Research and Monitoring plan Fish Migration River (FMR)

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Wageningen University &
Research report: C020/24

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Wageningen Marine Research
IJmuiden, April 2024

Wageningen Marine Research report C020/24

Keywords: Fish migration, fish passage, monitoring

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This report can be downloaded for free from https://doi.org/10.18174/654428
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Photo cover: Artist impression Vismigratierivier - Feddes-Olthof Landschapsarchitecten

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Verantwoordelijkheden voor potentiële aannemers (inschrijvers) om rekening mee te houden in hun aanbieding zoals aangedragen door opdrachtgever (Provinsje Fryslân) ten behoeve van de Europese tender voor de realisatie van het Werk Vismigratierivier

Voor deze aanbesteding wordt gevraagd om de voor de biotische en abiotische metingen noodzakelijke vooral fysieke faciliteiten nodig voor het doen van Wetenschappelijk Onderzoek & Monitoring in het ontwerp en de realisatie van dit deel van de VMR als onderdeel van het uitvoeringscontract aan te brengen c.q. te installeren. Provincie Fryslân stuurt aan op een verantwoordelijkheid van de aannemer dat het systeem VMR de eerste jaren (inregelfase) door de aannemer wordt aangestuurd en beheerd op zoutindringing en stroomsnelheid volgens gestelde eisen (geen ongewenste - onbeheerste zoutindringing in het IJsselmeer en een maximale waterstroomsnelheid waarbij het zand morfologisch stabiel is (geen zandverlies door te hoge stroomsnelheden) terwijl voor de hoofdfunctie vismigratie een maximale stroomsnelheden worden nagestreefd). Om dit te kunnen sturen en beheersen levert de aannemer daartoe alle fysieke maatregelen en apparatuur inclusief installatie (zie voorliggend rapport van WMR). De inschrijvers dienen te calculeren in de aanbieding:

1. Aanleg onderzoeksfaciliteiten abiotiek en biotiek door het hele systeem VMR (vanaf inzwemopeningen Waddenzee spuikom t/m Afsluitmiddel in het IJsselmeer)
2. Realisatie maatregelen om onderzoek & monitoring veilig mogelijk te maken.
3. Aanschaf, installatie, sturing – beheer (24/7 werking) & onderhoud meetinstrumenten abiotiek voor <u>hele</u> VMR
4. Inregelen beheerste hydrodynamiek (d.m.v. sturing toevoer zoetwater via afsluitmiddel, en door eventuele fysieke aanpassingen in de eerder gerealiseerde delen van de VMR. Zoals het riviergedeelte, estuariene deel en Waddenzee deel) voor de <u>hele</u> VMR op basis van hun eigen onderzoek aan de hand van de door hen zelf geïnstalleerde en te onderhouden meetinstrumenten (waterstanden, temperatuur, zoutgehalte, zuurstof, druk, troebelheid en stroomsnelheden). Om gedurende 'de inregelfase' (zie rapport WMR) deze metingen te gebruiken voor Wetenschappelijk Onderzoek is het van belang dat deze gegevens beschikbaar worden gesteld aan de onderzoekers, beheerders zoals Provinciale Waterstaat, It Fryske Gea en de opdrachtgever.

Het voorliggende rapport van WMR is een monitoringsplan die past bij een eerder verschenen rapport waarbij de onderzoeksfaciliteiten zijn beschreven (Griffioen en Perk et al. 2023). De gedetailleerde tabel in dat rapport geeft een overzicht van de diverse materialen, kenmerken en specifieke uitvraag aan aannemer. Met de beoogde beheerders, Provinciale Waterstaat en It Fryske Gea, wordt het rapport van WMR gedurende de lopende Europese tender nog afgestemd. Daar kunnen nog wijzigingen uit voortkomen. Dit document is leidend voor de inschrijving. In bouwteamverband worden de nodige voorgestelde maatregelen verder uitgewerkt binnen het uitvoeringsontwerp. Dus gedetailleerd, gespecificeerd en gecalculeerd.

Summary

This research and monitoring plan, building upon previous plans, aims to measure, evaluate and optimize the functioning of the Fish Migration River (FMR). The FMR is a large fishway facilitating two-directional tidal streams to restore fish migration between sea and freshwater. The FMR is currently being constructed alongside the sluice-complex at Kornwerderzand in the Afsluitdijk, a 32 km long dam separating the Wadden Sea and Lake IJsselmeer. The research activities proposed in this monitoring plan have four main goals:

1 Does the FMR meet the set targets and expectations:
   - Facilitating large scale fish migrations based on autonomous behaviour - passage through the Afsluitdijk. Is the 'barrier' Afsluitdijk a thing of the past for fish migration between Wadden Sea and lake IJsselmeer after this rehabilitation measure?
   - Which (diadromous) fish species, in what numbers and at which times (successfully) make use of the FMR?
   - Does the FMR contribute to the recovery of (diadromous) fish populations and in particular tidal migrants?
   - Does the FMR contribute to the recovery of the aquatic ecosystem, in terms of food web and biodiversity?

2 Evaluation and optimalization of the functioning of the FMR for migrating fish

3 Integral Water Management: applying new knowledge to discharge- and FMR management protocols (flexible and adaptive management)

4 Generate and export process insights and knowledge on passage of migratory fish (especially tidal migrants) along freshwater-salt transitions, to other locations (in the Netherlands and internationally)

Target species

The planned research program focuses on small diadromous fish such as flounder, European eel, three-spined stickleback, and smelt, which face challenges migrating upstream beyond the Afsluitdijk. The innovative Fish Migration River (FMR) aims to facilitate their passage by providing a natural regime of tidal currents. Larger diadromous species like river lamprey, sea lamprey, Atlantic salmon, sea trout, and North Sea houting will also benefit from the FMR. Despite existing knowledge and field research, many gaps remain in understanding fish behavior and passage success at tidal barriers. The program employs telemetry for larger fish and a combination of netting, mark-recapture experiments and modelling for smaller fish to assess passage efficiency and behavior. Small diadromous fish rely on selective tidal stream transport, facing difficulties in finding migration windows at the discharge sluices. The current Fish Friendly Sluice Management aids passive drift but only during very limited windows during specific tidal cycles. Additionally, freshwater species displaced into the Wadden Sea have the opportunity to return to Lake IJsselmeer via the FMR, potentially reducing mortality rates. Marine species like grey mullet, sea bass, and herring may also benefit by expanding their foraging areas into freshwater.

Current design and measurement infrastructure of the FMR

The FMR consists of six sections: 1) two entrances at the sea side, 2) two separate channels, 3) an open 'coupure' through the dyke with a parallel vertical slot fish passage, 4) a natural inland part, 5) a more meandering technical part with separation walls and 6) an inlet sluice complex (four gates, and vertical slots) at the IJsselmeer-side. Devices for continuously monitoring abiotic dynamics, e.g. water levels, flow and salinity, and infrastructure for later deployment of equipment, e.g. different types of nets, fish telemetry antennae and receivers, will be built in during the construction.

Research questions related to the functioning and effectiveness of the FMR

This study explores various aspects of fish migration in relation to FMR at the Afsluitdijk barrier. It discusses the processes influencing fish movement towards the barrier, emphasizing the significance of understanding fish attraction mechanisms and migration patterns. Environmental and biological cues

such as salinity gradients, tidal currents, and odors play crucial roles in attracting fish towards the barrier. Within the FMR, factors like migration windows, environmental variables, and potential disruptions affect fish behavior and passage efficiency. The FMR creates a new habitat with tidal currents and salinity gradients, influencing fish behavior. However, the impact of potentially disruptive factors like noise and artificial light on migration efficiency requires further investigation. Additionally, the effects of FMR passage on fish populations, including population size, energy budget, selection pressures, and other bottlenecks in the life cycle, should be examined. It also considers unintended migration routes (e.g. flushing out to sea), climate change effects, and the need for adaptive management strategies to optimize FMR functioning amidst changing environmental conditions and extreme conditions.

The research program concerning the FMR is structured around five main topics: abiotic functioning, passage success, optimization of the functioning, FMR as habitat, and the larger scale effect on populations, communities, and food webs:
Q1: Abiotic Functioning of the FMR: During the design phase, the abiotic functioning of the FMR was assessed using hydrodynamic modeling. The goal was to create optimal conditions for fish migration while preventing sediment washout and maintaining appropriate water levels and salinity gradients. However, uncertainties remain regarding model accuracy, potential optimizations, gate operation regimes, and the impact of freshwater discharge from Lake IJsselmeer.
Q2: Passage Success: Efficient fish passage through the Kornwerderzand complex is crucial. The monitoring program aims to determine overall passage efficiency, attraction efficiency of the FMR, and passage efficiency within the FMR. A detailed research program involves tagging fish and studying their behavior to identify potential bottlenecks and optimize passage routes.
Q3: Optimization of the Functioning of the FMR: If overall passage efficiency is considered too low, further optimization of the FMR can be necessary. This involves identifying and resolving bottlenecks in attraction and passage efficiency through a stepwise approach. Factors such as fish behavior, hydrodynamics, habitat structures, losses and physiological conditions are considered. The ultimate goal is to use insights from monitoring to adjust management schemes and optimize the functioning of the FMR using the growing insights provided by the research performed.
Q4: FMR as Habitat: In addition to facilitating fish passage, the FMR can serve as temporary habitat for migratory fish and predators. Research questions focus on acclimatization from saltwater to freshwater, habitat use by estuarine species, foraging opportunities, predation risks, and interactions with marine mammals and birds. Understanding the FMR's role as habitat is crucial for evaluating its overall effectiveness.
Q5: Effect of the FMR on population, fish community, and food web: The effectiveness of the FMR on fish populations, communities, and food webs can be assessed by considering factors such as population structure, spatial scales of habitat use, migration bottlenecks, human-impacted factors, trends in population abundance, and food web relations. However, addressing these questions requires comprehensive research investment due to the complexity of population dynamics and migratory behavior, which is outside the direct focus of this research and monitoring plan.

Overall, the research program aims to gain data and knowledge to optimize fish migration, restore ecological connectivity, and promote sustainable fish populations and ecosystem health in the region. By addressing knowledge gaps, evaluating passage efficiency, and considering the broader ecological context, the program seeks to develop effective management strategies for the FMR.

General approach and phasing of research and monitoring activities
The monitoring and optimization plan for FMR at Kornwerderzand is structured into four main phases:
1) FMR construction phase (pre-phase): 2024-2025. Preparatory activities include permit applications and optimization of the FMR design. Monitoring devices specific to the FMR are tested, and initial data collection begins.
2) Adjustment phase I: end 2025-2026. The FMR begins operation, focusing on evaluating its abiotic functioning under regular weather conditions. Biotic measurements and netting programs provide preliminary data on efficiency.
3) Adjustment phase II: 2027. Further optimization of the FMR under regular conditions and focus on exceptional tidal and meteorological conditions. Extended netting programs and bottleneck analyses are conducted.

4) Optimization phase: 2028 en thereafter. Adaptive research activities based on results from Adjustment Phases I and II, including bottleneck analyses.

We propose that the research and monitoring components will be carried out by a consortium of science partners, with involvement from PhD students and groups of students during field campaigns. Media awareness efforts will leverage the unique design of the FMR to highlight the importance of habitat restoration and connectivity for fish species. Adjustments Phases I and II will be key moments for public engagement activities.

Abiotic monitoring FMR: hydrodynamics and design
Continuous real-time monitoring of abiotic parameters and dedicated measurements will be used to closely monitor development in the physical functioning of the FMR and support biological monitoring and optimizing the FMR to facilitate fish passage while considering construction, maintenance costs, and ecological factors. The plan is divided into different phases: Construction Phase, Adjustment Phase I, Adjustment Phase II, and Optimization Phase.

During the Construction phase, numerical modeling is used to inform the contractor about the hydrodynamic functioning of the FMR. Stakeholders, including the client, contractor, hydrodynamic expert, and fish ecologists collaborate to optimize the design of the FMR to provide optimal conditions for fish passage while minimizing construction and maintenance costs.

In Adjustment Phase I, measurements from monitoring instruments are used to validate the numerical model. Simulations are conducted to determine the effects of opening and closing gates within the FMR under normal tidal conditions. The model is adjusted based on measurement results, and small adjustments may be made within the FMR to optimize hydrodynamic conditions for fish.

Adjustment Phase II follows a similar step-by-step approach, focusing on extreme conditions such as storms or periods of drought. The numerical model is applied to assess the optimal gate operations under these conditions, and adjustments are made when necessary. Procedures for different scenarios are documented to guide gate operations during extreme events.

The Optimization Phase considers long-term developments such as changes in bathymetry and vegetation growth within the FMR. The model is used to assess the impact of these changes on hydrodynamic conditions and fish passage. Based on biotic monitoring results, adjustments may be made to further improve hydrodynamic functioning for fish.

Throughout the process, collaboration among stakeholders is emphasized to ensure that decisions are well-informed and consider both engineering and ecological aspects. The adaptive management approach allows for ongoing monitoring and adjustment to maintain optimal conditions for fish passage over time.

Research and monitoring passage of small diadromous fish (tidal migrants)
The research program proposed for investigating the use of the FMR by small diadromous migrants is outlined in detail, focusing on integrating catch methodologies with tagging techniques to quantify spatio-temporal patterns in species composition, abundances, fluxes, residence times, condition and losses to determine overall passage efficiency and identify bottlenecks therein. The approach involves a combination of direct and indirect measurements, including mark-recapture experiments and netting programs, to assess passage success and bottleneck analyses for small diadromous fish:

Indirect measurements: Due to the size constraints of small diadromous fish, direct individual tracking techniques are not feasible. Instead, density and flux measurements combined with mark-recapture experiments are proposed to assess passage success, delay, and recurrence behavior of tidal migrants. Different mark-recapture techniques, such as visible implanted elastomers (VIE) tags and PIT-tags, are discussed based on species-specific requirements and effectiveness for small diadromous fish. Selection of marking methods depends on factors such as species size and behavioral impact. An extensive netting program in combination with mark-recapture techniques is proposed to complement and assess passage success and bottleneck analyses. Driftnets, lift-nets, and fine-meshed traps are identified as suitable methods for capturing small diadromous fish within the FMR to assess dynamics in abundance, densities and fluxes. Locations and operational considerations for netting activities are discussed, emphasizing the need for optimization and testing beforehand:

Construction phase: Preparations for the netting program are outlined, including the design and testing of specialized drift nets and traps. Technical questions related to netting campaign preparations are raised, focusing on optimizing net design and operational efficiency.

Adjustment phases I and II: These phases serve to further test and expand netting activities, including the installation and testing of traps and drift nets during Adjustment Phase I and an extensive program in Adjustment Phase II. Questions regarding net applicability, efficiency, and potential bottlenecks or need for optimizations are addressed.

Optimization phase: Collaborative efforts with contractors are proposed to optimize the FMR, focusing on operational adjustments rather than large-scale modifications. A stripped-down netting program is suggested to monitor the impact of operational adjustments and identify differences among years and circumstances.

Research and monitoring passage of larger diadromous fish

Behaviour, passage success and retention for larger diadromous fish species can be directly measured by telemetry techniques. This involves tagging and releasing fish near the sluice-complex and using acoustic and PIT-telemetry to track their passage, allowing for estimates of passage efficiency, retention times (‘delay’), behavioral patterns in relation to environmental conditions and predation losses.

Two main telemetry techniques discussed are acoustic telemetry and Radio Frequency Identification (RFID) telemetry using PIT tags. Acoustic telemetry involves the use of transmitters and a network of receivers to track fish movements, while PIT tags use antennae in the vertical slot passages and inlet.

Construction phase: installing receivers and preparing for the monitoring program, including obtaining necessary permits and organizing logistics.

Adjustment phase I and II: refining telemetry setups and tagging procedures, taking into account factors like hydrodynamics and fish behavior. This includes testing and installing PIT tag arrays and conducting netting programs to catch target species for tagging.

