The juveniles migrate downstream to estuaries whereafter they reach the sea. Here they spend the largest part of their lives and grow to mature size. The adults migrate back to freshwater to spawn and to complete their life cycle (Cooney, 2013).

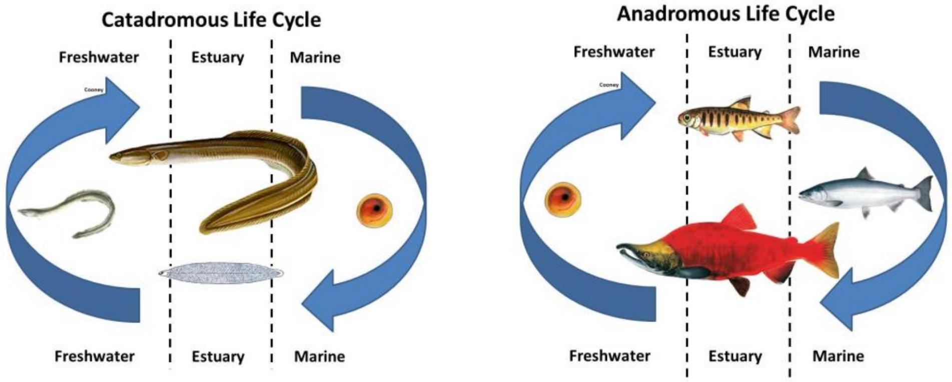

Figure 2: **The life cycle of anadromous and catadromous fish species** (Cooney, 2013). Catadromous fish are born in marine environment and migrate to freshwater for the remainder of their life until it is time to spawn, then they migrate to marine waters again. Anadromous fish spend most of their life cycle in salty marine environments and travel to freshwaters to spawn.

In the following section, both catadromous and anadromous fish species are described which are expected to use the Haringvliet for their migration. Based on data from before the closure of the Haringvliet and recent data, a set of migratory requirements and population details for every species is compiled. These requirements are based on adults of the species, because we consider the spawning migration to be most important. The migration of juveniles is not considered in this report, because there is little data available. The species that are included in this chapter act as representatives for other species that are not covered here. This is due to the diverse collection of species in terms of variables such as swimming speed, size, use of the water column and ability to cope with changes in salinity. To give information about the swimming speed of a fish species, critical stream velocity is used. Critical stream velocity (Ucrit) relates to the swimming speed a fish can maintain for about 20 minutes and thus over longer distances (Winter et al, 2014).

2.1 Catadromous

2.1.1 European Eel (*Anguilla anguilla*)

The geographic range of the European eel covers most freshwater systems in Europe as well as its coastal waters (Jacoby & Gullock, 2014). European Eels are born in the Sargasso Sea and the larvae (leptocephali) drift towards the coasts of Europe using the Gulf Stream (Friedland et al. 2007). Here they rely on accessible freshwater and an estuary in which they can acclimate to the new circumstances (Friedland et al. 2007). *A. anguilla* has been shown to be able to acclimate well in a relative short period (Rankin, 2009), hence the acclimatisation from salt- to freshwater can be considered as not very important for this species (Wilson et al., 2004). Once the freshwater is reached, the eels feed and grow up to adults until they are ready to reproduce. They have to migrate back to the sargasso sea to reproduce and rely on an unobstructed passage to the sea. Peak upriver migration, by juveniles, takes place mainly at night between March to May (Crivelli et al., 2008; van Emmerik, 2016; Griffioen & Winter 2017b; Haringvliet, 2017). When the adults are ready to spawn they migrate to the sea mainly between September to November (Emmerik, 2016; Haringvliet, 2017).

European Eels used to be a common species in the Netherlands with dedicated commercial fisheries. In the Haringvliet the species was present in considerable numbers. Historical data shows that between 1916 and 1939 the average recruitment of eel was 74.000 kg per year (Quack, 2016). Currently, however, the *A. anguilla* stocks have declined by up to 95% (Dekker, 2004; Jacoby & Gollock, 2014), with some reports stating even more dismal numbers (Dekker, 2003). For European Eel a critical stream velocity of 0.2m/s is specified (Emmerik, 2016). It is a benthic species so it is found primarily near the bottom or on the bottom of the river/sea.

2.1.2 European Flounder (*Platichthys flesus*)

The European flounder is a general occurring species along the Dutch North Sea coast, in the Wadden Sea and in the delta area (Kroon, 2009). It can be found in shallow coastal waters and estuaries in the tidal zone, in depths up to 50m (Kroon, 2009). This species is a benthic species that, from September to November, migrates downstream to the sea to spawn (Emmerik, 2016). In December to February, the flounder moves to deeper waters in the North Sea, approximately 20-50m, to spawn (Kroon, 2009; Skerritt, 2010; Emmerik, 2016). This takes place between February and may (Kroon, 2009). After spawning, the adults return to their foraging areas in the coastal zone and the hatched larvae drift to the coastal area by making use of the tidal current (Kroon, 2009; Skerritt, 2010). Some of these larvae and juvenile flounders migrate into freshwater using their weak swimming capacity of 0.3 m/s (Winter et al., 2014), sometimes up to 1000 km upstream (Kroon, 2009). The migration upriver takes place from April to July (van Emmerik, 2016). In two to four years, the flounders become mature and migrate to spawn for the first time. After this first spawning migration they do not migrate to freshwater again but stay in the coastal zone (Kroon, 2009).

Specific required circumstances during this migration are unknown, however, van Emmerik (2016) mentioned that, a sudden salt- to freshwater gradient makes the flounder vulnerable to water quality (van Emmerik, 2016). Under osmotic stress, flounders sometimes get a form of skin ulcers (Wanningen & Herk, 2007).

2.2 Anadromous

2.2.1 Allis shad (*Alosa alosa*)

The natural geographic range of the Allis shad is mainly centered around the estuaries and adjacent coasts and rivers of West Europe (Freyhof & Kottelat, 2008). This species spends its life in the sea but migrates towards freshwater for reproduction, up to 700 km upstream (Laak, 2009; Reeze et al, no date). During this migration it is dependent on estuaries and an unobstructed waterway. Adults migrate upstream between March and June, with a peak in may (Reeze et al, no date). Larvae migrate downstream between July and December, and live in the estuary for the first 1-2 years of their lives (Reeze et al, no date; van Emmerik, 2016). The Allis shad used to be fairly abundant, also in the Haringvliet. In 1885 approximately 340.000 specimens were sold on markets in the area (Quak, 2006). This, however, was the year with the highest recorded amount of this species. 30 Years later, in 1915, the amount had declined to approximately 1% of what it was back in 1885 (De Groot, 1992b). This decrease was mostly due to fisheries and the construction of dams. Currently Allis shad populations have practically disappeared. France is the only place where there is still a healthy population left (Freyhof & Kottelat, 2008). There is, however, a reintroduction project for this species in West-Europe, especially focussing on the North Sea and Rhine (Scharbert et al., 2011).

