An explanatory study into effective measures to strengthen diadromous fish stocks in the Wadden Sea

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Position Paper
An explanatory study into effective measures to strengthen diadromous fish stocks in the Wadden Sea

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Colophon

An explanatory study into effective measures to strengthen diadromous fish populations in the Wadden Sea is produced by the Wadden Academy.

A draft version was externally reviewed by Dutch experts Zwanette Jager (ZiltWater Advies), Peter Paul Schollema (Waterschap Hunze en Aa's), Henk van der Veer (NIOZ) and Erwin Winter (IMAR-ES) and by three independent scientific experts from ICES, i.e. Romuald Lipcius (Virginia Institute of Marine Science, USA), Dennis Ensing (Agri-Food and Biosciences Institute Northern Ireland, IRL), and Joey Zydlewski (University of Maine, USA).

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## ACKNOWLEDGEMENTS

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Aim of the report

The strong decline in Wadden Sea fish since the 1980s has called for action to strengthen local fish stocks. Proposed measures include the reduction of fisheries, restoration of natural dynamics in habitats and improving connectivity between marine and freshwater areas for migratory fish. The Wadden Academy was invited by the Waddenfonds to make an inventory of the most effective measures to strengthen (migratory) fish stocks in the Wadden Sea area in general, and on the added values of further investments in fish passages in particular. Hereto, the following questions were defined:

1. To what extent were local stocks of migratory fish in the Wadden Sea influenced by the construction of local barriers and fish passages?

2. Which local measures would be most promising to strengthen the stocks of migratory fish in the Wadden Sea, and what would be the optimal locations for these measures?

3. What would be the costs and benefits of different measures to strengthen the stocks of migratory fish in the Wadden Sea?

Based on the function of the Wadden Sea for fish migration between marine and freshwater systems, the audit was focussing on 12 diadromous fish species (i.e. River Lamprey, Sea Lamprey, European Sturgeon, European Eel, Allis shad, Twaitte Shad, European Smelt, Atlantic Salmon, Sea Trout, Houting, Three-spined Stickleback and European Flounder) supplemented with 2 species that had large stock sizes in the former Zuiderzee (i.e. European Anchovy and Atlantic Herring). For all of these species, the Wadden Sea is (or was) an essential area to fulfil a particular phase in their life cycle, often during a particular time of the year.

Impacts of local barriers and fish passages

To assess the consequences of creating (e.g. Afsluitdijk in 1932) and removing (e.g. fish passages) local barriers for fish migration for local fish stocks, long-term and consistent survey data sets of before and after the time which these interventions took place are required. The data should have the proper spatial scales and include quantitative information on other factors that may have additionally influenced local fish densities (e.g., fisheries, predation). Since such data do not exist, available data and additional information was used to at least qualitatively explore such impacts.

Developments in local fish stocks were compared with large-scale trends (e.g. in the NE Atlantic) to explore impacts of large-scale and local impacts, such as the effect of the closure of former estuaries in the Wadden Sea. Because scientific fish surveys in the Wadden Sea did not start before the 1960s, data on registrations of commercial fisheries that started around 1900 were used (“Landings”). Within a shorter time frame (< 50 yrs), time series of surveys were analyzed to further explore the nature of large-scale and local drivers, and subsequently the present options for managing local fish stocks (“Surveys”).

Landings

In the NE Atlantic, all of the 14 species targeted in this study were landed (as catch or by-catch) by commercial fishing activities between 1903 and 2013. At this scale, migratory fish have strongly declined, often to historic lows. Exploitation is a major factor, on top of other human-induced (e.g. pollution, habitat loss, blocked migration) and natural factors (e.g. hydrographical fluctuations).

In Lake IJssel, the closure in 1932 was followed by decrease in landings of Anchovy, Flounder, Herring and Smelt, and a temporal increase in the landings of European Eel. Eel possibly got stuck in the area.
and/or no longer needed to migrate further upstream the river. The decline in Eel since the 1950s remains so far unexplained. Landings of Smelt reached comparable levels in the 1980s as before the closure. Ongoing fishing pressure contributed, however, to a depletion of the local Smelt stocks in the 2000s. In the western Wadden Sea, the closure of the Afsluitdijk was followed by a temporal increase in the landings of Herring and Flounder. This might have been the result of an increase in fish abundances, but possibly also of enhanced fishing efforts as fishermen from the former Zuiderzee continued to fish in the Wadden Sea after 1932.

In Dutch freshwater systems including main rivers, landings of Allis Shad, Atlantic Salmon, Houting and Sturgeon strongly declined between the 1890s and the 1940s. These declines are attributed to habitat destruction (e.g., river engineering, removal of sand and gravel), deteriorated water quality (i.e. pollution) and overfishing.

Surveys
For all species for which sufficient data was available, local stocks in the Wadden Sea and Lake IJssel appear to be more or less influenced by large-scale long-term drivers such as fisheries, habitat destruction and climate. The impact of these large-scale drivers versus the influence of local drivers on fish stocks varies, however, between species and areas.

For European Eel, for example, synchrony in time series from North Sea and the Wadden Sea suggest a large-scale driver within the marine waters of the study area. Such possible large-scale drivers include atmospherically driven dispersal of juvenile Eel by ocean currents and changes in hydrology and exploitation. Within Lake IJssel, the effects of these large-scale climate-driven influences may have been obscured by local impacts, including the influence of the Afsluitdijk in 1932 and changes in fishery pressure and restocking hereafter.

For Twaite Shad, stock dynamics appear to be synchronised in the western and eastern part of the Dutch Wadden Sea and the adjacent coastal zone. As has been observed for the Scheldt estuary, stock dynamics of Twaite Shad in estuarine tidal basins such as the Marsdiep and the Ems might be driven by environmental conditions at their freshwater spawning grounds. Improvement of these conditions might then enhance stocks in the Wadden Sea.

For European Smelt and European Flounder, synchronisation appears to occur between the North Sea and the westernmost (Marsdiep) and easternmost (Ems estuary) tidal basins of the Dutch Wadden Sea. Both basins are characterised by a strong salinity gradient, suggesting freshwater discharges as a driving factor for local stocks.

Conclusions on local barriers and fish passages
Present data are insufficient to quantitatively analyse the impacts of barriers on local stocks. Long-term information on fish landings of the Wadden Sea and Lake IJssel clearly illustrated, however, the impacts of the closure of the Zuiderzee in 1932. Whilst some species were negatively impacted (e.g. Anchovy), others (e.g. Eel) increased temporally following the closure. Strong fishing pressure finally resulted in historical lows (e.g. Smelt). In the Wadden Sea, drivers of local stocks appear to be large-scale (e.g. Eel) or local (e.g. Twaite Shad, Smelt, Flounder). If fish stocks are strongly influenced by local short-term drivers, then improvement of local conditions might result into strengthening of local stocks, within the boundaries set by the large-scale long-term drivers.
Measures and optimal locations

Fish passages
The Dutch Wadden Sea area comprises 65 existing and 4 planned (or under construction) estuarine gradients. These gradients vary from small tidal creeks at the islands to large freshwater sluices along the mainland coast. Existing gradients include freshwater sluices, ship locks, pumps and culverts of which several are structurally operated (8) or equipped with technical facilities (17) to enhance fish migration from the sea to freshwater systems. Identifying best practices and finding optimal locations requires a quantitative assessment of fish passing efficiency of existing fish passages. Despite the generally high costs of building these facilities, however, no comparable data to perform a quantitative evaluation of the construction of fish passages was available.

As an approximation of spatial variation in supply of fish at small freshwater discharges, data on densities of several migratory fish species at 15 discharge points were analysed. Results indicated that local densities are related to local circumstances, including (1) the presence of sufficient flow of freshwater to attract fish to the entrance location, (2) the closeness of the entrance to deeper waters that have a salinity gradient, and (3) the presence of a deep and wave-sheltered basin to allow fish to safely wait before passing. Present and future fish passage facilities should, therefore, pay attention to selecting and/or creating such local conditions, including optimal habitats before and after passing.

At the Afsluitdijk, fish can pass to and from Lake IJssel via discharge sluices and shiplocks at Den Oever and Kornwerderzand. Based on a very limited small-scaled number of tagging experiments and several assumptions, the passing efficiency at Kornwerderzand under present regular discharge conditions (REG) appears to be around 15% for River Lamprey and Sea Lamprey, 50% for Sea Trout and Atlantic Salmon, and 60% for Houting. Fish migration has been temporally stimulated by changing the discharge regime and by enhancing the migration of fish using the ship locks at Den Oever and at Kornwerderzand, the so-called fish-friendly management (FFM). Compared to regular discharge management (REG), fish-friendly discharge management (FFM) appeared to at least double the passing efficiency for European Eel, European Smelt, Three-Spined Stickleback and Flounder. This is underlined by an observed increase in Flounder in Lake IJssel following fish-friendly discharge management in the early 1990s. An additional fish passage is planned directly west of the discharge sluices of Kornwerderzand, the so-called Fish Migration River (FMR). For Sea Trout and Flounder, projected passing via Fish Migration River (FMR) is comparable as presently observed during regular discharge management. Compared to fish-friendly discharge management (FFM), projected migration via the FMR is higher for Herring, Smelt and Three-Spined Stickleback, and lower for Eel.

Projections for the FMR were based upon a passing efficiency of 50% of fish present in a semi-enclosed area before the sluices of Kornwerderzand, as was done for the environmental assessment (MER). Taking the species-specific variation at present into account, an average added value of 50% most probably does not correctly addresses future passing efficiencies under FMR conditions for all target species. The Fish Migration River could have added value to FFM, but only when optimally designed. Existing data and information are presently, however, not sufficient to support design recommendations. However, making the design adequate for testing the factors related to attraction and passing efficiencies could gain this necessary knowledge. This would not only be relevant for strengthening migratory fish in the Wadden Sea area, but also in other coastal systems with comparable man-made barriers world-wide.

Fisheries
In the Wadden Sea, Flounder, Twait Shad, River Lamprey and Smelt are reported as by-catch from shrimp fisheries. In Lake IJssel, both European Eel and Smelt are fished (but fishing on Smelt is temporally banned). Such fishing activities appear to be an important source of mortality, both in the Wadden Sea (Flounder, River Lamprey, Smelt, Twaita Shad) and in Lake IJssel (European Eel, Smelt). In the Marsdiep tidal basin, the by-catch from shrimp fishing on diadromous fish is estimated to be almost
2.5 million fish per year, comprising of Twaite Shad (213,000 fish per year), Smelt (1,400,000 fish per year), Flounder (840,000 fish per year) and River Lamprey (4,500 per year). In Lake IJssel, catches were estimated to comprise approximately 6 million Eels and 200 million Smelt per year between 2000 and 2014. For these species, this fishing mortality appears to be in the same order of magnitude as the projected migration via the Fish Migration River.

Reduction of fishing efforts in Lake IJssel and the Wadden Sea might, therefore, be an alternative or additional measure to strengthen local fish stocks within the study area as a whole. Reduction of by-catch by shrimp fishing in the Wadden Sea as a whole would result in a decrease of fishing mortality of approximately 4 million fish per year, and beneficial for their predators (birds, seals). Reduction of the shrimp fishing efforts might increase additional natural values of the Wadden Sea (e.g. benthic organisms and biogenic structures such as mussel beds), whilst the yield might remain stable. Reduction of fishing activities in Lake IJssel is not only expected to favour local fish stocks, but also as an important source of fish (in particular Smelt) for local stocks in the Wadden Sea, strengthening fish stocks in the study area as a whole.

**Habitats**

Once fish has passed from the sea to the freshwater system, it should be able to reach its final destination and to close its life cycle. In general, this implies that connectivity between all tributaries, polder ditches and brooks are important to population sizes of migratory fish. In addition, fish might require particular conditions in freshwater habitats, e.g. to spawn. For Twaite Shad, for example, suited conditions for spawning can probably be found in (side channels of) the upstream Ems, a river presently characterized by high fluid mud concentrations and low oxygen levels during summer. Water and habitat quality of the river Ems needs to be improved drastically before becoming an important spawning ground.

For Sea Lamprey, local habitat improvement of potential spawning habitats in small streams in (side-channels of) larger rivers such as the Ems and IJssel can be achieved by re-meandering. Studies into River Lamprey show that both safeguarding of the habitat quality and improving the connectivity between various tributaries and the sea is required.

Within the Wadden Sea region, most estuarine gradients are presently characterised by an abrupt salinity gradient. In general, strongly developed salinity gradients appear to favour the estuarine recruitment of marine fish species. In former days, for example, Anchovy, Herring, Smelt and Flounder used the large open brackish water bodies with tidal influence in this area to spawn, to grow and to mature. In addition to protection and improvement of remaining estuarine gradients (e.g. small creeks and the Ems estuary), restoration of former gradients may aid in strengthening fish stocks in the Wadden Sea area. On the mainland bordering the Dutch Wadden Sea, several large freshwater bodies exist that potentially could be turned into brackish ecosystems, i.e. Lauwersmeer (Marnewaard), Amstelmeer (including the Balgzandkanaal) and the northern part of Lake IJssel. Alternatively, the southern part of the Marsdiep tidal basin could be made more permanently under the influence of freshwater discharges.

Construction of brackish zones within freshwater systems should be preceded by feasibility studies, however, including an assessment of the behaviour of salt water, and possible consequences for other use of the water (e.g. agricultural, drinking). To come up with an optimal design, additional measurements on flows, tides, salinity gradients and fish passage rates under present conditions might be required. If a construction of a more permanently brackish zone at the northern side of the Afsluitdijk is considered, potential impacts of pumps on migrating fish from freshwater to the sea should be kept to a minimum (e.g. by means of using fish-friendly pumps) and an inventory of possible effects of additional freshwater discharges on local species and habitats in this zone should be made.
**Conclusions on measures and optimal locations**

Most promising potential measures to strengthen local fish stocks and other natural values of the Wadden Sea region include the reduction of fishing efforts, the provisioning of suitable habitats (such as brackish zones and freshwater spawning grounds) and the facilitation of fish migration.

Reduction of fishing efforts in the Wadden Sea and in Lake IJssel is expected to be beneficiary for migratory fish stocks, their predators and bottom life in the whole Wadden Sea region. Present natural estuarine gradients should be safeguarded and, if necessary (e.g. Ems), be improved for provisioning suitable habitats for migratory fish. The Lauwersmeer (Marnewaard), Amstelmeer (including the Balgzandkanaal), the northern part of Lake IJssel and the southern part of the Marsdiep tidal basin are potentially suited for turning into large brackish habitats, but actual suitability still needs to be checked by means of feasibility studies.

Fish migration could be further facilitated by means of improving the connectivity with freshwater systems, and between freshwater and the sea. Potential measures include fish-friendly discharge management and fish passages, ranging from relatively simple (e.g. fish ladder) to very complex (e.g. Fish Migration River) solutions. At present, the efficiency of such fish passages cannot be quantified due to a lack of data. The set-up of a Migratory Fish Testing Facility, e.g. within the area as presently reserved for the FMR, would enable exploring the factors related to attraction and passing efficiencies of various types of technical solutions in the Wadden Sea region as a whole.

**Benefits and costs**

With regard to benefits and costs in relation to strengthen local fish stocks only indications can be given. Mainly because the effectivity of the proposed measures like the reduction of fisheries, restoration of natural dynamics in habitats and improving connectivity between marine and freshwater areas for migratory fish are only known within large margins of uncertainty and the costs of the various measures also show a great variety. Subsequently, it is very difficult to estimate the cost effectiveness of the reduction of fisheries, restoring habitats and for different options for fish passing the Afsluitdijk (see “Measures and optimal locations”) and the same holds for monetary valuation of the improvement in fish stock.

However, several types of costs and benefits can be distinguished and for some a monetary indication can be given. First of all, an increase in fish stocks has an intrinsic value in terms of a more natural ecosystem. In addition to that, this may in the medium and long run also have positive effects for the potential stocks of fish available for fishing but maybe at a smaller scale. The reduction of fisheries would deprive fishing and processing companies of a source of income, with annual foregone earning being estimated to be around 25 million Euro per year for shrimps in the Wadden Sea and approximately 2 million Euro per year for Eel and Smelt in Lake IJssel.

As far as could be derived from present information, the initial one-time investment costs of the technical solutions to create large brackish zones would be approximately 3 million Euro for Marnewaard (Lauwersmeer) and 40 million Euro for the northern part of Lake IJssel. One time investment costs (excluding maintenance costs) of technical solutions for fish passages range between approximately 20 thousand Euro for simple technical solutions (e.g. flaps and gates in sluice doors), 50 thousand Euro for more complicated facilities (e.g. fish ladders and spill ways), 500 thousand Euro for fish-friendly by-pass pumps, 4 million Euro for fish passages with salt water return flow systems, and 52 million Euro for the large and complex Fish Migration River. As already indicated, however, the efficiency of the existing fish passages and subsequently the identification of best practices (“value for money”) could not be quantified due to lack of information for the Wadden Sea region.
Migratory Fish Testing Facility, Monitoring & Modelling

Due to the lack of data, at present a quantitative assessment of the effectivity of existing fish passages in the Wadden Sea was not possible. With regard to the investment costs of building these structures, it is therefore strongly recommended to not only invest in the strengthening of fish migration by construction of fish passing facilities, but also to invest in appropriate testing and monitoring over a longer time period. Testing and monitoring is required for identification of best practices by means of quantitative evaluation of functioning of present facilities, for potentially allowing modifications in original designs to optimize the investments made, and for more adequate future investments.

Testing and monitoring programs should include measurements of (1) the numbers and characteristics (e.g., species, life phases, condition of fish passing), (2) the efficiency of the attraction flow, (3) the efficiency of the fish passage and, for larger fish passages, (4) the habitat use of the local area. Proper testing of the effectivity of different technical solutions can be done by means of experiments under set environmental conditions (e.g., indoor climate-controlled basins), or by experiments under natural conditions. The latter approach would require more replicates (i.e. the number of distinct and in principle similar experimental units) than the first approach to be able to extract the signal of treatment from the environmental noise.

To estimate the added value of a new fish passage, monitoring should be performed at all other surrounding fish passages before and after a new passage is constructed. This would require an integrated monitoring scheme for migratory fish in the Wadden Sea. With standard techniques, equipment and protocols, and addressing the preferred pathways of migratory fish species at various spatial (e.g., freshwater discharge points, tidal basins) and temporal (tide, season, year-to-year) scales. Incorporating the migratory behavior of fish into hydrodynamic models could produce biophysical models of fish movements through the Wadden Sea. Such models would allow for building scenarios for optimizing investments to strengthen (migratory) fish stocks in the Wadden Sea under various environmental conditions such as the creation of large brackish zones, climate change and sea level rise. Given the great interest and considerable investments in fish passages at a global scale, the insights derived from the Fish Migration Testing Facilities will lead to more efficient and effective investments in fish passages in the Wadden Sea and the rest of the world.
1.1 Recent changes in Wadden Sea fish

Many fish species rely on shallow coastal habitats for at least one of their life stages. A suite of marine fish species reaches these areas as postlarvae and spend their juvenile phase here (Zijlstra 1972, 1978; Elliott et al. 2007; Van der Veer et al. 2000, 2015). Other species temporarily inhabit the area or pass it on route to either marine or freshwater spawning sites (diadromous species), during certain times of the year or occasionally (Elliott et al. 2007). In addition to such temporary visitors, some species spend (almost) their entire life in the shallow waters (Elliott & Hemingway 2002). Naturally such coastal areas support large numbers of fish that make use of the suitable habitats characterised by a high food availability and shelter from predators (Gibson 1994; Elliott & Hemingway 2002, Tulp et al. 2015).

Structural monitoring of the fish fauna in the Dutch Wadden Sea takes place since 1960–1970 by two major monitoring programs: a fyke program in the western Wadden Sea and an annual beam trawl survey (DFS) covering the entire Dutch Wadden Sea. Results from these surveys show that total fish biomass increased from 1970 to 1980, had a peak in the mid-1980s that was followed by a strong decline especially from 1980–2000, with a stable trend since then in all tidal basins (Bolle et al. 2009; Jager et al. 2009; Tulp et al. 2015). The trends in the Dutch coastal zone differ from those in the Wadden Sea, especially in the past 10 years, with an ongoing decline in the Dutch Wadden coast and an increase along the mainland North Sea coast (Van der Veer et al. 2015; Tulp et al. 2015). The strong decline in Wadden Sea fish since the 1980s has called for action to strengthen local fish stocks. Proposed measures include the reduction of fisheries, wise sand nourishments, restoration of natural dynamics in habitats and improving connectivity between marine and freshwater areas for migratory fish (Van der Veer & Tulp, 2015).
1.2 Audit

The Wadden Academy was invited by the Waddenfonds to make an inventory of the most effective measures to strengthen (migratory) fish stocks in the Wadden Sea. Many parties are coming forward to request funding for building fish passages, including a large fish passage in the Afsluitdijk (52 MEuro in total, of which a part requested from the Waddenfonds). With already several projects on fish migration funded, the Waddenfonds requested advice on the added value of additional investments in fish passages compared to other measures that could be taken to strengthen migratory fish populations to improve the ecological quality of the Wadden Sea. More particularly, the following questions were defined:

1. To what extent were local stocks of migratory fish in the Wadden Sea influenced by the construction of local barriers and fish passages?
2. Which local measures would be most promising to strengthen the stocks of migratory fish in the Wadden Sea, and what would be the optimal locations for these measures?
3. What would be the costs and benefits of different measures to strengthen the stocks of migratory fish in the Wadden Sea?

Measures in consideration are restricted to the area covered by the Waddenfonds, being the Wadden Sea, the islands, the tidal inlets, the North Sea coastal zone (up to 3 nm from the coastline) and the municipalities at the mainland bordering the Wadden Sea (www.waddenfonds.nl; Fig. 1.1). This implies that potential measures in other areas (e.g., the North Sea and main rivers such as the Rhine and Meuse) will not be addressed in this report. Measures at the boundaries of the Waddenfonds area (e.g., Lake IJssel) will only be discussed if they might have a direct influence on the fish stocks within the study area.

Local experts and scientists from ICES (International Council for the Exploration of the Sea) have reviewed the draft report in November 2015. The first results were presented in December 2015 to the Executive Board of Waddenfonds. The final report was presented to the EB of the Waddenfonds in February 2016.

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Table 1.1 Overview of fish species targeted in this report, their main migration window (see last column for references) and mortality rate (www.fishbase.se).
1.3 Target fish species

Based on the function of the Wadden Sea for fish migration between marine and freshwater systems, the audit is focussing on 12 diadromous fish species supplemented with 2 species that had large stock sizes in Lake IJssel, i.e. European Anchovy and Atlantic Herring (Table 1.1). For all of these species, the Wadden Sea is (or was) an essential area to fulfil a particular phase in their life cycle, often at a particular time of the year. For the diadromous fish species, this shallow coastal sea functions as a corridor between freshwater systems and the open North Sea when adults and juveniles migrate to and from their spawning areas (Winter et al. 2014; Heessen et al. 2015).