Optimization phase aims to improve the passage efficiency based on results from previous phases, potentially expanding tagging efforts or adjusting management strategies. In addition to focusing on diadromous species, with the telemetric setup in place also larger freshwater species or marine species that can tolerate freshwater, e.g. mullets or sea bass, can be tracked if wanted.

FMR Habitat development and shelter functioning in relation to predation

The FMR can also serve as a habitat in the transition zone between salt and freshwater, providing acclimatization, shelter from predators and adverse conditions, and foraging habitat. Various structures and habitats within the FMR, such as rip-rap, sediments, and vegetation, will influence these functions. Habitat development in the FMR will be closely monitored during the Adjustment phases I and II. To optimize its effectiveness, maintenance and adjustments may be necessary, including controlling vegetation and adding habitat features based on research findings, e.g. high predation risks.

Predation by piscivorous birds, fish, and seals poses a threat to migratory fish passing through the FMR. Potential solutions include providing additional shelter structures. Experimentation with woody structures and shoreline habitats could reduce predation risk and provide foraging opportunities for resident fish. The construction phase involves debating and modeling the eventual placement of additional shelter structures, while the adjustment phases focus on monitoring habitat development and testing research questions related to fish behavior and habitat preferences. Intense field campaigns on tidal migrant and larger diadromous fish during this phase include monitoring predator presence and abundance to assess their impact on fish passage through the FMR.

Coupling abiotic dynamics and fish behaviour using modelling methods

The section discusses various modeling techniques to study the attraction and passage behavior of different target species in relation to abiotic dynamics, particularly focusing on fish movement and environmental data analysis. *Statistical Descriptive Models*: These models, such as generalised linear models (GLMs), correlate movement parameters with environmental variables like flow velocity or food availability. They can incorporate individual variability but require careful interpretation of absences in presence/absence data to account for detection probabilities. *Individual Based Models (IBMs)*: IBMs are mechanistic models that couple individual fish movements with hydrodynamic models, particularly suited for understanding fish behavior in relation to environmental conditions. They capture individual processes, behaviors, and responses to changing conditions, providing insight into fine-scale movement patterns. Coupling data on densities, fluxes and behaviour of tidal migrants and acoustic telemetry data for the larger diadromous fish species with hydraulic modeling enhances understanding of fish behavior and environmental cues. When validated models are available, these can then be used to explore different management protocols for the FMR on its effectiveness for facilitating migration of target species.

Links to other ongoing and future research projects
Collaboration and knowledge exchange between ongoing and future projects are important to better understand fish migration patterns, passage success, and ecosystem functioning within the FMR and its surrounding areas. Key points include:
Cross-pollination between projects: facilitating communication and collaboration among projects is essential for increasing data exchange, refining methodologies, and optimizing research approaches. This involves sharing data on acoustic transmitters, adjusting protocols for tagging fragile fish species, and refining methodologies based on lessons learned from other projects.
Utilization of technical developments: keeping track of technical advancements, such as video monitoring, eDNA analysis, and specific transmitter technologies, enhances data collection and modeling capabilities. This includes leveraging advancements in modeling techniques and software to improve understanding of fish behavior and habitat use.
Importance of international collaboration: engaging in international collaborations, such as the European Tracking Network, facilitates data exchange and enhances understanding of fish migration across different water systems and regions. Participation in such networks enables the FMR to gain insights into fish movements beyond its immediate vicinity.

Examples of ongoing projects: The section provides examples of ongoing projects in the Netherlands, such as the Waddentools- Swimway Wadden Sea, Haringvliet Kier, Ruim Baan voor Vissen, and Waddentools-Waddenmozaïek projects, which contribute valuable insights into fish migration patterns, habitat connectivity, and ecosystem dynamics. Potential benefits for the FMR: collaboration with these projects allows for the exchange of knowledge and experiences, which can inform the design and management of the FMR. Additionally, lessons learned from international initiatives contribute to a broader understanding of fish migration and ecosystem management. Overall, the section underscores the importance of collaboration, data exchange, and international engagement in advancing research efforts related to fish migration and ecosystem conservation within the FMR and its surrounding areas.

Evaluation of the FMR on population, fish community and food web levels
Potential approaches and opportunities to address research question Q5 are given, allowing to evaluating the long-term effects of the Fish Migration River (FMR) on fish populations, fish communities, and the food webs. Points that are addressed include:
Species-specific trends in long-term monitoring programs: analyzing species-specific trends in long-term fish monitoring programs in adjacent waters (such as the Wadden Sea, IJsselmeer, and Rhine basin) can provide insights into whether fish densities show an increase after the construction of the FMR. This approach involves comparing trends over time and assessing changes in fish populations. However, interpreting these trends requires considering various factors such as food availability, habitat connectivity, and spawning ground status.
Food webs: conducting food web analyses on both the Wadden Sea and IJsselmeer sides can offer a comprehensive understanding of ecosystem functioning and the impact of the FMR. This involves examining interactions among different trophic levels and taxa to assess changes in the food web structure over time.
Population levels: utilizing tools like micro-chemistry analyses and genetics can help quantify the effect of the FMR on population structure. For example, microchemistry analyses of otoliths can reveal the contribution of diadromous fish populations to spawning populations in Lake IJsselmeer. Genetic tools can also aid in identifying fish populations capable of crossing the Afsluitdijk barrier.

Fish communities: studying the entire fish community on both sides of the Afsluitdijk is crucial for understanding the broader impact of the FMR. This involves employing multivariate approaches to assess changes in the fish community composition and size structure over time. Additionally, mechanistic modeling approaches may provide insights into the underlying processes driving these changes.

Climate change considerations: recognizing the influence of climate change on fish populations and ecosystems is essential for interpreting the long-term effects of the FMR. Rising sea levels, increased temperatures, and altered precipitation patterns may affect species composition, migration patterns, and habitat suitability. Understanding these interactions is critical for evaluating the resilience and effectiveness of the FMR in the face of climate change challenges.

Future perspectives and resilience: designing the FMR to accommodate future challenges, such as climate change impacts and changing fish species composition, is crucial for ensuring its long-term effectiveness. The FMR's design, which focuses on improving connectivity while reducing risks associated with freshwater discharge and barrier flushing, offers a more robust solution compared to alternative measures dependent on river discharge.

Coupure of the FMR, one of the largest fishways worldwide, through the Afsluitdijk during construction

Nederlandse samenvatting

Doel van deze rapportage
Dit rapport is een update en herziening van eerdere plannen om het functioneren van de Vismigratierivier (VMR), na aanleg in de Afsluitdijk bij Kornwerderzand, te monitoren en te onderzoeken. De onderzoeksactiviteiten zoals voorgesteld in dit monitoringsplan hebben op hoofdlijnen vier doelen:

1 Voldoet de VMR aan de gestelde doelen en verwachtingen:
   - Grootschalige gelijktijdige op zelfstandig visgedrag gebaseerde vismigratie - passage door de Afsluitdijk. Is de 'barrière' Afsluitdijk voor vismigratie tussen Waddenzee en IJsselmeer met deze 'herstelmaatregel' verleden tijd?
   - Welke (trek)vissoorten, in welke hoeveelheden en wanneer maken (succesvol) gebruik van de VMR?
   - Draagt VMR bij aan het herstel van (trek)vispopulaties en met name getijdemigranten?
   - Draagt VMR bij aan het herstel van het aquatisch ecosysteem, i.r.t. het voedselweb en biodiversiteit?

2 Evaluatie en optimalisatie van het functioneren van de VMR voor migrerende vis
3 Integraal Waterbeheer: toepassen van nieuwe kennis in spui- en VMR beheerprotocollen (flexibel en adaptief beheer)
4 Genereren/exporteren van proceskennis zoet-zout passage van trekvis (m.n. getijdemigranten) naar andere locaties (nationaal en internationaal).

Het geeft een onderzoek benadering om het functioneren van de VMR op zowel op abiotisch (bijvoorbeeld hydrodynamica, zandtransport) als biotisch (bijvoorbeeld, passage succes en visgedrag) vlak te onderzoeken. Het algemene doel van de onderzoeksactiviteiten is het ontwerpen van een geïntegreerd en geoptimaliseerd bedieningsprotocol voor de VMR. Het resultaat van de onderzoeksperiode, op basis van onderzoekresultaten, is o.m. een geoptimaliseerd bedieningsprotocol voor de VMR. Daarnaast zal deze kennis over visgedrag bij grote zoet-zout overgangen beschikbaar zijn voor vismigratievraagstukken op andere locaties en zal er binnen en na de onderzoeksperiode over gepubliceerd worden.

De Afsluitdijk als barrière voor migrerende vis en aanleiding voor de Vismigratierivier (VMR)
Met de afsluiting van de Zuiderzee door de 32 km lange Afsluitdijk is de migratie van vis tussen Waddenzee en zoetwater ernstig geblokkeerd. Vis wordt vanuit de Waddenzee naar de spuisluizen 'gelokt' door de afvoer van zoetwater uit het IJsselmeer via de spuisluizen op de Waddenzee. Dat spuien gebeurt onder 'vrij verval', dus wanneer het water in de Waddenzee lager staat dan aan de IJsselmeer zijde. Doordat er veel vis bij de spuisluizen en de spuikom aan de Waddenzeezijde aanwezig is, is de VMR ook bij deze spuisluizen bedacht met een ingang van de VMR die aansluit op de spuikom. Sterke zwemmers als elft, houting, zeeforel en Atlantische zalm kunnen met een uiterste krachtinspanning zelfstandig naar de andere kant van de dijk zwemmen. Echter, zwakkere zwemmers zoals glasaal, spiering, driedoornige stekelbaars en bot(larven) zijn hierin niet, of slechts gedeeltelijk, toe in staat. Deze soorten, en met name de glasaal en de botlarven maken tijdens hun migratie gebruik van getijdestromen om met de stroom mee richting het zoete water mee te gaan. Het ontwerp van de VMR is juist voor deze vissen van groot belang omdat via de VMR er weer een stukje herstel is van deze getijdestroom. Met de komst van de VMR wordt dus een klein stukje estuarium hersteld met stroomsnelheden die vele malen lager zijn dan de spuistromen via de spuisluizen. Daarnaast biedt de VMR in principe 24/7 migratie kansen (voornamelijk via rinketten en *vertical slots*) voor alle vissoorten in tegenstelling tot de reguliere spuivensters die veel afhankelijker zijn van waterniveaus. Daarom kunnen vissen die veel actiever zwemgedrag laten zien (zoals de zalm, zeeforel) ook profiteren van de VMR.

Doelsoorten voor de VMR
De belangrijkste doelsoorten waarvoor de VMR wordt aangelegd zijn 'diadrome' vissoorten die voor het voltooien van hun levenscyclus afhankelijk zijn van migratie tussen zoet en zoutwater. Met name de

intrek van zee naar zoetwater is veelal ernstig belemmerd. De VMR heeft als doel het hele soortenspectrum aan trekvissen die naar binnen willen trekken te faciliteren. Sommige vissen trekken als volwassen vis van zee naar zoetwater om te paaien ('anadrome' soorten) en een deel juist vooral als jonge vis om op te groeien in zoetwater en als volwassen vis naar zee te trekken ('katadroom'). Kleine trekvissen hebben weinig zwemcapaciteit om tegen stromingen in te zwemmen. Om van zee naar zoetwater te komen zijn deze afhankelijk van het selectief gebruik te maken van de getijdenstromingen door tijdens opkomend water (ingaand tij, vloed) hoog in de waterkolom mee te liften met de stroming, en tijdens afgaand water (uitgaand tij, eb) drukken ze zich tegen de bodem en verliezen dan geen terrein. Met dit gedrag ('*Selectief Getijden Transport*') kunnen deze kleine trekvissen ('getijdenmigranten') in natuurlijke estuaria tot ver in de riviermondingen doordringen. Grotere trekvissen hebben meer zwemcapaciteit en kunnen ook actief tegen stromingen in zwemmen, maar gebruiken om energie te besparen ook selectief getijden transport. In de huidige situatie zijn juist de getijdenmigranten het meest belemmerd in hun stroomopwaartse migratie door de Afsluitdijk naar zoetwater.

Naast riviertrekvissen als doelsoorten, 'spoelen' er ook veel zoetwatervissen uit met het zoetwater dat via de sluizen bij Kornwerderzand naar de Waddenzee wordt gespuid met sterfte tot gevolg. Door deze zoetwatervissen ook goede mogelijkheden te geven via de VMR om weer terug te keren naar het IJsselmeer, kan deze extra sterfte onder zoetwatervis worden verminderd. Verder zijn er zoutwatervissoorten die ook zoetwater kunnen benutten (tolereren ook heel lage zoutgehalten), maar dit niet per se nodig hebben om hun levenscyclus te voltooien, zoals harders en zeebaars. Ook deze soorten kunnen gebruik maken van de VMR om hun foerageergebieden facultatief uit te breiden naar het IJsselmeergebied.

Verschillende soort-specifieke kenmerken, eigenschappen of criteria t.b.v. selectie van doelsoorten voor toekomstig gericht wetenschappelijk onderzoek.

Criterium	Aal (glasaal)	Bot (larve)	3d stekelbaars	Spiering	Elft	Fint	Houting	Europese steur	Atlantische zalm	(Zee)Forel	Rivierprik	Zeeprik	Atlantische haring	Sprot	Diklipharder	Zeebaars
Gilde	Dia	Dia	Dia	Dia	Dia	Dia	Dia	Dia	Dia	Dia	Dia	Dia	MJ	MS	MS	MS
Levenstadium tijdens uittrek naar zee	ad	all	all	all	all	all	all	all	juv	all	juv	juv	juv	all	all	all
Levenstadium tijdens intrek naar zoet	juv	larf	ad	ad	ad	ad	all	ad	ad	ad	ad	ad	juv	juv	all	all
periode intrek naar zoet (maand)	2-6	2-6	2-5	2-5	3-6	4-6	10-12	4-9	1-12	6-12	10-3	2-6	11-6	5-6	3-5	3-6
Zwemcap. intrek	-	--	-	-	++	++	+/-	++	++	++	-	+	-	-	+/-	+/-
Talrijkheid gedurende intrek	++	++	+	+	--	-	+	--	+/-	+/-	+	-	++	++	+	+
Vangbaarheid in lopende monitoringen	+	--	+	+	--	-	+	--	+	+	-	+/-	-	-	+	+
Belang voor Natuurbeleid: EU-richtlijnen, N2000, rode lijst	++	-	-	-	++	++	++	++	++	+/-	++	++	-	-	-	-
Huidige kennis nederlandse kustwateren	++	-	+	-	-	+	-	--	--	+/-	+/-	--	+	-	-	+
Lokale huidige kennis: Kornwerderzand	++	+/-	+/-	+	--	-	+	--	+	++	+/-	++	+/-	+/-	-	-
Huidige kennis (international)	++	+	++	+/-	+	+	++	+/-	++	++	+/-	+/-	++	+/-	-	++
Kwetsbaarheid bij vangst intrek ++ = sterk; -- = zeer kwetsbaar	++	--	++	-	-	-	+	++	+	+	++	++	-	-	++	++
Geschikt voor merk-terug-vangst exp. (gr=groepsmerk; ind=individueel merk	ba	--	ba/ind	ind	ind	ind	ind	ind	ind	ind	ind	ind	--	--	ind	ind
Geschikt voor akoestische telemetrie	-	-	-	+/-	-	+	++	++	++	++	+/-	++	-	-	++	++
Afhankelijk van estuarium als leefgebied?	-	++	+	+	++	++	+	+	--	+/-	-	--	+/-	-	-	-

Gilde: Dia=diadroom; MJ=Marien Juveniel; MS; Marien Seizoensgast

Merk-terugvangst: gr=groepsmerk (VIE-tagging, kleurmerken), ind=Individueel uniek merk (merken met ID, PIT-tags)

Huidige ontwerp van de Vismigratierivier

Het huidige ontwerp omvat 6 verschillende secties (zie ook nummering in onderstaande Figuur):

(1) Twee doorgangen van de spuikom naar de VMR (16m breed, 3-5m diep afhankelijk van getij), de zijkanten en bodem van de doorgang bestaan deels uit stortsteen en zand.