In an osmoregulatory study carried out by Leguen et al. (2007), young Allis shads were shown to be able to tolerate moderate salinities, such as those found in estuaries, but according to Griffioen and Winter (2014) they do need a period of acclimatisation. For adult *A. alosa*, the critical stream velocity is 0.5 m/s (Peak, 2008).

2.2.2 Atlantic salmon (*Salmo salar*)

Salmon spend most of their life at sea. Adults migrate to freshwater between May and August (but this migration has been seen to occur up until December) to lay their eggs (van Emmerik, 2016; Haringvliet, 2017; Griffioen & Winter, 2014). The larvae migrate to the sea from February to May (van Emmerik, 2016; Haringvliet, 2017). Salmon is a pelagic species with a strong swimming capacity. Adults can swim 4.0-7.8 m/s (Winter et al., 2014; van Emmerik, 2016). As adults, they can overcome a discharge of up to 2 m/s (van Emmerik, 2016), have a critical stream velocity of 0.95 m/s when migrating upstream (Tang, & Wardle, 1992; Peak, 2008). Juveniles migrating downstream, however, require a water discharge between 0.05-0.25 m/s (van Emmerik, 2016). Atlantic salmon require a gradual salt- to freshwater gradient transition to adapt to salinity changes (Deelproject visserij, 2017). Potter (1988) described the transition of salt to freshwater for adults, as 'not of a great concern'. However, when newly hatched salmon migrate to the sea, Hawkes, et al. (2017) identified that an abrupt change in salinity could be a cause for increased smolt mortality due to osmoregulatory stress which makes the fish vulnerable to predation (Handeland et al. 1996).

Salmon used to be a significant contributor to the Dutch fishing industry. However, since industrialization, the river channel has been manipulated with sluices and dikes which has changed the structure of their waterways (De Groot, 1992a). Sluices are not an absolute barrier though, as there are cases where salmon can pass through sluices (Larsson, 1984).

Nowadays there are salmon populations ranging along the coast from Portugal to Russia and they also still occur in small numbers off the coast of the Netherlands (van Emmerik, 2016, Nicola et al., 2018, Nilsson et al., 2001). There have also been cases of salmon at the Haringvlietdam (Griffioen & Winter, 2017b). The salmon are still present in very small numbers in the river Rhine and Meuse originating from upstream stockings (Raat, 2001).

2.2.3 Atlantic sturgeon (*Acipenser sturio*)

It is known that the sturgeon has inhabited Dutch waters in the past. However, due to overfishing and the loss of the estuarine character of the Rhine-Meuse delta, the number of sturgeons has been decreasing for the past 400 years (Raat, 2001; de Groot, 2002; Hop, 2011). This species is now practically extinct around the Dutch coasts and the Rhine (Raat, 2001; De Groot, 2002). A small natural population in the French Gironde estuary is present nearby (Lepage et al., 2005; Rochard et al., 2001). Pilot reintroduction programs have been set up with juveniles from the French population as well as American specimens (Ludwig et al., 2008; RAVON, 2018).

The critical stream velocity for *A. sturio* is unknown, however, they can withstand a water discharge of 2.2 m/s as adults and 0.8-1.0 m/s as juveniles (van Emmerik, 2016). In the past, Atlantic sturgeon have swum up the Rhine between April and September, traveling distances of 860 km up the Rhine to spawn (van Emmerik, 2016; Haringvliet, 2017). When the eggs hatch, the juveniles swim towards the estuary in March where they grow for 8-12 years, after which they migrate to the sea from September to December (Haringvliet, 2017). Their salinity tolerance increases with age up to 35 g/L after 2-4 years (van Emmerik, 2016).

2.2.4 Twaite shad (*Alosa fallax*)

Up until the 1950s a population of Twaite shad was present in the Rhine (Hoek, 1899; de Groot, 1989). Thereafter a large decline occurred due to the damming of the river which caused an absence of tidal currents and an increase in sedimentation (de Nie, 1996). Nowadays, the species is occasionally observed along the Dutch coasts and in the delta (van Emmerik, 2016). There are even recent reports regarding spawning events of *A. fallax* but a sign of successful reproduction is lacking since no juveniles have been found during monitoring (RAVON, n.d.a). No studies have been done regarding the osmoregulatory abilities of *A. fallax* (Lochet et al., 2009).

The Twaite shad migrates in April to June, from the sea towards freshwater areas that are under influence of the tides (van Emmerik, 2016; Griffioen & Winter 2017b; Haringvliet, 2017). They can withstand a discharge of 2 m/s (van Emmerik, 2016) and a critical stream velocity of 0.5m/s (Peake, 2008, Quak, 2012). Twaite shad lay their eggs on the edge of the fresh- saltwater transition (Wanningen & Herk, 2007) where the discharge is between 0.2 and 0.5 m/s (van Emmerik, 2016). Newly hatched juveniles start to migrate to the estuary in July until October where they may stay for a year or head directly to the sea (Haringvliet, 2017). It is important that a rich estuary is present for the Twaite shad for spawning and as a nursery (Winter et al., 2014). Acclimatisation in the estuary is required (Griffioen en Winter, 2014) but it is unclear how long or important the acclimatisation period is.

2.2.5 Sea trout (*Salmo trutta*)

Although the sea trout is still observed in the Rhine and Meuse, populations are not as common as they used to be (Raat, 2001). Sea trout is a pelagic species with a strong swimming capacity (Winter et al., 2014). The critical stream velocity of sea trout is 0.70 m/s (Peake, 2008), but it is not often found in rivers with a discharge higher than 0.60 m/s (van Emmerik, 2016). They migrate upriver to spawn from around June to December (van Emmerik, 2016; Griffioen & Winter 2017b; Haringvliet, 2017). The Juveniles migrate back to the sea from January to July and require a discharge of no more than 0.20 m/s (van Emmerik, 2016; Haringvliet, 2017). Although the population of sea trout in the river Rhine and Meuse is historically low, the past 25 years has seen an increase in trout populations in the river Rhine due to the water quality improving in the river (Cazemier, 1994). This is an positive indication that restoration of salmonid species in the river Rhine and Meuse is possible.

Little data has been published about the sea trout which could be due to this fish not having much historical relevance or that it has been mis-identified as a different species (Quak 2016, De Groot 2002). It seems that Sea trout do not need much time to adjust to changing salinity for they have been known to survive up to 5 months when removed from freshwater and placed in saltwater (de Laak, & van Emmerik, 2008; Griffioen & Winter, 2014). Other literature indicate that up to 30 hours are required for sea trout to adapt their osmoregularity (Hawkin et al., 1979; bij de Vaate & Breukelaar, 2001).

2.2.6 Houting Species (*Coregonus oxyrinchus, Coregonus maraena, Coregonus albula*)

Here three Houting species are covered, *C. oxyrinchus* is native to the Netherlands, *C. maraena* is a Danish species but can be also found Dutch waters and *C. albula* was formally found in the Rhine. Due to their similarities these species will further be referred to as Houting. Houting adults migrate in September to December to freshwaters adjacent to the North Sea and Western Baltic Sea to spawn. Winter et al. (2014) states that *C. oxyrinchus* has a strong swimming capacity. The critical stream velocity for *C. oxyrinchus* is reported to be0.3 - 0.7 m/s (Peake, 2008; van Emmerik, 2016), we expect the other Houting species to have similar values. Juveniles swim to the estuary throughout the year and can develop into adults in the shallow waters of the estuaries and coast (Haringvliet, 2017). There is a lack of information regarding migratory circumstances and water variables regarding these species. The acclimatisation period is unknown, but it is not expected to be of high importance (Griffioen & Winter, 2014).