The former Zuiderzee was a major spawning area for Anchoy (Petitgas et al. 2012), and the Anchovy larvae stayed in the area until October after hatching (Redeke 1939). In 1994, eggs of this fish species were found north of the Afsluitdijk (Boddeke & Vingerhoed 1996). In May 2010 and May 2011, schools of Anchovy were found in a pelagic survey in the Marsdiep area. Their mean length (14.5 cm) corresponded to age-1 fish that are likely to spawn. Hence, for the Wadden Sea area is important both as nursery as well as for spawning (Couperus et al 2016). Before 1932, the Zuiderzee might have harboured a subpopulation of Zuiderzee Herring, which entered the Zuiderzee from March until July for spawning (Redeke 1939). In 2006, Dutch fishermen landed 800 kg of Herring of which the morphology resembled that of Zuiderzee Herring (Witte, NIOZ), implying that a remnant stock might still be present.

<table>
<thead>
<tr>
<th>YEAR</th>
<th>CHANGE</th>
<th>DIKE (KM)</th>
<th>NEW HABITAT</th>
<th>NAME</th>
<th>AREA (KM²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zuiderzee (4953 km² before 1924)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1924</td>
<td>Dike built</td>
<td>3</td>
<td>Lake</td>
<td>Amstelmeer</td>
<td>7</td>
</tr>
<tr>
<td>1927</td>
<td>Land reclaimed</td>
<td>2</td>
<td>Polder</td>
<td>Andijk</td>
<td>1</td>
</tr>
<tr>
<td>1930</td>
<td>Land reclaimed</td>
<td>18</td>
<td>Polder</td>
<td>Wieringermeer</td>
<td>200</td>
</tr>
<tr>
<td>1932</td>
<td>Dike built</td>
<td>32</td>
<td>Lake</td>
<td>IJsselmeer</td>
<td>3440</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Tidal basins</td>
<td>Marsdiep, Eijerlandse Gat &amp; Vlie</td>
<td>1513</td>
</tr>
<tr>
<td>1942</td>
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<td>55</td>
<td>Polder</td>
<td>Noordoostpolder</td>
<td>480</td>
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<tr>
<td>1957</td>
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<td>90</td>
<td>Polder</td>
<td>Eastern Flevoland</td>
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<tr>
<td>1967</td>
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<td>70</td>
<td>Polder</td>
<td>Southern Flevoland</td>
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<tr>
<td>1975</td>
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<td>Markermee</td>
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<td></td>
<td></td>
<td></td>
<td>Lake</td>
<td>IJsselmeer</td>
<td>1100</td>
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<td>Lauwerszee (274 km² before 1969)</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1969</td>
<td>Dike built</td>
<td>13</td>
<td>Lake</td>
<td>Lauwersmeer</td>
<td>24</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Polder</td>
<td>Lauwersmeer</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Tidal basins</td>
<td>Lauwers &amp; Eilander Balg</td>
<td>183</td>
</tr>
<tr>
<td>Ems estuary (460 km² at present)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1924</td>
<td>Land reclaimed</td>
<td>15</td>
<td>Polder</td>
<td>Carel Coenraad</td>
<td>15</td>
</tr>
<tr>
<td>1979</td>
<td>Land reclaimed</td>
<td>3</td>
<td>Polder</td>
<td>Breebaart</td>
<td>1</td>
</tr>
</tbody>
</table>

1.4 Long-term changes in the environment

As the result of anthropogenic pressures such as fisheries, the construction of physical barriers between the marine and fresh waters, river channelization, deterioration of water quality and habitat destruction, fish stocks in coastal ecosystems including the Wadden Sea have been degrading from the medieval time onwards, with acceleration during the last 150 to 300 years (Wolff 2000; Jackson et al. 2001; Lotze et al. 2005, Jager et al. 2009).

During the past 100 years, for example, the Dutch part of the Wadden Sea was irreversibly impacted by damming and land reclamation (Table 1.2). Parts of former estuaries, such as the Zuiderzee and Lauwerszee, were closed off from the sea by means of dams and turned into freshwater lakes (i.e., Amstelmeer, IJsselmeer, Lauwersmeer). After the closure in 1932, large parts of Lake IJssel (IJsselmeer in Dutch) were reclaimed, whilst the lake itself was further subdivided into two freshwater basins in 1975 (Fig. 1.2; Table 1.2). This reduction and changes in habitat has most probably affected diadromous fish stocks. If considered to be irreversible (e.g. as the result of their role in safety against flooding or the high economic values of agriculture and freshwater supply), this limits the potential for strengthening local diadromous fish stocks.

Fig. 1.2 Maps of the western part of the study area. Left: Navigational map of the Zuiderzee in 1921, as made by M.H. Blokpoel of the Royal Dutch Meteorological Institute (originally printed by Roeloffzen-Hübner en Van Santen, Amsterdam; sold at the J.L. Willem Seyffardt bookshop, Amsterdam). Right: Map of the Wadden Sea, Lake IJssel and Markermeer in 2015 as derived from Open Street Map, layout Humanitarian Data Model, with present-day coastline, tidal basins, dikes and polders (see Table 1.3 for details).
Fig. 1.3 Annual landings (tonnes live weight) of 14 fish species as caught in the Northeast Atlantic (FAO fishing area 27; black dots and left y-axis) and the North Sea (FAO area 27 subarea IV; white dots and right y-axis) from 1903 to 2014. The dashed vertical lines indicates the year 1932 when the Afsluitdijk was closed, the dotted lines the closure of the Amstelmeer and Lauwersmeer in 1924 and 1969, respectively. Source: ICES database on www.ices.dk.
1.5 Long-term changes in fish landings

Comparison of fish stock developments within the study area with large-scale developments (e.g. in the NE Atlantic) might help to unravel large-scale and local impacts on fish stocks, such as the effect of the closure of former estuaries in the Wadden Sea. Fish surveys in the Wadden Sea did not start before the 1960s (see paragraph 1.1), however, which is long after major changes in fish stocks and habitats took place. Another source of information may be found in fish landings, which are registered since the beginning of the previous century. These data sets provide a long-term (> 100 years) view on the (changes in) intensity of fishery-induced mortality on fish stocks. Long-term changes in landings may also potentially reflect long-term changes in fish stocks or changes in the fishery management. Commercial catch data are usually collected systematically and consistently over long periods, and the data tend to be less noisy than survey data because of the much greater sampling effort.

However, proper acknowledgement of potential biases (e.g. misreporting, interaction between fishing fleets, technological improvements, commercial value of the fish species etc.) is a prerequisite when performing such interpretations (Engelhard et al. 2011).

NE Atlantic and North Sea (1903-2013)

As can be derived from catch statistics as supplied by International Council for the Exploration of the Sea (ICES; www.ices.dk), all of the 14 species targeted in this study are or were landed (as catch or by-catch) by commercial fishing activities in the North-East Atlantic (Fig. 1.3). Within the North Sea, however, some species were not caught (River Lamprey, Sea Lamprey, Sturgeon, Allis Shad and Houting) or hardly caught (Twaite Shad, Three-spined Stickleback) (Fig. 1.3).

On both sides of the Atlantic Ocean, diadromous fishes have strongly declined, often to historic lows (Limburg & Waldman 2009). Exploitation is a major factor (on top of hydrographic fluctuations influencing larval transport, pollution, blocked migration, diseases) in European eel decline (Dekker 2004a) and the nearly complete demise of the once-widespread European Sturgeon (Williot et al. 2002). In addition, habitat loss, pollution, climate change, and replacement with non-native species (hybridization, escapees from aquaculture) contributed to declines in this group (Limburg & Waldman 2009).
Zuiderzee (1892-2013)

For landings of fish caught in the northern and southern parts of former Zuiderzee before and after the closure in 1932 (Fig. 1.4), data sets from different periods and sources were combined, i.e. southern part in 1892-1906 from Redeke (1907), southern part in 1925-1938 from Redeke (1939), southern part in 1966-2012 for Smelt and Flounder from De Boois et al. (2014), southern part in 1907-1924 and in 1939-2013 for Eel from De Graaf & Deerenberg (2015), and northern part and all other years for the southern part from Fish Auction data as supplied by Jaap Quak (Sportvisserij Nederland).

It must be noted that where data sets of different origin overlapped, values on landings were not always similar. Whilst most of these differences were minor, some were more extreme such as landings of Smelt from Lake IJssel in 1968/1969 of 1588/1329 tonnes by De Boois et al. (2014) and 103/38 tonnes as supplied by Jaap Quak, possibly as the result of including by-catch or not.

In landings from the western Wadden Sea, a temporally increase of Herring and Flounder was observed (Fig. 1.4). This might be the result of an increase in fish abundances, but also of an increase in fishing efforts as fishermen from the former Zuiderzee continued to fish in the Wadden Sea after 1932 (Wolff 2005). In local landings from Lake IJssel, the closure of the Afsluitdijk in 1932 was followed by more or less abrupt decreases in landings of Anchovy, Flounder, Herring and Smelt, and a temporally increase in the landings of European Eel (Fig. 1.4).

Fig. 1.4 Annual landings (tonnes live weight) of five fish species as caught in the northern part of the former Zuiderzee (western Wadden Sea since 1932; black dots) and southern part of the former Zuiderzee (Lake IJssel since 1932; white dots). The dashed vertical lines indicates the year 1932 when the Afsluitdijk was closed, the dotted lines the closure of the Amstelmeer and Lauwersmeer in 1924 and 1969, respectively. Sources: Redeke (1907), De Boois et al. (2014), De Graaf & Deerenberg (2015) and Jaap Quak.
Anchovy immediately disappeared after the closure (Fig. 1.4). The loss of Herring spawning grounds in 1932 led to the nearly complete disappearance of the Herring stock within a few years (Wolff 2005). Flounder did not fully disappear after the closure (Fig. 1.4), possibly because of its tolerance to low salinities (Winter 2009). Landings of Smelt reached comparable levels as before the closure (Fig. 1.4). Smelt has developed a land-locked population (Phung et al. 2015). Ongoing fishing pressure on Smelt in Lake IJssel contributed, however, to a depletion of the local stocks (Masterplan Toekomst IJsselmeer 2014).

The initial increase in Eel catches in Lake IJssel after 1932 might have resulted from an inability for Eel to take advantage of selective tidal transport for migrating upstream and, therefore, Eel got stuck in Lake IJssel (Willem Dekker, pers. comm.). Alternatively, owing to the freshening of Lake IJssel, Eel no longer needed to move away from the brackish Zuiderzee into rivers and inland waters (Redeke 1939). The cause of the subsequent decline of the local stock of European Eel in Lake IJssel is still unexplained (Dekker 2004b). Worldwide there are multiple causes identified that have adverse effects on eels but the relative importance of each cause is not known yet (Kettle et al. 2011).

Several freshwater fish and fisheries benefited from the new conditions after the closure. Landings of Pike-perch (Sander lucioperca), for example, rose from 111 kg in 1933 to more than 125,000 kg in 1938 (Redeke 1939).

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**Fig. 1.5** Annual landings (number or kg) of four fish species caught in large rivers of The Netherlands. The dashed vertical lines indicates the year 1932 when the Afsluitdijk was closed, the dotted lines the closure of the Amstelmeer and Lauwersmeer in 1924 and 1969, respectively.

Source: www.compendiumvoordeleefomgeving.nl.
1.5 Outline of the report

To quantify impacts of barriers and passages on fish populations in the Wadden Sea, long-term and consistent survey data sets of the period during which these interventions took place (e.g., the construction of the Afsluitdijk in 1932) are required, at the proper spatial scales and including quantitative information on other factors that may have influenced local fish densities (e.g., fisheries, predation). Since such data do not exist, we have used available data sets and additional information to at least qualitatively explore such impacts. Limits of using these data sets for this purpose are addressed throughout the report.

In Chapter 2, annual fish surveys at different spatial scales were compared to see if year-to-year densities of fish in the tidal basins of the Wadden Sea were dominated by local variation, possibly including local effects such as barriers and passages, or by underlying variation at larger spatial scales (possibly indicating larger-scale drivers of variation).

In Chapter 3, the abundance of migratory fish species in the Wadden Sea at a tidal basin scale and at local scale (small freshwater sluices and fish passages) was examined to explore the spatial variation in potential for strengthening populations of migratory fish by means of additional fish migration projects.

In Chapter 4, information on local densities, sources of mortality (fisheries, predation by fish, birds and seals) and transport via sluices, ship locks and the proposed Fish Migration River are compared to identify the relative contribution of these factors to changes in fish populations in the Wadden Sea and Lake IJssel.

In Chapter 5, an overview is given of possible measures to strengthen populations of migratory fish in the Wadden Sea (o.a. by reducing present threats), including an indication of costs and possible effectiveness.
2. POSSIBLE DRIVERS OF LOCAL FISH DENSITIES

2.1 Introduction

Long-term changes in fish stocks are influenced by a suite of drivers, including fisheries pressure and environmental factors such as sea surface temperatures, and interactions between these drivers (Pauly et al. 2002). Correlations between simultaneously measured time series can help to provide insight into possible driver-response relationships. If the data were perfect (noise-free, bias-free, infinitely long), we should be able to detect, at least in some cases, which of the coupled systems is the driver (or at which scale the driver operates) and which is the response (Fig. 2.1).

Synchronization in population sizes that takes place over large spatial scales may point to common large-scale drivers such as climatic conditions. Even locally regulated populations can be synchronized by large-scale environmental shocks (Moran 1953). Synchronous dynamics on smaller spatial scales can result from spatial trends in regional variables. For instance, regional trends in food availability, predation and coastal fisheries could lead to distinct regional synchronization patterns. Synchronous dynamics among nearby stocks can also result from distance-limited dispersal of fish between stocks (Bjørnstad et al. 1999; Ranta et al. 2006).

Analyses of synchrony in time series at different spatial scales might help to unravel the nature of drivers, and eventually the possibilities and limitations for local management of local fish stocks, e.g. by means of facilitating fish migrations.

Fig. 2.1 Possible spatial relationships between drivers and synchrony in time series.
<table>
<thead>
<tr>
<th>CODE</th>
<th>NAME</th>
<th>SURVEY</th>
<th>AREA</th>
<th>YEARS</th>
<th>GEAR</th>
<th>UNIT</th>
<th>MONTHS</th>
<th>LIFE PHASE</th>
<th>SOURCE</th>
</tr>
</thead>
<tbody>
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<td>NS_TER</td>
<td>North Sea Ecoregion</td>
<td>NSER</td>
<td>North Sea</td>
<td>1977-2013</td>
<td>Bottom trawls</td>
<td>Index</td>
<td>8 – 9</td>
<td>Juv. + Adult</td>
<td>IMARES (H Heessen)</td>
</tr>
<tr>
<td>NS_T404</td>
<td>Dutch coastal zone</td>
<td>DFS</td>
<td>North Sea</td>
<td>1970-2014</td>
<td>Beam trawls</td>
<td>N ha(^{-1})</td>
<td>9 – 10</td>
<td>Juv. + Adult</td>
<td>IMARES (I Tulp)</td>
</tr>
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<td>NIOZ</td>
<td>Wadden Sea</td>
<td>1960-2014</td>
<td>Kom-fyke</td>
<td>N d(^{-1})</td>
<td>3-6 + 9-10</td>
<td>Juv. + Adult</td>
<td>NIOZ (H vd Veer)</td>
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<td>Wadden Sea</td>
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<td>9 – 10</td>
<td>Juv.</td>
<td>IMARES (I Tulp)</td>
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<td>DFS</td>
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<td>Beam trawl</td>
<td>N ha(^{-1})</td>
<td>9 – 10</td>
<td>Juv.</td>
<td>IMARES (I Tulp)</td>
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<td>Juv.</td>
<td>IMARES (I Tulp)</td>
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<td>N ha(^{-1})</td>
<td>9 – 10</td>
<td>Juv.</td>
<td>IMARES (I Tulp)</td>
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<td>N ha(^{-1})</td>
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<td>Juv.</td>
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<td>Juv.</td>
<td>IMARES (I Tulp)</td>
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<td>WFD</td>
<td>Wadden Sea</td>
<td>2007-2014</td>
<td>Stow net</td>
<td>N h(^{-1}) (80m(^{2})) (^{-1})</td>
<td>5 + 9</td>
<td>Juv. + Adult</td>
<td>RWS / ZiltWater (Z Jager)</td>
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<td>Oterdum</td>
<td>WFD</td>
<td>Wadden Sea</td>
<td>2006-2014</td>
<td>Stow net</td>
<td>N h(^{-1}) (80m(^{2})) (^{-1})</td>
<td>5 + 9</td>
<td>Juv. + Adult</td>
<td>RWS / ZiltWater (Z Jager)</td>
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<td>WFD</td>
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<td>Stow net</td>
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<td>5 + 9</td>
<td>Juv. + Adult</td>
<td>RWS / ZiltWater (Z Jager)</td>
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<td>Lake IJssel</td>
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<td>4 – 5</td>
<td>Glass eel</td>
<td>IMARES C003/15 &amp; C006/04</td>
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<td>Den Oever 2</td>
<td>Glass eel</td>
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<td>1 m(^{2}) lift net</td>
<td>N net(^{-1})</td>
<td>4 – 5</td>
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<td>Wadden Sea</td>
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<td>1 m(^{2}) lift net</td>
<td>N net(^{-1})</td>
<td>4 – 5</td>
<td>Glass eel</td>
<td>IMARES C003/15 &amp; C006/04</td>
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<td>N net(^{-1})</td>
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<td>Glass eel</td>
<td>IMARES C003/15 &amp; C006/04</td>
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<td>N net(^{-1})</td>
<td>4 – 5</td>
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<td>IMARES C003/15 &amp; C006/04</td>
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<td>1996-2014</td>
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<td>4 – 5</td>
<td>Glass eel</td>
<td>IMARES C003/15 &amp; C006/04</td>
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</table>
2.2 Time series on fish abundance

Time series used for the synchronization analyses are based on surveys only; landings are not considered here. It is assumed that survey data are consistently sampled in time and space and are not as biased by changes in effort and gear as data on landings often are (Heessen et al. 2015). The time series comprise surveys of the North Sea (i.e. bottom-trawl surveys of the North Sea ecoregion and of the coastal zone north of the islands), the Wadden Sea (i.e. bottom-trawl surveys of tidal basins including the Ems estuary, and surveys with a fyke, lift-nets and stow-nets) and Lake IJssel (i.e. bottom-trawls and fykes) (Table 2.1, Figure 2.2). Note that these surveys differ not only in sampling area (North Sea, Wadden Sea, Lake IJssel) and sampling gear (bottom-trawls, fykes, lift-nets, stow-nets), but also in sampling period. This implies that, although targeting similar species, time series on densities are not fully comparable due to differences in catchability (e.g. low catches of pelagic fish when using bottom-trawls) and in life-phases (e.g. surveys of 1x1m lift nets select for small species and juveniles of larger species).

Fig. 2.2 Locations of the fish surveys. Blue circle: Marsdiep Fyke, Pink circles: Glass Eel survey, Orange circles: Ems estuary stow net survey, Green circles: Lake IJssel fyke survey, Red lines: locations of trawls in Lake IJssel trawl survey, Black lines: locations of trawls in Demersal Fish Survey (the direction of the line does not indicate trawl direction), Brown: Boundaries of Demersal Fish Survey (DFS) areas and codes. North Sea Ecoregion surveys are not shown on this map.
North Sea Ecoregion surveys (NS_TER)
The survey index for the North Sea Ecoregion is based upon a combination of data from a variety of national and international surveys in the North Sea, which use otter trawls and beam trawls (Heessen et al. 2015). All data were scrutinized (e.g. for reporting of less common species, misidentifications), corrected (e.g. for differences in coding and fish lengths), and standardized (Heessen et al. 2015).

It should be noted that the sampling was targeted at commercial species (such as Herring, Cod and Plaice) and not geared to get a representative index for Lampreys, Salmon and Trout (Henk Heessen, IMARES, pers. comm.). This might imply that trends for the latter group of fish species contain relatively low signal to noise ratio.

The Demersal Fish Survey (DFS) is part of an international coastal and inshore survey, which started in 1970, is performed in autumn (Sep-Oct) and aiming at monitoring young plaice and sole in their nursery grounds in the North Sea coastal zone, Wadden Sea and South Western Delta. The Dutch survey areas included in this analysis comprise the coastal zone of the North Sea north of the Wadden Sea islands (DFS404), the Wadden Sea (from west to east: DFS610, DFS612, DFS616-619), and the Ems-Dollard estuary (DFS620) (Figure 2.2).

Within the Wadden Sea and Ems estuary, fishing with a 3-m beam trawl was restricted to the tidal channels and gullies deeper than 2 m because of the draught of the research vessel, whereas the North Sea coastal zone was fished with a 6-m beam trawl. The mean abundance per area was calculated for all subareas in the period 1970-2013 weighed by surface area for five depth strata (intervals of 5 m) within the subareas (Tulp et al. 2015).

As result of the sampling gear, the DFS results are considered to reflect the densities of demersal fish, such as Flounder, best and less those of the other target species (Ingrid Tulp, IMARES, pers. comm.). The combination of low fishing speed (2-3 knots) and fine mesh size (20 mm) results in selection of the smaller fish species and younger year classes of (particularly demersal) fish and other epibenthos. Furthermore, the timing of occurrence in the Wadden Sea needs to coincide with the survey period (September-October) (Tulp et al. 2015).

Kom-fyke surveys Marsdiep (WS_FMD)
Since 1960, a passive kom-fyke trap has been operating at the entrance of the Marsdiep basin in the western Dutch Wadden Sea (Van der Veer et al. 1992). Fishing normally started in March - April and lasted until October. In winter the trap was removed because of possible damage by ice scouring and from 1971 onwards no fishing took place during part of the summer (July-August) because of fouling and potential clogging of the net by macroalgae and jellyfish. All catches were sorted out immediately and identified to species level (Van der Veer et al. 2015). Fixed gears require mobility (active movement or passive transport) of the organism. The location of the fyke near a tidal inlet implies that in spring catches will contain fish that were migrating from the North Sea into the Wadden Sea and in autumn fish on their way to migrate to the North Sea including the locally produced young-of-the-year (Fonds 1983).