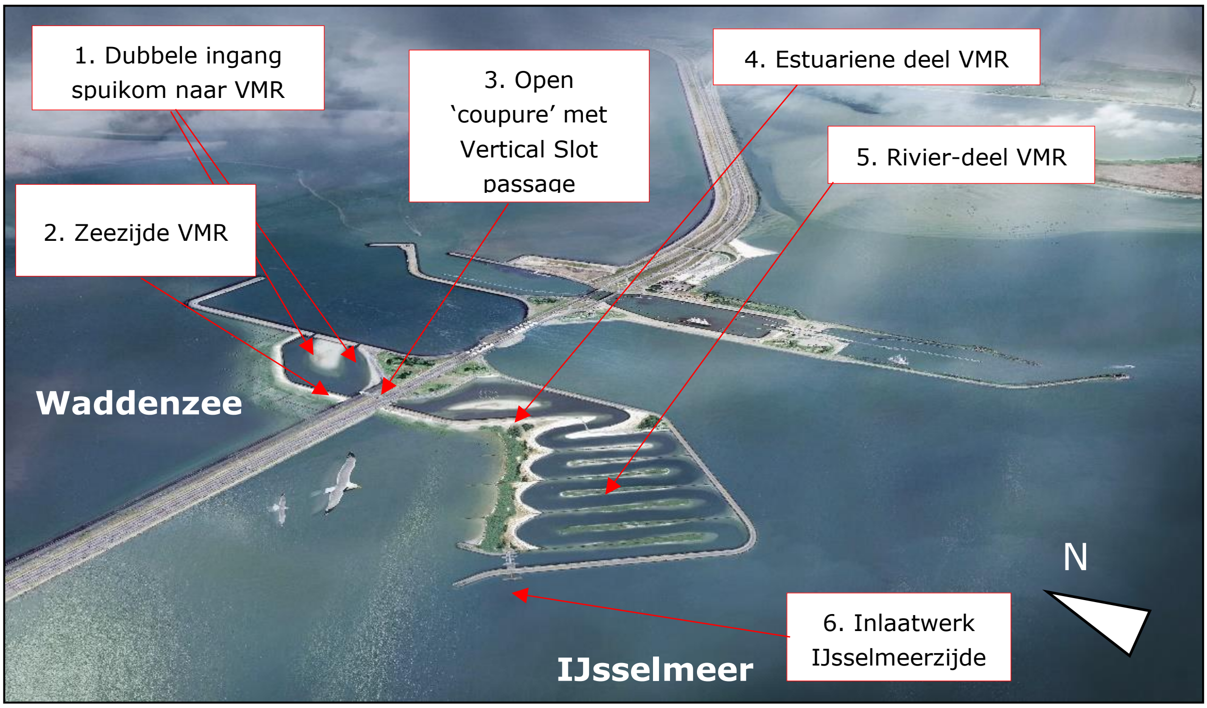
(2) Buitengaatse deel van de VMR (Waddenzee-zijde van de Afsluitdijk) bestaat uit twee afzonderlijke watergangen afgezet met strotsteen en daarbinnen meer natuurlijke habitats met zand en slibbodems.

(3) De passage door de Afsluitdijk ('coupure') is 100m lang en kan worden afgesloten (t.b.v. veiligheid zeewering en beheer van VMR). De passage bestaat uit een 9m brede open doorlaat en parallel daaraan een 3m brede 'vertical slot' vispassage (met verticale sleuven waarlangs vis ook tegen de stroming in kan passeren). De bodem in de coupure bestaat uit stortsteen en de waterdiepte is 3-5 m afhankelijk van het getij.

(4) Een open 'estuarien' deel direct aan de binnenzijde van de Afsluitdijk waarin de getijde-dynamiek een natuurlijke ontwikkeling van zandoevers en banken mogelijk maakt.

(5) Een meer technisch (kunstmatig) meanderend rivier-deel tussen hardsubstraat-afscheidingen zodat de VMR voldoende lengte heeft om getijdebewegingen tijdens de gehele (of soms grootste deel van de) getijdencyclus mogelijk te maken.

(6) Inlaatwerk van de VMR aan de IJsselmeerzijde met sluizen met vier houten deuren die gesloten kunnen worden. Via de rinketten in de deuren kan ook als deze gesloten zijn vismigratie plaatsvinden. Verder is er een vertical slot vispassage naast de sluisdeuren aanwezig, waardoor vis ook kan passeren.



Meet-infrastructuur in de VMR
Tijdens de aanleg (constructie-fase), wordt ook de infrastructuur en permanente meetapparatuur (met name abiotische metingen zoals waterhoogte, stroomsnelheid, zoutgehalte) die nodig is voor de uitvoering van het onderzoeks- en monitoringsprogramma na constructie. Hierbij kan worden gedacht aan bevestigingspunten voor netten of zenderonderzoek naar vis. Deze is gedetailleerd gerapporteerd in Griffioen, Perk, Gerkema, Röell, Winter (2023). 'Beschrijving onderzoeksfaciliteiten Vismigratierivier.' Wageningen Marine Research report C019/23.

Onderzoeksvragen voor het functioneren, evalueren en optimaliseren van de VMR
Om het functioneren van de VMR te kunnen meten en eventuele knelpunten te identificeren en op te lossen, is zowel goede proceskennis (onderzoek) nodig als ook het meetbaar maken van de abiotische en biotische dynamiek in tijd en ruimte (monitoring). De onderzoeks- en monitoring vragen zijn ingegeven door wetenschappelijke kennisbehoefte en vanuit beheersvragen hoe de VMR het beste kan worden beheerd en operationeel uitgevoerd kan worden (op gebied van inrichting en de fine tuning van bedieningsprotocollen). Belangrijke factoren die hierbij een rol spelen:

- Aantrekking of vindbaarheid van de ingangen van de VMR voor vis die stroomopwaarts van
- Passage succes via de VMR
- Alternatieve routes bij Kornwerderzand spuicomplex
- Onbedoelde verplaatsingen van vis (intrek-uitspoeling)
- Bottleneck analyse op verschillende schaalniveaus: VMR, Complex, populatie, ecosysteem
- Klimaatverandering

De vijf hoofdvragen zie zijn geïdentificeerd zijn:

- **Q1: Hoe functioneert de VMR in abiotisch opzicht?** Welke stromingsdynamiek, sedimentatieprocessen, zoutgehalten treden op in de verschillende delen van de VMR en hoe is de stabiliteit van de VMR tijdens extreme omstandigheden?
- **Q2: Wat is het passage-succes van de doelsoorten?** Welk deel van het aanbod aan riviertrekvissen weet de ingangen van de VMR te vinden (attractie efficiëntie), en succesvol te passeren (passage efficiëntie),en met welke verblijftijd (vertraging) of conditieverlies?
- **Q3: Zijn er nog knelpunten in het functioneren van de VMR?** En hoe zijn deze te verbeteren met gerichte maatregelen en optimalisatie van bedieningsprotocollen?
- **Q4**: **Wat zijn de ontwikkelingen en het gebruik van de VMR als habitat voor vis en vispredatoren**? Hoe ontwikkelen de habitats (o.a. dynamiek in stroming, zoutgehalte en vegetatie) zich in de VMR, hoe worden deze door de diverse vis gebruikt voor acclimatisatie, foerageren en schuilgelegenheid; welke vispredatoren foerageren in de VMR en rondom het sluizencomplex bij Kornwerderzand?
- **Q5**: **Wat is de bijdrage van de VMR in het herstellen van vispopulaties, -gemeenschappen en voedselweb en evaluatie van effect op ecosysteem functioneren**?

Algemene opzet en fasering van het onderzoeks- en monitoringsprogramma
Er worden vier fasen onderscheiden:

- Constructiefase (bouwfase, pre-fase) voorzien in 2024-2025
- Aanpassingsfase I (inregelfase I): voorzien eind 2025-2026
- Aanpassingsfase II (inregelfase II): voorzien in 2027
- Optimalisatie-fase: 2028 en daarna.

	2024-2025 Constructie-fase	Eind 2025-2026 Aanpassing-fase I	2027 Aanpassing-fase II	2028 → Verdere optimalisatie
Abiotiek:	inbouw vaste app.	Continue metingen Flexibele meetunits	Continue metingen Flexibele meetunits	Continue metingen Flexibele meetunits
Kleine vis/ getijden-migranten	Voorbereiding, Aanschaf materialen	Pilots, testen methodiek	Intensieve meet-campagne net+merk	Adaptieve campagne afh. resultaten Fase I-II
Grote vis:	Voorbereiding, Aanschaf materialen	Installatie netwerk, Zenderen vis	Zenderen vis	Adaptief zenderen vis afh. resultaten Fase I-II
Modellen:	Abiotische modellen	Abiotische modellen	Bouw IBM modellen	Finetuning modellen calibratie, scenario tests
Habitat (gebruik):	Keuze inbrengen schuilgelegenheid?	Ontwikkeling VMR Vegetatie, Schuilen	Ontwikkeling VMR monitor.predatoren	Adaptief afh. van resultaten Fase I-II

Abiotisch meetprogramma
Monitoring van de abiotiek in de Vismigratierivier (VMR) zijn essentieel tijdens de verschillende fasen:
Constructiefase: Voortbouwend op de numerieke modellering die is ontwikkeld voor verder inzicht in VMR-functies. Samenwerking tussen de opdrachtgever, aannemer, hydrodynamische expert en visecologen om het ontwerp op detail niveau verder te optimaliseren voor zowel hydrodynamica als visbiotoop is belangrijk.
Aanpassingsfase I: Voeden van het numerieke model met de continue abiotische metingen met de vaste en mobiele meetapparatuur. Simulaties worden uitgevoerd om verschillende beheerprotocollen te testen. Model wordt stapsgewijs gevalideerd tegen meetresultaten. Beheerprotocollen voor normale getijdenomstandigheden worden vastgesteld.
Aanpassingsfase II: Focus op extreme omstandigheden zoals droogte, stormen, enz. Vergelijkbare aanpak als in fase I maar met de nadruk op meer extreme scenario's. Beheerprotocollen worden uitgebreid naar extreme omstandigheden.
Optimalisatiefase: Langdurige monitoring om beheerprotocollen aan te passen op basis van veranderende omstandigheden (bijv. vegetatie ontwikkeling, veranderingen in bodemdiepte). Integratie van de ontwikkelde en verbeterde numerieke abiotische modellen met de resultaten van biotische monitoring om hydrodynamische omstandigheden te kunnen koppelen en eventueel verbeteren.
Hydrodynamische modellering op de schaal van het sluizencomplex, mogelijk gekoppeld aan visgedrag analoog aan wat beschikbaar is voor sluizencomplex Den Oever.

Vismigratie onderzoek en -monitoring
Omdat er voor kleine vis (getijdemigranten) en grotere vis verschillende meetmethoden worden toegepast worden deze hieronder apart behandeld. Aangezien getijdenmigranten in de situatie voor de aanleg van de VMR de grootste beperkingen ondervinden, en de VMR door zijn innovatieve ontwerp met een in- en uitgaand getijderegime goed aansluit bij het natuurlijke gedrag van getijdemigranten (‘selectief getijden-transport’) en juist voor deze vissoorten de meeste kennishiaten bestaan, ligt een belangrijk deel van de focus van het onderzoeks- en monitoringprogramma op kleine diadrome vis (getijdemigranten).

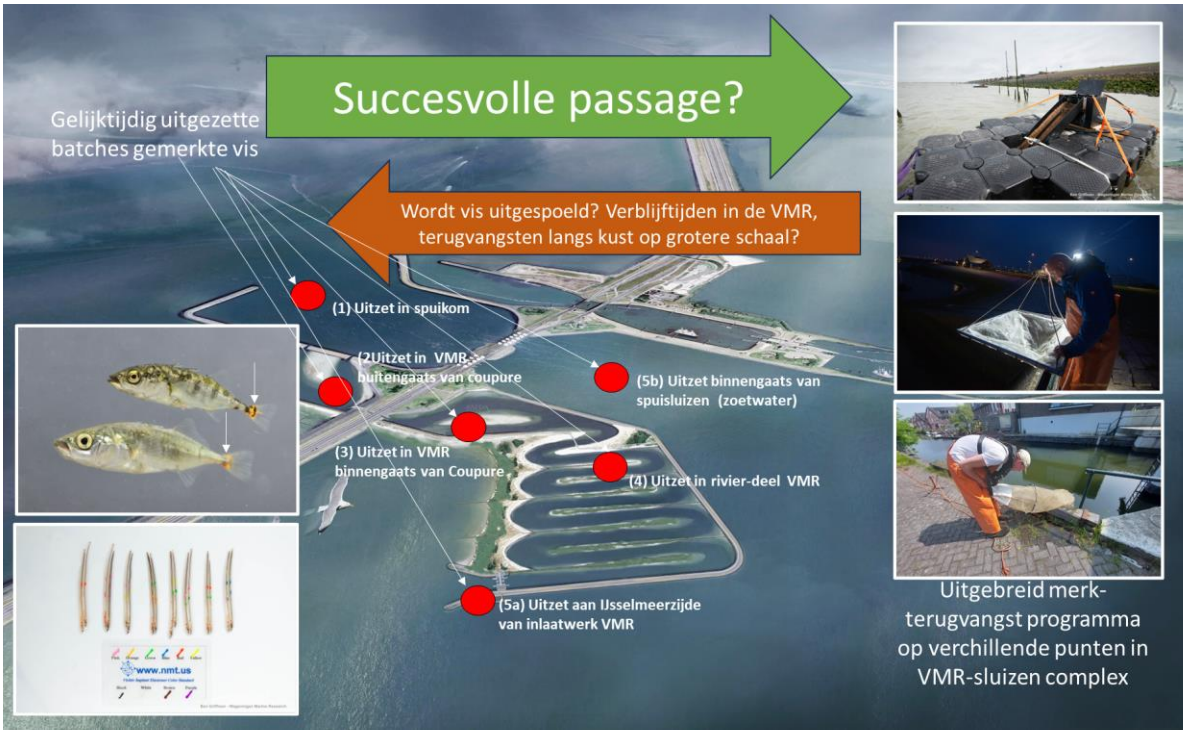
Onderzoek- en monitoringsprogramma voor kleine diadrome vis (getijdemigranten)
Het onderzoek voor deze kleinere vissoorten (sommige migratie stadia zijn slechts enkele millimeters groot) kent een basis in een uitgebreid nettenprogramma en indien mogelijk aangevuld met merk-terugvangst technieken en/of (akoestische) zenders. Het is niet mogelijk om voor alle kleine diadrome vissoorten te werken met geavanceerde zenders zoals dat met grotere vissen mogelijk is. Echter, voor een soort, zoals een botlarve van slechts enkele millimeters groot, die niet gemerkt kan worden zal voor deze soort informatie verkregen worden door gevangen dichtheden en fluxen op strategische plekken binnen de VMR en nabij de VMR worden opgewerkt (naar afvoer-volumes en -stroming in tijd en ruimte). Binnen het netten/vangtuigen programma worden vissen gemerkt met VIE-tags en indien mogelijk met PIT tags (o.a. driedoornige stekelbaars) of wellicht zelfs met kleine akoestische zenders (grote spiering). Op die manier kan er aanvullend op de opwerking met dichtheden, fluxes, afvoervolumes en stromingen ook bepaald worden wat verblijftijden op verschillende plekken in en rond de VMR, wat het passage succes is en of vissen bijvoorbeeld weer worden uitgespoeld met het spuien. Met de gegevens kan er op basis van terugvangst ook een absolute aantalsschatting per gemerkte soort worden gedaan.