As with most fish species in our selection, these houting species were formerly abundant along the Dutch coasts and also in the Rhine (de Groot, 2002; Quak, 2016). Nowadays, only a small spawning population remains in Denmark (de Groot, 2002), however there are currently projects that aim to reintroduce houting species in the waters of North-West Europe (Borcherding, 2010; Jäger, 1999; Jepsen et al., 2012). This has led to the first signs of an increase in abundance in Dutch waters, especially in the Lake IJssel and River IJssel (Borcherding, 2006; Kranenbarg, 2002; Winter et al., 2008).

2.2.7 European river lamprey (*Lampetra fluviatilis*)

In the early twentieth century, the river lamprey was abundant in the Dutch waters (Hop, 2011). While the population numbers plummeted when the Haringvliet was closed, the river lamprey never disappeared. Since the eighties, the river lamprey populations have been slowly recovering (Raat, 2001; Hop, 2011), possibly due to a reduction of pollution and an increase in water quality (Hop, 2011). It is estimated that currently around 100.000 adult river lamprey migrate upstream to spawn in the Netherlands (Winter & Griffioen, 2007). An open route free of barriers is essential for migration from the estuary to their spawning grounds. Their spawning area should contain plenty of hiding places and gravel to spawn (Maitland, 2003). The recently hatched river lamprey bury themselves in the ground in nursery areas with slow flowing freshwater and sandy/silt sediment (Maitland, 2003). When grown to sufficient size they migrate to the estuary from October until March (van Emmerik, 2016; Haringvliet, 2017).

Acclimatisation of *L. fluviatilis* is not mentioned in literature but it is expected that the acclimatisation is of little concern as they live in (brackish) estuaries and rivers (Arcadis, 2018; Winter et al., 2014). This species migrates upriver from October to March (van Emmerik, 2016; Griffioen & Winter 2017b; Haringvliet, 2017) when the river discharge is high. This indicates that they are strong or at least moderate swimmers, as emphasized by (Winter et al., 2014). Van Emmerik (2016) states that an adult river lamprey can swim upstream in water velocities of up to 2 m/s and can swim 2,6 to 3,4 m/s.

2.2.8 Sea lamprey (*Petromyzon marinus*)

P. marinus migrate upriver from April to July (Griffioen & Winter, 2017) and has a critical stream velocity of 0.75 m/s (Peake, 2008). Sea lampreys are primarily a nocturnal species (Almeida et al., 2002). However, at the end of their spawning migration, when the spring draws near, they become day active. This is due to the rising water temperatures. Shortly before they migrate, sea lampreys stop feeding. Thus, they need to complete the migration and spawning on stored energy alone (Binder & Gaden, 2010). Swimming in cold water costs a lot more energy. This is why they time their migration to their ideal temperature (Binder & Gaden, 2010). The sea lamprey acclimatizes easily to changes in salinity (Winter et al., 2014).

The populations of sea lamprey in the Rhine and Meuse have seen a decreasing trend in the last 50 years (Raat, 2001). However, since the nineties, the populations in the Netherlands have been slowly increasing again (Raat, 2001). During a research in 2010, 50 sea lampreys were marked. Of these 50, only six migrated through the Haringvliet sluices. When migrating through these sluices, it was noted that they migrated shortly after the opening, or shortly before the closure, since this is when the water discharge is lowest. Currently the sea lamprey appears to reproduce in the entire Rhine area, excluding the parts in the Netherlands (Hop, 2011). Just like the river lamprey, the sea lamprey also requires a migratory route that is free of barriers. The water flow should also not exceed 2 m/s (Maitland, 2003).

2.2.9 European smelt (*Osmerus eperlanus*)

There are two forms of smelt present in Dutch waters: A landlocked, non-migratory and an anadromous form. The anadromous form is found in the estuaries and lower reaches of the large rivers. No anadromous smelt have been caught in the lower reaches of the Rhine since 1966 (de Groot, 2002). Anadromous smelt used to spawn in the lower reaches of the Rhine and freshwater tidal areas and was rare up river, near Arnhem and Nijmegen (de Groot, 2002). Spawning occurs in February up to May (van Emmerik, 2016; Griffioen & Winter 2017b; Haringvliet, 2017). The larvae migrate downstream from May to July where they first live in estuaries as juveniles, before moving on to coastal areas where they feed (van Emmerik, 2016; Haringvliet, 2017). The adults live in estuaries, coastal areas and at sea(de Groot, 2002; van Emmerik, 2016). The adults migrate upriver from February to March and downriver in July/August (de Groot, 1990; van Emmerik, 2016; Haringvliet, 2017). The critical stream velocity for this species is 0.30-0.46 m/s (Peake, 2008; Quak, 2012; van Emmerik, 2016). This indicates that European smelt has a weak to moderate swimming capacity (Winter et al., 2014). The acclimatisation time needed from salt- to freshwater is not known but it is possibly important (Kruitwagen, 2009).

2.2.10 Three-spined stickleback (*Gasterosteus aculeatus*)

G. aculeatus has a weak swimming capacity (Winter et al., 2014) with a critical stream velocity of 0.2 m/s (Peake, 2008; van Emmerik, 2016). The acclimatisation to salinity is not of large importance (Griffioen & Winter, 2014). The three-spined stickleback migrates upriver to spawn from February to May (van Emmerik, 2016; Griffioen & Winter 2017b; Haringvliet, 2017). Juveniles migrate to the estuaries from July to September (van Emmerik, 2016; Haringvliet, 2017).

Both anadromous populations and non-migrating freshwater populations of three-spined stickleback exist of three-spined stickleback exist. While the non-migratory populations are found in rivers and creeks that hold no direct connection to the sea, the migratory three-spined sticklebacks can be found around almost every freshwater outlet into the sea, where they attempt to enter the freshwater (Emmerik, 2006). Due to the barriers that are now present, populations of the migratory variant have strongly declined (RAVON, n.d.b).

2.4 Compendium

In general, it can be said that most fish species described above can be considered to be rare in the Dutch waters nowadays. This is due to various factors of which the obstruction of the migration path is probably an important one. Only a few species remain (relatively) common in the Dutch waters but even these species have seen a population decline since the closure of the Haringvliet. In Table 1 an overview is given of the most important details of the species described above.

Table 1. **Characteristics overview of fish species from Chapter 2**. For swimming speed, Ucrit (critical stream velocity) relates to the swimming speed which can be maintained for about 20 minutes and thus over larger distances, or the maximum aerobe cruising speed (Winter et al, 2014). The data in this compendium reflects what is written in Chapter 2. The references are given in the corresponding text.