Stow-net surveys Ems estuary (WS_SSP, WS_SOT & WS_STB)
Within the Ems estuary, WFD (Water Framework Directive) fish monitoring is carried out at three stations, i.e. Spijk (coded as WS_SSP in this report, see Table 2.1), Oterdum (WS_SOT) and Terborg (WS_STB), in the Ems at river 70.5, 52.5 and 24.5 km, and thus relates to the polyhaline, mesohaline and oligohaline zone, respectively (BioConsult 2009; Jager et al. 2011). The fishing gear is a stow net with a width of 10 m and a variable vertical opening of max. 10 m. For fishing a commercial fishing vessel is chartered in spring (May) and autumn (September). The vessel puts out its anchor and deploys the nets; the tidal current flows through the net during 3.0 to 4.5 hours. One catch per station was carried out over most of the ebb tide phase and one catch over most of the flood tide phase. All fish catches were standardized to annual averages of numbers per hour per 80 m² surface of the net opening per station (Jager et al. 2011).
Lift-net surveys freshwater sluices (WS_LD1, WS_LD2, WS_LHA, WS_LLA & WS_LTZ)

Glass Eel is caught per lift net haul at the freshwater sluices in Den Oever (coded as WS_LD1 in this report, see Table 2.1) in the period April-May, using a 1 m² lift net with mesh size 1x1 mm, annually since 1938 (Dekker 2002). Monitoring is carried out daily in 5 hauls every 2 hours between 22:00-5:00 h. In addition, recruitment of Dutch waters is monitored at twelve sites along the Dutch coast. Five of these are located in the Wadden Sea, i.e. near Den Oever (WS_LD2), Harlingen (WS_LHA), Lauwersoog (WS_LLA), Termunterzijl (WS_LTZ) and Nieuwe Statenzijl (WS_LNZ). At these stations, glass eel was caught by 1 m² lift nets in 2 hauls between 18:00 and 8:00 h in the period April-May with a weekly frequency (De Graaf & Deerenberg 2015). Sampling efforts were more diverse than the long-term survey at Den Oever 1 (WS_LD1), with shorter time series and missing years (De Graaf & Deerenberg 2015).

Bottom-trawl surveys Lake IJssel (LIJ_TLIJ)

The longest time-series in Lake IJssel stems from the open-water monitoring program with active fishing from a vessel. From the start of the survey in 1966 up to 2012, sampling was performed by means of a large (7.4 m wide, 26.9 m long, 1 m high) bottom trawl net (in Dutch: “kuil”), which was replaced by a smaller beam trawl (4 m wide, 19.95 m long, 1 m high) in 2013 (Van der Sluis et al. 2014). Catches of the new gear were corrected for differences with the old gear in catchability for biomass of Smelt and numbers of Flounder (Van Overzee et al., 2013). Since 1989, sampling is consistently performed at 29 locations in the open waters of Lake IJssel. In 2002, the sampling frequency was reduced from three times a year (May, Aug, and Oct-Nov) to once a year (Oct-Nov). For long-term trends, data are taken for the Oct-Nov period only (Van der Sluis et al. 2014). For most fish species, with exception of European Eel, Smelt and Three-spined Stickleback, these gears are selective for juveniles (Van der Sluis et al. 2014).

Fyke surveys Lake IJssel (LIJ_F01 & LIJ_F02)

This fishery survey was executed from 1994 to 2013 in order to sample freshwater fish abundance in large water bodies of The Netherlands (Van der Sluis et al. 2014). During this survey, professional fishermen under scientific guidance register by-catch of fisheries. The catch effort (number of nets per day and the fishing duration per day) was registered since 1994 (Van der Sluis et al. 2014). Since 2014 a different survey set-up has been followed and these surveys have been abandoned.

Fish were caught using Eel fyke nets with a stretched mesh size of 18-20 mm. This survey started with 33 locations in lakes and rivers but the number of locations declined. Lake IJssel had two locations, one at the Afsluitdijk near Kornwerderzand (IJsselmeer01, in this report coded as LIJ_F01, see Table 2.1) and one at the Houtribdijk (IJsselmeer02, LIJ_F02), although in fact at this location two nearby fykes were applied (labelled Ijm02a and Ijm02b in Figure 2.2). Eel fishing, and thus registration of catches, is allowed from December to October (Van der Sluis et al. 2014).
2.3 Statistical analysis survey data

Synchronization is defined as the correlation between the time series of normalized densities of fish species for the different surveys. For each pair of time series, synchronization is calculated using Pearson’s correlation coefficient ($r$). Correlation coefficients were calculated between areas and stations with non-zero densities. This resulted in symmetric correlation matrices, of which the size differed per fish species. For each species, the correlation matrix was visualized by plotting ellipses shaped as contours of a bivariate normal distribution with unit variance and correlation $r$. More elliptical and more intense colour means higher correlation; colour (red or blue) is indicating the respective negative or positive nature of the correlation. The points of the contour are given by $(x,y) = (\cos(\theta+d/2), \cos(\theta-d/2))$ and $d = \arccos(r)$ where $\theta \epsilon [0, 2\pi]$ (Murdoch & Chow 1996).

In addition, the results for each fish species are presented within schematized maps of the study area (Fig. 2.3). Within the maps, the connectivity between sampling areas is depicted by lines with rounded endpoints. The colour of these lines is an indication of the sign and value of the correlation between the times series of the normalized abundances of fish from both subareas. If no or not enough data were available to calculate the correlation, then this line was not drawn. R 2.15.2 (R Development Core Team 2009) was used for data handling, estimation, and plotting. For spatial data handling and statistics the R packages sp (Pebesma & Bivand 2005; Bivand et al. 2008), rgeos (Bivand & Rundel 2011), and rgdal (Keitt et al. 2011) were used and for mixed modelling the R package lme4 (Bates and others 2012). For plotting, ellipse (Murdoch & Chow 1996, 2012) and ggplot2 (Wickham 2009) were used. Data analysis was performed by Eelke Folmer (EcoSpace).

![Fig. 2.3 Compartmentalization of the study area based upon fish abundance as determined by means of surveys in the North Sea (NSER), the North Sea coastal zone (DFS), and the Wadden Sea including the Ems estuary (DFS), and Lake IJssel (LIJ). Within the Wadden Sea, the blue boxes refer to DFS areas (MD = Marsdiep, EG = Eijerlandse Gat, VL = Vlie, BD = Borndiep, ZL = Zoutkamperlaag / Pinkegat, LS = Lauwers / Schild, ED = Ems-Dollard) and the white boxes to islands (TX = Texel, VL = Vlieland, TR = Terschelling, AM = Ameland, SO = Schiermonnikoog, RP = Rottumerplaat). Blue lines with rounded endpoints indicate (potential) corridors for migratory fish between different compartments. Note that potential migration points to inland waters are not indicated (e.g. all sluices along the Dutch Wadden Sea coast).](image-url)
2.4 Results & Discussion

2.4.1 Lampreys (Petromyzontidae)

River lamprey (Lampetra fluviatilis) – River Lamprey was caught during all surveys and in almost all surveyed areas, with exception of the tidal basin of the Eijerlandse Gat (Fig. 2.4.1.1). Although the time series of densities of River Lamprey in the North Sea and the Wadden Sea suggests an increase since the 1990s (Fig. 2.4.1.1), it cannot be excluded that misidentification during the surveys might have caused this (Heessen et al. 2015). On average, densities in the North Sea coastal zone and the Wadden Sea are around 0.1 fish ha\(^{-1}\), and less than 0.01 fish ha\(^{-1}\) in Lake IJssel (Fig. 2.4.1.1).

Fig. 2.4.1.1 Time series of normalized densities of River Lamprey as determined by means of surveys in the North Sea, Wadden Sea and Lake IJssel.
Comparison of trends from the different surveys in time show that year-to-year variations of fish caught by the three stow nets in the Ems estuary are more or less comparable with each other and with the variation of fish caught by beam trawls in the Vlie tidal basin (Fig. 2.4.1.2). In Lake IJssel, the variation in the by-catch of the fyke near Kornwerderzand is negatively correlated with that in the beam trawl surveys in Lake IJssel (Fig. 2.4.1.2).

When comparing the trends in the beam trawl surveys in the study area, it appears that there is some correlation between the North Sea and the Marsdiep tidal basin, between the NS coastal zone and the Vlie tidal basin and between the tidal basins of the Lauwers and the Ems estuary (Fig. 2.4.1.3).

Within the Netherlands, “Gasterense Diepje” (a branch of the small river “Drentsche Aa”) is one of the few locations where these fish are presently known to spawn (Winter & Griffioen 2007). River Lampreys can reach this area via the sluices of Delfzijl in the Ems estuary and adjacent canals in the Province of Groningen (Winter et al. 2013). Other but still unknown spawning areas might be reached when River Lamprey migrates upstream in the rivers IJssel and Vecht after accessing Lake IJssel via the Afsluitdijk (Erwin Winter, IMARES, pers. comm.).
**Sea Lamprey** (*Petromyzon marinus*) - Sea Lamprey was caught in all types of surveys (except for the beam trawl survey in Lake IJssel), but only in 10 of the 16 surveyed areas and locations (Fig. 2.4.2.1). For half of these locations, Sea Lamprey was caught only in 1 year or in 2 years of the study period (Fig. 2.4.2.1). Given that adult Sea Lamprey are parasitic feeders that attach to large preys, i.e. big fish and marine mammals, the catchability of Sea Lamprey with the nets used in the different surveys is very small (Erwin Winter, IMARES, pers. comm.). Due to possible misidentifications, the time series of densities in Sea Lamprey for the North Sea cannot be trusted (Heessen et al. 2015). In general, catches were too low to perform a correlation analyses.

**Fig. 2.4.2.1** Time series of normalized densities of Sea Lamprey as determined by means of surveys in the North Sea, Wadden Sea and Lake IJssel.
2.4.2 European Eel (Anguilla anguilla)

European Eels were caught during all surveys and in all areas (Fig. 2.4.3.1, Fig. 2.4.3.2). It must be noted that the surveys can be grouped according to the life phases of the fish caught, i.e. (i) adults & juveniles (all surveys in the North Sea and the North Sea coastal zone, fyke catches in the Marsdiep tidal inlet and Ems estuary, and all surveys in Lake IJssel), (ii) mainly juveniles (all surveys for the tidal basins of the Wadden Sea), and (iii) Glass Eel (lift net surveys at freshwater discharge points in the Wadden Sea). The time series of the adults and juveniles suggest that densities were generally higher in the 1980s than in the 1990s and 2000s except for the Ems estuary (Fig. 2.4.3.1). At sampling stations near the Afsluitdijk, Eels appear to have declined at both sides during the past decades, i.e. adults and juveniles in Lake IJssel near Kornwerderzand (Fig. 2.4.3.1) and Glass Eel at the sampling stations near Den Oever in the Wadden Sea (Fig. 2.4.3.4).

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Fig. 2.4.3.1 Time series of normalized densities of European Eel (juveniles and adults) as determined by means of surveys in the North Sea, Wadden Sea and Lake IJssel.
The ellipse matrix of correlations suggests synchronous dynamics in European Eel (including Glass Eel) between the marine waters of the North Sea (including the coastal zone) and the Wadden Sea (including the Ems estuary) (Fig. 2.4.3.2, Fig. 2.4.3.3). Correlations were particularly high between Glass Eel catches at Den Oever, Harlingen and Lauwersoog (Fig. 2.4.3.2, Fig. 2.4.3.3). At the stations Terborg (TB) and Spijk (SP) in the Ems estuary, (juvenile and adult) Eel showed opposite trends compared to most other stations and larger marine areas (Fig. 2.4.3.2, Fig. 2.4.3.3).

When comparing the trends in the beam trawl surveys in the study area, it appears that trends in many subareas are positively correlated, in particular the Marsdiep with its adjacent basins (Vlie, Eijerlandse Gat) and the North Sea, and the tidal basins of Borndiep and Zoutkamperlaag (Fig. 2.4.3.2). Correlations were low or absent between the Marsdiep tidal basin and Lake IJssel, and between the North Sea coastal zone and the tidal basins of Zoutkamperlaag and Lauwers (Fig. 2.4.3.3).

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**Fig. 2.4.3.2** Ellipse matrix of the correlations between times series of normalized densities of European Eel (juveniles and adults) as determined by means of surveys in the North Sea, the Wadden Sea and Lake IJssel. Colour indicates positive (blue) or negative (red) correlation, colour intensity the (absolute) size of the correlation coefficient.

**Fig. 2.4.3.3** Correlations between times series of normalized abundance of European Eel (juveniles and adults) between adjacent basins as determined by means of surveys in the North Sea, the Wadden Sea and Lake IJssel. Colour indicates positive (blue) or negative (red) correlation, colour intensity the (absolute) size of the correlation coefficient.
This large-scale synchronicity suggests a common driver of Eel dynamics, e.g. an atmospherically driven dispersal by ocean currents connecting the putative spawning grounds of the European eel and the Gulf Stream, determining the arrival of juveniles at the European coast (Baltazar-Soares et al. 2014). An alternative explanation is given by Kettle et al. (2011), who point to a change in hydrology and exploitation in the southwest corner of the geographical range of European Eel, particularly the Atlantic coast of Morocco. Possibly, Glass Eel trends are more dominated by large-scale drivers (hydrographic), whereas those of the (Yellow and Silver) Eel are more determined by local drivers (e.g., entrance to fresh/inland water, fisheries) (Zwanette Jager, ZiltwaterAdvies, pers. comm.).

Dekker & Casselman (2014) showed that in Europe recruitment of (Glass) Eel has declined by 90%–99% since 1980. Global oceanic changes, as well as direct and indirect impacts (barriers to migration, contaminants, fisheries exploitation, habitat loss, parasite introductions, and water quality deterioration), have been suggested as causes for the decline (a.o., Castonguay 1994; Feunteun 2002; Friedland et al. 2007; Palstra et al. 2007; Robinet & Feunteun 2002).

Since its closure in 1932, Lake IJssel has been subject to a suite of management regulations with regard to Eel, including changes in fishery pressure (e.g. fishing efforts, fishing season, engine power, and increases in mesh size; De Leeuw et al. 2008) and restocking (Dekker & Beaulaton 2016b). Furthermore, the increase in Eel in Lake IJssel directly after the closure might have resulted from the fact that Eel was no longer able to take advantage of selective tidal transport for swimming up rivers and got stuck in this area (Dekker & Beaulaton 2016a). Alternatively, a new suitable and vast habitat came available for a large part of the Glass Eel entering Lake IJssel and therefore there was no need for more dispersal further upstream. This fill-up principle is also observed in French rivers at the Bay of Biscay after barriers were taken away (Erwin Winter, IMARES, pers. comm.).
2.4.3 European Anchovy (*Engraulis encrasicolus*)

Anchovy was caught in 11 of the 20 surveyed areas or locations, and caught only in 1 year or in 2 years of the study period within 6 of these 11 areas (Fig. 2.4.4.1). The peaks in the stow-net catches in 2007 in the Ems estuary (Spijk, Oterdum, Terborg) are in concordance with the only catch in the beam trawl survey for this area, and was also observed in the North Sea (Fig. 2.4.4.1; Fig. 2.4.4.2). Another peak in 1998 coincided simultaneously in the tidal basins of Vlie, Borndiep and Zoutkamperlaag (Fig. 2.4.4.3). Correlations in trends between tidal basins and adjacent marine waters (North Sea, North Sea coastal zone) are poor, with exception of the high correlation between Vlie, Borndiep and Zoutkamperlaag resulting from the simultaneous peak in 1998 (Fig. 2.4.4.3). In general, the time series of the Wadden Sea tidal basins

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Fig. 2.4.4.1 Time series of normalized densities of European Anchovy as determined by means of surveys in the North Sea, Wadden Sea and Lake IJssel.
Fig. 2.4.4.2 Ellipse matrix of the correlations between times series of normalized densities of European Anchovy as determined by means of surveys in the North Sea, the Wadden Sea and Lake IJssel. Colour indicates positive (blue) or negative (red) correlation, colour intensity the (absolute) size of the correlation coefficient.

Fig. 2.4.4.3 Correlations between times series of normalized abundance of European Anchovy between adjacent basins as determined by means of surveys in the North Sea, the Wadden Sea and Lake IJssel. Colour indicates positive (blue) or negative (red) correlation, colour intensity the (absolute) size of the correlation coefficient.
were characterized by one (1998 or 2007) or two years (1975 and 1998) with occurrences of Anchovy, and zero observations for other years within the study period (1970–2014). This can be explained by the fact that Anchovy is a summer (May–July) visitor and is not found in autumn in these waters when these surveys are performed.

In the North Sea, anchovy abundance has fluctuated, with periods of high abundance being followed by periods of near absence (Aurich 1953). Data from trawl surveys and commercial information landings indicate a strong increase in Anchovy abundance since 1995 after a period of absence (Beare et al. 2004). This increase is considered to be the result of an improved productivity of existing populations, associated with an expansion in thermal habitats and/or wind-induced variations in the inflow of Atlantic water in winter, and probably not due to a northward shift in the distribution of a southern (Bay of Biscay) population (Corten & Van de Kamp 1996; Petitgas et al. 2012). The former Zuiderzee used to support the largest spawning population of Anchovy in northwestern Europe (Petitgas et al. 2012), but catches rapidly declined after the closure in 1932 (see Chapter 1, Fig. 1.4) and this species is no longer caught in Lake IJssel (Fig. 2.4.4.1). Within the western Wadden Sea, spawning individuals were reported up to 1962 (sequence of cold winters) and eggs were observed again in 1994 north of the freshwater discharge sluices of Kornwerderzand, close to former spawning areas in the Vlieter tidal gully (Boddeke & Vingerhoed 1996). In May 2010 and May 2011, schools of Anchovy were found in a pelagic survey in the Marsdiep area. Their mean length (14.5 cm) corresponded to age–1 fish that are likely to spawn. Hence, for anchovy the Wadden Sea area is important both as nursery as well as for spawning (Couperus et al. 2016).

In historical times, Anchovy formed the basis of a substantial fishery in the Ems estuary, which came to an end before 1855 (Stratingh & Venema, 1855), which was before the blooming of the fishery in Zuiderzee between 1880 and 1903 (Gmelich Meijling-van Hemert 2008). Possibly, the recent catches of Anchovy in the (spring) stow-net survey in the middle and outer part of the Ems estuary indicate a return of this fish species in this formerly rich area.
2.4.4 Herrings (Clupeidae)

Atlantic Herring (Clupea harengus) – Herring was caught in all marine survey areas and locations, and during two years (1991, 1992) in the trawl catches in Lake IJssel (Fig. 2.4.5.1). On average, marine bottom-trawl catches in the North Sea and the Wadden Sea were low in the 1970s, and increased hereafter (Fig. 2.4.5.1). The variation in stow-net catches at Terborg appears to be positively correlated with the beam trawl catches in tidal basins of Eijerlandse Gat, Borndiep and Zoutkamperlaag (Fig. 2.4.5.2).
Fig. 2.4.5.2 Ellipse matrix of the correlations between times series of normalized densities of Atlantic Herring as determined by means of surveys in the North Sea, the Wadden Sea and Lake IJssel. Colour indicates positive (blue) or negative (red) correlation, colour intensity the (absolute) size of the correlation coefficient.

Fig. 2.4.5.3 Correlations between times series of normalized abundance of Atlantic Herring between adjacent basins as determined by means of surveys in the North Sea, the Wadden Sea and Lake IJssel. Colour indicates positive (blue) or negative (red) correlation, colour intensity the (absolute) size of the correlation coefficient.
When comparing the trends in the beam trawl surveys in the study area, it appears that trends in the tidal basins are positively correlated, and that variation in Herring densities in the eastern tidal basins is correlated with that in the North Sea coastal zone (Fig. 2.4.5.3). In the North Sea, numbers increased steadily in the 1980s reflecting a period of recovery after the collapse of the Herring stock as the result of overfishing in the 1970s and remained more or less stable thereafter (Dickey-Collas et al. 2010). Relatively low stocks in the 2000s are ascribed to low recruitment (2002–2010) caused by an increase in temperature, a regime shift in the ecosystem and/or predation by the large stock of adult Herring on its own larvae (Corten 2013). These large-scale changes are, however, not synchronised with changes in the Dutch coastal zone nor in the tidal basins of the Wadden Sea (Fig. 2.4.5.2). A critical factor for the survival of the larvae of Herring born in the central and northern North Sea appears to be their transport in winter across the North Sea towards the shallow coastal nursery areas in the east, including the Wadden Sea (Corten 2013).

There is evidence that this winter transport of larvae across the North Sea was interrupted for a number of years prior to 1980 as the result of a reduced inflow from the Atlantic Ocean (Corten 2013), which might explain the relatively low densities during that time in the Marsdiep tidal inlet and the western tidal basins of the Wadden Sea (Fig. 2.4.5.1). There appears to be a synchronisation in Herring abundances in the coastal zone and the eastern part of the Wadden Sea, probably due to local circumstances reducing fish numbers such as competition for food with the invasive ctenophore since 2005 (Kellnreitner et al. 2013), temperature-related infections by parasites (Schade et al. 2015) or enhanced predation by fish (Cardoso et al. 2015), birds and seals (Van der Veer et al. 2015).

The occurrence of Herring in Lake IJssel in 1991 and 1992 might have been the result of a change in sluice management in 1991-1993, where discharge sluices were kept open until water levels at both sides of the sluices were equal, as was observed for Flounder (Winter 2009).
**Allis Shad** (*Alosa alosa*) – Allis Shad was only caught in the North Sea bottom trawl survey, and therefore not further considered for analyses (Fig. 2.4.6.1). In 2013, three young-of-the-year *Alosa alosa*, probably originating from natural reproduction, were documented for the first time in a period of nearly 100 years in the River Rhine. In 2014, a further increase was observed when 57 juveniles and eight adults were caught; seven of these eight adults were derived from stocking (Hundt et al. 2015).

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**Fig. 2.4.6.1** Time series of normalized densities of Allis Shad as determined by means of surveys in the North Sea, Wadden Sea and Lake IJssel.
**Twaite** (*Alosa fallax*) – Twaite Shad was caught by most surveys in the North Sea, the coastal zone of the North Sea, in all tidal basins of the Wadden Sea, only not by the bottom trawl surveys in Lake IJssel (Fig. 2.4.7.1). The year 1982 was an outlier with large numbers of fish caught in the coastal zone (Fig. 2.4.7.1; Heessen et al. 2015). This peak in 1982 occurred in several tidal basins of the Wadden Sea as well (Fig. 2.4.7.1). For two of three stow net surveys (Oterdum, Spijk), variation in Twaite Shad was positively correlated with that in the North Sea (Fig. 2.4.7.2). Variation at Oterdum was, however, negatively correlated with that of the third (oligohaline) stow net at Terborg and with that of the (freshwater) fyke catches at Kornwerderzand (Fig. 2.4.7.2).

When comparing the trends in the beam trawl surveys in the study area, the variation in Twaite Shad appeared to be synchronised in the North Sea, the Dutch coastal zone and the westernmost and easternmost tidal basins of the Wadden Sea (Fig. 2.4.7.3).