Driedoornige stekelbaars en glasaal met VIE-tags

Voor kleine diadrome vis (getijdemigranten) is een integraal en steekproefsgewijs meetprogramma van diverse netten en vangtuigen voorgesteld. Kruisnetten (dichtheden), driftnetten (aantalsfluxen), passieve vistuigen (fuiken, glasaaldetectoren of ‘ELFIs’) in combinatie met merk-terugvangst experimenten met unieke batch-codes worden gecombineerd waarbij o.a. de volgende parameters worden bepaald:

- Soort-, lengtesamenstelling en conditie in tijd & ruimte in spuikom, ingang/uitgang VMR
- Aantalsbalans/soort op basis van dichtheden, fluxen en abiotische dynamiek/opwerking
- Merk-terugvangst: verblijftijden, passage succes, absolute aantalsschattingen in tijd/ruimte
- Identificatie eventuele knelpunten en verliesposten
- Input-data voor koppeling abiotische modellen en Individual Based Modellering

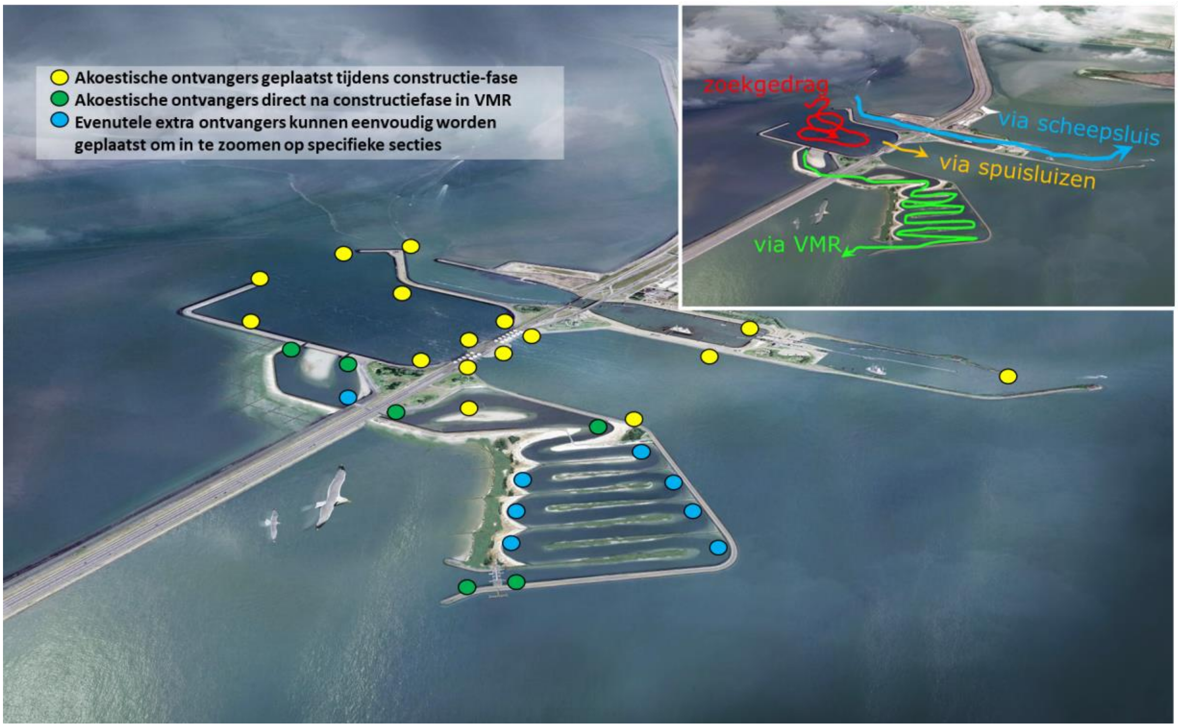
Pilots en eerste tests zullen in Aanpassingsfase I plaatsvinden, een intensieve meetcampagne in Aanpassingsfase II. Zie figuur hieronder:



Onderzoek- en monitoringsprogramma voor grotere diadrome vis (zenderstudies)
Het passage succes en gedrag van grotere diadrome vissen kan met telemetrische methoden (zendertechnieken) direct worden gemeten. De ontwikkelingen in telemetrie gaan snel, met steeds meer verschillende sensoren om diepte, temperatuur, acceleratie en predatie-events te kunnen meten. En met steeds kleinere zenders en/of langere batterijduur, waardoor ook steeds meer kleinere vis geschikt kan worden voor zenderonderzoek (bijvoorbeeld PIT-tags wordt al veelvuldig toegepast voor driedoornige stekelbaars, en recentelijk kleine akoestische zenders voor spiering). Met fuikopstellingen en eventueel voor sommige soorten aangevuld met samenwerkende sportvissers (via Sportvisserij NL) worden per doelsoort groepen gezenderd en vrijgelaten in de buurt van het complex. Een gecombineerd meetnet van akoestische ontvangers en PIT-antennes wordt gebruikt om hun migratie via de verschillende potentiële intrekroutes te kunnen volgen. Deze technieken bieden inzicht in individueel zoekgedrag, attractie efficiëntie en passage efficiëntie, evenals de verblijftijden en zoekgedrag in en rond het sluizen-complex en in de VMR. PIT-tagging geeft inzicht in gebruik van de Vertical Slot passages in de coupure en bij de Vertical Slot en rinketten bij het inlaatwerk aan IJsselmeerzijde.

Er wordt voorgesteld om een deel van de akoestische receivers al tijdens de constructie-fase in en rond het sluizen-complex te installeren, zodat er al gegevens van vissen die in andere studies zijn gezenderd kunnen worden verzameld (in aanvulling op bestaande T0 metingen). De plaatsing van PIT-tag stations is maatwerk en moeten worden ingeregeld door onderzoekers.

Tijdens de aanpassingsfase I en II worden aanvullende ontvangers geïnstalleerd en worden grotere diadrome vissen gezenderd. M.b.v. fuiken die voor de standaard monitoring worden ingezet en aanvullende fuiken (evt. met grotere maaswijdten, zogenaamde 'zalmsteken') en medewerking van sportvissers worden grotere diadrome vissen gevangen (met name zeeprik, rivierprik, houting en de moeilijker te vangen en zeldzamere zeeforel en zalm). Akoestische zenders met predatie-sensoren en temperatuursensoren worden gebruikt om predatieverliezen en potentiële predatoren te identificeren (temperatuur direct na predatie-event geeft indicatie of het roofvis, vogels of zeezoogdieren zijn). Afhankelijk van de resultaten van de aanpassingsfase I en II, kunnen tijdens de optimalisatiefase op specifieke soorten en knelpunten worden ingezoomd. Met dezelfde opzet, meetnet en zendertechnieken (zie overzichtsfiguur hieronder) kan ook terugtrek-succes van uitgespoelde zoetwatervis bepaald worden. Of passage gedrag van mariene vissoorten met hoge zoetwater-tolerantie (bijvoorbeeld harders of zeebaars) die het IJsselmeergebied kunnen benutten als uitbreiding van hun foerageergebied.



Ontwikkeling van habitats en schuilgelegenheid in relatie tot predatie in de VMR
De VMR kan ook fungeren als habitat in de overgangszone tussen zout en zoet water, voor acclimatisatie, schuilgelegenheid tegen vispredatoren en ongunstige omstandigheden (bijvoorbeeld harde wind, hoge golven), en foerageerhabitat biedt. Diverse structuren en habitats binnen de VMR, zoals steenstort, sedimentsamenstelling en vegetatie, zullen deze functies beïnvloeden. Habitatontwikkeling in de VMR zal tijdens de aanpassingsfasen I en II nauwkeurig worden gemonitord. Om de effectiviteit te van de VMR te optimaliseren, kan onderhoud en aanpassingen nodig zijn, waaronder beheer van vegetatie en het toevoegen van habitatstructuren op basis van onderzoeksresultaten uit Aanpassingsfase I en II als bijvoorbeeld blijkt dat er hoge predatieverliezen van bepaalde doelsoorten optreden.

Predatie door visetende vogels, vissen en zeehonden kunnen substantiële verliezen van migrerende vissen veroorzaken. Mogelijke oplossingen omvatten het bieden van aanvullende schuilgelegenheid door extra habitatstructuren aan te brengen (dat kan modulair, zoals bijvoorbeeld met perenboomhout in de Waddenzee is uitgevoerd binnen het project Waddenmozaïek). Tijdens de intensieve meetcampagnes voor getijdemigranten en grotere diadrome vissen in de Aanpassingsfase I en II zou er ook frequent moeten worden bepaald hoeveel en welke visetende vogels en zeezoogdieren (met name zeehonden) in de VMR en rondom het sluizen-complex bij Kornwerderzand aanwezig zijn.

Koppelen van abiotische dynamiek en gedrag van vis middels modellering
Om de vindbaarheid van de ingangen (attractie) en passage gedrag van verschillende doelsoorten in relatie tot abiotische dynamiek (bijvoorbeeld stromingscondities en -patronen, gradiënten in zoutgehalten) en prikkels in zowel VMR als rondom het sluizen-complex verder te onderzoeken, kunnen verschillende modelleringstechnieken worden gecombineerd. Individual-Based Modellering (IBM) is een zeer geschikte methode om individuele visbewegingen te koppelen aan hydrodynamische modellen die zijn ontwikkeld voor de VMR en het sluizen-complex bij Kornwerderzand. Met hulp van IBM modellen kan proceskennis worden gegenereerd en getest tegen veldwaarnemingen. Als deze IBM modellen goed zijn gevalideerd met velddata (van zowel de resultaten van de getijdemigranten onderzoeken als het telemetrie-onderzoek naar grotere vissen) kunnen ze ook worden ingezet als 'tool' om verschillende beheerprotocollen te verkennen en de effectiviteit hiervan voor doelsoorten te evalueren. De IBM-modellen die zullen worden ontwikkeld binnen lopende Haringvliet-Kierstudies, kunnen dienen als basis voor aanpassing en toepassing van deze voor het VMR.

Kruisbestuiving met andere lopende en toekomstige projecten en onderzoeken
Samenwerking en kennisuitwisseling tussen lopende en toekomstige projecten zijn belangrijk om de vismigratiepatronen, factoren die passagesucces bepalen en ecosysteemfuncties op verschillende schaalniveaus van lokaal (VMR), complex niveau, tot ecosysteem niveau van omliggende wateren beter te begrijpen. Technische ontwikkelingen gaan snel, zoals videomonitoring, eDNA-analyses en specifieke zendertechnologieën (telemetrische methoden). Bijvoorbeeld op het gebied van akoestische telemetrie neemt het aantal nationale en internationale netwerken aan ontvangers snel toe, waarvoor een internationaal samenwerkingsverband is opgericht met een centrale database: het Europese Tracking Netwerk (ETN). Dit vergemakkelijkt de uitwisseling van gegevens en verbetert het begrip van vismigratie over verschillende watersystemen en regio's. Bovendien kunnen vissen met zenders uit andere onderzoeken opduiken in het studiegebied rond de VMR en andersom kunnen vissen gezenderd bij de VMR ook op grotere schalen worden gevolgd, bijvoorbeeld zeebaarzen die zijn gezenderd in de westelijke Waddenzee binnen Swimway-project tot aan het Engels Kanaal bij Cornwall (Engeland).

Voorbeelden van lopende projecten: In dit gedeelte worden voorbeelden gegeven van lopende projecten in Nederland, zoals de Waddentools-Swimway Waddenzee, Haringvliet Kier en Zuidwestelijke delta, Ruim Baan voor Vissen, Vissen voor Verbinding, Eems Vissen in Beeld en Waddentools-Waddenmozaïek-projecten, die waardevolle inzichten bieden in vismigratiepatronen, habitat connectiviteit en ecosysteem-dynamiek.

Evaluatie van de VMR op populatie-, visgemeenschap- en voedselweb-niveaus
Dit onderzoeks- en monitoringsplan richt zich met name op het verkrijgen van proceskennis om het functioneren van de VMR te kunnen evalueren en de vismigratiemogelijkheden voor een breed spectrum aan migrerende vissoorten te optimaliseren en herstellen in de VMR en op sluizen-complex niveau. In hoeverre dit ook op grotere schaalniveaus doorwerkt op vispopulaties, visgemeenschappen en voedselwebben in wateren die via de VMR met elkaar in verbinding staan, hangt af van veel factoren. Voor specifieke populaties kunnen nog andere knelpunten in hun levenscyclus optreden die de effecten van herstelde vismigratie tussen Waddenzee en IJsselmeer nog niet tot uitdrukking laat komen.

Een analyse van soort-specifieke trends in lange termijn-vismonitoringsprogramma’s in omliggende watersystemen kan correlatieve verbanden tussen de VMR en populatie-trends identificeren. Er wordt een overzicht gegeven van lange termijn datareeksen (>10 jaar) van verschillende monitorings-programma’s gegeven die hiervoor kunnen worden gebruikt. Diepgaandere onderzoeksmethoden zoals micro-chemische analyses en genetica kunnen inzicht geven in de bijdrage van verschillende subpopulaties aan de totale populatie in omliggende zoute en zoete watersystemen en stroomgebieden.

Een volgende uitdagende stap is een analyse van veranderingen in visgemeenschappen en voedselwebben. Om deze te kunnen duiden is veel proceskennis en onderzoeksdata nodig. Het evalueren van het effect van de VMR op het voedselweb vereist diepgaande studies die meerdere trofische niveaus en taxa bestrijken aan zowel de Waddenzee- als IJsselmeer-zijde.

In de evaluatie van de effectiviteit van de VMR op lange termijn zal ook Klimaatverandering een steeds grotere rol spelen: Stijgende zeespiegels en een toename van extremen van zowel piekafvoeren als zeer droge zomers als gevolg van klimaatverandering kunnen het functioneren van de VMR op verschillende manieren beïnvloeden. Zo zullen de beheerprotocollen waarschijnlijk aangepast moeten blijven worden. Klimaatverandering kan echter ook de soortensamenstellingen beïnvloeden en van invloed zijn op de doelsoorten voor de VMR, bijvoorbeeld spiering en salmoniden zijn koude minnende soorten die in toenemende mate negatieve gevolgen van extreem hoge temperaturen ondervinden. Het is belangrijk om de langetermijngevolgen van klimaatverandering voor vispopulaties mee te wegen in evaluaties en verwachtingspatronen van effecten van de VMR op ecosysteem niveau.

Bovenaanzicht van de VMR, een van de grootste vispassages ter wereld, tijdens de aanleg met links de stortstenen bodemwaarlangs met opkomend tij kleine vis kan meeliften en rechts de parallel aangebrachte Vertical Slot vispassage die ook bij afgaand tij vis de mogelijkheid geeft om tegen de stroming in te passeren.

1 Introduction

Goal of this report
This report is a revised and updated research and monitoring program of previous plans (Calles et al. 2014) (Griffioen and Winter 2017, Philippart and Bruins Slot 2021) aiming at determining and optimizing the effectiveness of restoring fish migration at the sluice-complex in the Aflsuitdijk at Kornwerderzand after the construction of the Fish Migration River (FMR). The main research questions underlying the monitoring program will be outlined. The proposed research and monitoring approach will outline in detail which monitoring techniques can be applied and what set-up and schedule of different research components is required to answer those questions.

The general aim of the monitoring and research activities is to design an integrated operating protocol for the FMR. In other words, after the research period, an optimized protocol is available based on research focussed biotic (e.g., fish behaviour) and abiotic (e.g., hydrodynamics, sand transport) knowledge. In addition, new knowledge on fish behaviour at large freshwater-sea barriers in relation to underlying mechanisms and particularly diadromous fish using tidal streams, will be gained and made available for fish migration issues at other sites.

The Fish Migration River (FMR)
Worldwide much attention and efforts were put in rehabilitating fish migration along barriers in rivers. For tidal barriers however, there are still many knowledge gaps on fish behaviour and migration success in relation to tidal dynamics, especially for small diadromous fish such as flounder larvae and glass eel (Winter et al. 2014). Moreover, behaviour and migration success are strongly site specific due to different local hydrodynamics, management protocols, migration opportunities and migration windows that allow fish to pass. In the last few years, following Water Framework Directive guidelines, many barriers are, or will be, equipped with fish migration management measures.