Species name	Population status Dutch waters	Swimming speed	Adult Migration period	Acclimatisation to salt-/freshwater
European Eel (*Anguilla anguilla*)	95% decline since 1916-1939	Ucrit 0.2 m/s	September - November	not important
European Flounder (*Platichthys flesus*)	General occurrence along Dutch coast	Swimming capacity juveniles 0.3m/s	September - November	Important

Allis shad **(*Alosa alosa*)**	Practically disappeared, reintroduction project for lower Rhine	Ucrit 0.5 m/s	April - July	Important
Atlantic salmon (*Salmo salar*)	Large decline from historical numbers, occasional occurrence	Can maintain swimming speed of 0.91 m/s, Ucrit specified as 0.95m/s	May - December	(Important for juveniles)
Atlantic sturgeon (*Acipenser sturio*)	Practically extinct, pilot reintroduction projects happening	Unknown, can withstand discharge of 2.2 m/s	April - September	(Important for juveniles)
Twaite shad **(*Alosa fallax*)**	Large decline from historical numbers, now occasional occurrence	Ucrit 0.5m/s	April - June	Important
Sea trout **(*Salmo trutta*)**	Low however increasing trend over the past 25 years	Ucrit 0.70m/s	June-December	Not important
Houting Species (*Coregonus oxyrinchus, C. maraena, C. albula*)	No natural spawning population left but increasing numbers due to reintroduction projects	Ucrit 0.3 - 0.7	September - December	Unknown, probably not important
European river lamprey **(*Lampetra fluviatilis*)**	Estimated upstream migrating population of 100.000 individuals	Can withstand up to 2m/s discharge, swimming capacity 2.6 - 3.4m/s. Ucrit possibly comparable with related Sea lamprey	October - March	Unknown, probably not important
Sea lamprey (*Petromyzon marinus*)	Low however since 1990 slow upward trend	Ucrit 0.75 m/s	April - July	Unknown, probably not important
European smelt (*Osmerus eperlanus*)	No migratory populations left	Ucrit 0.30-0.46 m/s	February - March	Possibly important
Three-spined stickleback (*Gasterosteus aculeatus*)	Strong decline since construction of Deltaworks	Ucrit 0.2 m/s	February - May	Not important

Chapter Three - Fish Migration System Requirements

To create a fish migration system which facilitates the migration of as many diadromous fish species as possible, the requirements from the selected fish species in Chapter 2 need to be taken into account. Due to the stakeholders that are involved within this area, various societal aspects are also important to consider. The requirements are therefore divided over two categories; the physical and chemical requirements that facilitate fish migration and the societal requirements.

3.1 Physical and chemical requirements

In this part, the requirements needed for the diadromous fish species to migrate between fresh- and saltwater are acknowledged. Attraction flow, entrance location, timing of upstream migration, salinity, acclimatisation, water velocity and turbulence are determined as important factors to consider when designing a fish passage. There may be more requirements to bear in mind, however, this selection was made based on chapter 2 and similar fish passage projects, such as the migratory fish river at the Afsluitdijk (ARCADIS, 2018).

3.1.1 Attraction flow & Entrance location.

A fish passage can only be effective when it is both passable and attractive (Bunt, 2001; Monden, 2007). The attractiveness of a fish passage is the ability to draw fish towards the entrance of the fish passage. Fish rely mainly on chemical and olfactory cues during migration to find an appropriate route upstream, the attraction is therefore primarily created by a freshwater outflow, the 'attraction flow' (Monden, 2007; Sola, 1995; Wisby & Hasler, 1995). It is important that the attraction flow is large enough so that fish are able to trace it and naturally swim toward the system. ARCADIS (2018) states that an outflow rate of at least 3% of the main current, corresponding to 10-20 m^3/s in their project, is sufficient for the recognisability of the attraction flow. In a fish migration system in the Rhone delta, an attraction flow of 2-8% of the river discharge was used, corresponding to 60 m^3/s (Larinier, 1998). Generally, 'the more attraction flow, the better', applies, this will enhance the recognisability of the migratory route (Monden, 2007). To create an effective attraction plume of freshwater in an efficient manner the outflow should be directed perpendicular on the main current.

The amount of attraction outflow has to be specifically calculated and modelled relative to other freshwater flows and variables that may occur in the area (Larinier, 1998). Within the Haringvliet these variables are dependent on the discharge of the Rhine and the Meuse as well as the tides that will come in from the North Sea. It can be hard to maintain an effective attraction flow in times when river discharge is very low or very high (ARCADIS, 2018). For an attraction flow for a fish migration system in the Rhine this would mean that we have to work with discharge values of ±800 m^3/s at minimum, ±2000 m3/s as average and ±13000 m^3/s at maximum (see Figure 3). If we assume that the outflow should be 3% of the main river discharge, based on similar projects described above, an outflow of 24 m3/s at minimum discharge is required here to have a traceable attraction outflow. At average discharge an outflow of 60 m^3/s is needed and at maximum discharge 390 m3/s.