*Fig. 2.4.7.1 Time series of normalized densities of Twaite Shad as determined by means of surveys in the North Sea, Wadden Sea and Lake IJssel.*
Twaite Shad need tidal freshwater systems to spawn successfully and estuaries for nursing, thus the occasional fish in Lake IJssel at present is considered to be have entered these waters without successful spawning (De Groot 2002). Improvement of the water quality, in particular with regard to the oxygen conditions, resulted in a comeback of Twaite Shad in the Western Scheldt since 1996 with spawning individuals since 2010 (Peter Herman, NIOZ, pers. comm.). In the Ems, at least in some years, successful spawning occurs (Erwin Winter, IMARES, pers. comm.).
2.4.5 European Smelt (*Osmerus eperlanus*)

Smelt was caught in all surveys in the North Sea, the Wadden Sea and Lake IJssel (Fig. 2.4.8.1). Stow-net catches at Spijk and Oterdum are positively correlated, whilst the stow-net catches at Spijk are negatively correlated with those of the bottom-trawl surveys and the fyke catches near Kornwerderzand in Lake IJssel (Fig. 2.4.8.2).

When comparing the trends in the beam trawl surveys in the study area, annual variations in Smelt in the Marsdiep tidal basin appears to be correlated with those in the North Sea and in Lake IJssel (Fig. 2.4.8.3). In addition, some correlation is found between the North Sea coastal zone and Zoutkamperlaag tidal basin, and between the tidal basins of Lauwers and Ems estuary (Fig. 2.4.8.3). This suggests that drivers of the abundance of Smelt at the edges of the Dutch Wadden Sea occur in the North Sea, but not in the coastal zone (Fig. 2.4.8.3). It seems, however, unlikely that drivers in the North Sea steer Smelt abundance. The main drivers will likely be the two large freshwater discharges from Lake IJssel and Ems (Erwin Winter, IMARES, pers. comm.).

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*Fig. 2.4.8.1 Time series of normalized densities of European Smelt as determined by means of surveys in the North Sea, Wadden Sea and Lake IJssel.*
Smelt was formerly abundant in the Zuiderzee. After closure of the dike in 1932, a landlocked population developed, that matures after only 1 year instead of after 2-3 years as for the diadromous smelt, while the diadromous population still inhabits the coastal waters of the Wadden Sea. The diadromous population may either be seeking spawning grounds in open estuaries (e.g. Ems estuary) or may be entering Lake IJssel through the sluices, although the contribution of diadromous smelt is negligible in the current situation (Tulp et al. 2013). Within Lake IJssel, the Smelt populations have declined strongly since 1990 (Fig. 2.4.8.1), and Smelt fishery was closed during five years in the last decade because of low biomass (De Leeuw et al. 2008).

Barium and Strontium concentrations in the otoliths of Wadden Sea Smelt suggest a mixture of two populations, i.e. those who were born in the Wadden Sea (55%) and in Lake IJssel (5%) or Markermeer.
and migrated to the Wadden Sea (Phung et al. 2015). This implies that variation in the Wadden Sea stocks of Smelt is at least partly driven by import from Lake IJssel.

Water Board Hunze en Aa’s observes migration of adult Smelt through the sluice of Nieuwe Statenzijl in the Ems estuary. Monitoring with fykes in inland waters shows that they migrate up to 20 km upstream. Possibly they spawn in the Westerwoldse Aa considering the fact that juvenile 0+ individuals are caught in local fykes (Peter Paul Schollema, Waterschap Hunze en Aa’s, pers. comm.).

2.4.6 Salmonids (Salmonidae)

Atlantic Salmon (Salmo salar) - The time series of the North Sea just shows the incidental catches (Heessen et al. 2015; Fig. 2.4.9.1). Within all other surveys, Salmon was only caught in the two fykes in Lake IJssel (Fig. 2.4.9.1). This species was therefore not considered for further analyses. Low to zero catches are most probably due to the low catchability of Atlantic Salmon, resulting from their strong swimming capacity (escaping nets) and their periodic occurrence (smolts in late spring, and adults mainly during summer and autumn) when using the Wadden Sea.
Sea as corridor to the open ocean (Erwin Winter, IMARES, pers. comm.).

Sea Trout (Salmo trutta) – Within the study area, Sea Trout was caught by the bottom trawls in the North Sea (irregularly) and Lake IJssel (in 1995 and 1996 only), fykes in the Marsdiep (regularly) and Lake IJssel, and some of the stow nets in the Ems estuary (Fig. 2.4.10.1). This species was therefore not considered for further analyses. Although the small catches in the North Sea were quite irregular since the late 1970s, reports have been more frequent in the 1990s than in the last decade (Heessen et al. 2015). In contrast to Atlantic Salmon (using the Wadden Sea only as a corridor to the open ocean), Sea Trout is roaming the coastal areas and estuaries directly downstream their spawning rivers to feed. The Wadden Sea will also be partly used as a feeding habitat, but this fast swimmer is difficult to catch with most of the survey gears (with exception of fykes, and possibly stow nets), and these surveys will therefore grossly underestimate its abundance (Erwin Winter, IMARES, pers. comm.).
Houting (*Coregonus oxyrhinchus*) - Within the study area, Houting was caught once (2010) in the Marsdiep tidal basin and furthermore only caught in Lake IJssel, in the bottom trawls as well as in the fykes (Fig. 2.4.11.1). This species was therefore not considered for further analyses. Houting was historically distributed in the Wadden Sea extending from Jutland (Denmark) to the Schelde delta (The Netherlands). The species has been considered extinct in the River Rhine since the 1940s (Fig. 1.5).

A successful re-introduction programme, however, re-established a self-reproducing population (Borcherding et al. 2014). The River IJssel, a lower branch of the River Rhine, and/or its tributaries serve as spawning ground. Freyhof & Schöter (2005), however, conclude that *C. oxyrinchus* is a globally extinct species and recently re-introduced coregonids in the Rhine catchment from Danish rivers are in fact *C. maraena*, a species not native to the Rhine.
In 2010, justly hatched larvae were caught directly upstream from Kampen, where the IJssel discharges into Lake IJssel, most probably hatched in upstream areas of the River IJssel (Borcherding et al. 2014). The fish caught in the Lake IJssel survey since 2006 and in the Marsdiep in 2010 are, therefore, most likely originating from the newly established spawning population in the River IJssel. Fyke monitoring programmes and seine-net efforts to catch Houting for telemetry experiments showed that many Houting use Lake IJssel for feeding and that only part of the population migrated to marine environments (Borcherding et al. 2008, 2014).
2.4.7 Three-spined Stickleback
*(Gasterosteus aculeatus)*

Within the study area, Three-Spined Sticklebacks were caught in the bottom-trawl surveys in the North Sea and Lake IJssel, in fykes in the tidal basins of the Marsdiep and Lake IJssel, and in the stow-net surveys in the Ems estuary (Fig. 2.4.12.1). Variations in stow-net catches appear to be correlated with each other, as the stow-net catches near Terborg and the fyke catches near Kornwerderzand, and the bottom-trawls in Lake IJssel with the fyke catches near Flevoland (Fig. 2.4.12.2). In the North Sea, catches have been quite variable from year to year without any clear trend. However, bottom-trawl catches are not representative of annual fluctuations in Three-Spined Sticklebacks (Heessen et al. 2015).

**Fig. 2.4.12.2** Ellipse matrix of the correlations between times series of normalized densities of Three-Spined Stickleback as determined by means of surveys in the North Sea, the Wadden Sea and Lake IJssel. Colour indicates positive (blue) or negative (red) correlation, colour intensity the (absolute) size of the correlation coefficient.
2.4.8 European Flounder  
(*Platichthys flesus*)

Flounder was caught in all surveys in the North Sea, the Wadden Sea and Lake IJssel (Fig. 2.4.13.1). When comparing trends in the bottom-trawl catches in the study area, annual variations in Flounder in the Marsdiep tidal basin appears to be correlated with those in the North Sea, the Vlie tidal basin and Lake IJssel (Fig. 2.4.13.3). This positive relationship between the North Sea and the Marsdiep might be explained by a stock-recruitment relationship, i.e. high number of spawning adults in the North Sea result in high numbers of juvenile Flounders in the western Wadden Sea (Zwanette Jager, ZiltwaterAdvies, pers. comm.).

Within Lake IJssel, the abundance of Flounder increased rather suddenly from less than 5 individuals per ha up to more 30 individuals per ha in the early 1990s (Fig. 2.4.13.1).

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*Fig. 2.4.13.1 Time series of normalized densities of European Flounder as determined by means of surveys in the North Sea, Wadden Sea and Lake IJssel.*
This increase has been attributed to a change in sluice management in 1991-1993, where discharge sluices were kept open until water levels at both sides of the sluices were equal allowing some salt water near the bottom to enter Lake IJssel (originally sluices were closed when water levels at the seaside were still 10 cm lower than in Lake IJssel) (Winter 2009). In addition to sluice management, a strong correlation with Flounder densities and discharge rates in late summer (Aug/Sept) was observed, with an approximate slope of +0.3 individuals per ha per m³ discharge for the period between 1991 and 2000 (Winter 2009).

After an initial decrease of the proportion of Flounder with skin ulcers in front of the drainage sluices of the Afsluitdijk from some 30% to 10% since 1988, the situation improved further at Den Oever and Kornwerderzand following the adapted sluice management between 1991 and 1993 (Vethaak et al. 2004). If the diseases led to increased mortality or weaker growth and smaller sized fish, this may have affected the reproductive potential of part of the population through size-specific fecundity (Rijnsdorp 1994; Van der Veer et al., 2000).

The cause of the outbreak of disease in Flounder in front of the Afsluitdijk drainage sluices has been attributed to cumulating stress factors affecting the fish’ immune system, making the fish more susceptible to a variety of diseases. The most important stress factors include long periods of time in the unfavourable water conditions outside the drainage sluices, including abrupt and extreme salinity fluctuations due to the discharge of fresh water from Lake IJssel (Vethaak et al. 2004). Reduction of these stress factors may result in increased fecundity and, subsequently, in increased stock size.

Fig. 2.4.13.2 Ellipse matrix of the correlations between times series of normalized densities of European Flounder as determined by means of surveys in the North Sea, the Wadden Sea and Lake IJssel. Colour indicates positive (blue) or negative (red) correlation, colour intensity the (absolute) size of the correlation coefficient.
A decrease, however, was found in the Marsdiep tidal inlet that more or less coincided with changes in the coastal zone (Fig. 2.4.13.3). The absence of synchronicity with the other areas suggest the presence of a local driver in the coastal zone that is reflected in the fyke catches in the Marsdiep tidal inlet. Van der Veer et al. (2015) found a correlation between time series of decreasing fish numbers and increasing volumes of sand nourishments, for example, but it is unclear if this relationship is causal or not. As was suggested for Smelt (Erwin Winter, IMARES, pers. comm.), variations in stocks of Flounder might also or additionally be driven by large freshwater discharges from Lake IJssel and Ems. This is in line with the positive correlation in bottom-trawl catches of the North Sea and the Ems estuary (Fig. 2.4.13.2).

Fig. 2.4.13.3 Correlations between times series of normalized abundance of European Flounder between adjacent basins as determined by means of surveys in the North Sea, the Wadden Sea and Lake IJssel. Colour indicates positive (blue) or negative (red) correlation, colour intensity the (absolute) size of the correlation coefficient.
2.5 Conclusions

From a historical perspective (100–2000 yrs), long-term stock dynamics of the fish species under consideration were driven by overfishing, pollution and habitat destruction, including the interruption of the river continuum by barriers (Chapter 1). Within a shorter time frame (< 50 yrs), the synchronies in abundances suggest an influence of additional factors, from large-scale climate variation to local import from freshwater systems (Fig. 2.5), depending on the species.

For River Lamprey and Sea Lamprey, synchronisation patterns were difficult to assess as the result of possible misidentifications and low catchabilities, in particular for Sea Lamprey. For River Lamprey, abundances in the Ems estuary might be driven by spawning success in the “Gasterense Diepje”, a branch of the “Drentsche Aa” river.

For European Eel, synchrony in time series from North Sea (including the coastal zone) and the Wadden Sea (including the Ems estuary) suggest a large-scale driver within the marine waters of the study area. Such possible large-scale drivers include atmospherically driven dispersal by ocean currents and change in hydrology and exploitation. Within Lake IJssel, the effects of these large-scale climate-driven influences may have been obscured by local impacts, including the influence of the Afsluitdijk in 1932 and changes in fishery pressure and restocking hereafter.

For European Anchovy, the lack of correlations between basins and adjacent marine waters (North Sea, North Sea coastal zone) suggest the absence of a common driver. Since Anchovy visits the study in summer whilst most of the surveys were performed in autumn, however, possible existing correlations might have been missed. It cannot be excluded that the climate-driven increase of Anchovy stocks in the North Sea results in time in larger stocks in the study area.

For Atlantic Herring, the synchronisation in stock dynamics in all tidal basins suggests the existence of a local driver at the scale of the Dutch Wadden Sea.

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**Fig. 2.5** Potential long-term and short-term drivers (as derived from synchrony in time series of surveys) of stock sizes of migratory fish in the Dutch Wadden Sea.
The correlation structure of the stock dynamics of
the tidal basins with the coastal zone of the North Sea
further suggests that the central and eastern part of
this zone are part of the synchronisation area as well.
Possible local drivers include competition for food
with ctenophores, parasitic infections and predation by
fish, birds and seals.

For **Allis Shad** and **Twaite Shad**, only
synchronisation patterns of the latter could be
analysed. Stock dynamics of Twaite Shad appear to
be synchronised in the western and eastern part of
the Dutch Wadden Sea and the adjacent coastal zone.
As has been observed for the Scheldt estuary, stock
dynamics of Twaite Shad in estuarine tidal basins
such as the Marsdiep and the Ems might be driven by
environmental conditions at their freshwater spawning
grounds. Improvement of these conditions might then
attribute to larger stocks in the Wadden Sea.

For **Atlantic Salmon** and **Sea Trout**, the catchability
of the fishing gear used during the surveys was
generally too low to get reliable information on
variation in local densities. Whilst Atlantic Salmon
uses the Wadden Sea only as a corridor to the open
ocean, Sea Trout is roaming the coastal areas and
estuaries to feed and local stocks might therefore
benefit from available resources.

For **Houting**, fish numbers caught were too low
for further analysis. Incidental catches of this species
throughout the study area suggested, however, that
offspring of successful reproduction of introduced fish in
River IJssel was caught in the Marsdiep tidal basin in the
same year. This implies that successful re-introduction
programs of diadromous fish in rivers might contribute
to local stocks in the Wadden Sea area.

For **Three-Spined Sticklebacks**, most of the
sampling gear used in the surveys was not suited to get
reliable estimates of local densities of this species. This
species is better caught by means of 1x1 m lift nets, as
been used during a monitoring study at relatively small
freshwater discharge points along the mainland coast
of the Wadden Sea area. Results of this study will be
discussed in Chapter 3.

For **European Smelt** and **European Flounder**,
synchronisation appears to occur between the North
Sea and the westernmost (Marsdiep) and easternmost
(EMS estuary) tidal basins of the Dutch Wadden Sea.
Both basins are characterised by a strong salinity
gradient, suggesting freshwater discharges as a
driving factor. Possible mechanisms include a stock-
recruitment relationship, with high adult numbers
offshore resulting in high numbers of larvae and
juveniles inshore. An alternative driver might be
supply of fish to the Wadden Sea and North Sea from
lakes and rivers via freshwater discharges, as has been
observed for Smelt from Lake IJssel to the Marsdiep
tidal basin.

Summarized, local stocks of all targeted fish species
are influenced by large-scale long-term drivers
such as fisheries, habitat destruction and climate.
For some species, however, local short-term drivers
such as re-introductions, freshwater discharges and
environmental quality of the freshwater spawning
areas might obscure the influence of these drivers. If
so, then improvement of local conditions might result
in strengthening of local stocks, within the boundaries
set by the large-scale long-term drivers.
3. FINDING OPTIMAL LOCATIONS FOR FISH MIGRATION FROM MARINE TO FRESHWATER SYSTEMS

3.1 Introduction

In order to aid in identifying optimal areas and locations for fish migration from the Wadden Sea to adjacent freshwater systems, the following basic information is provided in this chapter. First, an overview of the existing options for fish passing (including natural estuarine gradients) is presented as potential locations for optimisation within present conditions. Second, the density of migratory fish at a larger (tidal basin) scale is given as an index of potential supply of migratory fish for local options. When fish supply is high, a large number of fish is able to migrate to inland freshwater systems. Third, the spatial variation in density of migratory fish at the seaside of existing discharge stations is statistically analysed. These local-scale densities are compared to large (tidal basin) scale spatial variation in densities and discussed with regard to local conditions (e.g. freshwater discharge).

This analysis has some strong limitations, which should be taken into account when interpreting the results. The supply of fish (number of fish that can potentially migrate within one day; fish d⁻¹) in a fish passage sampling point is actually the product of density (e.g., number of fish per m²), area (m²) and the turnover rate of fish (net flux of fish entering and leaving the study area within a day; fish fish⁻¹ d⁻¹). This implies that, for example, a relatively high passing efficiency (with many fish migrating from the sea to freshwater systems) may result in relatively low abundances and densities of fish in front of the fish passage (Zwanette Jager, ZiltwaterAdvies, pers. comm.). Unfortunately, such information is not available. Fish densities might, therefore, only be weakly related to fish supply (Erwin Winter, IMARES, pers. comm.). Furthermore, finding optimal locations requires a quantitative assessment of fish passing efficiency of existing fish passages in the area. Despite the general high costs of building these structures, however, no comparable data to perform a quantitative evaluation of the construction of fish migration facilities were available. So far, only one study (at Roptazijl) compared the density of fish measured in front of the fish passage with the number of fish that goes through (Allix Breninkmeijer, Altenburg & Wymenga, pers. comm.). Interpretation of the results is not easy, however, because different fishing gears were used at both sides of this fish passage. In another study (at Nieuwe Statenzijl), passage efficiency was measured by means of mark-recapture experiments with dyed Glass Eel, but results are not yet available (Peter Paul Schollema, Waterschap Hunze en Aa’s, pers. comm.). More details on these studies are given in the discussion of this chapter.
3.2 Estuarine gradients in the Dutch Wadden Sea

Within the Dutch Wadden Sea area there are 65 locations that can be considered as estuarine gradients as originally put forward by De Boer & Wolff (1996) and four more locations, which are planned or under construction. These gradients vary from tidal creeks in saltmarshes to large freshwater sluices that discharge over 300 m$^3$ s$^{-1}$ on average at an annual basis. The discharge of freshwater is a reflection of the size of the inland potential habitat available. We have actualised and revised the list of estuarine gradients by De Boer & Wolff (1996) and grouped them according to (Figure 3.1, Table 3.1):

- **Sluices** – characterised by an abrupt salinity gradient, caused by relatively large discharges of freshwater into the sea at low tide, resulting in an almost freshwater environment during low tide and a nearly full saline environment during high tide;
- **Pumps** – characterised by an abrupt salinity gradient, caused by inputs of freshwater into the sea during pumping, resulting in a temporary freshwater environment;
- **Culverts** – characterised by an abrupt salinity gradient, caused by relatively small inputs of freshwater into the sea with an almost freshwater environment during low tide and a nearly full saline environment during high tide;
- **Locks** – characterised by an abrupt salinity gradient on either side of the ship locks. Leakage of freshwater into the sea or salt water into the lake does not neutralize abrupt salinity gradients;
- **Salt Water (SW) inlets** – found at De Bol on the island of Texel and in Polder Breebaart. Both are enclosed brackish areas, where seawater is taken in during high tide;
- **Fresh Water (FW) seepages** – at several island locations seepage of freshwater is resulting in estuarine gradients near the coast. These areas can be flooded with salt water during storm tides;
- **Creeks** – open connections between freshwater and seawater characterised by a gradual salinity gradient, caused by freshwater (rainwater) coming from the dunes and marshes, and by saltwater flowing in at the seaside during high tide. These include island saltmarsh creeks that are fed by water from the Wadden Sea, with the exception of De Slufter that is fed by North Sea water.
- **Estuaries** – open connection between a river and the sea.

![Fig. 3.1 Locations of estuarine gradients in the Dutch Wadden Sea.](image)
Many of the estuarine gradients are freshwater sluices, pumps, culverts or locks, some of which are equipped with facilities to enable fish to migrate from the sea to the freshwater system, or to prevent damage to fish when migrating from freshwater to the sea through discharge facilities. Some pumping stations are not suitable for anadromous migration upstream, but downstream migration may be possible for small fish that migrate to the sea (George Wintermans, WEB, pers. comm.). Within the Wadden Sea, there are five main types of fish passage facilities installed, tested or planned (Table 3.1):

- Tide gates or tidal flaps in culverts, or small openings or slots made in medium-scale to large-scale locks;
- Fish friendly discharge sluice and ship lock management (FFM). The effectivity varies depending on the way the sluices or locks are operated and on the amount of seawater that is allowed to flow landwards;
- Pumps used for fish bypasses (usually with low capacity pumps, and relatively low numbers of fish passing) or fish-friendly pumps (usually with a high pump capacity);
- Fish ladders (“cascade”), siphon spillways (“vishevel” in Dutch; using freshwater discharges) or Eel gutters;
- Large-scale fish passage constructions that include a collection basin for the inflow of salt water with the incoming flood tide.

Table 3.1 Names, characteristics and freshwater discharge ($m^3/s$) of estuarine gradients in the Dutch Wadden Sea at the islands of Texel (TX), Vlieland (VL), Terschelling (TS), Ameland (AM), Schiermonnikoog (SC), Rottumerplaat (RP), Rottumerroog (RO) and the coastal mainland of the Provinces Noord-Holland (NH), Fryslân (FR) and Groningen (GR). Information on estuarine gradients is an update of the overview published by De Boer & Wolff (1996), information on fish passages as supplied by George Wintermans (WEB) and Allix Breninkmeijer (Altenburg & Wymenga).
3.3 Fish densities in tidal basins of the Dutch Wadden Sea

A tidal basin is defined as a water body in a semi enclosed coastal area that is subject to tides. Tidal basins are useful for comparative research because they are logical units from morphological, hydrodynamic, and ecological perspectives (Kraft et al. 2011). Within the Dutch Wadden Sea, Kraft et al. (2011) distinguished ten tidal basins, i.e. Marsdiep, Eijerlandse Gat, Vlie, Amelander Zeegat, Pinkegat, Zoutkamperlaag, Eilander Balg, Lauwers, Schild, and Ems-Dollard (from west to east).