One of these barriers is the Afsluitdijk, a 32 km long dam that closed off the former estuary Zuiderzee in 1931 and formed a large tidal barrier for migratory fish. Besides the disappearance of a natural estuary and creating a whole new freshwater ecosystem (Lake IJsselmeer), the Afsluitdijk dam has had a major impact on fish migration between fresh and salt water (Griffioen et al. 2014b, Winter et al. 2014). Some fish species adapted to the new situation and others disappeared (for review see Winter et al. 2014). The Afsluitdijk has two discharge sluice complexes (Den Oever and Kornwerderzand), where excess freshwater from Lake IJsselmeer is discharged into the Wadden Sea. According to the sluice management protocol, freshwater is only discharged when water level in the freshwater lake is higher compared to the Wadden Sea to prevent saltwater intrusion in the lake. Because of the role of Lake IJsselmeer in provisioning drinking water and for agriculture purposes, salt water intrusion is highly unwanted. Besides an abrupt transition from salt water to completely fresh water, upstream migrating fish are confronted with high water velocities up to several meters per second (Kolvoort and Butijn 1990, Griffioen et al. 2022d) resulting in only very short migration windows at the start and the end of the discharge event that can only be traversed by fish with sufficient swimming capacity.

At the Afsluitdijk, previous telemetry research has been conducted on passage success of some of the diadromous fish species, though numbers of test fish were small (De Vaate et al. 2003, Griffioen et al. 2022d). Passage success of sea trout alongside the two sluice complexes in the Afsluitdijk was assessed using RFID inductive coupling telemetry (NEDAP system). In this study with tagged sea trout at least 47 % successfully entered Lake IJsselmeer in the current situation. Passage success of sea lamprey (*Petromyzon marinus*) was 16% based on passage behaviour of sea lampreys (Griffioen et al. 2022d). Griffioen et al. (2014) and ~70% houting (*Coregonus oxyrinchus*). Passage success for other diadromous fish such as river lamprey (*Lampetra fluviatilis*), European (glass) eel (*Anguilla anguilla*), flounder (*Platichthys flesus*), twaite shad (*Alosa fallax*), three-spined stickleback (*Gasterosteus aculeatus*) and smelt (*Osmerus eperlanus*) at this location are still largely unknown (Griffioen and Winter 2019). Other studies focussed more on migration strategies and life history along the coast of the

Netherlands including the Afsluitdijk and the Wadden Sea (Deelder 1952, 1958, Dekker and van Willigen 1997, Dekker 1998, Dekker 2000, Bult and Dekker 2007, Borcherding et al. 2008, Winter et al. 2008, Borcherding et al. 2013, Tulp et al. 2013, Phung et al. 2015).

Lake IJsselmeer side of the coupure through the Afsluitdijk of the FMR, with the 'happy fish logo'

2 Target fish species for the FMR

Target species of the planned research program are especially small diadromous fish (tidal migrants): flounder (*Platichthys flesus*), European (glass) eel (*Anguilla anguilla*), three-spined stickleback (*Gasterosteus aculeatus*) and smelt (*Osmerus eperlanus*), since these species were most hampered in migrating upstream through the Afsluitdijk and the innovative FMR allows especially these species to enter lake IJsselmeer using incoming tides using selective tidal stream transport. Further target species are the larger diadromous fish species: river lamprey (*Lampetra fluviatilis*), sea lamprey (*Petromyzon marinus*), Atlantic salmon (*Salmo salar*), sea trout (*Salmo trutta*) and North Sea houting (*Coregonus oxyrinchus*), which, depending on their swimming capacities, have limited opportunities to pass the Aflsluitdijk in the current situation. Although for the diadromous species twaite shad (*Alosa fallax*), connectivity will be enhanced by the FMR, the critical estuarine tidal habitats needed for successful spawning (freshwater tidal zone of estuaries) and nursery (dynamic estuary), will still be missing alongside the Afsluitdijk. The diadromous species European sturgeon (*Acipenser sturio*) and Allis shad (*Alosa alosa*) became extinct in the 20th century. Currently reintroduction plans in the Rhine are ongoing for these species, but they have not been observed at Kornwerderzand yet. They may become target species in the near future, and the dimensions and design of the FMR is also suitable for large sturgeons to successfully pass. (Winter et al. 2014). The proposed research techniques (telemetry) applied on larger diadromous fish can also be used for sturgeon and allis shad.

2.1 Current passage efficiency estimates and behaviour of diadromous fish at Kornwerderzand (T0)

To come up with advice on the design and management of the FMR in the phase before the construction, a literature study has been carried out to review relevant knowledge on the behaviour of diadromous fish species(i.e. those that migrate between marine and freshwater environments) during upstream migration towards freshwater (Winter et al. 2014). This literature study gives an overview of the population status in relation to the Afsluitdijk, timing of migration, migration and orientation behaviour, swimming capacity and passage strategies. After the literature study, several field research programs have been executed to fill in several relevant knowledge gaps (Griffioen 2014, Griffioen and Winter 2014a, b, Griffioen et al. 2014a, Griffioen et al. 2014b). In addition, several international expert meetings with specialists in diadromous fish ecology, hydrodynamics, technicians, and others were organized to combine the available interdisciplinary knowledge and discuss and judge different design options of the FMR. Despite that a lot of knowledge has been collected in this process, there are still many knowledge gaps present, especially concerning passage success and behaviour of fish at tidal barriers (Griffioen et al. 2014b, Winter et al. 2014, Griffioen and Winter 2019). A summary of the current state of knowledge and expert judgement on fish behaviour regarding search behaviour, swimming behaviour and passage success is given in Table 1.

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Monitoring glass eel migration with liftnets

Table 1 *Overview of the current state of knowledge on the level of searching behaviour, swimming strategy and passage success. Each cell is marked with a coloured dot indicating: ● = conclusions based on research (either extensive or small number of measurements) ● = conclusions based on expert judgement or by analogy with other, comparable, species. ● = unknown or expert judgement.*

Species	Knowledge on searching behaviour*	Swimming behaviour	Passage succes in current situation**
Atlantic Salmon	● at discharge basin level at minimum	● Active swimming	● >50% by analogy with sea trout (NEDAP-Trial)
Flounder Larvae	● discharge basin level	● Selective tidal stream transport	● assumed to be low (Winter 2009) ● (small number of) measurements in 2018 indicated 0.2-0.9% (Griffioen and Winter 2019)
Three spined stickleback	● discharge basin level, southern part	● Selective tidal stream transport and active swimming	● unknown. Best guess: low – moderate ● (small number of) measurements in 2018 indicated 0.4-2.0% (Griffioen and Winter 2019)
European eel (glass eel)	● discharge basin level, southern part	● Selective tidal stream transport and active swimming	● unknown. Best guess: low – moderate ● (small number of) measurements in 2018 indicated 1.7-9.2% (Griffioen and Winter 2019)
Twaite shad	● Unknown, most likely discharge basin level	● Active swimming	● unknown.>50% by analogy with sea trout
Houting	● at discharge basin level at minimum	● Active swimming	● >50% by analogy with sea trout and limited acoustic telemetry experiment results (Griffioen et al. 2014b)
River lamprey	● at discharge basin level and complex level at minimum	● Active swimming	● < 33%, by analogy with sea lamprey (Griffioen and Winter 2014b, Griffioen et al. 2014b, Griffioen et al. 2022d)
Smelt	● discharge basin level, southern part	● Active swimming, Selective tidal stream transport	● unknown: best guess: low-moderate (Tulp et al. 2013, Phung et al. 2015) ● (small number of) measurements in 2018 indicated 9.5-52.2% (Griffioen and Winter 2019)
Sea trout	● at discharge basin level at minimum	● Active swimming	● > 50% (De Vaate et al. 2003, Griffioen et al. 2014b)
Sea lamprey	● at discharge basin level at minimum	● Active swimming	●16-33% (Griffioen et al. 2022d)

** The spatial scale 'discharge basin level' refers to the section of the sluice complex in between the piers on the Wadden Sea side of the discharge sluices, where the water is discharged into. It is an area of approximately 600x400m (LxW). Complex level is the Kornwerderzand area: discharge basin + shiplock.*
*** Passage success does not only include passage percentage of numbers of fish motivated to pass, but also delay or extra energy losses, which are less often determined in studies.*

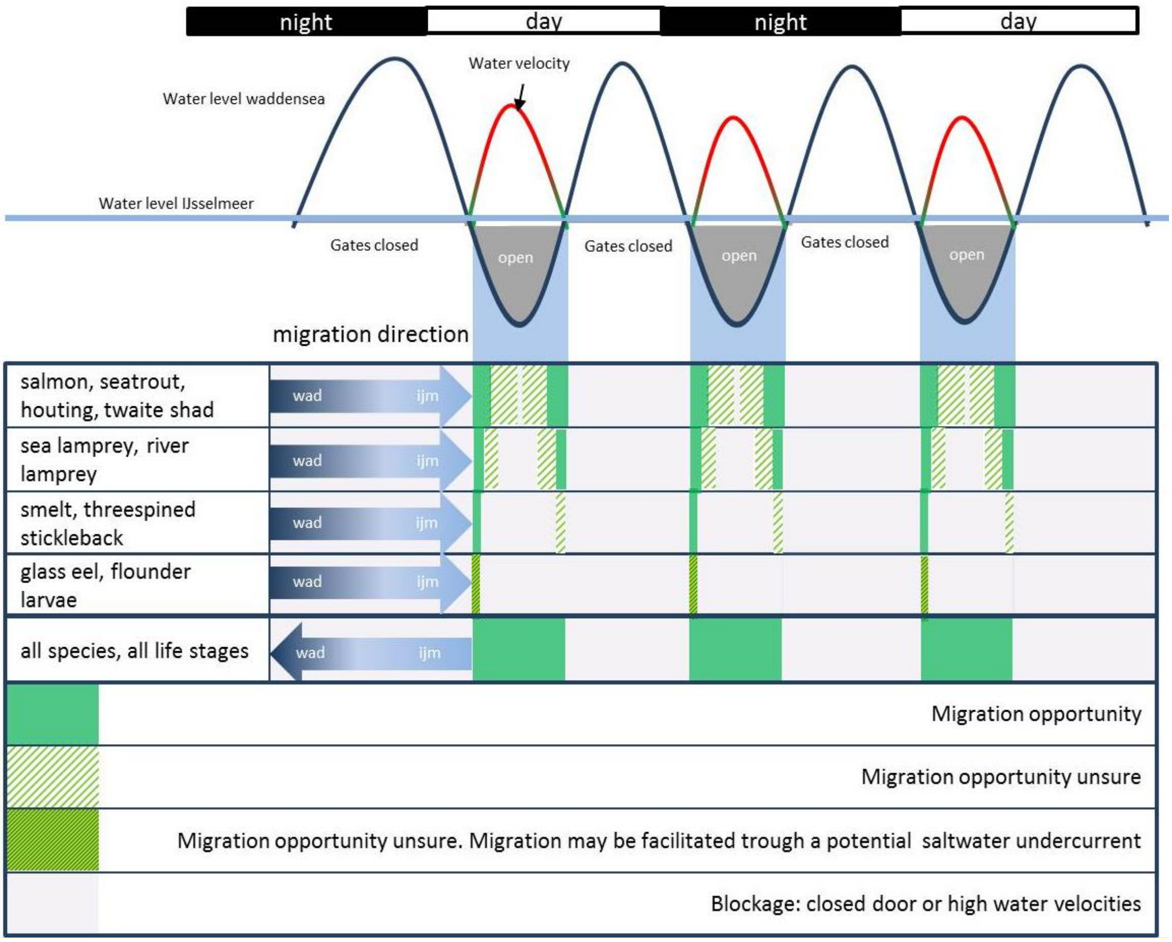

Figure 1. Potential migration opportunities for diadromous fish at the discharge sluices of Kornwerderzand in time in relation to the tidal cycle.

As mentioned above, many small diadromous fish strongly rely on tidal currents for their migration towards freshwater water by using Selective Tidal Stream Transport (Jager 1998, Bos 1999, Jager 1999, 2001), it is assumed that especially small diadromous fish have major difficulties in finding and using migratory windows at the discharge sluices. The current management protocol does not allow for saltwater intrusion into IJsselmeer due to drinking water intake and agricultural use. Passage by active upstream swimming in the present situation is restricted to small temporal windows that allow migration (Figure 1.). As of 2015, a discharge sluice management aiming to aid passive drift with inflowing water during short time intervals in the ebb phase of part of the tidal cycles to Lake IJsselmeer has been implemented the so called 'Fish Friendly Sluice Management' (Vriese et al. 2014).

In table 2 an overview is given on biological characteristics of diadromous fish species (migratory behaviour, life stages involved in upstream migration, seasonal occurrence, swimming capacity) and methodological considerations that play a role in the selection of research and monitoring approaches. In addition to the target diadromous species for the FMR, some marine species that are likely affected by providing the FMR as well (e.g. herring, mullets and sea bass) are also presented in Table 2. The importance for the different policy directives does not necessarily have to directly encompass specific fish species. Some diadromous fish species are in itself no subject within directives, but important food sources for fish-eating species that are protected by directives, e.g. seal, terns, fish eating ducks etc.

Table 2. Species specific guilds, migratory traits, local present abundance, species-specific methodological considerations and relevance for nature management, based on existing literature and completed with expert judgement.

Criterium	Eel (glass eel)	Flounder (larvae)	Three spined stickleback	Smelt	Allis shad	Twaite shad	Houting	European Sturgeon	Atlantic salmon	Seatrout	River lamprey	Sea lamprey	Atlantic herring	Sprat	Thicklip grey mullet	Seabass
Guild	Dia	Dia	Dia	Dia	Dia	Dia	Dia	Dia	Dia	Dia	Dia	Dia	MJ	MS	MS	MS
Stage downstream migration	ad	all	all	all	all	all	all	all	juv	all	juv	juv	juv	all	all	all
Stage upstream migration	juv	larvae	ad	ad	ad	ad	all	ad	ad	ad	ad	ad	juv	juv	all	all
Period upstream migration (month)	2-6	2-6	2-5	2-5	3-6	4-6	10-12	4-9	1-12	6-12	10-3	2-6	11-6	5-6	3-5	3-6
Swimming capacity upstream	-	--	-	-	++	++	+/-	++	++	++	-	+	-	-	+/-	+/-
Abundance during upstream migration	++	++	+	+	--	-	+	--	+/-	+/-	+	-	++	++	+	+
Catchability during long term monitoring	+	--	+	+	--	-	+	--	+	+	-	+/-	-	-	+	+
Importance for Nature Policy (N2000, red list, EU directive)	++	-	-	-	++	++	++	++	++	+/-	++	++	-	-	-	-
Current knowledge in Dutch coastal waters	++	-	+	-	-	+	-	--	--	+/-	+/-	--	+	-	-	+
Current knowledge (Local: Kornwerderzand)	++	+/-	+/-	+	na	-	+	na	+	++	+/-	++	+/-	+/-	-	-
Current knowledge (International)	++	+	++	+/-	+	+	++	+/-	++	++	+/-	+/-	++	+/-	-	++
Vulnerability when captured ++ = not fragile; -- = very fragile	++	--	++	-	-	-	+	++	+	+	++	++	-	-	++	++
Mark recapture applicable (ba=batch mark; ind=individual mark (e.g. PIT tag)	ba	--	ba/ind	ind*	ind	ind	ind	ind	ind	ind	ind	ind	ba/ind	--	ind	ind
Telemetry techniques applicable (e.g. acoustic transmitters)	-	-	-	+/-	-	+	++	++	++	++	+/-	++	-	-	++	++
Dependent on estuary as habitat	-	+/-	+/-	+/-	+	++	+/-	+	--	+/-	-	--	+/-	-	-	-

* possibly only larger individuals (as recently successfully carried out at Statenzijl in RBvV-project)

Guild: Dia=diadromous; MJ=Marine Juvenile; MS; Marine Seasonal

Mark recapture: ba=batch mark (VIE-tagging, vital dyes), ind=Individual unique mark (tag with identical number, PIT-tags)

Some of these target species are especially susceptible to climate change. Smelt on lake IJsselmeer is already hampered by peak temperatures in some summers, and with further rising temperatures conditions may become unsuitable for this species to maintain viable populations (Keller et al. 2020). Also for Atlantic salmon and sea trout rising peak temperatures during summer may cause increasing problems. This may override potential beneficial effects of the FMR in the upcoming future.