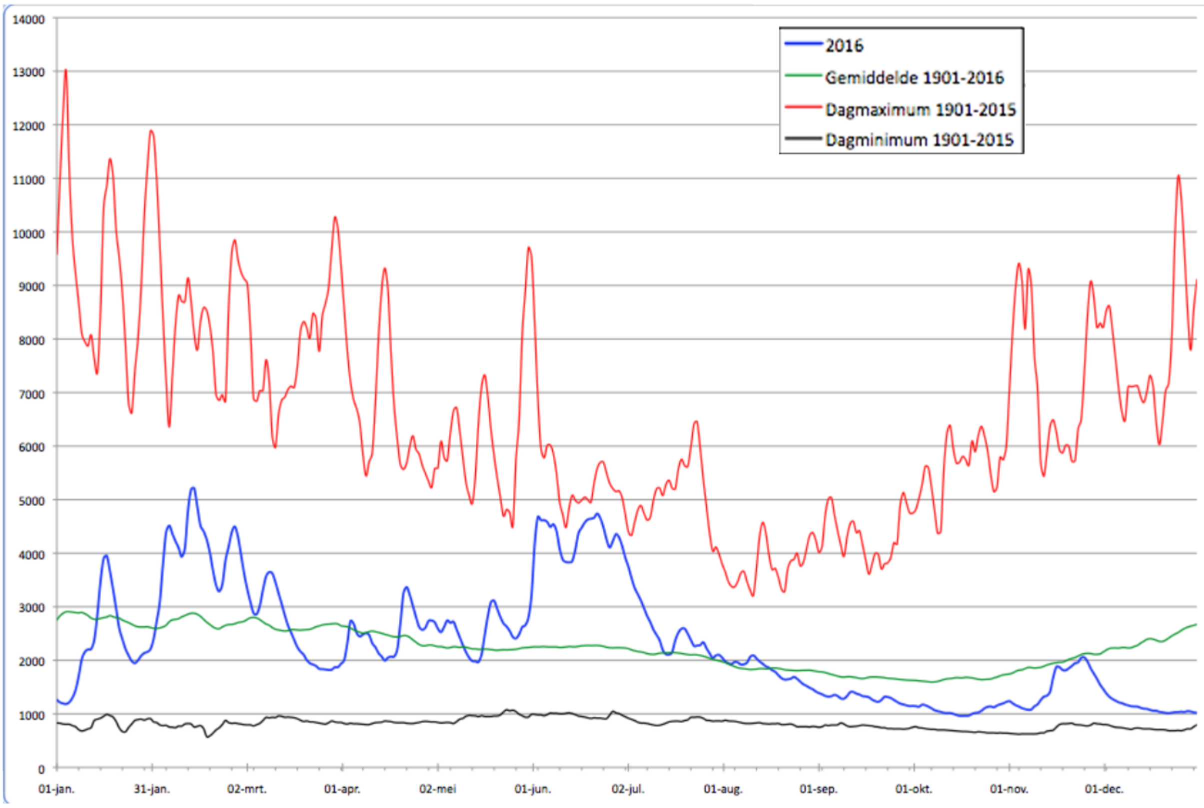

Figure 3: **Discharge river Rhine in the period of 1901-2016**. The red line indicates the maximum discharge that has been recorded over the period of 1901-2015 for every day of the year for the river Rhine. The green line indicates the average discharge of the Rhine at every day of the year over the same period. A trend can be seen. In winter the discharge of the river Rhine is highest, at the end of the summer discharge is lowest. (Waterpeilen.nl, 2016)

The location of the entrance of the fish migration system in relation to the attraction flow is also of great importance for its effectiveness (Beach, 1984). Most migratory fish will naturally follow the main current of the river. When the fish encounter a barrier while following the main current, they start to search for alternative routes within a small area in front of the barrier, the so called 'migratielimietlijn' (MLL) (Kroes & Monden, 2005, Kranenbarg & Kemper, 2006), see Figure 4. The exact location of the MLL is dependent on the discharge and swimming capacity of the fish species, therefore every species has its own unique MLLs. The MLL of weak swimmers, such as the three-spined stickleback and glass eel, is located further away of the barrier than strong swimmers, such as salmon and houting. Since the water velocity is generally lower at the river banks, fish tend to accumulate there (Kroes & Monden, 2005). The optimal placement of the entrance of a fish migration system will be within or at the border of the MML on one of the river banks (ATKB, 2013; Mondes, 2007). This will also create an optimal attraction plume due to the perpendicular outflow relative to the main current.

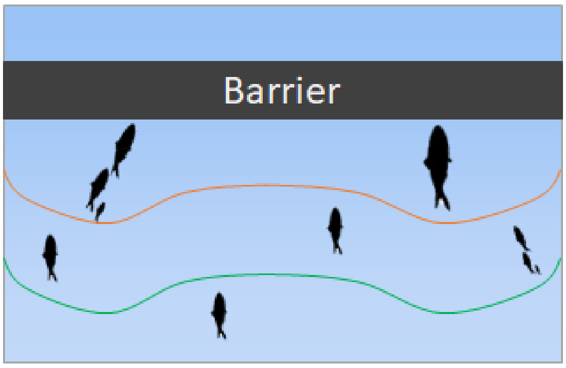

Figure 4. **Examples of a 'migratielimietlijn'**. The orange line indicates a migratielimietlijn of a stronger swimming species, for example Salmon. Such species search for a path close to the barrier. The green line represents the migratielimietlijn of a weak swimming species, such the three-spined stickleback. They are weak swimmers and look for route further away of the barrier. The main current causes the dent in the centre.

3.1.2 Timing of adult migration

Fish time their migration to maximise their reproductive success. For different fish species, the migratory periods can occur during different times of the year. Drivers like mating opportunities, temperature, currents, food availability and population densities affect fish to start to migrate. For a lot of species there is a lack knowledge of what exactly triggers their migratory behaviour. Fish species don't migrate the whole year round, but do this only at specie specific times of the year. Many species in our selection migrate upstream during the spring and summer between the months march and august (see Table 2). This is also the time when the water discharge of the river is lowest (see Figure 3). However, there are also many species that migrate during fall or winter (see Table 2). Some species, such as European eel, also tend to migrate at night, instead of during the day (Crivelli et al., 2008).
To enable migration, management should consider these windows in time. Since there is a vast variety in the migration period of the selected species, the system should be closed as little as possible to facilitate the migration of as many species as possible.

Table 2. **Overview migration period of the adults of several fish species constructed from information in Chapter 2.** The blue boxes indicate that the species is migrating during this month. The white boxes indicate that the species is not migrating during that month.

	Winter		Spring			Summer			Autumn			
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
European eel									■	■	■	
European flounder									■	■	■	
Allis shad				■	■	■	■					
Atlantic salmon					■	■	■	■	■	■	■	■
Atlantic sturgeon				■	■	■	■	■	■			
Twaite shad				■	■	■						
Sea trout						■	■	■	■	■	■	■
Houting									■	■	■	■
River lamprey	■	■	■							■	■	■
Sea lamprey				■	■	■	■					
European smelt		■	■	■								
Three-spined stickleback		■	■	■	■							

3.1.3 Salinity & Acclimatisation

Migratory fish have to overcome the transition between fresh- and saltwater. When migrating from the sea to a lower salinity, water enters the cells through osmosis due to higher ion concentrations in the cells, which make the cells swell (McCormick et al., 2013). When fish migrate from freshwater to a higher salinity, the opposite is the case, hence the cells shrink (McCormick et al., 2013). Abrupt and large changes in salinity can disturb water and ion regulation in fish, causing additional energetic costs, which reduces the energy available for vital functions for fish health and the immune system (Vethaak, 2013). The ability of euryhaline fish to maintain homeostasis under changing salinity conditions depends on how fast the fish is able to detect these changes and react by osmoregulation in cells (Kültz, 2015).

For all species mentioned in chapter 2, absolute values of the period of acclimatisation are hardly available. The information available is qualitative information about the importance of acclimatisation. Acclimatisation is considered important to a certain extent for European flounder, Twaite shad, Allis shad, juveniles of the Atlantic salmon and juveniles of Atlantic sturgeons (van Emmerik, 2016). For salmon, sturgeons and Twaite shad, it is described that salinity tolerance increases with age. The same is possibly the case for Allis shad, which is together with Twaite shad resident in the estuary in the first one or two years of its life (Lochet et al. 2009), where salinities are normally moderate because of mixing of fresh- and saltwater. This could imply that acclimatisation could be important for these species during downstream migration. With regard to the Haringvliet, acclimatisation is probably the most important for Twaite shad, as this species reproduces in the fresh part of the estuary or just upstream (van Emmerik, 2016). Twaite shads would therefore encounter the fresh-salt transition in an earlier life stage than salmon and Allis shad, which reproduce further upstream (Reeze et al., n.d.). Flounder is known to experience health problems (ulcer) when exposed to osmotic stress (Vethaak, 2013), but it is not specified whether this is during specific life stages. Acclimatisation is also mentioned to be of possible importance for European smelt, but the extent is not specified.