The Dutch survey area of the Demersal Fish Survey (DFS) comprises the coastal zone north of the Wadden Sea islands (DFS404), the Wadden Sea (from west to east: DFS610, DFS612, DFS616 -619), and the Ems-Dollard estuary (DFS620). The DFS areas within the Wadden Sea not fully match the tidal basins as proposed by Kraft et al. (2011). Within this report, tidal basins are therefore based upon the DFS areas, i.e. Marsdiep (DFS610), Eijerlandse Gat (DFS612), Vlie (DFS616), Borndiep (DFS617), Zoutkamperlaag (DFS618), Lauwers/Schild (DFS619) and Ems-Dollard (DFS620), (Fig. 2.2).

![Fig. 3.2 Normalized densities of migratory fish (from top to bottom: European Eel, Twaite Shad, Herring, Houting, Anchovy, River Lamprey, Smelt, Flounder & Sea Lamprey) as determined by means of the Demersal Fish Survey (DFS) between 1970 and 2013.](image-url)
The Demersal Fish Survey (DFS), which started in 1970, was able to fish for most years in most of these tidal basins and the adjacent Dutch coastal zone. On average, fish densities showed strong variations between years and basins with many low values and only a few high values (see Chapter 2). To reduce the strong influence of the extreme values on the overall patterns, annual fish densities \( (F_i; \text{numbers per ha}) \) were rescaled to normalised fish densities \( (F_{tn}) \) for each species, according to:

\[
F_{tn} = \frac{F_i - \min(F_i)}{\max(F_i) - \min(F_i)}
\]

where \( \min(F_i) \) and \( \max(F_i) \) are the lowest and highest values within the data set.

As result of the sampling gear, the DFS results are considered to reflect the densities of demersal fish, such as Flounder, best and less those of the other target species (Ingrid Tulp, IMARES, pers. comm.). Furthermore, one should consider the timing of occurrence in the Wadden Sea in relation to the survey period (September-October) (Tulp et al. 2015). Although densities varied from year to year (see Chapter 2 for a more elaborate discussion on this), some species show more or less stable spatial distribution patterns in time (Fig. 3.2). Smelt, for example, generally showed higher densities in the larger tidal basins of the western Wadden Sea (Marsdiep, Vlie) compared to the eastern part of the Dutch Wadden Sea (“O. eperlanus” in Fig. 3.2). Anchovy is most commonly found in the Marsdieptidal basin (“E. encrasicolus” in Fig. 3.2). Most other species show temporal variation as well as spatial patterns. Houting (“C. oxyrhinchus” in Fig. 3.2) was observed once in the Marsdiep tidal basin in 2010 (see Chapter 2). Flounder, for example, shows high densities in the central part of the Dutch Wadden Sea (Borndiep, Zoutkamperlaag) during the beginning of the study period (1970-1974), but densities were relatively high in the Marsdiep tidal basin between 1994 and 2004 (“P. flesus” in Fig. 3.2).
3.4 Fish densities near small freshwater sluices discharging into the Wadden Sea

3.4.1 Introduction

As part of the project “Making way for fish in the Wadden Sea area”, the northern angling federations and regional water authorities initiated a four-year monitoring study (2012-2015) on the density of migratory fish at the seaside of relatively small sluices, pumps and fish passages along the mainland coast of the Wadden Sea. During these surveys, 15 out of the 65 transitions between sea and freshwater systems in this area were consistently sampled during late winter and next spring. Sampling was performed by means of 1x1m lift net with a funnel of 75 cm and a mesh size of 1 mm and took place within 2 hrs around local high tide, with 3 to 5 hauls per sampling day, during 4 to 5 months per year (February - June). Freshwater discharges were always zero during sampling.

Recent data (2012-2015; Period II) could be compared with older data (2001-2003; Period I) on fish densities derived by similar method at the same locations. Sampling was performed by volunteers, and coordinated by WEB in 2012-2015 (Wintermans 2014) and by WEB and RIKZ in 2001-2003 (Wintermans & Jager 2003).

The catch data were used to explore the spatial variation of the density of migratory fish species along the small sluices and fish passages. The statistical analysis was restricted to those species (Table 3.4.1), which were consistently sampled. Flounder was, for example, excluded because larvae were not counted at each station. Eel was subdivided into Glass Eel and Yellow Eel. Herring and Sprat were lumped, because not all volunteers could identify these fish up to species level. Species-specific fish densities (Catch Per Unit Effort; CPUE) was calculated as the total number of fish of a particular species caught divided by the total number of hauls taken during that year.

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Table 3.4.1 Overview of small freshwater discharge sluices that were analysed for spatial variation in densities of European Eel, Herring (lumped with Sprat), Smelt and Three-Spined Stickleback. NB: The originally planned sampling stations “Harlingen” (nr. 03) and “Polder Brebaart” (nr. 16) were excluded from the analyses, because sampling was performed differently than at the other stations.
3.4.2 Statistical analyses

After data exploration (Zuur et al. 2010), data were analysed according to the following stepwise procedure for each species (and for Eel for both age groups as well).

**Step 1: Effect of Period**

The analysis was started by applying a Generalized Linear Model (GLM) with the log-transformed catching effort (number of hauls) as an offset (so that in essence we model the ratio) with only Period as an effect, assuming a Poisson distribution of the numbers of fish caught per sampling event (Zuur et al., 2009):

\[ \text{M1a: } \]

\[
\begin{align*}
E(\text{Catch}) &= \mu_i \\
\log(\mu_i) &= \beta_1 + \beta_2 \times \text{Period} + \log(\text{Effort})
\end{align*}
\]

The results show, assuming a Poisson distribution, if the number of fish caught significantly differed for the two periods or not. The fit of the model was checked for overdispersion (i.e. the observed variance is higher than the variance of a theoretical model) and underdispersion (i.e. less variation in the data than predicted by the model).

If overdispersion or underdispersion occurred, then the GLM was fitted assuming a negative binomial distribution of the numbers of fish caught per sampling event:

\[ \text{M1b: } \]

\[
\begin{align*}
\text{Catch} &\sim \text{NB}(\mu_i, k) \\
E(\text{Catch}) &= \mu_i \\
\log(\mu_i) &= \beta_1 + \beta_2 \times \text{Period} + \log(\text{Effort})
\end{align*}
\]

The negative binomial distribution is a valid choice when the variation in the data is larger than allowed for by a Poisson distribution.

The results show, assuming a negative binomial distribution, if the number of fish caught significantly differed for the two periods or not. If overdispersion or underdispersion still existed, then this could be attributed to another distribution of the data then Poisson or negative binomial, or as the result of a spatial effect (i.e. differences between numbers of fish caught at the different locations).

**Step 2: Effect of Location**

As a next step, the Pearson residuals of the Poisson or negative binomial GLM (model 1a or 1b) were checked for the presence of a pattern related to the different sampling locations (freshwater sluices and fish passages). This can either be done visually via a boxplot of the residuals versus locations or by applying a linear regression model in which the residuals are modelled as a function of the categorical covariate location. A significant covariate effect indicates that there are residual patterns, which means that the Poisson or negative binomial GLM is faulty. In that case a Poisson or negative binomial GLMM that takes into account the location effect should be applied.

\[ \text{M2: } \]

\[
\begin{align*}
\text{Residuals} &\sim N(\mu, \sigma^2) \\
E(\text{Residuals}) &= \mu_i \\
\mu_i &= \beta_1 \times \text{Passage}
\end{align*}
\]

The results give information on how much of the variation in the residuals (in %) can be explained by the differences between fish numbers at the different locations.

**Step 3: Interaction between Period and Location**

If fish numbers differed for the locations per period, there might be an additional need to add a so-called “interaction” term, i.e. highest density of fish was observed at other locations during in the early 2000s than in the early 2010s. The existence of such a difference was checked by means of comparing the fits of two different Generalised Linear Mixed Models (GLMM’s), assuming a Poisson or negative binomial distribution of the data. GLMM’s allow for the analysis of grouped data and complex hierarchical structures in data (e.g., different catches at the locations for the different periods). One GLMM model included Period as fixed term and Fish Passage as random effect (M3), whilst the other model included Period as fixed term, Fish Passage as random intercept and a random slope for Period (M4):

\[ \text{M3: } \]

\[
\begin{align*}
\text{Catch} &\sim \text{NB}(\mu_i, k) \\
E(\text{Catch}) &= \mu_i \\
\log(\mu_i) &= \beta_1 + \beta_2 \times \text{Period} + \log(\text{Effort}) + a_i \\
a_i &\sim N(0, \sigma^2_{\text{random}})
\end{align*}
\]

\[ \text{M4: } \]

\[
\begin{align*}
\text{Catch} &\sim \text{NB}(\mu_i, k) \\
E(\text{Catch}) &= \mu_i \\
\log(\mu_i) &= \beta_1 + \beta_2 \times \text{Period} + \log(\text{Effort}) + a_i + b_i \times \text{Period} \\
a_i &\sim N(0, \sigma^2_{\text{random}}) \\
b_i &\sim N(0, \sigma^2_{\text{random}})
\end{align*}
\]
The accuracy of the fit of these models was checked by comparison of additional models assuming Poisson distribution of the data and by taking the presence of catches with no individuals of the particular species (zero-inflated data sets) into account. The best model (M3 versus M4) was identified by means of the Akaike Information Criterion (AIC), a measure of the relative quality of statistical models for a given set of data (Akaieke 1980). The AIC deals with the trade-off between the goodness-of-fit of the model and the complexity of the model. If the difference in AIC between the models is smaller than 2, then the most simple model (in this case M3) is considered to be the best one explaining the data.

Step 4: Spatial and temporal correlation
Significant differences between fish caught at different locations can be the result of local conditions at the small freshwater sluices or fish passages or reflecting a wider spatial pattern (e.g., more fish in the western than in the eastern part of the Dutch Wadden Sea). Significant differences between fish caught at different periods can be the result of the periods themselves or reflecting a dependency between years (e.g., if fish is abundant in one year it may also be abundant in the next and vice versa).

The existence of such spatial and temporal correlations was analysed by means of interpretation of variograms, i.e. graphs that visualise the autocorrelation of a variable such as the density of fish at sluices and passages in relationship to space (km) or time (year). The number of unique years (n=7), however, was not sufficient to analyse the existence of temporal correlation. It was therefore assumed that temporal correlation, if present, was captured by the random effect of location (the term “Passage” in models 3 and 4).

Step 5: Identification of significantly different stations
To include uncertainties in anticipated performance indices (e.g., fish densities at fish passages), the statistical analysis of the best model (model 3 or 4, with or without spatial correlation) was performed by means of Markov Chain Monte Carlo (MCMC) methods. The Markov Chain refers to a random process that undergoes transitions from one state to another on a state space, where the probability distribution of the next state depends only on the current state and not on the sequence of events that preceded it (e.g., rolling a dice). Monte Carlo refers to running a computer simulation to simulate this random process many times (e.g., as rolling a dice time after time) and see the probability as the number of a particular outcome divided by the number of simulations performed (e.g., the number of times that you rolled a five divided by the total number of rolls).

The Deviance Information Criterion (DIC), an estimate of expected predictive error, is a measure of how well the model fits the data (lower deviance is better). The outcomes of the model allow for Bayesian post-hoc test to identify which locations are significantly different from each other with respect to anticipated fish densities. These results can be used to group locations according to their commonalities (i.e., no significant differences in densities between locations).

Statistical analyses were performed by Alain Zuur (HighStat) using R and relevant packages (lmer). Interpretations of the results were checked by George Wintermans (WEB).
3.4.3 Results
European Eel (Anguilla anguilla)

Glass Eel stage
Summary results stepwise analysis
• No significant effect of Period
• Significant effect of Location (60% of variation explained)
• No spatial correlation
• Densities high at ROZ, ZWH, NPZ & NSZ, and lower at other stations
• Locations fall into 13 density groups

The best model for Glass Eel with regard to testing the effect of Period was the model that assumed a negative binomial distribution of the data (lowest AIC for Model 1b compared to Model 1a; see Table 3.4.2.1), with a non-significant effect of Period on fish densities near fish passages (p > 0.05). The overdispersion of this model (d = 1.88) might be due to a spatial effect. The residuals of Model 1b showed a strong spatial effect (p < 0.001) and explained more than 60% of the variation. The AIC of Models 3 and 4 were not different enough (difference < 2) to be used as a criterion for best model, so the parsimony rule was applied (identifying the most simple model as best model, which was Model 3). This implies that fish densities over locations showed a more or less similar pattern during the two periods. The variogram did not show the presence of spatial correlation in the data set. The parameter values for Intercept and Period of the fit of Model 5 were comparable to those of Model 3 and the DIC was relatively low, indicating a good predictive power of this model for the differences in densities of Glass Eel between locations.

In conclusion, the densities of Glass Eel were highest at the fish passages of Roptazijl (ROZ) followed by Zwarne Haan (ZWH), Noordpolderzijl (NPZ) and Nieuwe Statenzijl (NSZ), whilst lowest densities were found at Den Helder2 (DH2) and Fiemel (FIE) (Fig. 3.4.2; Table 3.4.2.2). This spatial distribution was similar for both periods and not due to larger spatial patterns (Fig. 3.4.2; Table 3.4.2.2). Locations were significantly different with regard to density of Glass Eel and could be divided into 13 groups with no overlap between the first three groups (that included the four locations with highest densities of Glass Eel) and the remaining ten locations where densities were significantly lower (Table 3.4.2.2).

<table>
<thead>
<tr>
<th>STEP</th>
<th>MODEL</th>
<th>PARAMETER</th>
<th>Value</th>
<th>P-VALUE</th>
<th>REMARKS</th>
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Table 3.4.2.1 Summary of results of stepwise statistical analyses of European Eel (Glass Eel stage). Less than 1% of this data set consisted of zero counts.
Table 3.4.2.2 Grouping of sampling locations for European Eel (Glass Eel stage) as derived from a Bayesian post-hoc test. Locations are ranked from high to low fish densities as derived from Model 2. Green blocks indicate similarity (non-significant differences) within a column.

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<th>E</th>
<th>F</th>
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<th>H</th>
<th>I</th>
<th>J</th>
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<th>GROUPS</th>
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Fig. 3.4.2 Boxplots of densities (CPUE) of Glass Eel (Anguilla anguilla) as caught by lift nets at various freshwater sluices and fish passages along the mainland of the Dutch Wadden Sea during 2001-2003 (Period I) and 2012-2015 (Period II).
Yellow Eel stage
Summary results stepwise analysis

• A significant effect of Period
• Significant effect of Location (47% of variation explained)
• The Period effect did not change over time
• No spatial correlation
• Densities high at ROZ, NSZ, ZWH & NPZ, and lower at other stations
• Locations fall into 5 density groups

The best model for Yellow Eel with regard to testing the effect of Period was the model that assumed a negative binomial distribution of the data (lowest AIC for Model 1b compared to Model 1a; see Table 3.4.3.1), with a significant effect of Period on fish densities near freshwater sluices and fish passages (p < 0.001). This model was slightly underdispersed (d = 0.79), indicating that the Period effect would be even more significant if the heterogeneity in the data would be fully covered. The residuals of Model 1b showed a strong spatial effect (p < 0.001) and explained almost 47% of the variation. The AIC of Models 3 and 4 was different enough (> 3) to be used as a criterion for best model, being Model 3.

This implies that the Period effect on fish densities at sampling locations did not change over time, i.e. between the two periods. The variogram showed a weak presence of spatial correlation in the data set. The parameter values for Intercept and Period of the fit of Model 5 were comparable to those of Model 3 and the DIC was relatively low, indicating a good predictive power of this model for the differences in densities of Yellow Eel between sampling locations.

In conclusion, the densities of Yellow Eel were highest at Roptaziqjl (ROZ) followed by Nieuw Statenzijl (NSZ), Zwarte Haan (ZWH) and Noordpolderzijl (NPZ), whilst lowest densities were found at Den Helderd2 (DH2) and Fiemel (FIE) (Fig. 3.4.3; Table 3.4.3.2). The densities were higher during the first period compared to the second period, but similarly distributed over the locations and could not be attributed to larger spatial patterns (Fig. 3.4.3; Table 3.4.3.2). Locations were significantly different with regard to density of Yellow Eel and could be divided into 5 groups with no overlap between the first three groups (that included the four locations with highest densities of Yellow Eel) and the remaining ten locations where densities were significantly lower (Table 3.4.3.2).

<table>
<thead>
<tr>
<th>STEP</th>
<th>MODEL</th>
<th>PARAMETER</th>
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Table 3.4.3.1 Summary of results of stepwise statistical analyses of European Eel (Yellow Eel stage). More than 67% of this data set consisted of zero counts.
Table 3.4.3.2 Grouping of sampling locations for European Eel (Yellow Eel stage) as derived from a Bayesian post-hoc test. Locations are ranked from high to low fish densities as derived from Model 2. Green blocks indicate similarity (non-significant differences) within a column.

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Fig. 3.4.3 Boxplots of densities (CPUE) of Yellow Eel (Anguilla anguilla) as caught by lift nets at various freshwater sluices and fish passages along the mainland of the Dutch Wadden Sea during 2001-2003 (Period I) and 2012-2015 (Period II).
Herring/Sprat
Summary results stepwise analysis
• No significant effect of Period
• Weak effect of Location (21% of variation explained)
• No spatial correlation
• Densities gradually declining from LO2 to DZ2
• Locations fall into 7 (partly overlapping) density groups

The best model for Herring/Sprat with regard to testing the effect of Period was the model that assumed a negative binomial distribution of the data (lowest AIC for Model 1b compared to Model 1a; see Table 3.4.4.1), with no significant effect of Period on fish densities near freshwater sluices and fish passages (p > 0.9). This model was slightly overdispersed (d = 1.79), indicating a possible spatial effect. The residuals of Model 1b showed a weak spatial effect (p = 0.055) and explained approximately 21% of the variation. The AIC of Models 3 and 4 was different enough (> 3) to be used as criterion for best model, being Model 3. This implies that the Period effect on fish densities at sampling locations did not change over time, i.e. between the two periods. The variogram showed no presence of spatial correlation in the data set. The parameter values for Intercept and Period of the fit of Model 5 were more or less comparable to those of Model 3 and the DIC was relatively low, indicating a reasonably good predictive power of this model for the differences in densities of Herring/Sprat between locations.

In conclusion, the densities of Herring/Sprat were highest at the ship locks of Lauwersoog (LO2) and declined gradually to the lowest densities as observed at the discharge sluices of the Ems canal (DZ2) (Fig. 3.4.4; Table 3.4.4.2). The densities similarly distributed during both periods and could not be attributed to larger spatial patterns (Fig. 3.4.4; Table 3.4.4.2). Locations were significantly different with regard to density of Herring/Sprat and could be divided into 7 groups with large overlaps between groups of locations (Table 3.4.4.2).

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Table 3.4.4.1 Summary of results of stepwise statistical analyses of Atlantic Herring & Sprat. Almost 50% of this data set consisted of zero counts.
Table 3.4.4.2 Grouping of sampling locations for Atlantic Herring & Sprat as derived from a Bayesian post-hoc test. Locations are ranked from high to low fish densities as derived from Model 2. Green blocks indicate similarity (non-significant differences) within a column.
Smelt (*Osmerus eperlanus*)

Summary results stepwise analysis

- No significant effect of Period
- Weak effect of Location (21% of variation explained)
- Weak spatial correlation
- Densities gradually declining from NPZ to DEF
- Locations fall into 6 (all partly overlapping) density groups

The best model for Smelt with regard to testing the effect of Period was the model that assumed a negative binomial distribution of the data (lowest AIC for Model 1b compared to Model 1a; see Table 3.4.5.1), with no significant effect of Period on fish densities near freshwater sluices and fish passages ($p > 0.5$). This model was overdispersed ($d = 2.36$), indicating a possible spatial effect. The residuals of Model 1b showed a very weak spatial effect ($p = 0.067$) and explained approximately 21% of the variation. The AIC of Models 3 and 4 was different enough (> 10) to be used as criterion for best model, being Model 3. This implies that the Period effect (which was not significant in the first place) on fish densities at sampling locations did not change over time, i.e. between the two periods. The variogram showed a weak presence of spatial correlation in the data set. The parameter values for Intercept and Period of the fit of Model 5 were more or less comparable to those of Model 3 and the DIC was relatively low, indicating a reasonably good predictive power of this model for the differences in densities of smelt between locations.

In conclusion, the densities of Smelt were highest at the pumps of Noordpolderzijl (NPZ) and declined gradually to the lowest densities as observed at Fiemel (FIE) (Fig. 3.4.5; Table 3.4.5.2). The densities similarly distributed during both periods and could not be attributed to larger spatial patterns (Fig. 3.4.5; Table 3.4.5.2). Locations were significantly different with regard to density of Smelt and could be divided into 6 groups with overlaps between groups of locations (Table 3.4.5.2).

### Table 3.4.5.1 Summary of results of stepwise statistical analyses of European Smelt. Less than 5% of this data set consisted of zero counts.

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Table 3.4.5.2 Grouping of sampling locations for European Smelt as derived from a Bayesian post-hoc test. Locations are ranked from high to low fish densities as derived from Model 2. Green blocks indicate similarity (non-significant differences) within a column.

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Fig. 3.4.5 Boxplots of densities (CPUE) of Smelt (Osmerus eperlanus) as caught by lift nets at various freshwater sluices and fish passages along the mainland of the Dutch Wadden Sea during 2001-2003 (Period I) and 2012-2015 (Period II).
Three-Spined Stickleback (*Gasterosteus aculeatus*)

Summary results stepwise analyses

- No significant effect of Period
- Significant effect of Location (71% of variation explained)
- No spatial correlation
- Densities high at ZWH, ROZ & NPZ, and lower at other stations
- Locations fall into 9 density groups

The best model for Three-Spined Stickleback with regard to testing the effect of Period was the model that assumed a negative binomial distribution of the data (lowest AIC for Model 1b compared to Model 1a; Table 3.4.6.1), with no significant effect of Period on fish densities near freshwater sluices and fish passages (p > 0.6). This model was slightly overdispersed (d = 1.50), indicating a possible spatial effect. The residuals of Model 1b showed a strong spatial effect (p < 0.001) and explained more than 70% of the variation. The AIC of Models 3 and 4 was not different enough (< 3) to be used as criterion for the best model, therefore Model 3 (the most simple model) was considered to be the best model. This implies that the Period effect (which was not significant in the first place) on fish densities at sampling locations did not change over time, i.e. between the two periods. The variogram showed no presence of spatial correlation in the data set. The parameter values for Intercept and Period of the fit of Model 5 were comparable to those of Model 3 and the DIC was relatively low, indicating a good predictive power of this model for the differences in densities of Three-Spined Stickleback between locations.

In conclusion, the densities of Three-Spined Stickleback were highest at Zwarte Haan (ZWH), Roptazijl (ROZ) and Noordpolderzijl (NPZ) and lowest densities were observed at the ship locks of the Ems canal (DZ4) and Duurwaterdijl (DZ3) (Fig. 3.4.6; Table 3.4.6.2). The densities similarly distributed during both periods and could not be attributed to larger spatial patterns (Fig. 3.4.6; Table 3.4.6.2). Locations were significantly different with regard to density of Three-Spined Stickleback and could be divided into 9 groups with no overlap between the first group (that included the three locations with highest densities of Three-Spined Stickleback) and the remaining twelve locations where densities were significantly lower (Table 3.4.6.2).