2.2 Other fish species that may benefit from the FMR

In addition to diadromous species, freshwater species that are displaced into the Wadden Sea by discharged freshwater via the sluices, will be given the opportunity and suitable conditions to return to Lake IJsselmeer via the FMR. As a result, it can be expected that mortality rates of freshwater species in Lake IJsselmeer will be reduced. To what degree depends on the success rate of 'washed/flushed out' fish, the salinity conditions at the Wadden Sea side of the Kornwerderzand sluice complex, predation risk, and on the impact of current losses relative to total population numbers on the IJsselmeer side.

Finally, also marine species that can tolerate freshwater, such as thin-lipped grey mullet, thick-lipped grey mullet, sea bass and herring may also use the FMR to expand their foraging areas into freshwater. These species do not need connectivity to freshwater, but if conditions on the IJsselmeer side are suitable for them, they may benefit from the FMR.

3 Current design and measurement infrastructure of the FMR

3.1 Current design of FMR

The current design of the FMR comprises of six different sections, from sea to freshwater (Figure 2):

(1) two entrances which are approximately 16m wide, 3-5m deep depending on the tide, on the bottom there is habitat (e.g. riprap and sand) to facilitate local differences in water velocity for small diadromous fish. The entrances are always open and accessible. (built in 2023/2024).
(2) The inside section of the FMR at the marine side of the Afsluitdijk. This part has two separate channels and a more or less natural habitat type (e.g. sand, silt and rocks). (built in 2023/2024).
(3) The passage through the Afsluitdijk. This part can be closed or controlled with gates for safety issues and optimizing passage efficiency. The passage is 9m wide and has a separate 3m wide vertical slot pathway. The bottom is covered by riprap. The passage is 100m long and 3-5m deep depending on the tide. (this part was finished in 2023, see Figure 3).
(4) The more natural 'estuarine' part on the freshwater side of the Afsluitdijk. This part can be completely flooded around high tide and there are no concrete walls or technical parts, allowing a natural development in time with sloping shores and sandy bottoms. (built in 2023-2024).
(5) The more technical (artificial) 'river' part has walls to ensure that the FMR has sufficient total length to accommodate tidal movement of water within the FMR for the entire (or sometimes most of) tidal cycle. These walls are made of wooden poles and riprap. (this part will be built during 2023-2024).
(6) At the end of the FMR (at the freshwater inlet side of Lake IJsselmeer) there are sluices that can be closed. Four gates with wooden doors which are manageable through so called 'rinketten' (levelling gates') to also provide migration opportunities when the doors are closed. In addition, also one vertical slot is present here (this part will be designed in 2023).

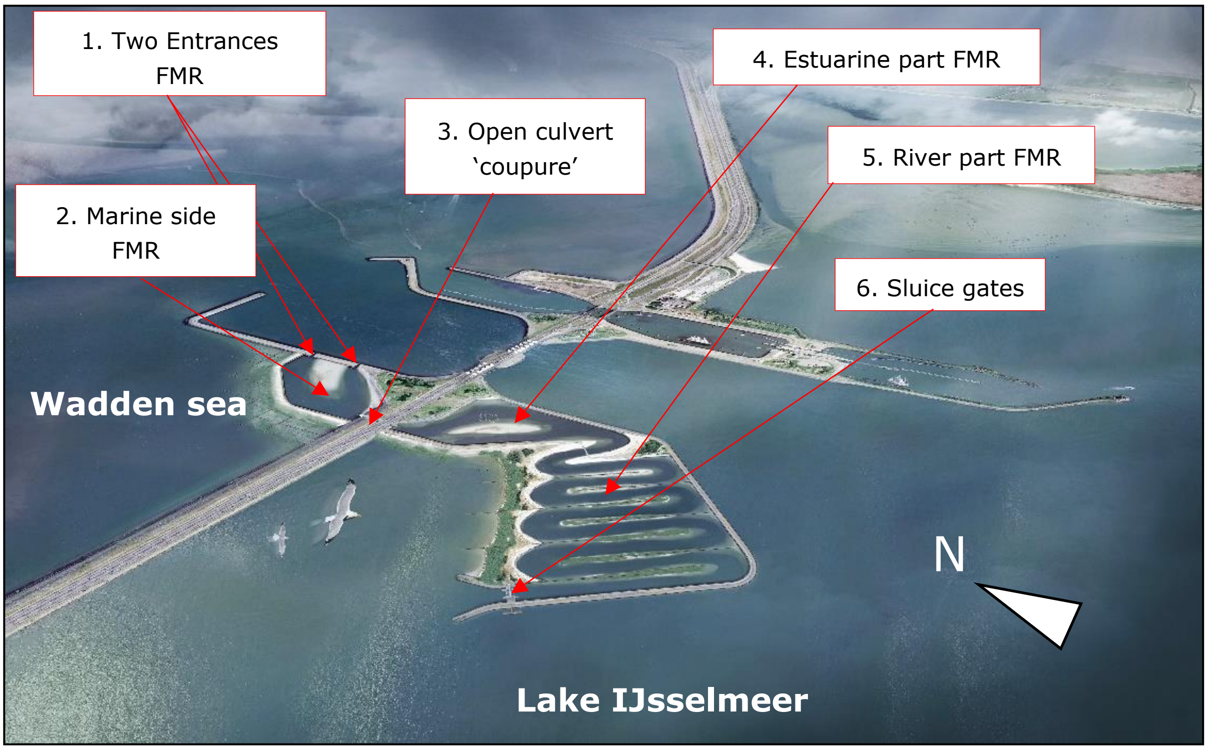

Figure 2. Design of the Fish Migration River (FMR), with two entrances, two separate channels, an open coupure through the dyke, a natural part, a technical part with separation walls and a sluice complex (four gates, and vertical slots). In principle the FMR is always open and accessible depending on salinity levels and safety issues. Artist impression of the FMR: source: Feddes/Olthof-landschapsarchitecten.

Figure 3. Current situation of the construction process of the FMR (photos taken in March 2023)

3.2 Built-in measurement infrastructure and devices in FMR during construction

Within the FMR abiotic, and biotic facilities, measurement devices (probes) and infrastructure are proposed in a previous assessment (Figure 4, see Griffioen et al. 2023 for a detailed description). These facilities are needed to measure abiotic conditions in the FMR, later deployment of traps/nets, to install and attach telemetry equipment (e.g. PIT-antennae) and to execute lift-net monitoring.

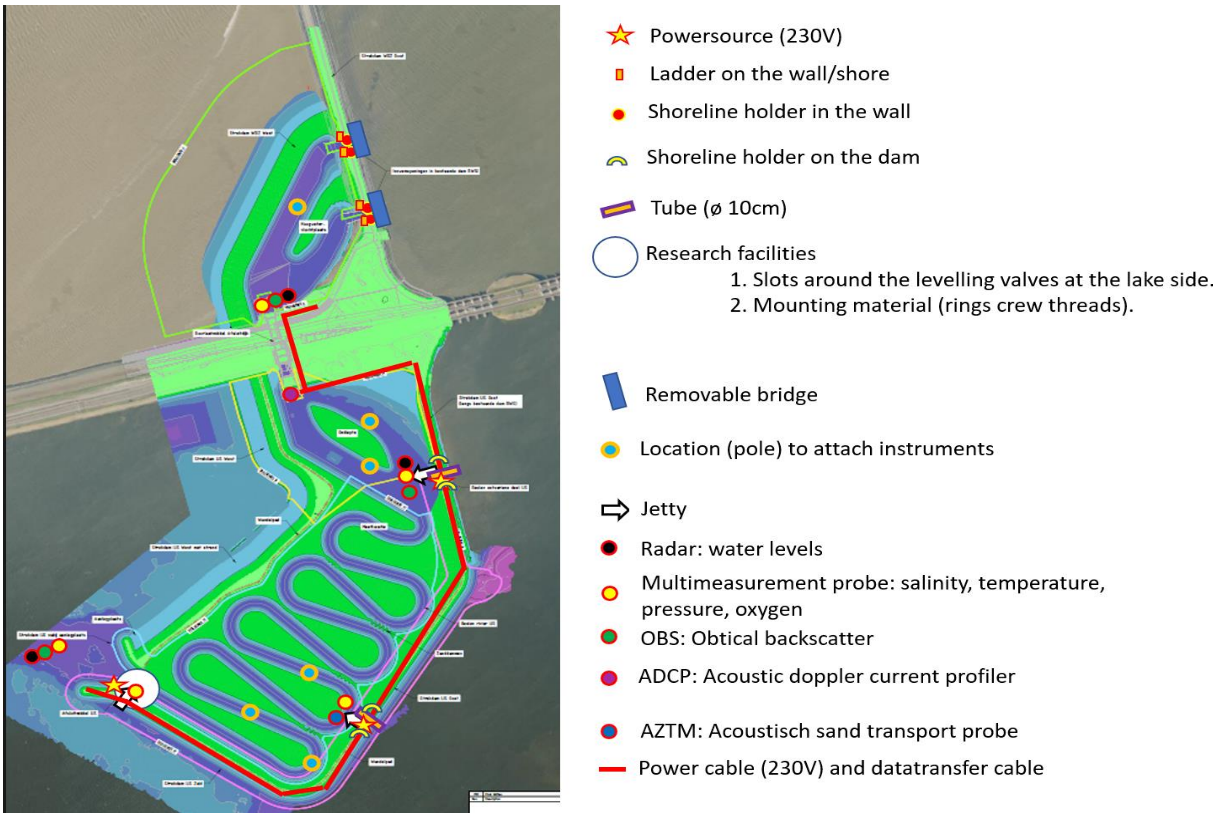

Figure 4. Research facilities as proposed in Griffioen et al. 2023.

4 Research questions related to the functioning and effectiveness of the FMR

4.1 Considerations on fish migration related to the FMR

As a starting point for the questions that need to be answered and the monitoring program to do so, we will start off with some considerations on processes acting on fish migration at a manmade barrier such as the Afsluitdijk and the fishway FMR. Following from these, we will then channel towards the practical research questions that will follow in the next paragraph.

Here we first follow the route that fish take coming from the sea towards the Afsluitdijk and the FMR and we will discuss the different processes that play a role underway and determine how many fish will be able to pass and eventually contribute to the population.

4.2 Attraction to the FMR

While most of the fish migration research is executed in situations with unidirectional river flows, much less is known about fish migration in estuaries and at coastal barriers. Therefore, knowledge about the utilization of migration windows at coastal barriers is limited as compared to freshwater river systems. Amongst estuaries, the FMR can be viewed as a (small scale) estuary with resorted tidal currents that fish can use to reach the Lake IJssel. Information on abundance, searching behaviour, delay, and residence time of diadromous fish in relation to abiotic circumstances are therefore important for the interpretation of passage success of the Kornwerderzand complex (including the FMR). Knowledge about these factors is also needed to optimise the functioning and the passage efficiency of the FMR and the combination with the management of the discharge sluices.

To determine how many fish are successful in passing a barrier such as Kornwerderzand, it is important to know how many fish are attracted to and are present at seaside of the barrier. The migration behaviour of the fish towards the barrier is mostly determined by various environmental cues (e.g., salinity gradients, tidal currents, odours, water temperature, light regime, wind direction, etc) and biological cues (e.g., pheromones). Attraction of fish towards Kornwerderzand at larger distances will be created by discharge events, whereas attraction close by is created by the freshwater attraction flow of the FMR itself. Most fish are hampered at the discharge sluices due to high water velocities or blockage, the passage success for fish of the Kornwerderzand complex (including the FMR) can be optimized when the attraction of the fish towards the FMR is high at the seaside of the complex. The local abundance of fish during the migration season is dynamic and related to new arrivals from the sea, searching behaviour, passage success, and losses for various reasons (e.g., predation or fisheries). Fish can use various routes within the Kornwerderzand complex (ship locks, discharge sluices, FMR) to reach the freshwater lake. The fish flux in all routes combined will determine the overall passage efficiency of the Kornwerderzand complex.

4.3 Inside the FMR

The duration of the migration windows that fish can use and the timing of these windows in relation to environmental variables play an important role at Kornwerderzand and especially in the FMR. In order to optimize the overall passage efficiency, the usage of the various routes needs to be studied and optimized when possible/applicable.

After attraction towards the FMR (or by passive, volume driven, migration), the fish will enter the FMR. Some fish will potentially use the FMR to forage or only use the FMR as a corridor to reach the hinterland.

Besides species-specific migratory cues used for and guiding orientation and navigation, also cues that may distract fish or can hamper migration efficiency can occur. This includes noise, artificial light and electromagnetic fields around power cables. Relatively little is known about the impact of such disruptive factors and, if disruption occurs, how mitigation measures can be taken to improve passage efficiency.

By building the FMR a new habitat will be created with tidal currents and different salinity gradients. Fish will use the FMR for various reasons including the main purpose of the FMR for reaching the freshwater lake. However, settlement or temporal usage of the FMR (forage, acclimatisation) might also be one of them. Fish can use the FMR for acclimatisation to get used to a different salinity level. Also, sea mammals and birds may use the FMR for foraging of resting. Research on acclimatisation to changing salinity has mainly been conducted in relation to the migration of young salmonids to the sea (released smolts). Various migratory fish can also use small streams that are connected to the sea without a gradual fresh-salt gradient and can cope with rapid transitions from fresh to salt and vice versa. Also, in glass eel and stickleback no additional mortality is observed after rapid transitions from fresh to salt and vice versa occur. Only for the North American shad *Alosa sapidissima* there is evidence for the importance of acclimatization during migration (Dodson et al. 1972, Leggett and Oboyle 1976). For most other species, the necessity and duration of acclimatization are still largely unknown.

If changes of the FMR will occur due to vegetation or the introduction of shelter structures, this will change bathymetry and the hydrodynamic functioning of the FMR. Tracking the ecological functioning of the FMR in terms of habitat use, settlement, succession, settlement, etc is important to observe the use and functioning of the FMR as a newly created habitat and corridor for migrating fish, but also to adjust changing hydrodynamics.

4.4 Effect on populations

The main purpose of the FMR is to contribute to an increased passage success of the Afsluitdijk. An increased passage success may add to the size of fish populations and contribute to food web relations in the freshwater lake.

Population size

For most diadromous fish species, it is unknown what the total size of the population is that shows up near the Afsluitdijk and wants to reach the Lake IJssel or further upstream. In previous studies a first (rough) estimate was made based on various monitoring programs (Griffioen et al. 2014a). In order to determine the potential effects of the increased migration opportunities with the FMR for fish populations, it is important to know what role passage via the FMR plays within the population. For a local diadromous fish species that lives locally on both sides of the Afsluitdijk the effect is likely largest. Fish species that move further into the catchment area of the Maas and Rhine can also migrate via alternative routes such as the Nieuwe Waterweg and the Haringvlietsluices. However, there are species of which part of the population does not migrate along fresh-salt transitions, such as trout. Part of the population spends their entire life upstream in freshwater while a larger part migrates to the sea. However, little is known to what extent and in what proportions this occurs. For a panmictic species (a large mixing world population) such as European eel, the effect of the FMR on the total European population will be negligible, but there may be a major effect on the subpopulation that enters an inhabits the Lake IJssel IJsselmeer.

When individuals manage to successfully pass the barrier they can contribute to the population. The passage success of the FMR might however partly be reduced due to predation by fish-eating birds and sea mammals.