For some of the fish species, the importance of acclimatisation to a salinity gradient is not yet known. This includes species like sea lamprey, river lamprey and houting. However, it is assumed that these species don't have a very high need for acclimatisation (Griffioen & Winter, 2014). Acclimatisation is not expected to be expected to be of high importance for European eel (Wilson et al 2004), sea trout (Hawkin et al., 1979; bij de Vaate & Breukelaar, 2001; Griffioen & Winter, 2014), adult salmon (Potter, 1988), and three spined stickleback (Griffioen & Winter, 2014). However, based on the fact that the goal is to facilitate migration for all species, also the species that have difficulties with fast acclimatisation, a gentle salinity gradient needs to be realised to provide a sufficient acclimatisation period.

3.1.4 Water velocity

Not all fish species are equally good swimmers. As mentioned in Chapter 2, salmon have a critical stream velocity of 0.95 m/s, while three-spined sticklebacks are far worse swimmers and can only swim with a speed of 0.20 m/s at most. The aim of the fish migration system is to allow as many fish species as possible to utilise it. This means that measures need to be taken to ensure that the weakest swimmers are also able to swim upstream. The aim should be that every fish species has a path through the entire system that is lower than their critical stream velocity. Species could possibly overcome short distances of faster flowing water with bursts of high speed, higher than the critical stream velocity (Videler & Wardle, 1991). If this is the case, resting areas of slower flowing water are needed at regular intervals.

Another point that should be taken into account is a statement from M.A. Beach (1984), who stated that 'non- leaping species have to swim at least 30% faster than opposing flows to progress upstream'. Perhaps the water velocity should thus be 30% lower than the critical stream velocity of the species. By creating a system with several zones of different water velocities occur, the species are able to choose their own path depending on their swimming capacity.

3.1.5 Turbulence

The extent to which fish are affected by turbulence is dependent on the swimming capacity and the size of the fish species. The larger the size, the higher turbulence they can withstand (Lupandin, 2005). During fish migration the fish are either on their way to spawn as adults or on their way to feeding grounds as juveniles. Both of these periods can be considered as times at which fish are relatively susceptible for stress (Wendelaar Bonga, 1997). Schreck et al. (2010) emphasizes that stress has various negative effects during fish reproduction. Therefore there should be an aim towards a system with little turbulence to assure that fish will not be impaired by too much turbulence (Cada et al., 1999). Turbulence lower than 0.05 m^2/s^2 is considered low, while above 0.05 m^2/s^2 is considered as high turbulence for fish passages according to Marriner et al. (2014). Based on the lack of specific knowledge, the fish migration system should aim for a turbulence below 0.05 m^2/s^2 to minimize stress during the migration of diadromous fish.

3.2 Societal requirements

Besides the physical and chemical requirements, there are also societal requirements that need to be considered. These requirements are based on the goals of Delta21. The first societal requirement that the fish migration system needs to adhere to, is that it must not interfere with the prevention of salt intrusion. It must also safeguard the water safety in case of a high river discharge and/or extreme tides. Finally, the fish migration system should not impair shipping activities in the Haringvliet area.

3.2.1 Salt intrusion

A very important criterion is that the freshwater supply is guarded against the saltwater intrusion. This is because many farmers depend on the freshwater for their crops and the city of Rotterdam also depends on the freshwater of the Haringvliet for their water supply (Meerkerk et al, 2013; Buitenhuis, 2017). Upon implementation of the 'Kierbesluit' a promise was made that the saltwater would never intrude further than the line between Middelharnis and the opening of the Spui (deingenieur.nl, 2018), see Figure 5. The Spui is an important inlet for freshwater for the city of Rotterdam. Many points where freshwater was obtained for societal purposes had to be moved further inland due to this new policy (deingenieur.nl, 2018). Thus, not only does the fish migration system need to allow fish to migrate, it also should not interfere with the criteria against salt intrusion.

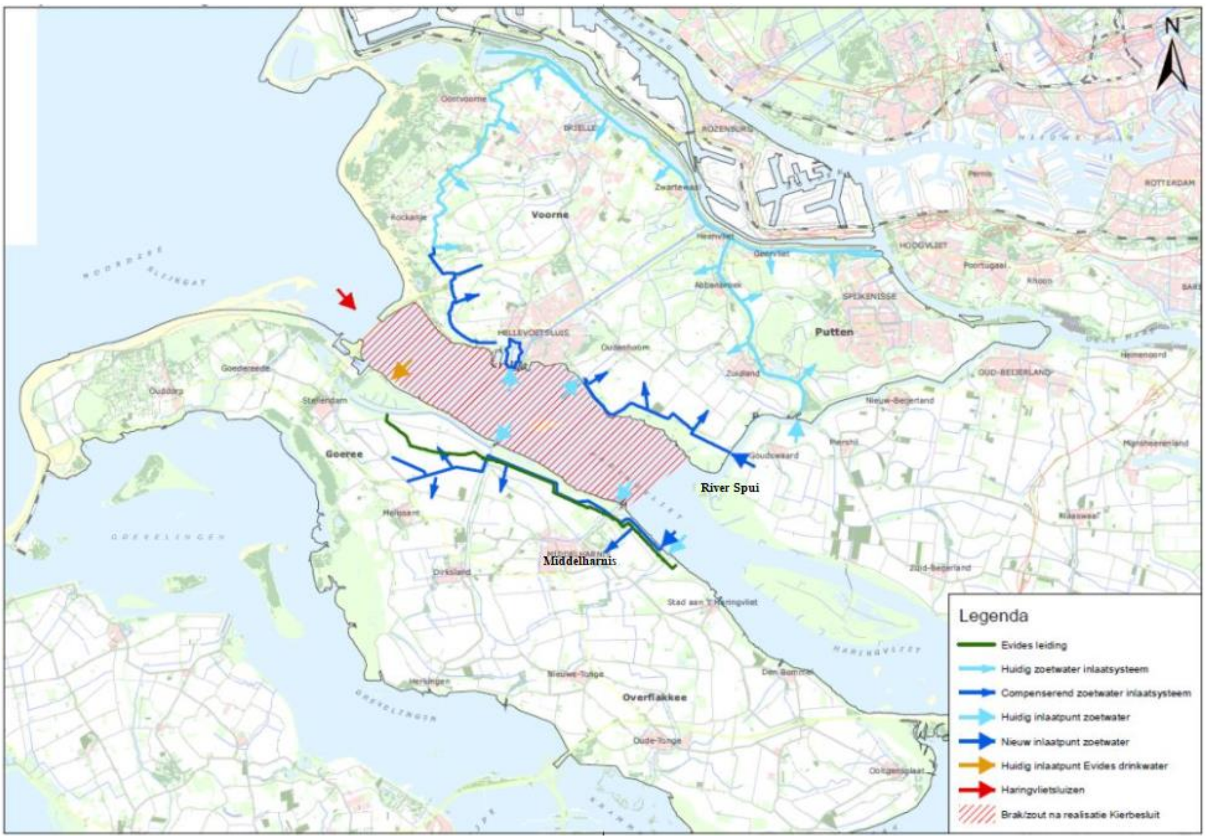

Figure 5: **Saltwater intrusion under the 'Kierbesluit'**. The dashed red area indicates the area which is predicted to become salt to brackish under the 'Kierbesluit' (deingenieur.nl, 2018).