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*Table 3.4.6.1 Summary of results of stepwise statistical analyses of Three-Spined Stickleback. For this species, there were no zero counts in the data set (i.e., these fish were caught in every haul).*
Table 3.4.6.2 Grouping of locations for Three-Spined Stickleback as derived from a Bayesian post-hoc test. Locations are ranked from high to low fish densities as derived from Model 2. Green blocks indicate similarity (non-significant differences) within a column.

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Fig. 3.4.6 Boxplots of densities (CPUE) of Three-Spined Stickleback (Gasterosteus aculeatus) as caught by lift nets at various freshwater sluices and fish passages along the mainland of the Dutch Wadden Sea during 2001-2003 (Period I) and 2012-2015 (Period II).
3.4.4. Discussion

Period
European Eel (Yellow Eel) was the only group for which a significant effect of Period on densities (Period II < Period I) was observed (Table 3.4.3.2; Fig. 3.4.3). This observation is in line with the observed decline in densities of European Eel at tidal-basin scale between 1970 and 2013 in general (Fig. 3.3.1) and for the periods of lift-netting (2001-2003 and 2012-2015) in particular (Fig. 3.4.8). This decline is observed for Eels at a large-scale, and attributed to atmospherically driven dispersal by ocean currents and change in hydrology and exploitation (see Chapter 2). For Glass Eel and the other fish species, the effect of period was not significant, implying that densities at the freshwater sampling points did not show an overall increase or decrease from Period I (2001-2003) to Period II (2012-2015).

Location
The Location effect was significant for all species, explaining 21% (Herring/Sprat and Smelt), 47% (Yellow Eel), 60% (Glass Eel) and 71% (Three-Spined Stickleback) of the variation in local densities. This implies that densities, in particularly of Glass Eel and Three-Spined Sticklebacks, were consistently low or high at particular sampling points.

Spatial correlation
For most species, the spatial correlation was not significant. Only for Smelt, a weak spatial correlation was found, implying that there might be a larger (e.g., a gradual shift from west to east) than local (freshwater discharge point) spatial pattern in densities for this species. Results of the lift-net surveys (Table 3.4.5.2) and bottom trawl surveys during Periods I and II (Fig. 3.4.8) revealed, however, no obvious spatial pattern.

Stations
Stations differed significantly in species-specific densities of fish, with highest densities found at Roptazijl and Zwarte Haan (4 out of 5), Noordpolderzijl and Nieuwe Statenzijl (3 out of 5), Lauwersoog shiplock (2 out of 5) and Den Helder Helsdeur, Lauwersoog discharge, Spijksterpompen, Ems channel shiplock, Termunterzijl and Fiemel (1 out of 5) (Fig. 3.4.8). Annually averaged freshwater discharge rates vary strongly between these stations, i.e. with more than 40 m³ s⁻¹ at the discharge sluices of Lauwersoog, between 2 and 11 m³ s⁻¹ at Nieuwe Statenzijl, Den Helder Helsdeur, Den Helder Oostoeover and Termunterzijl, around 1 m³ s⁻¹ at Roptazijl and Zwarte Haan, and less than 1 m³ s⁻¹ at the shiplocks near Lauwersoog and the Ems channel (Table 3.1).
At Roptazijl (Gemaal Ropta), highest densities of Glass Eel, Yellow Eel, Smelt and Three-Spined Stickleback were found (Fig. 3.4.8). Roptazijl is positioned in the Vlie basin and discharges directly into the relative deep water of the Kimstergat. A location near deep water is advantageous for the attraction of migratory fish. Moreover, the configuration of the breakwaters near Roptazijl is such that there is a deep and wave-sheltered basin in which fish can wait for a suitable moment to pass through, possibly increasing local densities (Fig. 3.4.9). In 2001, a siphon spillway (“vishevel”) has been constructed at Gemaal Ropta (George Wintermans, WEB, pers. comm.).

At Roptazijl, fish passage efficiency was measured from 2002 to 2014 by means of a comparison on density of fish at the seaward-side measured in spring with a 1x1 m lift net and the fish that passed the fish passage at the inside of Roptazijl in the same period using a fyke net (Brenninkmeijer et al., in prep.). As the result of the species-specific differences in catchability of the fishing gear, this type of data is very difficult to interpret. The authors have been looking for a multiplication factor for the CPUE with the lift net (the numbers of fish caught in 5 lift-net hauls) as a proxy for the numbers of fish inside (the numbers caught in the fyke net). They found a multiplication factor of 7 for the CPUE of Glass Eel and a factor 17 for Three-Spined Stickleback to calculate the numbers of fish inside. Furthermore they also found large interannual differences and recommended determining the efficiency of fish passages with mark-recapture experiments with fish tags (3S-Sticklebacks) or fish dyeing (Glass Eel).

At Zwarte Haan (Gemaal Miedema), highest densities of Glass Eel, Yellow Eel, Herring and Three-Spined Stickleback were found. In contrast to the conditions at Roptazijl, the freshwater at Zwarte Haan is not discharged in deep water, but on the tidal flat. Because the end of the discharge channel has silted up, there is no connection with the sea during low tide (Fig. 3.4.9). The sluice discharges freshwater every 1 to 2 days, so there is locally only an intermittent freshwater discharge. Local conditions can, therefore, not easily explain the consistently high densities of fish caught by the lift nets at this point. Zwarte Haan is, however, under the influence of freshwater discharges from Lake IJssel at Kornwerderzand (Duran-Matute et al. 2014; Fig. 3.4.10). The large-scale gradient in salinity towards the mainland coast may attract fish that will eventually detect small-scale salinity gradients near local freshwater sluices.
Recently (2015) a fish passage has been realized at Zwarte Haan. Fish are lured with freshwater into a collection basin of 100 m³. This water then flows into the polder by gravitational current under a mild slope, so the fish do not swim against the flow. The efficiency of this mechanism has to be validated. It now seems that small Eels are trapped within the culvert since they always swim against the current (Allix Brenninkmeijer, Altenburg & Wymenga, pers. comm.).

**NOORDPOLDERZIJL**
Noordpolderzijl is located more or less at the tidal divide between the Lauwers and Ems tidal basins. The configuration of the freshwater sluice at Noordpolderzijl is comparable to Zwarte Haan and there is a high density in fish. The freshwater is discharged into a long gully that runs through the tidal flats. In 2013 a fish passage with a cat-flap has been constructed here. Due to regular dredging activities carried out in the Noordpolderzijl channel, the lift-net sampling data might underestimate the attractiveness of this location without this disturbance (George Wintermans, WEB, pers. comm.).

**NIEUWE STATENZIJL**
Eight freshwater sluices have been studied in the Ems Dollard tidal basin. The one that has the highest density of fish is Nieuwe Statenzijl. In 2013, a cat-flap as well as an eel-gutter have been constructed. In spring 2014 and 2015 extensive research has been committed by the regional water authority Hunze en Aa’s (Peter-Paul Schollema) and Van Hall Larenstein University of Applied Sciences (Jeroen Huisman). Besides standard sampling with lift nets and fykes, a large-scale experiment with dyed glass eel was carried out. A large number of dyed glass eels were released on the seaside. Glass Eel was subsequently caught day and night at the seaside, in the eel-gutter and at the cat-flaps during a one-week period. The results of this experiment will become available in the beginning of 2016 and will shed light on the fish passage effectiveness of Nieuwe Statenzijl.

The regional water authority Hunze en Aa’s is also studying the fate of fish further upstream in the water system (Peter Paul Schollema, Hunze en Aa’s, pers. comm.). A number of fish passage facilities is, and will be, equipped with PIT antennas. This enables the tracking of tagged fish that use Nieuwe Statenzijl and provides quantitative information on the fish passage effectiveness in the water system of the Westerwolde river basin. This project receives funding from the Waddenfonds.

**DEN HELDER HELSDEUR**
Both freshwater sluices in Den Helder, i.e. Helsdeur and Oostoever, do not seem to attract that many fish. Helsdeur is located in the back of Den Helder Harbour. This layback position might explain a low attractiveness. The sluice Oostoever discharges directly into the Wadden Sea, in a shallow subtidal gully. Two of the four sluice openings are equipped with boosters with a combined pump capacity of 28 m³ s⁻¹. One of the four sluice openings has been equipped with a fish passage, but due to malfunctioning this has been removed. At present the Regional Water Authority HHNK operates with fish-friendly sluice management in all four openings. It has breakwaters and a basin that make a good resting place. The problem seems to be the low frequency of discharge, so there is a lack of freshwater to lure and retain fish. Wintermans & Dankers (2003) studied possibilities to optimise this functionality.

**LAUWERSOOG DISCHARGE SLUICE & SHILOCK**
The Lauwersoog sluice and ship locks discharge directly into deep water of the Wadden Sea and in large flows. These are large-scale barriers so the sampling strategy at one spot with a 1x1 m lift net is likely to underestimate the quantity of fish. Furthermore, with a discharge rate of more than 40 m³ s⁻¹, it is not unlikely that the fish abundance and supply at the freshwater discharge sluices of Lauwersoog is relatively high compared to stations with similar densities but lower discharge rates.
3.5 Conclusions

Due to the lack of data, a quantitative assessment of the effectivity of existing fish passages in the Wadden Sea was not possible. With regard to the costs of building these structures, it is therefore strongly recommended to invest not only in the strengthening of fish migration (a.o. by construction of fish passing facilities) but also in appropriate monitoring before and after strengthening. Not only to quantitatively evaluate the activity such as the functioning of the facilities, but also for modifications to optimize the investments made. Such programs should include monitoring of (1) the numbers and characteristics (e.g., species, life phases, condition of fish passing), (2) the efficiency of the attraction flow, (3) the efficiency of the fish passage and, for larger fish passages, (4) the habitat use of the local area (e.g., for acclimatisation to freshwater conditions).

Large-scale patterns in fish densities as determined by means of demersal fish surveys for tidal basins do not show a strong overlap with local densities of migratory fish near small freshwater sluices and fish passages. With the exception of Smelt for which a spatial correlation was present but weak, the densities of the species near the freshwater sluices showed no spatial pattern. These results indicate that local densities in migratory fish at freshwater discharge points are mainly driven by local circumstances. High migratory fish densities near freshwater discharge points appear to be locally facilitated by (1) the presence of sufficient flow (amount and frequency) of freshwater to attract fish to the entrance location, (2) the closeness of the freshwater sluice to deeper waters that have a salinity gradient, and (3) the presence of a deep and wave-sheltered basin to allow fish to safely wait before passing, and (4) good possibilities for survival, growth and migration in the freshwater systems. Present and future fish passage facilities should, therefore, pay attention to selecting and/or creating such local conditions, including optimal habitats before and after passing.

The relatively high densities at locations that are under the influence of freshwater discharges at a larger than local scale, underlines the necessity of the presence of large-scale salinity patterns to guide migratory fish through the Wadden Sea. A variety of studies suggest that migratory fish commonly use olfactory cues to locate streams from oceans or lakes (Creutzberg 1959; Dodson & Leggett 1974; Doving et al. 1985). Small inorganic ions such as calcium (Bodznick 1978), larger organic compounds associated with microbial decay (Tosi & Sola 1993), and pheromones (Nordeng 1977; Li et al. 1995; Vrieze et al. 2011) have all been suggested to serve as innately, or by imprinting during certain life stages, recognized cues. Salinity patterns in the Wadden Sea might, therefore, reveal preferred pathways for migration of anadromous fish and aid in identifying optimal areas and locations for fish migration from the Wadden Sea to adjacent freshwater systems.
4. NUMERICAL BUDGETS OF LOCAL STOCKS

4.1 Introduction

In order to explore the most effective measures for the strengthening of fish stocks in the Wadden Sea, quantitative information on major inputs and outputs of fish are compared. This exercise was performed for the Marsdiep tidal basin, Lake IJssel and the main connections between these basins to identify the added value of the planned Fish Migration River as projected by the Provincie Fryslan (2015) under the present conditions.

Stock dynamics describes the ways in which a given stock grows and shrinks over time, as controlled by birth, death, and migration. The basic accounting relation for stock dynamics is the BIDE (Birth, Immigration, Death, Emigration) model, according to:

\[ N_1 = N_0 + B - D + I - E \]

where \( N_1 \) is the number of individuals at time 1, \( N_0 \) is the number of individuals at time 0, \( B \) is the number of individuals born (recruitment), \( D \) the number that died (mortality), \( I \) the number that immigrated, and \( E \) the number that emigrated between time 0 and time 1 (Pulliam 1988). Within a stable stock, \( N_1 \) equals \( N_0 \). Numerical fish budgets require actual and local information on standing stocks, and on rates of recruitment, mortality and migration. Within our study area, this implies information is needed on (1) local stocks in the Wadden Sea and Lake IJssel, (2) recruitment and mortality (a.o., fisheries, predation) rates, and (3) exchange by transport (or migration) of fish between the study area and adjacent waters and exchange within the study area between these basins via the Afsluitdijk.

There is no quantitative information on the annual exchange of fish between the Wadden Sea, other tidal basins and the North Sea, nor on the exchange of fish between Lake IJssel and its surrounding rivers and streams. With regard to passing the Afsluitdijk, various pathways are considered, i.e. (i) via freshwater discharge sluices under regular discharge management, (ii) via freshwater discharge sluices and shiplocks under fish-friendly management, and (iii) via the projected Fish Migration River (Fig. 4.1). Our annual budgets are fully based upon values as derived from existing information as supplied in cited reports, articles and websites.

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Fig. 4.1 Overview of inputs, outputs and local population dynamics (recruitment and mortality) that jointly define the dynamics in abundance of the local fish stocks in the Marsdiep tidal basin of the Wadden Sea and Lake IJssel.
4.2 Factors

4.2.1 Standing stocks

**Marsdiep tidal basin**
The stock estimates were based upon beam trawl survey data (Demersal Fish Survey; WS_T610 in Table 2.2.1) and taken as average densities (number of fish per ha) for the period from 2000 to 2014 (autumn surveys). These densities were subsequently converted to stocks (number of fish per tidal basin Marsdiep) by multiplication of the densities with the total sublittoral area (assumed to be 66% of the total Marsdiep area of 675 km²).

**Lake IJssel**
The stock estimates were calculated as average densities (number of fish per ha) as determined by the bottom trawl surveys (WFD; LIJ_TLIJ in Table 2.2.1) multiplied by the total surface area of Lake IJssel (1100 km², i.e. excluding Markermeer). Because the beam trawl surveys were generally performed in autumn, which is outside the migration window in spring, and sampling methods are not geared to many of the target species in this report, stock values have to be generally considered as an underestimate of actual stocks.

4.2.2 Recruitment & Mortality

**Recruitment and natural mortality**
No data are available for local recruitment and mortality rates of fish species. For Lake IJssel, the productivity of Smelt in Lake IJssel was estimated to be 3.1 kg kg⁻¹ in the late 1990s (Mous 2000), but this value is based upon biomass and not upon numbers. For the North Sea, natural mortalities of the target species range between 0.05 (European Sturgeon) and 2.96 (Three-Spined Stickleback) (Table 1.1). These estimates refer to late juvenile and adult phases and are based upon maximum length and temperature (www.fishbase.se). Natural mortality includes non-human predation, disease and old age. Therefore, these values are probably not representative for natural mortality of fish stocks in the Wadden Sea and Lake IJssel because of the different environmental conditions (e.g., temperature, predation) and life-phases of the fish in these areas.

**Fishing mortality**
In the Wadden Sea, commercial fisheries target none of the migratory fish species under consideration. However, Flounder, Twaite Shad, River Lamprey and Smelt are reported as by-catch from shrimp fisheries (Glorius et al. 2015). Data on annually averaged fishing mortality within the Wadden Sea of Flounder (3.78 fish per ha fished), Twaite Shad (0.95 fish per ha fished) and Smelt (6.05 fish per ha fished) were derived from Glorius et al. (2015). Tessa van der Hammen (IMARES) supplied shrimp-fishing induced mortality for River Lamprey (0.02 fish per ha fished). Total area fished per year (ha y⁻¹) was calculated by multiplying the area fished by one fishing vessel per hour (ha h⁻¹) with total fishing time per year (h y⁻¹) of shrimp vessels as supplied by Van Overzee et al. (2008). The number of fish that die annually as the result of shrimp fisheries (fish y⁻¹) is subsequently calculated as the area-related fishing mortality (fish ha⁻¹) times the area fished per year (ha y⁻¹).

In Lake IJssel, both European Eel and Smelt are fished. For both species, average landings (tonnes) for the period from 2000 to 2014 were multiplied by average weight of an individual Eel or Smelt (33.3 and 2.9 gram fresh-weight, respectively) as could be derived from the Lake IJssel surveys (WFD; LIJ_TLIJ in Table 2.2.1) by dividing the fresh-weight per ha by the number of fish per ha.

**Predation mortality**
Mammals - Predation by mammals was assumed only to take place in the Wadden Sea (although it is known from tagging studies that these species undertake extensive feeding trips to the North Sea) by Harbour Seals (Phoca vitulina) and Grey Seals (Halichoerus grypus) with daily intakes of 4 kg (Härkönen et al. 1991) and 4.8 kg fish (Hammill & Stenson 2000), respectively. It was assumed that the diet of Grey Seals, which includes Flounder and Herring, was similar as that described for Harbour Seals by Brasseur et al. (2004). Total numbers of seals in the Marsdiep tidal basin were taken from data as available 2002-2013 via IMARES websites (www.wageningenur.nl/nl/Expertises-Dienstverlening/Onderzoeksinstituten/imares/show/..) for Harbour seal (.../Populatie-Gewone-Zeehonden-in-de-Nederlandse-Waddenzee.htm) and Grey Seal (.../Populatie-Grijze-Zeehonden-in-de-Nederlandse-Waddenzee.htm) and the WaLTER dataportal (www.walterwaddenmonitor.org/tools/dataportal/). Total predation rate (numbers per year) was subsequently calculated as the species-specific daily uptake multiplied by the number of seals and the number of days per year.
Since seals not only feed in the Wadden Sea but also in the North Sea (Brasseur et al. 2004), predation of fish by seals is most probably overestimated.

Birds - Predation by birds in the Marsdiep tidal basin and Lake IJssel was estimated for Great Cormorants (Phalacrocorax carbo) only. For the Marsdiep tidal basin, annual abundance indices for Cormorants (www.compendiumofdeleefomgeving.nl) were back-calculated to actual numbers using the information of the year 1992 where both types of data were available (Leopold et al. 1998). For Lake IJssel, annual abundance indices for Cormorants in a wider area around Lake IJssel (www.compendiumofdeleefomgeving.nl) for the period from 2000 to 2011 were back-calculated to actual numbers in the actual Lake IJssel area using the information during the period 1995-2001 where both types of data were available (RIZA 2002). Information on daily predation pressure on fish from Lake IJssel (460 gram per bird; Leopold et al. 1998) and diet (including European Eel and Smelt) was derived from Van Rijn & Van Eerden (2001).
Predation by birds is probably underestimated, because also other birds than Cormorants feed on fish in the Wadden Sea and in Lake IJssel (e.g. terns, Dänhardt & Becker 2011).

Fish - Predation by fish was only available for Lake IJssel, where mainly Pike and Pikeperch were consuming 49% of the annual production (3.1 kg kg\(^{-1}\)) of Smelt between 1976 and 1994 (Mous 2000), resulting in a fish-induced mortality of 1.5 kg kg\(^{-1}\).
For the stock budget of Smelt, it was assumed that the present proportion consumed by fish is similar to that period. In the Wadden Sea, predation of fish by fish is assumed to be moderate, because of the relatively low densities of top-predator fish in this area (being one of the reasons that the Wadden Sea is thought to be a good nursery) (Zwanette Jager, ZiltwaterAdvies, pers. com.).
4.3 Stock Budgets

The calculated budgets first of all illustrate the enormous gaps in data and knowledge that do not allow us to come up with confident results for most of the considered species (Fig. 4.2- Fig. 4.11). There are no data on basic information, such as recruitment, mortality and rates of exchange between the study area and adjacent waters. But even for those budgets that are more or less filled in with regard to the other factors, comparison is not fully possible as the result of different sampling methods (e.g., beam trawls versus diet studies) and different times of the year in which the information is gathered (e.g., import via FFM to Lake IJssel in spring, and densities in the Marsdiep tidal inlet in autumn). Furthermore, some estimates are overestimated (e.g., predation by seals) whilst others are most likely underestimated (e.g., predation by birds). Interpretation of the budgets to derive the added value of the FMR and other possible measures (e.g., reduction of fisheries) to strengthen local fish stocks should therefore be done with all these limitations in mind.

For River Lamprey, the projected FMR migration is higher than observed under regular discharge management conditions (REG), but the summed value for import from the Wadden Sea to Lake IJssel of REG and FMR is of the same order of magnitude as the export via the discharge sluices and to the fishing mortality in the Wadden Sea (Fig. 4.2). Stock estimates appear comparable for the Marsdiep tidal basin and the Wadden Sea, but probably much too low as the result of the low catchability of this species with bottom trawls (see Chapter 2). Assuming that River Lamprey shows more or less similar migratory behaviour as Sea Lamprey (Griffioen et al. 2014b), then its present passing efficiency would be 15%.

For Sea Lamprey, the projected FMR migration is higher than observed under regular discharge management conditions (Fig. 4.3). But, as for River Lamprey, no information is available on import rates if fish-friendly discharge management (FFM) is applied. Of the 25 individuals that were tagged and released in the Wadden Sea, however, 4 found their way to Lake IJssel under regular discharge management conditions, implying a passing efficiency of at least 15% under these conditions (Griffioen et al. 2014b).

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[Fig. 4.2 Budget for River Lamprey.]

[Fig. 4.3 Budget for Sea Lamprey.]
For **European Eel**, migration by fish-friendly discharge management (FFM) appears to be much more effective than projected for the Fish Migration River (Fig. 4.4). It must be noted, however, that the FFM surveys caught relatively more juveniles than were caught by fykes (i.e., on which the estimates of passing via the projected FMR are based). In Lake IJssel, fisheries and predation by birds appear to be an important source of mortality for Eel.

For **Atlantic Herring**, the projected FMR migration is higher than observed for regular and fish-friendly discharge management (Fig. 4.5). The FMR estimate that is based upon densities at the seaside of the discharge sluices, however, might be much too high because Herring does not favour freshwater systems. This might also explain the relatively high numbers observed to migrate back from Lake IJssel to the Wadden Sea, which might be washed in unintentionally as the result of FFM and tried to get back to the sea. Herring is on the diet of seals.