Energy budget

Passage success alone may not safeguard a relevant contribution to the population. Migratory delay can have a negative effect on the condition of fish. To our knowledge little is known about the additional energy losses caused by delay or multiple (unsuccessful) efforts in passing a barrier. Migratory fish often do not forage during migration and must use energy budgets to get to their spawning grounds or to inhabit freshwater areas. Condition loss due to delay may negatively affect fitness of the fish and contribution to the population.

Selection
As in any animal also within fish populations there is variation between individuals in many characteristics (Sih et al. 2015, Jolles et al. 2016). Due to various human pressures (passage options at barriers, selective fishing) selection can take place during migration also in the FMR / Kornwerderzand complex. Certain individual characteristics can be selected for when they are beneficial. This could include differences in size (for example due to differences in growth rate), differences in salinity gradient tolerance, differences in personality (coping styles/personality traits), or other genetically inherited traits (such as body shape, fin size/position, but also physiological characteristics such as hemoglobin types).

Other bottlenecks
The added value of the FMR including increased migration opportunities can be annulled if other major bottlenecks occur to complete the life cycle. For example, if the spawning grounds in upstream areas are severely limiting a potential increase of the fish population, the increased migration opportunities by the FMR will remain invisible. Migratory fish populations in particular have often declined sharply or disappeared in the past due to a combination of various bottlenecks and anthropogenic impacts such as overfishing, habitat destruction, water pollution, migration barriers and the introduction of exotic species and diseases. When the functioning of the FMR is evaluated, it should also be evaluated in light of other potential bottlenecks.

4.5 Unintended migration both ways

In addition to migratory fish, there may also be migration or dispersal of freshwater fish (e.g., bream, pike perch) from the Lake IJsselmeer towards the Wadden Sea. Freshwater fish occurs at the seaside of the Kornwerderzand area either by accidental migration/swimming or when flushed out during the discharge events. Possibly those fish want to migrate back to the lake and may use the FMR to do so.

Vice versa, marine or estuarine fish species can accidentally get trapped in Lake IJssel after closing the discharge gates. Potentially they can swim back to the sea using the FMR. Currently the fate of these fish is unknown and also not whether this process constitute a large sink for the population. The added value of the FMR can be studied when these fish will migrate back to the sea again using the FMR in between discharge events. So, the effect of both these unintended migration routes require additional research on other than only the strictly diadromous species.

The risk of freshwater fish that potentially will be flushed out with a migration measure such as the FMR is also expected to be reduced compared to measures taken with sluice management (tidal gates). Velocity rate are lower and fish can access both sides 24/7 via the vertical slot present in the FMR.

4.6 Climate change

When considering the functioning of the FMR on the longer term, we would like to address to effects of climate change in particular. Climate change will change both the local operational functioning by changing freshwater discharge dynamics and water level changes and impact the ecology of migratory fish. These will be addressed here in more detail.

Climate change will likely increase sea water levels and increase the number of summer droughts. A decrease of access water derived from the rivers will decrease the discharge volumes. An increase of sea water levels will potentially decrease the time windows that sea water will flow into the FMR. In general, functioning of the manmade fish passages along the coast will be challenged to maintain efficiency. Attraction flow volumes at certain times of year will decrease, and sea water level increase will hamper saltwater intrusion. Climate change can be a cause for a reduction of freshwater availability and therefore reduced discharge (attraction) flows. The functioning of the FMR will likely change over time due to climate change. But the design of the FMR is expected to allow for a more robust future perspective in contrast to measures which are more directly dependent on river discharge (e.g. 'fish friendly sluice management' or the Kier-management).

However, during periods of droughts, it is important to study the most efficient settings in the FMR or discharge sluices to optimize attractions flows when freshwater is limited. As a result of climate change some fish species may disappear altogether because conditions become unfavourable, whereas other might be introduced. Target species might change in the future. Species of which we already know to be sensitive to climate change include for instance smelt (Keller et al. 2020, Veraart et al. 2022).

Migratory fish often have species-specific migration periods. In fish migration water temperature is a strong trigger. Due to climate change, timing of migration can therefore alter (van Walraven et al. 2017), which in turn can lead to a mismatch with food availability. Water temperature also has a strong effect on growing conditions of fish (Teal et al. 2012, Bento et al. 2016, Lyashevska et al. 2020, Bolle et al. 2021). Under energetically costly warm conditions food availability can become limiting to maintain growth.

4.7 Research questions

Research questions related to the function and effectiveness of the FMR are subdivided in five main topics: Q1 abiotic functioning, Q2 passage success, Q3 optimization of the functioning, Q4 FMR as habitat, Q5 effect on population, community and food web level.

4.7.1 Q1: abiotic functioning of the FMR

During the design phase of the FMR the abiotic functioning of the FMR (flow velocities, water levels, salinity distribution, etc.) has been assessed using a three-dimensional hydrodynamic model. The model has been used to determine the flow regime under various tidal conditions in the Wadden Sea and water levels at Lake IJssel. A large number of FMR alternatives were included to assess which shape, width, depth, etc. of the FMR are optimal to arrive at abiotic conditions in which:

- Flow conditions are not too high; flow velocities in the river sections of the FMR should not exceed approx. 0.35 m/s to prevent bottom sediment to be washed out
- There is enough fresh water outflow; fresh water should be discharged through the FMR primarily and attract fish to swim towards the FMR
- No salt water from the Wadden Sea flows towards Lake IJssel under any daily tidal or extreme condition
- The maximum water levels do not exceed NAP 1.2 m. At higher water levels water can overflow the surrounding dikes

The current layout of the FMR is the result of an iterative approach based on the following aspects (1) the result of the numerical modelling simulations, (2) the set of abiotic requirements on flow, discharge, salt and water levels, and (3) knowledge on fish behaviour and migration from various discussions and expert meetings with fish ecologists. Although it is expected that the numerical model results give a good indication of the hydrodynamic functioning of the FMR, there are a number of aspects which give uncertainties:

- The numerical model has never been calibrated with measurements. It is thus uncertain how accurate the model is able to represent the actual hydrodynamics after the FMR is actually built. It is advised to thoroughly calibrate and validate the model on water levels, flow, discharge and salt to improve the accuracy of the model predictions.
- During the engineering phase the contractor in conjunction with the Client can propose a number of optimisations on the FMR. These adaptations will affect the hydrodynamic climate within the FMR

- During the design of the FMR a number of daily and a number of extreme conditions have been studied. However, not all conditions have been assessed and the optimal opening- and closure regime of the gates in the coupure are still uncertain.
- There is no final design of the sluice gates at the Lake IJssel side of the FMR. Changes in this design will affect the functioning of the FMR.
- The sluice gates of Kornwerderzand can discharge large volumes of fresh water from Lake IJssel towards the Wadden Sea decreasing the salinity levels in the Wadden Sea. The effect of this on the FMR was not assessed in detail yet.
- There are a number of recommendations from fish ecologist to further optimize the present design of the FMR for fish migration. For example the groynes present in the most southerly river arm, required to dissipate energy of the flowing water and limit flow velocities but also generates high turbulence, is an aspect which is requested to be improved.
- The present design of the FMR is based on literature knowledge on fish behaviour. Based on fish monitoring within the FMR (as part of this plan) new insights on fish behaviour might become available. These new insights should be included in the abiotic functioning of the FMR as well at a later stage, when such insights become available.

Based on above, the following research questions are addressed:

a. How can we best further optimize the abiotic conditions within the FMR for fish during the engineering & construction phase of the FMR?
b. How accurate can we calibrate the numerical model on abiotic measurements such that the numerical model can accurately predict the abiotic conditions in the FMR under all tidal and extreme conditions?
c. System understanding. What can we learn from the abiotic measurements and model simulations. How does the abiotic system function and do we understand the effects of opening / closing gates on the system?
d. How can we apply our system understanding and the calibrated numerical model to assess:
    1. The optimal opening- and closure regime of the gates in coupure and sluice under normal tidal conditions to obtain the optimal hydrodynamic conditions for fish
    2. The optimal opening- and closure regime of the gates in coupure and sluice under extreme conditions to obtain the optimal hydrodynamic conditions for fish. Considering e.g. the following conditions:
        i. Periods of drought and limited availability of fresh water
        ii. Periods with large water level gradients between Wadden Sea and Lake IJssel
        iii. Periods of storms (very high or very low water levels at Wadden Sea or Lake Ijssel)
e. As under bullet d but now including long term trends inside the FMR (local scale):
    I. changing bathymetry within the FMR
    II. growth of vegetation within the FMR
f. Is it possible to adjust the steering of the FMR when, based on the biotic monitoring results performed in the first years after FMR construction, it is expected that the hydrodynamic functioning of the FMR can be further improved for fish?
g. As under bullet d but now for conditions in which also the regional aspects are considered:
    I. fresh water discharge at Kornwerderzand. Are there large differences between the situation without- and with fresh water drainage at Kornwerderzand and how does this affect the functioning of the FMR?
h. As under bullet d and e but now including long term effects outside the FMR (regional and national scale). How do these effects affect the abiotic conditions and how does this affect the functioning of the FMR? Considering:
    I. sea level rise and effect on water levels Wadden Sea
    II. adjustment of water level at Lake IJssel
    III. adjustments in discharge regime Kornwerderzand

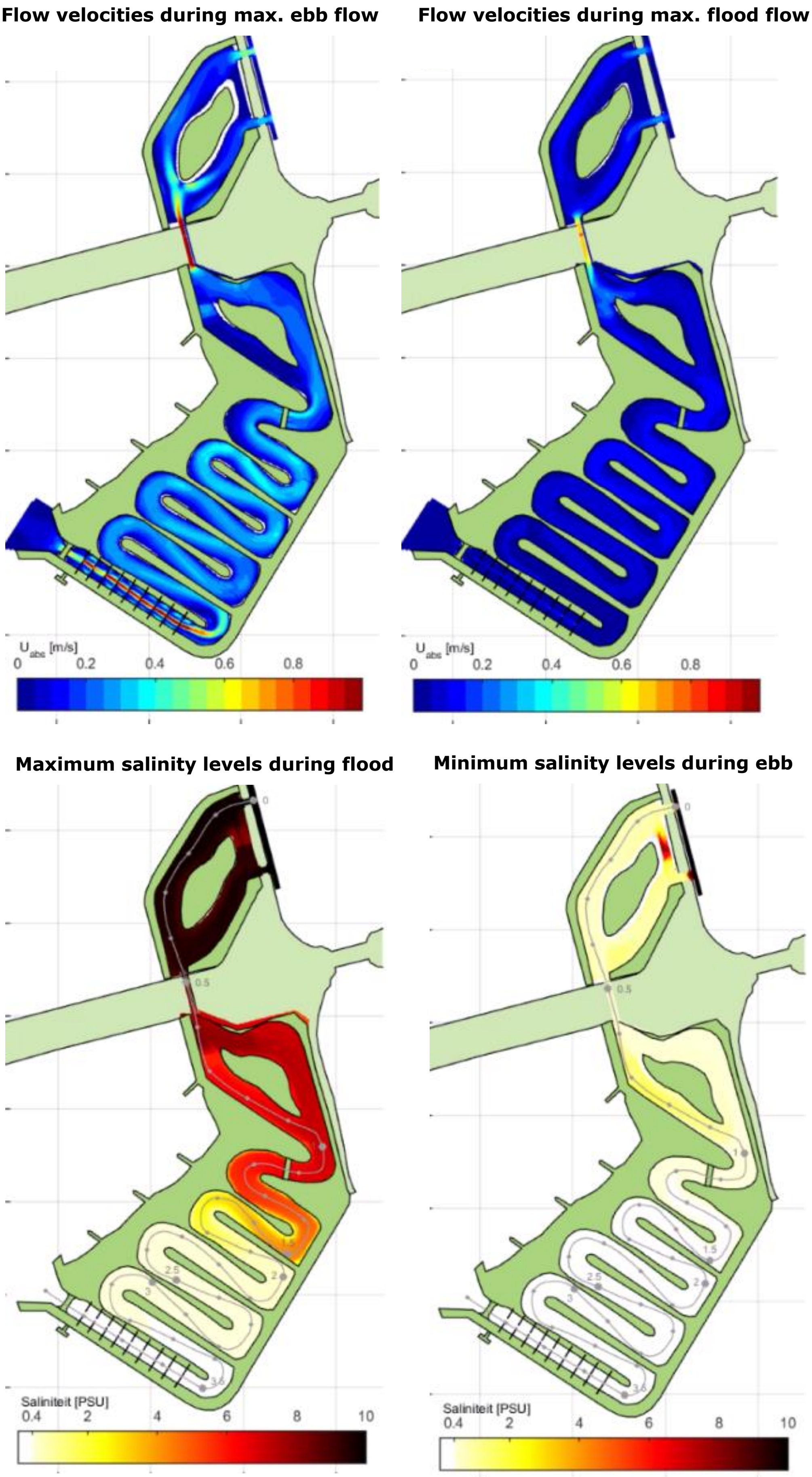

Figure 5. Maximum flow velocities during ebb (upper left panel) and flood (upper right panel) and maximum (lower left panel) and minimum (lower right panel) salinity levels along the bottom in the FMR following from the numerical model.

4.7.2 Q2: passage success

The end goal of facilitating the discharge sluices and shiplock complex in the Afsluitdijk dam at Kornwerderzand with the FMR is to rehabilitate fish migration between the Wadden Sea to Lake IJsselmeer, where at present, migration into freshwater is most severely affected. Migration is restored when each migrant fish, motivated to move to freshwater, is able to successfully pass the Kornwerderzand Complex, with no or neglectable delay and energy losses. The first goal of the monitoring program will be addressing to what extent fish can pass the different potential passage routes in the Kornwerderzand sluice complex: i.e. through the FMR, the discharge sluices and the shiplock (see Figure 6).

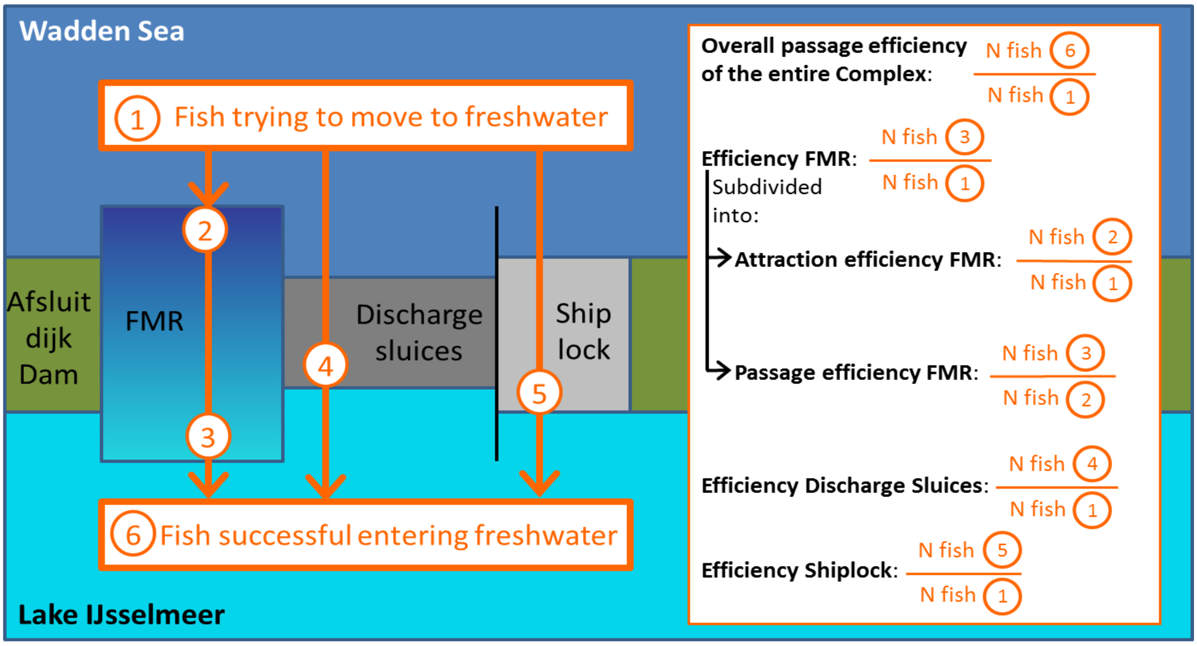

Figure 6. Schematic overview of determining passage efficiency through the different potential migratory routes FMR, discharge sluices and shiplock at the Kornwerderzand Complex. For each of the different routes, the formulas in the right hand panel indicate how efficiencies can be determined. In addition to the efficiency, also delay and passage rates are important to consider in the evaluation of FMR performance.