3.2.2 Water safety

Occasionally the river discharge will be exceptionally high, up to 13000 m3/s (see Figure 3). The fish passage should not produce a build-up of water which jeopardizes water safety. If this is the case, it should be mitigated by, for example, an additional waterway which can facilitate the discharge of excess water.

3.2.3 Shipping activities

A third societal requirement that needs to be taken into account is the use of the Haringvliet for shipping and transportation purposes. Next to the 'Haringvlietdam' lies the 'Goereese sluis'. This sluice facilitates the travel of ships between the North sea and the Haringvliet (Ministerie van VenW, 2004). The importance of shipping activities in the Haringvliet are further elaborated in Ministerie van VenW (2004). The fish migration system should not impair the commute of ships through the Haringvliet.

Chapter Four - Drawbacks

Every project encounters problems that have to be considered and could impair the quality or implementation of it. Delta21 is no exception. In this chapter we outline several drawbacks that could hinder the implementation of Delta21. The drawbacks are selected based on the knowledge of Tide for Change, the information from experts such as L. Nagelkerke and J. Fiselier from Royal Haskoning as well as personal communication during meetings with the commissioner.

4.1 Artificial discharge

The Delta21 spatial plan aims to create a 'Valmeer' (see Figure 1) to store energy. In order to store the energy, water needs to be pumped from the tidal lake into the basin so that sustainable energy can be produced. The pumping of water into the lake could be an obstacle for fish as they can be sucked up by the turbines into the lake. Discharging water through these turbines can also cause extreme artificial water flows, causing high turbulence, that can possibly obstruct fish from reaching the Haringvliet and cause stress (Cada et al., 1999). It needs to be considered that these artificial water flows may interfere with the ability of fish to reach the fish migration system. Management should keep this in mind.

4.2 Reduced discharge, Nieuwe Waterweg

An important point of consideration revolves around the Nieuwe Waterweg. The Nieuwe Waterweg is a deep channel that is important for ship passage in and out of Rotterdam (Meyer & Hermans, 2009). This channel is open to the sea and requires a high discharge form the river Rhine to keep the saltwater at bay. At low discharge (mostly in the summer months, see Figure 3), the salt intrusion moves further up river. The discharge in the Nieuwe Waterweg needs to be maintained and is prioritised which results in less freshwater discharge to the Haringvliet area. This contributes to the importance of a border which can be closed to prevent salt intrusion in the Haringvliet (Ministerie van VenW, 2004). In turn, this would hinder the migration of the fish at periods when the migration of most fish species is occurring. It would also interfere with freshwater needed for a sufficient attraction flow as discussed in 3.1.1. Drawbacks of varying discharge levels of the Rhine are further elaborated in section 6.4 of this report.

4.3 Upstream obstacles

The fish migration system in the Haringvliet is not the only obstacle that fish have to overcome. Improving one point of the entire trajectory that migratory fish have to traverse yields no guarantee that you get results, unless the rest of the trajectory is also suitable for migration and spawning. For example, Germany has tried to restore salmon populations in the river Rhine by setting up large projects to grow and release juvenile salmon (Rhine & Salmon 2020, 1991). However, in the Netherlands the Haringvliet sluices remained closed, preventing these salmon from reaching the sea through what was historically their primary migratory route. As long as these sluices remain closed, the efforts of the Germans will be relatively ineffective (Ad hoc review group, 2008). A similar problem could arise in this project. Although re-opening the Haringvliet migration route for diadromous fish species is an essential first step in population restoration of diadromous fish species, population restoration is not expected if there are obstacles further upstream or if their spawning grounds are destroyed. This is therefore an important factor to take into account when the aim is to restore the population of an anadromous or catadromous fish species.

4.4 Loss of current system

Although the introduction of an estuary system in the Haringvliet and fish migratory system enables the migration of diadromous fish and increases the living area of estuary inhabiting species, the current freshwater system of the Haringvliet will be lost. The species that currently live in the Haringvliet and rely on freshwater will be lost when the water becomes more saline. This means that the current system, a Natura2000 area, is expected to undergo large changes in terms of species composition. The ecological value of an introduced estuary system in the Haringvliet would probably outweigh the ecological value of a much more common freshwater lake, as discussed in Chapter 1.

4.5 Pollution due to hydrological changes

Hydrological aspects are bound to change in the Haringvliet due to the return of the tides and the addition or removal of obstructions. A possible effect of these changes in water flows is the erosion of sediment. The sediment that is eroded could be deposited at other places in the Haringvliet, starting the process of sedimentation. In addition, there is a lot of polluted sediment buried in the Haringvliet (Kuijpers, 1995). This might get resuspended, causing an increase in pollution in the area, which could possibly decrease the ecological value of the system.

4.6 Fishery activities

When visiting the area, ongoing fishing activities were seen. If a fish migration system is constructed, with a focus on allowing migratory fish to return, these fishing activities might negatively impact the ability of migratory fish to actually reach the fish migration system. The area of the Haringvliet is also a Natura2000 area (Ministerie van LNV, n.d.c). To aid fish population growth, the Natura2000 regulations should be respected and enforced. By ensuring that there is little to no fishing activity in these areas, the fish will have a greater chance of reaching the river and increasing their populations.

4.7 Last island in Dutch river delta

Another possible drawback is that Tiengemeten is the last remaining island in the Dutch river delta. Historically, the river delta consisted of many islands and sandbanks (Schenk, n.d.), but one after another these have been connected to the mainland through roads and dams or removed. Perhaps building new structures on or near Tiengemeten or even connect it to the mainland through dams would cause additional resistance from the local population.. This is an societal issue which is based on the emotional value of the island.

Chapter Five - Conclusion

The research question of this report was: *What are the most important requirements for a fish migration system in the Haringvliet that is able to facilitate the migration of anadromous and catadromous fish between the North Sea and the Rhine and Meuse?* We have identified important aspects to bear in mind on an ecological and societal basis. These are divided over three sub-questions. We have encountered knowledge gaps some areas hence we have proposed some recommendations.

The first sub-question of this report was: *Which catadromous and anadromous fish species will presumably make use of a future system facilitating fish migration in the Haringvliet?* These fish species are compiled in the selection in Chapter 2, subdivided in catadromous and anadromous fish species. In total we described 12 species that could make use of the fish migration system. We, however, found that many of the covered species have experienced large population declines when compared to historical numbers. The current population status can be seen as an indication of the likelihood that a species could naturally return to the Haringvliet without assistance.