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![Fig. 4.4 Budget for European Eel.](image)

![Fig. 4.5 Budget for Atlantic Herring.](image)
For **Twaite Shad**, the projected FMR migration is higher than presently measured during regular discharge management (Fig. 4.6). Again, the added value of fish-friendly discharge management is not known here. Twaite Shad is one of the species accidentally caught during shrimp fishing, and on the menu of Cormorants. For this species, however, facilitation of migration to Lake IJssel is not considered to be of added value to its stock size (Griffioen et al. 2014b).

For **European Smelt**, the most complete budget could be made (Fig. 4.7). Fish-friendly management strengthened upstream migration compared to regular discharge management and is in the same order of magnitude as projected for the FMR. During regular discharge management, the export of Smelt to the Wadden Sea is comparable to the import into Lake IJssel, and relatively high compared to the stock. This is in line with observations by Phungh et al. (2015) that almost half of the Smelt stock in the western Wadden Sea originated from Lake IJssel and Markermeer. In Lake IJssel, fisheries and predation by fish and birds appear to be an important source of mortality. In the Wadden Sea, Smelts are caught by shrimp fishers and eaten by cormorants.
For, the projected FMR migration is in the same order of magnitude as measured during regular discharge management (Fig. 4.8). Export seems, however, larger than the import (Fig. 4.8). This is in line with the results of tagged Sea Trout, which were released in the Wadden Sea in 1996-1999 and found their way to Lake IJssel: five out of nine (59%) that were tagged in Den Oever and 28 out of 61 (46%) that were tagged in Kornwerderzand migrated into Lake IJssel (Bij de Vaate et al. 2003). In a recent study by Griffioen et al. (2014b), the one and only tagged Sea Trout found its way to Lake IJssel through the discharge sluices.

For **Houting**, the projected FMR migration is in the same order of magnitude as measured during regular discharge management (Fig. 4.8). This is in line with the result of tagged Houting, of which 3 out of 5 (60%) of the individuals released in the Wadden Sea found their way to Lake IJssel through the discharge sluices (Griffioen et al. 2014b). Export seems in the same order of magnitude as the import (Fig. 4.9).

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**Fig. 4.8 Budget for Sea Trout.**

**Fig. 4.9 Budget for Houting.**
For **Three-Spined Stickleback**, the projected FMR migration is higher than the migration as determined under regular and fish-friendly discharge management (Fig. 4.10). During regular discharge management, the export of Three-Spined Stickleback to the Wadden Sea is comparable to the import into Lake IJssel (Fig. 4.10).

For **European Flounder**, the projected FMR migration is in the same order of magnitude as measured during regular and fish-friendly discharge management (Fig. 4.11). During regular discharge management, however, the export of Flounder to the Wadden Sea is higher than the import into Lake IJssel (Fig. 4.11). Flounder is eaten by cormorants and seals, and induced to fishing mortality.
4.4 Discussion & Conclusions

Compared to regular discharge management, fish-friendly discharge management appeared to enhance the migration or transport of at least European Eel, Smelt and Three-Spined Stickleback (Fig. 4.12) within one order of magnitude. This is underlined by observations during previous testing of discharge management to enhance fish migration in the early 1990s, which resulted in an increase of Flounder (Winter 2009) and, possibly, Herring (Chapter 2) in Lake IJssel.

Migration as projected for the Fish Migration River is comparable as observed for Sea Trout and Flounder during regular discharge management (Fig. 4.12). Compared to fish-friendly discharge management, projected migration via the FMR is higher for Herring, Smelt and Three-Spined Stickleback, but lower for Eel (Fig. 4.12).

It is not clear if and, if so, how much the additional import of fish into Lake IJssel will strengthen local stocks, because of the yet unknown survival rate of the fish after entering. Fykenet programs show that Sea Lamprey and Sea Trout use Lake IJssel as a corridor to more upstream rivers and tributaries during part of the year (Winter et al. 2014). Tagged and subsequently released Sea Trouts have been recorded back in the river IJssel, indicating that they do survive (Peter Paul Schollema, Waterschap Hunze en Aa’s, pers. comm.). The number of fish that migrate yearly from Lake IJssel via the discharge sluices to the Wadden Sea is comparable (European Eel, Flounder, Houting) or an order of magnitude higher (Herring, River Lamprey, Sea Lamprey, Sea Trout, Smelt) than the estimates of the local stocks in the Marsdiep tidal basin (Fig. 4.2-Fig.4.11). It cannot be excluded that this fish migrates back to Lake IJssel. The high proportion of Smelt in the Wadden Sea that originated from Lake IJssel and Markermeer indicates, however, that these freshwater lakes are an important source for the Wadden Sea stocks of this fish species.

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**Fig. 4.12** Indication of relative effectiveness of measures to strengthen migratory fish populations in the Marsdiep tidal basin (Wadden Sea) and Lake IJssel by means of reduction of fisheries (red) or sluice management (blue) as derived from local stock budgets. The number of stars indicates relative order of magnitude, e.g. within a row, a measure of 3 stars is 1000 (10^3) times as much effective as another with 1 star (10^1). REG = regular discharge management, FFM = fish-friendly sluice management; FMR = projected fish migration river.
Fisheries (catch and bycatch) appear to be an important source of mortality, both in the Wadden Sea (Flounder, River Lamprey, Smelt, Twaite Shad) and in Lake IJssel (European Eel, Smelt) (Fig. 4.2-Fig. 4.11). For these species, the mortality as the result of commercial fishing (catch, bycatch) appears to be in the same order of magnitude as the projected migration via the Fish Migration River. Furthermore, although it is not allowed at present to land Eel by recreational fishers in Lake IJssel, illegal fishing might still occur (Van der Hammen et al. 2015). In the Marsdiep tidal basin, the by-catch from shrimp fishing on diadromous fish is estimated to be almost 2.5 million fish per year, comprising of Twaite Shad (213 000 fish per year), Smelt (1 400 000 fish per year), Flounder (840 000 fish per year) and River Lamprey (4500 per year). Reduction of fishing activities in Lake IJssel and the Wadden Sea might, therefore, be an alternative or additional measure to strengthen local fish stocks within the study area as a whole.

For the estimations in this chapter, a total passing efficiency of 50% (see 4.2.3) for the proposed Fish Migration River complex was assumed in accordance with Provincie Fryslan (2015). Based on a very limited small-scaled number of tagging experiments and several assumptions, however, the passing efficiency at Kornwerderzand under present regular discharge conditions appears already to be around 15% for River Lamprey, 25% for Sea Lamprey and 50% or more for Sea Trout, Atlantic Salmon and Houting (Bij de Vaate et al. 2003, Griffioen et al. 2014b, Ben Griffioen, IMARES, pers. com.). And, compared to regular discharge management, fish-friendly discharge management appeared to at least double the passing efficiency for European Eel, European Smelt, Three-Spined Stickleback and Flounder (Vriese et al., 2015, this chapter). Taking such species-specific variation at present into account, an average value of 50% probably does not correctly addresses future passing efficiencies under FMR conditions for all target species.

Winter et al. (2014) give an extensive overview of the complex and multifactorial configuration of the FMR that affects the passing efficiency. They indicate that migratory fish need to make many choices, and need to be very motivated to pass through. Fish has to be able to find the entrance of a fishway such as the FMR (i.e. attraction efficiency), and subsequently to successfully pass the fishway itself (i.e. passing efficiency) (Bunt et al. 2012). With regard to finding the entrance, a choice has to be made to migrate either towards the FMR, the ship locks or the discharge sluices (Winter et al. 2014). Once within the FMR complex, fish can decide to just stay there (e.g., to forage) or pass the FMR, including several potential barriers (e.g., the breach in the Afsluitdijk and the sluice doors between the FMR and Lake IJssel). Once the fish has successfully passed the FMR, it runs the risk of being flushed back to the Wadden Sea again via the discharge sluices (Winter et al. 2014). Because the FMR is designed as one river consisting of several parts that are aligned after each other, a bottleneck for fish in one part will strongly limit the overall passing efficiency. In addition, when taking species-specific needs and behaviour into account, an optimal situation for one fish species might be limiting to another.

An overview of efficiencies of riverine fishways indicated that, for nature-like fishways (with 21 evaluations), both the attraction and passing efficiency varied between 0 and 100% (Bunt et al. 2012). On average, the passing efficiency was higher (mean=70%, median=86%) than attraction efficiency (mean=48%, median=50%) (Bunt et al. 2012). Taking both aspects into account, the mean of the total passing efficiency of nature-like fishways would then be 50% x 70% = 35%. When considering all types of fishways (technical and nature-like), variations in attraction efficiency appeared to be mostly related to variation in entrance location, near-field hydraulic conditions and entrance configuration. Although passing efficiency was positively correlated to naturalness and negatively to slope, it could not be excluded the performance of nature-like types was largely attributable to slope rather than to any other intrinsic benefit of their design (Bunt et al. 2012). Bunt and co-authors (2012) conclude that more work is needed on the design of nature-like fishways before they can be reliably prescribed, as they often are, for passing a broad variety of species.

Although the Fish Migration River has the potential to be of added value, present data and knowledge do clearly not justify the projected passing efficiency of 50% for all fish species. Species-specific questions that remain include (1) the conditions of fish species (e.g. life phase, size, physiology, condition) under which they are motivated to migrate from the sea to freshwater, (2) species-specific aspects of attraction efficiency (e.g. entrance location, near-field hydraulic
conditions and entrance configuration), (3) species-specific aspects of passing efficiency (e.g. currents, salinity gradient, bottom structure), and (4) habitat requirements of fish when passing (e.g. for feeding and acclimatisation to freshwater conditions). To gather such knowledge, a dedicated Fish Migration Testing Facility would be needed with access to natural seawater and freshwater. To our knowledge, such a testing facility does not presently exist, but these conditions could be created at Kornwerderzand.

Summarized, the size of fish stocks in the Wadden Sea area is generally driven by a combination of natural factors (e.g. predation by fish, birds and seals) and by human-induced drivers (e.g. fisheries and supplied options to pass via the Afsluitdijk). Reduction of fishing activities in the Wadden Sea and Lake IJssel is most probably beneficial for stocks of River Lamprey, European Eel, Twaite Shad, European Smelt and European Flounder. Fish-friendly discharge management (FFM) at a structural base would be beneficial for European Eel, European Smelt, Three-Spined Stickleback and Flounder. The Fish Migration River could have added value to FFM, but only when optimally designed. Existing data and information are presently, however, not sufficient to support design recommendations. By making the design adequate for testing facilities, however, this necessary knowledge could be gained, which is not only relevant for strengthening migratory fish in the Wadden Sea area but also in other coastal systems with comparable man-made barriers world-wide.
5. POTENTIAL MEASURES AND COSTS

5.1 Introduction

From a historical perspective, large-scale and long-term anthropogenic pressures such as fisheries, pollution and habitat destruction have impacted fish stocks in coastal ecosystems including the Wadden Sea to historic lows (Wolff 2000; Jackson et al. 2001; Lotze et al. 2005; Limburg & Waldman 2009). Although improvement of local conditions might result in strengthening of local stocks, this can only occur within the boundaries set by the large-scale long-term drivers. Large-scale regulations are also taken and prove to be successful, as shown for the recovery of Herring in the North Sea following a fishing ban (Dickey-Collas et al. 2010). Acting locally while fish stocks are still hampered by large-scale anthropogenic pressures might still be worthwhile, in anticipating (and possibly even stimulating) further international measures to strengthen fish populations globally.

For all species addressed in this study, the Wadden Sea is (or was) an essential area to fulfil a particular phase in their life cycle (Zijlstra 1978; Van der Veer et al. 2000, 2015). For the diadromous species Atlantic salmon, Allis shad, Sea Lamprey, and European Eel, this shallow coastal sea functions as a corridor between freshwater systems and the open sea. Flounder, Herring and Anchovy use this area as a nursery, and as spawning grounds (Anchovy). Sea Trout and Twaite Shad use it for feeding, whilst juvenile European Smelt, Houting and River Lamprey migrate from freshwater to the Wadden Sea to grow and mature. Improving environmental conditions for fish recruitment, growth, survival and migration in the Wadden Sea area might counteract the observed declines in local fish stocks.

Furthermore, fish abundance in the Wadden Sea area is considered to be of main importance for fish-eating birds such as Great Cormorants (Phalacrocorax carbo), Common Terns (Sterna hirundo) and Eurasian Spoonbill (Platalea leucorodia) (Dänhardt & Becker 2011; El-Hacen et al. 2014) and for seals (Brasseur et al. 2004). The importance of particularly Herring, Twaite Shad, Smelt and Flounder as a food source for local birds and mammals (Chapter 4) underlines the importance of strengthening local fish stocks to enhance these natural values of the Wadden Sea as well.

In this Chapter, an overview is given of potential measures (including indications of efforts and costs, if available) to strengthen local stocks of migratory fish in the Wadden Sea, based upon the information from the previous chapters and within the boundaries of the Wadden Sea area covered by the Waddenfonds, i.e. the Wadden Sea, the islands, the tidal inlets, the North Sea coastal zone (up to 3 nautical miles from the coastline) and the municipalities at the mainland bordering the Wadden Sea (including a part of Lake IJssel). Measures addressed include the reduction of fisheries, the provisioning of suitable habitats (such as brackish zones and freshwater spawning grounds) and the facilitation of fish migration.
5.2 Fisheries

5.2.1 Wadden Sea
Annual fishing mortality in the Marsdiep tidal basin as derived from reported by-catch of shrimp fisheries (individuals per ha fished; Glorius et al. 2015; Tessa van der Hammen, IMARES, pers. comm.) and fishing pressure (ha y⁻¹; Van Overzee et al. 2008), adds up to almost 2.5 million fish per year (see Chapter 4). This by-catch includes Twaite Shad (213 000 fish y⁻¹), Smelt (1 400 000 fish y⁻¹), Flounder (840 000 fish y⁻¹), and River Lamprey (4500 y⁻¹). Total numbers of diadromous fish caught in the entire Dutch Wadden Sea would add up to more than 4 million fish per year. If this fishing mortality limits local fish stocks, then a reduction of by-catch could be strengthening these fish species and their predators (birds, seals). Reduction of the fishing efforts is considered to increase additional natural values of the Wadden Sea (e.g. benthic organisms and biogenic structures such as mussel beds (Ramsay et al. 1998; Jongbloed et al. 2014), whilst the yield might remain stable (Temming & Hufnagl 2015). Turenhout et al. (2016) recently published an overview on economic aspects of shrimp fisheries. They calculated that, on average between 2012 and 2014, 23% of landed shrimp by Dutch shrimping vessels was caught in the Wadden Sea. In 2014, 3446 tonnes of Wadden Sea shrimp was landed. The direct revenues were 19.6 million Euro in 2013 and 11.2 million Euro in 2014. In 2013, the subsequent processing of the shrimps created an added value of 9.2 million Euro. Additionally, the feasibility of possible alternative sources of income for fishermen are explored in case shrimp fishing in the Wadden Sea would be no longer possible.

5.2.2 Lake IJssel
In this freshwater lake, there is direct fishing on European Eel (but not for fish smaller than 28 cm, and not allowed between September and November; www.sportvisserijnederland.nl/vispas/visserijwetten-regels/binnenwater/paling.html) and a recently (possibly temporarily) abandoned fishery on Smelt. Landings of European Eel were, on average, almost 6 000 000 fish and on Smelt almost 200 000 000 fish per year during the last 15 years (De Boois et al., 2014; De Graaf & Deerenberg 2015; see Chapter 1).

A proportion of the stocks of these fish species in Lake IJssel migrate (or are being transported) to the Wadden Sea via the sluices, i.e. approximately 16 000 Eels and 22 600 000 Smelt per year (see Chapter 4). The Eels are probably silver eels on their way to the open ocean for reproduction, but Smelt might add to the local stocks of the Wadden Sea. For Smelt, for example, almost half of the population (45%) in the Marsdiep tidal inlet originated from Lake IJssel and the adjacent Markermeer (Phung et al. 2015). Strengthening of the fish population in Lake IJssel, e.g. by means of structural reduction of fishing efforts, can therefore be expected to also to strengthen fish stocks in the Wadden Sea.

For European Eel, the annual market value of fish caught in Lake IJssel en Markermeer was approximately 1.5 million Euro (10% silver eel; 90% larger eel) between 2003 and 2012 (Kees Taal & Wim Zaalmink, LEI Wageningen UR, presentation 2/12/2013). For Smelt, the annual landings of Smelt amounted 2 to 3 million kg in the 1980s and 1990s, but this was considered an unsustainable yield. According to fishermen the maximum sustainable yield is 0.8 million kg per year. Assuming a market price for Smelt of 0.50 Euro per kg, the economic revenue for Smelt fishery would then be 400 thousand Euro per year.
5.2.3 Coastal zone

For several migratory fish species, long-term variation in the coastal zone north of the Wadden Sea islands appears to be different than that in the adjacent North Sea and tidal basins of the Wadden Sea (Chapter 2). This might be due to natural circumstances typical for this area, but impacts of fisheries or coastal protection cannot be excluded (Van der Veer et al. 2015).

Sand nourishments, for example, usually take place at the foreshore in water depths of -5 to -8 m NAP (De Ronde 2008), an area that has special significance as nursery habitat for fish (Teal & Van Keeken 2011). The recovery time for benthic communities, a potential food source for fish, is 4 to 6 years (Baptist et al. 2008). Shoreface nourishments from Texel to Ameland occurred on average and at different subareas, however, once every 3 yrs between 2004 and 2014 (Rijkswaterstaat 2014). Impacts might be reduced when natural sediments are used, and when foreshore sand is nourished outside the seasonal windows with high fish abundances in the coastal zone (Annelies De Backer, ILVO, presentation 28/1/2016). Foreshore nourishment started only in 1993, sand was supplied onto beaches before that time. Measures could, therefore, include adaptations of the timing (outside nursery and migration windows) and location (beach) of sand nourishment.

5.3 Brackish water zones

5.3.1 Introduction

Within the Wadden Sea area (within the Waddenfonds boundaries), most estuarine gradients are presently characterised by an abrupt salinity gradient. In former days, Anchovy, Herring, Smelt and Flounder used the large open brackish water bodies with tidal influence in this area to spawn, to grow and to mature (Redeke 1939). According to Redeke (1939), Anchovy spawned in the northern funnel-shaped part of the area (with salinities of 10 ppt). After hatching of the eggs, larvae moved (by drift and active migration) to the central part of the basin. Herring deposited its eggs spawned on the stems and branches of hydroids, especially Laomedea gelatinosa, which grew abundantly on the sand banks near the western and southern coasts of the former Zuiderzee (with salinities of 5 ppt). Herring larvae and juveniles subsequently fed on the diatoms and copepods that occurred in this brackish environment, until seaward migration in autumn. Smelt was generally found in the less brackish parts, and this fish species migrated upstream to the IJssel and other, smaller, rivers to spawn. Juvenile Flounder entered the former Zuiderzee in early spring, feeding mainly on benthic fauna, i.e. small polychaetes during the first weeks after arrival, and then switching to Corophium volutator and Nereis diversicolor. In de Zuiderzee, Flounder stayed approximately 3 to 4 years until they were mature.

In general, strongly developed salinity gradients appear to favour the estuarine recruitment of marine fish species (Schlacher & Wooldridge 1996). In addition to protection and improvement of such areas at present (e.g. small creeks and the Ems estuary), restoration of former gradients may aid in strengthening fish stocks in the Wadden Sea area. Basically, there are two alternative ways to create such large habitats with estuarine gradients, i.e. input of seawater into freshwater systems or (continuous) input of freshwater into marine waters. On the mainland bordering the Dutch Wadden Sea, several large freshwater bodies exist that potentially could be turned into brackish ecosystems, i.e. Lauwersmeer, Amstelmeer and Lake IJssel. Alternatively, the southern part of the Marsdiep tidal basin could become more permanently under the influence of freshwater discharges.
5.3.2 Lauwersmeer

This freshwater lake was formed when a tidal inlet to the former Lauwerszee was closed off in 1969. Full restoration of tidal brackish water dynamics is considered not feasible due to ecological and technological constraints (Raad voor de Wadden 2008). Because of subsidence of the mainland due to peat settling, the (formerly natural) brooks in the area can no longer drain by gravity into the Wadden Sea. In addition, the Lauwersmeer is considered crucial for the freshwater management of the northern provinces. The migration of fish from Lauwersmeer to streams in Drenthe is dependent on water level management and future plans might hinder migration. Furthermore, the natural spawning habitat for Zuiderzee-Herring and Anchovy is coarse sand whilst at present the bottom of Lauwersmeer consists of soft muddy sediments. Restoration and maintenance of the bottom of this lake would require another major operation unless full tidal dynamics can be restored.

The Marnewaard located in the northeastern part of the Lauwersmeer area, however, appears to be suitable to be further developed as a brackish zone (Raad voor de Wadden 2008). This would require a newly built sluice in the sea defence at the (former) Vierhuizergat connecting with the Nieuwe Robbengat in the Wadden Sea (Raad voor de Wadden 2008). A rough cost estimate can be obtained by comparing with a similar project near Delfzijl (Oterdum), where building a new sluice including fish passage facility and brackish transfer zone was estimated to be approximately 3 million Euro (Verhoogt et al., 2014).

A fish passage from the Wadden Sea towards Amstelmeer via the Balgzandkanaal appears feasible at the freshwater discharge sluice at Oostoever near Den Helder (Wintermans & Dankers 2003). Although a fish passage facility has been realised in the discharge sluices Oostoever, this is not working properly at the moment (George Wintermans, WEB, pers. comm.). The Amstelmeer is already connected with Lake IJssel via the water system south of Wieringen and the discharge sluice Stontelerkeer near Den Oever. Since the water level of Lake IJssel is higher than the Amstelmeer, the flow direction is towards the Amstelmeer. The water system Oostoeve-Balgzandkanaal-Amstelmeer-Stontelerkeer offers good opportunities for a small fish migration river. When the sluices at Oostoever will be opened at flood tide, this can bring in salt water and fish into the Balgzandkanaal. Brackish conditions with reduced tidal amplitude can thus be created in the Balgzandkanaal. An existing sill at the end of the canal prevents further transport of salt into the Amstelmeer. The Amstelmeer has rather brackish water at the bottom, but its waters are still used for irrigation. Moreover, by opening the sluices at Stontelerkeer, fresh water from the IJsselmeer can flush out the salt water in the Amstelmeer. An additional advantage is that a larger freshwater current can be maintained over a longer period at Oostoever, thereby attracting migratory fish to this sluice.

Flushing with fresh water from Lake IJssel is currently not part of the operational water management by the responsible water board. Realisation is thought to be feasible for only several Euros per day (Sas & Wanningen 2014). Measures to increase the capacity of the fish passage at Stontelerkeer are necessary as well. No estimate for the construction costs is available at this moment.