The second sub-question of this report was: *Which physical and chemical conditions are most important for catadromous and anadromous fish species during their migration between fresh- and saltwater?* An overview of the physical and chemical conditions that are most important for the selected fish species are described in the Compendium in Chapter 2. These consist of acclimatisation period, critical stream velocity, and the period in which their migration takes place. The acclimatisation period is found to be of less importance in most species, however, some species do require a more gradual acclimatisation such as the Allis and Twaite shad. Therefore a gradual salinity gradient is still preferred. The minimum critical stream velocity is 0.2 m/s, while the maximum is 0.95 m/s, which has to be taken into account. For some species these values are not known hence is a point for further research. The migration periods of our selected species have shown to occur throughout the whole year. Due to this, the system should be open for as much time as possible, which has to be considered in management of the system.

The final sub-question of this report was: *Which requirements are essential in a system that has to facilitate fish migration between fresh- and saltwater?* Using Chapter 2 in combination with Chapter 3 and Chapter 4, we have identified aspects to bear in mind when designing a fish migration system in the Haringvliet delta. This study showed that a fish migration system needs to account for a vast range of different factors. Firstly, it needs to facilitate a wide range of different fish species that migrate between salt- and freshwater. Not only do these fish differ in swimming capacities, they also have different acclimatisation capabilities as well as migration period. Not only does the fish migration system need to account for these diverse characteristics of the selected fish species, it also needs to adhere to several societal requirements. It is of the utmost important that this fish system prevents saltwater intrusion inland and guarantees the freshwater supply to the region of Rotterdam. In some periods the discharge of the Rhine can be exceptionally high. During these periods the fish migration system should not be a barrier or there is a risk of flooding. Adhering to all these requirements should provide a system that will facilitate the migration of many, if not all, selected fish, while not interfering with the freshwater supply and water safety.

Chapter Six - Recommendations

Based on the literature gathered in this report, the requirements and drawbacks, several recommendations have been formulated. These recommendations range from advice for future investigation to aspects that Delta21 should pay attention to in the building of a fish migration system. Additional courses of action are also formulated, which can be of importance for other aspects of the Delta21 plan, besides the fish migration system.

6.1 Acclimatisation

While the acclimatisation of fish to changing salinity is a crucial part of their migration, very little is known about the length of these acclimatisation periods for the different fish species, and whether it stays the same throughout their lives. Some sources mention vulnerability to changing salinity in an early stage of the life cycle (van Emmerik, 2016; Hawkes, 2017). Juvenile salmon, for example, are more vulnerable to changing salinity than adults and thus require a longer period to adapt to changes in salinity (Hawkes, 2017). It is therefore necessary to gain insight into the life stages of the fish species that pass through the fish migration system. Then it can be determined whether an acclimatisation period is important for the species at the time it migrates through the Haringvliet. It is also important to gain a better insight into the length of the acclimatisation periods required for the different fish species that might make use of the fish migration system.

6.2 Swimming capacity

The fish migration system should be passable for many different fish species. These fish species vary vastly in swimming capacity, as can be seen in Chapter 2. Some fish, like salmon, are very capable swimmers. Others, such as flounder, are far worse swimmers. If the goal is that both of these species can make use of the fish migration system, the water velocity needs to account for that. It is therefore important that the system has areas where the water velocity is very low to aid the weaker swimmers. These can then follow a path by following the spots with lower flow rates. These spots can also be used by species with better swimming capacities as resting spots to regain their strength.

6.3 Varying river discharge

The fish migration system needs to maintain a reasonably low discharge, to allow fish to swim against the current. Additionally, the attraction flow needs to be adjusted to the current discharge levels to be effective. How will these aspects be maintained while the discharge from the Rhine varies? This question should be further investigated. Perhaps by an engineer who can focus on the technical properties that are needed to realise such a system.

6.4 Maintenance

A fish migration system does not only facilitate fish to pass but debris will also be transported through the system. Large debris, especially logs, can cause obstructions to fish migration and may damage the fish migration system. Slow flowing water can also result in a build-up of sediment. In order to keep the migration system free and functioning, sufficient maintenance is required. Removing obstacles or removing sediment to maintain the necessary depth and flow capacity are important to keep it functional at all times.

6.5 Monitoring

After implementing the Delta21 project, it is critical to monitor the fish activity through the new fish migration system. This will create an accurate picture of which of the expected fish species are using the fish migration system and which are not. This can reveal if there might still be bottlenecks for some species which can be used for optimising the system. Potential bottlenecks can be detected by monitoring on different locations in and around the system and analysing for patterns.

With Delta21 being such a large project, it is also valuable to monitor other areas that are affected, such as the estuarine area or the tidal basin. Besides fish, other (preferably all) trophic levels should also be monitored to create a clear image of how the nature in the whole project area is developing. Many unforeseen and unpredictable scenarios are possible, such as algal blooms or overgrowth of sea lettuce (Janssen, 1998). This makes it even more important to keep close track of the developing nature. The data gathered is essential for sufficient management of the area.

6.6 Estuarine value

This report has focussed on fish migration and how to facilitate it. For this purpose, the focus was on catadromous and anadromous fish species. However, amphidromous fish species living in the estuary are also of great ecological importance. Future research could look into how the estuarine area might possibly develop, and what the biodiversity in this area might look like.

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Glossary

Amphidromous	Migratory fish species that uses an estuary at some point of its lifecycle this can be for different purposes.
Anadromous	Migratory fish species that is born in freshwater, then migrates to saltwater to eventually return to freshwater as an adult to spawn.
Benthic	The flora and fauna found on the bottom, or in the bottom sediments, of a water body.
Biome	A community of animals or vegetation that lives together in a certain environment or climate.
Brackish water	Water with a salinity between that of fresh- and saltwater. For example found in areas where fresh- meets saltwater such as natural estuaries.
Catadromous	Migratory fish species that is born in saltwater, then migrates to freshwater to eventually return to saltwater as an adult to spawn.
Diadromous	Migratory fish species that is migrates between fresh- and saltwater at some point(s) in its life. Therefore, catadromous and Anadromous fish are both diadromous.
Estuary	A coastal body of water where the river meets the sea, creating areas with brackish water. It often described as a productive system with high biodiversity.
Euryhaline	Euryhaline organisms are able to adapt to a wide range of salinities and are common in tide pools and estuaries. Diadromous fish are euryhaline organisms as they are able to adapt to a big change in salinity.
Homeostasis	The dynamic state of equilibrium of internal chemical and physical conditions maintained by living systems. These conditions are kept within certain pre-set limits, which include variables like, body temperature, pH, ion concentrations, blood sugar levels and extracellular fluid.
Natura2000	Natura2000 is an institution that is focussed on preserving nature areas of exceptional importance in Europe. These can be rare habitats or important areas for rare species. These protected areas make up the Natura2000 network of Europe. In the Netherlands there are over 160 protected Natura2000 areas (Ministerie van LNV, n.d.a.).
Nocturnal	Species that are active at night.

Olfactory cues	Biological odors and chemicals dissolved in the water that fish smell/taste. The ability to perceive olfactory cues variates per species due to varying olfactory organ development.
Osmoregulation	The passive regulation of the osmotic pressure of an organism's body fluids to maintain homeostasis.
Pelagic fish	Fish that mainly use the middle and upper layers of a water body.
Salinity	The amount of salt dissolved in a body of water, freshwater generally contains <0.5g/kg while saltwater contains ±35 g/kg.