5.3.3 Amstelmeer

In this freshwater lake, the restoration to full tidal estuarine conditions with brackish gradients might be possible but only with large adaptations to existing infrastructure. There is, however, an opportunity to create a salinity gradient including a brackish zone in the Amstelmeer and Balgzandkanaal, the channel that connects the lake with the Wadden Sea (Wintermans & Dankers 2003). The bottom layer of water of the Amstelmeer and Balgzandkanaal is already brackish due to saltwater seepage from the neighbouring Wadden Sea (Rijkswaterstaat 1979). The Balgzandkanaal has a length of 8 km and the borders of the first 3 km of this channel do not have any users that are dependent on freshwater. The sluices might be operated such that a brackish zone persists along this 3 km length that extends to the brackish water into the deep parts of the Amstelmeer, which creates favourable conditions to, for example, Three-spined Sticklebacks in this area. This species spawns in inland waters with aquatic vegetation, and overwinters in large freshwater bodies or at sea. A wintering population can be found in the Amstelmeer (George Wintermans, WEB, pers. comm.).
5.3.4 Lake IJssel

Because Lake IJssel is a main source of drinking water for The Netherlands, salt intrusion is kept to a minimum. In 2015, a fish passage facility was created near the discharge sluices of Den Oever. This facility will be operational together with fish-friendly sluice management at the sluices and locks of Den Oever and Kornwerderzand. To overcome potential drinking water problems from the saline Wadden Sea water coming into the lake, a salt-water return system will be installed at both locations (Den Oever and Kornwerderzand). Here the relatively heavy seawater is taken in at the bottom near the sluice and pumped back into the Wadden Sea (Staatscourant 2014; www.rijkswaterstaat.nl/water/projectenoverzicht/verbeteren-vismigratie-afsluitdijk/index.aspx).

This new system may even allow for an extension of the brackish zone in Lake IJssel, in particular if this area is semi-enclosed by means of a wall. First calculations of such a design suggest that even without additional pumping, salinity in Lake IJssel can be controlled by management of freshwater discharges (Marcel Klinge & Coen Kuiper, Witteveen+Bos, presentation 5/3/2015). The advantages of having a brackish water zone in Lake IJssel are threefold, i.e. (i) migratory fish such as Flounder (Jager 1998) that enter Lake IJssel via the discharge sluices will get more time to adapt to freshwater conditions than at the present situation, (ii) unintentional transport of marine fish in Lake IJssel can be corrected by return flushing, and (iii) unintentional flushing of freshwater fish might be reduced as the increase of salinity towards the sluices might act for them as an early warning system. Total costs were estimated to be between around 40 million Euro, excluding VAT (Marcel Klinge & Coen Kuiper, Witteveen+Bos, presentation 5/3/2015).

Because The Netherlands is highly depending on Lake IJssel as a source for drinking water, such measurements can only be considered if the restriction of intrusion of salt water into this freshwater lake can be guaranteed.

5.3.5 Wadden Sea

Alternatively to creating brackish environments in these freshwater systems, it might be considered to establish a large and permanently brackish zone at the seaside of the Afsluitdijk. At present, this area is already brackish during and after discharge of freshwater from Lake IJssel (Fig. 3.4.10). The discovery of eggs of Anchovy north of the sluices of Kornwerderzand in 1994 (Boddeke & Vingerhoed 1996) and the observed increase in Anchovy stocks in NW European waters since 1995 (Beare et al. 2004), underlines the potential of this area for development into a brackish water zone. In addition, the coarse sediments in this area might provide ample spawning grounds.

However, when discharges are limited (e.g., during high tide and in periods of drought) this area becomes saline again. Due to expected accelerated sea level rise it will become more difficult to discharge freshwater using gravity at low tides. To compensate for sea level rise, Rijkswaterstaat plans to install pumps at Den Oever in order to maintain the present drainage capacity of Lake IJssel (mirt2016.mirtoverzicht.nl/mirtgebieden/project_en_programmabladen/527.aspx). Such discharge pumps could potentially offer a continuous outflow of freshwater into the Wadden Sea. Average discharges of Den Oever and Kornwerderzand add presently up to 530 m$^3$ s$^{-1}$, implying that high and continuous pumping capacity is required in order to create a continuous brackish zone. In particular during dry periods, such amounts of freshwater might not be available for discharging into the Wadden Sea (Theo van der Kaaij, Deltares, pers. comm.). Limiting the additional supply of freshwater to the Wadden Sea during the periods with surplus of freshwater, however, is in line with natural salinity variations in estuaries and might be sufficient to aid in strengthening local fish stocks by supplying brackish conditions during their main migration and spawning periods.
5.4 Freshwater habitats

Once fish has passed from the sea to the freshwater system, it should be able to reach its final destination. In general, this implies that connectivity between all tributaries, polder ditches and brooks are important to population sizes of migratory fish. In addition, fish might require particular conditions in freshwater habitats, e.g. to spawn.

Twaite Shad is a species that spawns on gravel beds or coarse sand of tidal rivers near freshwater tidal interfaces. It is presently unknown if and, if so, where Twaite Shad spawns in the Dutch Wadden Sea region. Suited conditions for spawning can, however, probably be found in (side channels of) the upstream Ems, a river presently characterized by high fluid mud concentrations and low oxygen levels during summer. Since fine sediment, either in suspension or when deposited, can have multiple negative impacts on fish (Kemp et al. 2011), the water and habitat quality of the river Ems needs to be improved drastically before becoming an important spawning ground.

Sea Trout, Atlantic Salmon and Allis Shad spawn in upstream parts of river basins, mainly in the Rhine and accessible via the IJssel (De Groot 2002). It is questionable if sufficient habitat is available for a spawning population of Sea Trout in small Dutch streams such as the Drentsche Aa (Peter Paul Schollema, Waterschap Hunze en Aa’s, pers. comm.).

River Lamprey is known to spawn in the Gasterensche Diep, a tributary to the Drentsche Aa (Riemersma & Kroes 2004, Brouwer et al. 2008; Winter et al. 2013, Hofstra 2014; Schollema 2015) and can find suitable habitat in the IJssel and Vecht tributaries. Studies into River Lamprey in the Drentsche Aa show that not the availability of spawning and nursery habitat is currently limiting, but migration is. The biggest problem is in the long stretches of almost stagnant water in the canals between the sea sluices and the Drentsche Aa. In years with wet winters and high freshwater discharges towards sea, the resulting increased flow velocities attract and accommodate the landward migration of River Lampreys (Peter Paul Schollema, Waterschap Hunze en Aa’s, pers. comm). For River Lamprey, both safeguarding of the habitat quality and the connectivity between various tributaries in the northeastern part of The Netherlands and the sea are important for strengthening their populations in the Wadden Sea region.
5.5 Fish passages

5.5.1 Introduction

Over the past years, many studies have listed bottlenecks for fish migration in The Netherlands (e.g. Jager 1999, Wanningen & Van Herk 2007, Wymenga & Breninkmeijer 2007, Kroes et al. 2008). These studies stress the importance of unhindered fish migration for sustainable populations of migratory species. To facilitate migration via potential barriers, a suite of technical solutions is available. The construction costs for the realisation of fish passages differ widely and are dependent upon type and scale (Table 5.1 and references herein).

Relatively simple and low cost solutions for tidal barriers are tide gates, tidal flaps or valves in small-scale barriers, or small openings or slots made in medium to large-scale locks. These can be realised for 5 to 27.5 thousand Euro. Another low-cost solution is formed by fish-friendly sluice management, which can be realised in medium to large-scale barriers for 5 to 50 thousand Euro.

More expensive solutions are pumps. Pumps can be used for fish bypasses (usually with low capacity pumps) or the pumps themselves are fish-friendly (usually with a high pump capacity). The construction costs for pumps are highly dependent on the capacity and the ‘hydraulic head’, i.e. the difference in surface elevation between the two water bodies. The costs for pumps range between 50 and 900 thousand Euro. Fish passages can, in some cases, also be realised without pumps in the form of fish ladders, sliding doors or siphon spillways (“vishevel” in Dutch). The construction costs are dependent on the design and scale and fall in a similar range as for pumps, i.e. 45 to 657 thousand Euro.

The most expensive are fish passage constructions that include collection and return flow for the inflow of salt water with the incoming flood tide, of which the costs range between 2.9 and 5 million Euro. The high costs (52 million Euro) of the Fish Migration River are related to its size and its complexity.

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<th>Remarks</th>
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<tr>
<td>2</td>
<td>Self regulating tide gate</td>
<td>tidal</td>
<td>small</td>
<td>27,500</td>
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### Fish-friendly lock management

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<th>Ref.</th>
<th>Type of passage</th>
<th>Barrier</th>
<th>Scale</th>
<th>Costs (Euro)</th>
<th>Remarks</th>
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<td>1</td>
<td>Fish-friendly lock management</td>
<td>tidal</td>
<td>medium to large</td>
<td>5,000</td>
<td>Software costs</td>
</tr>
<tr>
<td>2</td>
<td>Fish-friendly lock management</td>
<td>inland</td>
<td>small</td>
<td>10,000</td>
<td>For defining a protocol</td>
</tr>
<tr>
<td>2</td>
<td>Fish-friendly lock management</td>
<td>tidal</td>
<td>medium to large</td>
<td>37,500</td>
<td>Software costs; 25 to 50 thousand Euro</td>
</tr>
</tbody>
</table>

### Fish ladders, siphon spill ways, sliding doors

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Type of passage</th>
<th>Barrier</th>
<th>Scale</th>
<th>Costs (Euro)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>DeWit fish ladder</td>
<td>inland</td>
<td>small</td>
<td>45,000</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Manshanden siphon spillway fish passage</td>
<td>tidal</td>
<td>small</td>
<td>155,000</td>
<td>Range of 130 to 180 thousand Euro</td>
</tr>
<tr>
<td>3</td>
<td>Fish bypass at pumping station</td>
<td>tidal</td>
<td>medium to large</td>
<td>500,000</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Siphon spillway fish passage</td>
<td>tidal</td>
<td>small</td>
<td>510,000</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>100 m long culvert with two sliding doors</td>
<td>tidal</td>
<td>small</td>
<td>657,000</td>
<td></td>
</tr>
</tbody>
</table>

### Fish-friendly by-pass pumps

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Type of passage</th>
<th>Barrier</th>
<th>Scale</th>
<th>Costs (Euro)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fish bypass at pumping station</td>
<td>tidal</td>
<td>small</td>
<td>140,000</td>
<td>Pump capacity 7.25 m³/min</td>
</tr>
<tr>
<td>1</td>
<td>Fish-friendly screw pump</td>
<td>inland</td>
<td>medium</td>
<td>130,000</td>
<td>Pump capacity 2x 25 m³/min, Head 1.0 m</td>
</tr>
<tr>
<td>1</td>
<td>Fish-friendly screw pump</td>
<td>inland</td>
<td>medium</td>
<td>200,000</td>
<td>Pump capacity 2x 32 m³/min, Head 0.8 m</td>
</tr>
<tr>
<td>1</td>
<td>Fish-friendly pumping stations by Venturi system</td>
<td>inland</td>
<td>small</td>
<td>250,000</td>
<td>Pump capacity 18 m³/min, Head 1.05 m</td>
</tr>
<tr>
<td>1</td>
<td>Archimedes screw pump with return flow and lights</td>
<td>inland</td>
<td>small</td>
<td>388,000</td>
<td>Pump capacity 8.3 m³/min, Head 2.68 m</td>
</tr>
<tr>
<td>1</td>
<td>Fish-friendly screw pump</td>
<td>inland</td>
<td>medium</td>
<td>335,000</td>
<td>Pump capacity 2x 60 m³/min, Head 1.5 m</td>
</tr>
<tr>
<td>1</td>
<td>Fish-friendly screw pump</td>
<td>inland</td>
<td>medium</td>
<td>677,000</td>
<td>Pump capacity 2x 40 m³/min, Head 1.95 m</td>
</tr>
<tr>
<td>1</td>
<td>Fish bypass at pumping station</td>
<td>inland</td>
<td>small</td>
<td>900,000</td>
<td>Pump capacity 1.2 m³/min, Head 4.35 m</td>
</tr>
</tbody>
</table>

### Fish passage with salt water return flow system

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Type of passage</th>
<th>Barrier</th>
<th>Scale</th>
<th>Costs (Euro)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Fish bypass at pumping station with brackish basin</td>
<td>tidal</td>
<td>medium to large</td>
<td>2,900,000</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Siphon spillway fish passage with brackish basin</td>
<td>tidal</td>
<td>large</td>
<td>4,500,000</td>
<td>Range of 4 to 5 million Euro</td>
</tr>
</tbody>
</table>

### Fish Migration River

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Type of passage</th>
<th>Barrier</th>
<th>Scale</th>
<th>Costs (Euro)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Fish migration river</td>
<td>tidal</td>
<td>large</td>
<td>52,000,000</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.1 Estimated costs of various types of fish passages. Sources:
1 Heemstra & Veneberg (2012);
2 www.scheldestromen.nl/actueel/nieuwsberichten/@215422/innovatieve;
3 Verhoogt et al. (2014);
4 Heuer et al. (2011);
5 Breninkmeijer & Wymenga (2007);
6 Ecorys (2015)
5.5.2 Small passages

Based on the comparison of fish densities near freshwater outlets at the mainland into the Wadden Sea, it appears that high densities near freshwater discharge points are locally facilitated by (1) the presence of sufficient flow (amount and frequency) of freshwater to attract fish to the entrance location, (2) the closeness of the freshwater sluice to deeper waters that have a salinity gradient, and (3) the presence of a deep and wave-sheltered basin to allow fish to safely wait before passing, and (4) good possibilities for survival, growth and migration in the freshwater systems (see Chapter 3).

The relatively high densities at locations that are under the influence of freshwater discharges at a larger than local scale, underlines the necessity of the presence of large-scale salinity patterns to guide migratory fish through the Wadden Sea. Present and future fish passages should, therefore, pay attention to creating such conditions at basin-wide and local scale, including optimal habitats for migration through the Wadden Sea and for retention areas before passing.

5.5.3 Passing at the Afsluitdijk

A study by Arcadis (2014) on preferred alternatives of fish-friendly lock and sluice management (FFM) at the Afsluitdijk gives a qualitative estimate of its costs (Table 5.2). The implementation of fish-friendly management mainly requires adjustments in the working protocols because of the number and complexity of additional actions controlling the sluices and locks. Some alternatives require large changes in control actions and additional staff might be necessary. For some alternatives technical adjustments in the control panel for the lock and sluice operation are desired (Table 5.2).

To estimate the potential added value of a Fish Migration River (FMR), the prospected numbers of fish passing the Afsluitdijk were compared with those being observed during fish-friendly discharge management (FFM) of sluices and shiplocks (Table 5.3). It must be noted that this comparison is based on a relatively small data set (FFM) and on abundances on fish in front of the Afsluitdijk of which 50% of all fish species was assumed to pass the FMR, and that no distinction was made between fish of different size and/or age classes (see Chapter 4).

<table>
<thead>
<tr>
<th>Afsluitdijk discharge sluices</th>
<th>Open both doors at large water level difference (10 – 20 cm)</th>
<th>Open both doors at small water level difference (&lt; 10 cm)</th>
<th>Use sluice doors separately as fish lock</th>
<th>Use sluice doors with variable opening</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costs</td>
<td>Minor adjustment to sluice control</td>
<td>Minor adjustment to sluice control</td>
<td>New action; extra personnel needed, control panel adjustments desired</td>
<td>New action; extra personnel needed, control panel adjustments desired</td>
</tr>
<tr>
<td>Afsluitdijk ship locks</td>
<td>Use small openings in both lock doors</td>
<td>Use one open door and small openings in the other</td>
<td>Use two open doors</td>
<td></td>
</tr>
<tr>
<td>Costs</td>
<td>Few extra personnel needed, control panel adjustments desired</td>
<td>Some extra personnel needed, control panel adjustments desired</td>
<td>Many extra personnel needed, no adjustments</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2. Qualitative assessment of costs for fish-friendly lock and sluice management at the Afsluitdijk (Arcadis 2014).
Under these assumptions, the FMR appears to be more effective than FFM for Herring and Three-Spined Stickleback (Table 5.3). For Smelt, Sea Trout and Flounder, the numbers of fish passing as the result of fish-friendly sluice management (FFM) appear to be comparable to that as projected for the FMR (Table 5.1). Because Smelt has a migrating and a landlocked population (Tulp et al. 2013, Phung et al. 2015), improving connectivity between both populations by either method might increase population size of Smelt in the Wadden Sea. For European Eel, fish-friendly sluice and shiplock management (FFM) would bring in much more fish than the FMR. Since the facilities are already in place, fish-friendly management via discharge sluices and shiplocks appears to be a highly cost-effective measure that can contribute to the restoration of the Eel population on Lake IJssel.

The total initial one-time investment cost of the FMR is 52 million Euro, i.e. 18 million Euro (including VAT) for the passage in the Afsluitdijk, and approximately 34 million Euro (excluding VAT) for the facilities at the northern and southern side of the Afsluitdijk including 1 million for maintenance and management. If annual costs for maintenance and management range between 1% (FMR specific; Meinard Bos, DNA, pers. comm.) and 2% of the investment costs (general investments Afsluitdijk; Ecorys 2015), then this would be approximately 500 000 thousand to 1 million Euro per year. These costs will be annually budgeted.

<table>
<thead>
<tr>
<th></th>
<th>REG (x10³)</th>
<th>FFM (x10³)</th>
<th>FMR (x10³)</th>
<th>Ratio REG:FFM:FMR</th>
<th>Ratio FFM:FMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>River Lamprey</td>
<td>0.12</td>
<td>no data</td>
<td>2.4</td>
<td>1 : nd : 20</td>
<td>no data</td>
</tr>
<tr>
<td>Sea Lamprey</td>
<td>0.06</td>
<td>no data</td>
<td>0.9</td>
<td>1 : nd : 14</td>
<td>no data</td>
</tr>
<tr>
<td>European Eel</td>
<td>0.6</td>
<td>105094</td>
<td>608</td>
<td>1 : 17516 : 1015</td>
<td>17 : 1</td>
</tr>
<tr>
<td>Herring</td>
<td>800</td>
<td>200</td>
<td>11800</td>
<td>4 : 1 : 559</td>
<td>1 : 559</td>
</tr>
<tr>
<td>Twaitie Shad</td>
<td>no data</td>
<td>no data</td>
<td>1203</td>
<td>no data</td>
<td>no data</td>
</tr>
<tr>
<td>Smelt</td>
<td>400</td>
<td>9700</td>
<td>19400</td>
<td>1 : 24 : 49</td>
<td>1 : 2</td>
</tr>
<tr>
<td>Sea Trout</td>
<td>0.06</td>
<td>no data</td>
<td>0.9</td>
<td>1 : nd : 2</td>
<td>1 : 2</td>
</tr>
<tr>
<td>Houting</td>
<td>2</td>
<td>no data</td>
<td>no data</td>
<td>no data</td>
<td>no data</td>
</tr>
<tr>
<td>Stickleback</td>
<td>400</td>
<td>1100</td>
<td>30100</td>
<td>1 : 3 : 75</td>
<td>1 : 27</td>
</tr>
<tr>
<td>Flounder</td>
<td>20</td>
<td>50</td>
<td>60</td>
<td>1 : 3 : 3</td>
<td>1 : 1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1623</strong></td>
<td><strong>116114</strong></td>
<td><strong>163174</strong></td>
<td><strong>1 : 72 : 101</strong></td>
<td><strong>1 : 1</strong></td>
</tr>
</tbody>
</table>

Table 5.3 Numbers of fish potentially passing annually through the Afsluitdijk with regular discharge management (REG), fish-friendly discharge management (FFM) and as projected for the fish migration river (FMR; assuming 50% total passing efficiency). Ratios are given in rounded numbers (see Chapter 4 for details on estimates).
5.6 Concluding remarks

Construction of brackish zones within freshwater systems should be preceded by feasibility studies, including the behaviour of salt water and possible consequences for other use of the water (e.g., agricultural, drinking). To come up with an optimal design, additional measurements on flows, tides, salinity gradients and fish passage rates under present conditions might be required. If a construction of a more permanently brackish zone at the northern side of the Afsluitdijk is considered, potential impacts of pumps on migrating fish from freshwater to the sea should be kept to a minimum (e.g., by means of using fish-friendly pumps) and an inventory of possible effects of additional freshwater discharges on local species and habitats in this zone should be made (c.f. Smit et al. 2003).

Unfortunately, the efficiency of existing fish passages could not be quantified due to lack of data. For present and future passages, measurements on fish abundances should be performed in a comparable way before and after such facilities, e.g., by means of comparable fishing gear and/or mark-recapture experiments. To evaluate efficiency and to develop knowledge on optimal designs, monitoring programs should include monitoring of (1) the numbers and characteristics (e.g., species, life phases, condition) of fish passing, (2) the efficiency of the attraction flow, (3) the efficiency of the fish passage and, for larger fish passages, (4) the habitat use of the local area (e.g., for feeding or acclimatisation to freshwater conditions).

All potential actions to strengthen fish stocks in the Wadden Sea area, in particular the ones that are long-term and costly, should be considered and ranked in the light of climate change. The supply of Anchovy, European Eel and Herring to our waters appears to be driven by large-scale climate-induced currents and increasing water temperature. At a more local scale, Smelt migrates to deeper and cooler places (such as old gullies or sand mining pits in Lake IJssel, or to the open North Sea) when confronted with water temperatures higher than 20°C (De Leeuw et al. 2008). The strength and locations of estuarine gradients will be determined by the supply of freshwater and by wind-driven currents (Duran Matute et al. 2014). Sea level rise will hamper the future natural flows of freshwater by gravity into the sea.

To estimate the added value of a new fish passage, monitoring should be performed at all other surrounding fish passages before and after a new passage is constructed. Otherwise, it will not be possible to distinguish between additional fish passing or fish passing through the new facility (and no longer through the old facilities). This would require an integrated monitoring scheme for migratory fish in the Wadden Sea. With standard techniques, equipment and protocols, and addressing the preferred pathways of migratory fish species at various spatial (e.g., freshwater discharge points, tidal basins) and temporal (tide, season, year-to-year) scales. Incorporating the migratory behavior of fish into hydrodynamic models could produce biophysical models of fish movements through the Wadden Sea. Such models would allow for building scenarios for optimizing investments to strengthen (migratory) fish stocks in the Wadden Sea under various environmental conditions such as the creation of large brackish zones, climate change and sea level rise.
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Chapter 3


Chapter 4


Chapter 5


Teal, L.R. & Keeken, O.A. van (2011). The importance of the surf zone for fish and brown shrimp in The Netherlands; A literature review. IMARES rapport C054/11.