To answer *Q2 overall passage efficiency* of the entire Kornwerderzand sluice complex, the fraction of the number of fish that approaches the complex from the Wadden Sea side and is motivated to pass, 1 in Figure 6, that successfully passes one of the three routes; FMR, discharge sluices and/or shiplock, 6 in Figure 6, needs to be determined, i.e. the ratio between 6:1. And further subdivided into determining the ***attraction efficiency of the FMR***; which fraction of the fish motivated to pass the complex is attracted to the entrances of the FMR, ratio between 2:1, and the ***passage efficiency of the FMR***; which fraction of the fish entering the FMR will successfully pass to Lake IJsselmeer, ratio between 3:2. The ***passage efficiency of the discharge sluices***, is determined by the ratio between 4:1, and ***passage efficiency of the shiplock*** by the ratio between 5:1, (see Figure 6). Efficiency rates should be considered in relation to time (Castro-Santos and Haro 2003, Castro-Santos 2004).

Anticipating on Q3

To anticipate on potential bottleneck analysis (Q3), we opt for a careful designed research program that both answers question Q2 but also gives information about potential bottlenecks (Figure 7). This will allow to use less fish for tagging which is preferred by animal ethics committee, but it also will make full use (cost efficient) of the extensive netting effort. Firstly, to study the main question of the FMR whether fish are successful to pass the Kornwerderzand complex including the FMR (O2), but also to study behavioural patterns of fish within the Kornwerderzand complex (e.g., active swimming, 'flushing out' in relation to high water velocity rates, disorientation, etc).

For example, when tagged fish that were released at the discharge basin (location 1, Figure 7) recapture fraction of tagged fish at location 5 determines passage success (**Q2**). In addition, if the fish are released at location 1, they can also be recaptured at location 2, 3 and 4 to study differences in recapture rates. If differences occur this can be an indication of a potential bottleneck (**Q3**). Data can also be used to estimate residence time, dispersal dynamics in relation to hydrodynamics, delay (time between release and recapture), and to estimate abundance.

This approach is most relevant for the small diadromous fish that cannot be followed in time with telemetry. Therefore, an extensive netting program *including* mark-recapture will both answer Q2 (passage efficiency and abundance) as give insight in potential bottlenecks and residence time (Q3). This will be further described in section 0.

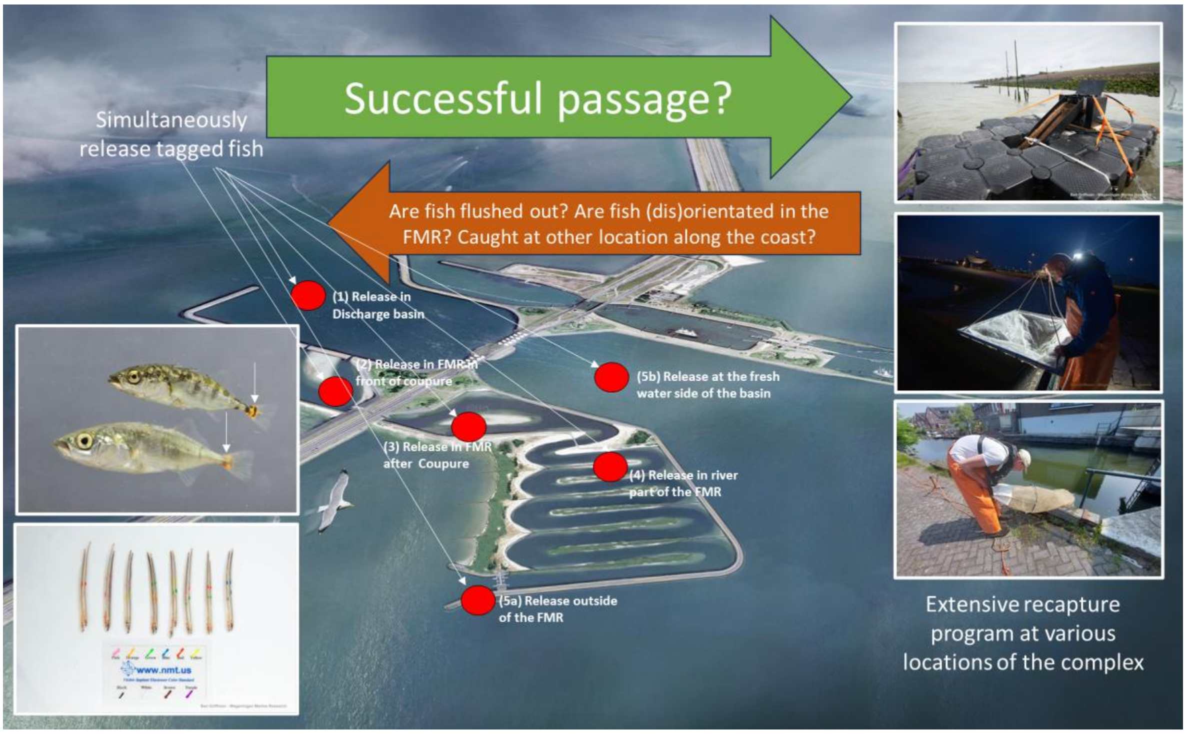

Figure 7. Batch mark recapture approach for small diadromous fish (e.g., glass eel or stickleback) and potential migration routes after release. By releasing multiple groups throughout the FMR and throughout the season both research question Q2 as Q3 can be answered.

4.7.3 Q3: optimization of the functioning of the FMR

When the results of the overall passage efficiency for a certain species or group of species are low, then it needs to be determined whether the functioning of the FMR can be improved or optimised. This can be due to insufficient attraction of fish to the entrance of the FMR (bottleneck in attraction efficiency, e.g. in approach or entry of the fishway) or due to insufficient passage of fish within the FMR (bottleneck in passage efficiency) or both. Based on the data from monitoring research questions Q2, a further stepwise zooming into potential bottlenecks is needed to determine where attraction or passage is hampered, i.e. studying efficiencies in smaller sections of the FMR (Figure 7). Determining where passage efficiency is suboptimal is important, but to take away identified bottlenecks, also insight is needed in the factors causing reduced efficiency and how these are related to options for altering management schemes of the FMR. Testing different 'discharge scenarios' may result in finding optimal migration opportunities for fish. Outcomes of the adjustment phase I and II will be used for IBM-modelling, to understand migration in relation to environmental factors (e.g. migratory cues, velocity, tidal currents, turbulence, depth, etc) in order to optimize functioning of the FMR.

Depending on the results as found by Q2, the following research questions can potentially arise:

a) For which species is optimising of FMR functioning needed, i.e. passage efficiencies insufficient?
b) Which bottlenecks hamper optimal attraction and passage efficiency of the FMR?
c) Are these bottlenecks related to attraction efficiency (approach or entry) or passage efficiency of the FMR or both?
d) Where does reduced efficiency take place, i.e. step-wise narrowing down the locations?
e) How can identified species-specific bottlenecks in efficiency be mitigated or resolved, i.e. which alterations or adaptations in management schemes, options or constructions can be performed?
    - Which operational options are possible to mitigate potential bottlenecks in the FMR i.e. What optimalisation is needed to optimize the passage efficiency of the Kornwerderzand complex?
f) What factors and processes reduce efficiency, i.e. insight into behaviour and physical abilities of the species and life stages of concern is needed in relation to the local environmental conditions and dynamics in time
    - What migratory cues are relevant to optimize passage efficiency and how can this be optimized?
    - Are habitat structures used by the migratory fish in order to efficiently pass the Kornwerderzand complex? And how can this be optimised if needed?
    - How is fish movement related to hydrodynamic conditions in the FMR and do these conditions reduce efficiency? E.g. How are tidal currents related to migration behaviour in the FMR? What attraction flows are optimal to attract diadromous fish?
    - How is physiological condition of the migratory fish affected by delay, water velocity, turbulence, etc and what conditions of the FMR are needed to optimise physiological condition of the fish?
g) How does Kornwerderzand function as a corridor on a wider (regional/national) scale in relation to structures and water systems in the vicinity and how does this need to be optimized?

4.7.4 Q4: FMR as habitat

In addition to providing passage for migratory fish, the FMR can also serve as a temporary habitat for (migratory) fishes and fish predators (Figure 8). Migratory fish might use the salinity gradients in the FMR for acclimatization from marine to freshwater conditions, when needed. The FMR can also provide food, making it potentially interesting for fish to use the FMR to forage. Relatively high densities of fish within the FMR can also attract top predators like predatory fish, birds or marine mammals and due to predation affect the efficiencies. Lastly, depending on the scale and dynamics in the salinity gradients it might also serve as a habitat for estuarine fish species than inhabit the area from prolonged periods.

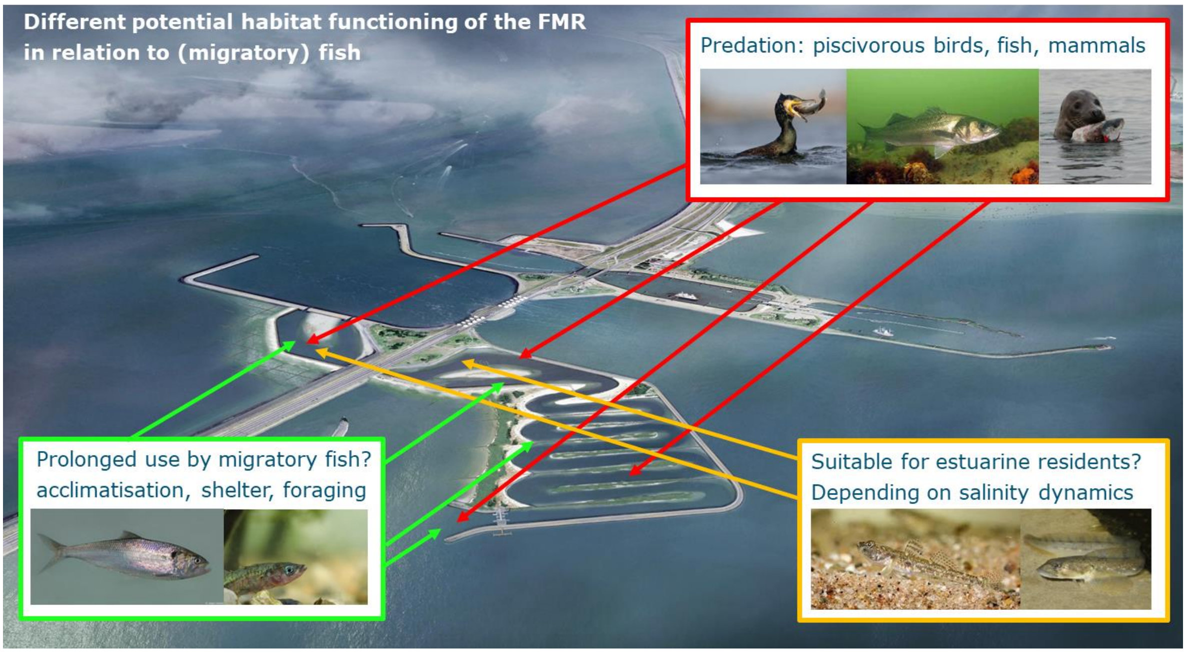

Figure 8. Overview of different types of habitat use in the FMR in relation to fish.

Habitat use withing the FMR by fish can encompass the following research questions:

a) Will fish use the FMR for acclimatisation fro saltwater to freshwater and what environmental conditions are needed for acclimatisation?
b) How does the FMR function as a new habitat for estuarine or other fish species?
c) To what extend does the FMR function as feeding area for fish species (e.g. fresh of marine fish species)?
d) What predation risks are present in the FMR or in the Kornwerderzand area and does this influence the passage efficiency (related to Q1)? If predation occurs how can this be reduced (related to Q2)?
e) How is the FMR used by marine mammals, predator fish or birds and does this influence the passage efficiency (related to Q1)? I.e. What is the predation risk for migratory fish by these predators?
f) How does the FMR function as a newly created habitat on a wider (regional) scale for surrounding water systems and coastal areas?

4.7.5 Q5: Effect of the FMR on population, fish community and food web

The ultimate goal of improving fish migration at barriers and restore ecological connectivity is to restore populations of migratory fish. When providing the FMR at the Kornwerderzand Complex and altered sluice management to improve fish passage leads to increased fish migration opportunities, i.e. high overall passage efficiency, this will not automatically imply that populations of migratory fish will increase in abundance. If obstruction of migration was the only (or most severe) limiting factor to population size of a given migratory fish population that passes the Kornwerderzand complex, then providing the FMR will lead to an increase in population size. When there are still other bottlenecks or limiting factors, e.g. other migratory barriers in upstream sections of the river system or a lack of critical habitats (e.g. for spawning), acting upon a migratory fish population during the completion of its lifecycle then next to improving migration opportunities at Kornwerderzand also additional management measures are needed to obtain an increase in population size.

When determining the effectiveness of management measures, e.g. providing the FMR, on a population level, then an important first step is to determine:

a) What can be defined as populations that use Kornwerderzand as a corridor between different critical habitats to complete their life cycle, in terms of population structure and/or links to other populations?
b) On what marine and freshwater spatial scales do these populations operate?

The spatial scale of habitat use is very different between species and can also differ between the marine phase and freshwater phase for a given species (Figure 9).

Populations of migratory fish that mainly use local scales on both the marine side (e.g. restricted to the Western Wadden Sea) and freshwater side (e.g. restricted to Lake IJsselmeer) are three-spined stickleback and smelt. For both species applies that there are also non-migratory freshwater populations.

Other species, e.g. the Atlantic salmon, act on large scales on both the marine side (migrate to the open North Atlantic ocean for feeding) and the freshwater side (migrate upstream into the small tributaries of the Rhine in Germany, France and even Suisse). Populations that show intermediate scales, e.g. river lamprey migrating upstream River Vecht and River IJssel and their tributaries for spawning in freshwater, whereas the juveniles after metamorphosis from ammocoetes migrate downstream to marine coastal habitats in the Wadden Sea and adjacent areas of the North Sea.

When determining the effects of improving migration with the FMR at Kornwerderzand on a population level, not only the scale of the areas used by fish populations that pass Kornwerderzand is important, but also the population structure and rate of exchange between populations. For migratory populations that perform very local movements between the western Wadden Sea and Lake IJsselmeer, such as migratory smelt and three-spined stickleback a more direct link between improving migratory opportunities and response in population level can be expected than for instance for a panmictic migratory species as European eel, where there is one mixing world population. A response in population level for European eel can only be achieved with simultaneous measures taken Europe- wide. Thus, for local populations and populations that show strong homing to native rivers, such as Atlantic salmon, sea trout and houting, and form river-basin specific populations, it is more likely that a response in population level can be observed due to mitigating migration barriers in a particular river basin. Even if restoring fish passage at the Afsluitdijk might not drastically change overall population level of the European eel or flounder, local abundance in Lake IJsselmeer might however, strongly be increased due improved migratory opportunities.

Considering the fish community and foodweb relations, trap monitoring (Dutch statutory task, see chapter 12) is of use to track fish species. However, eDNA sampling, video monitoring (including AI), sonar/acoustic monitoring could add to the data collected. To monitor food wed relation stomach content analysis (and DNA analyses) can be done either by killing the fish or to flush the stomachs (Kamler and Pope 2001, Griffioen et al. 2022a). Also birds and seas mammals could be taken into account (observations, predation tags, etc).

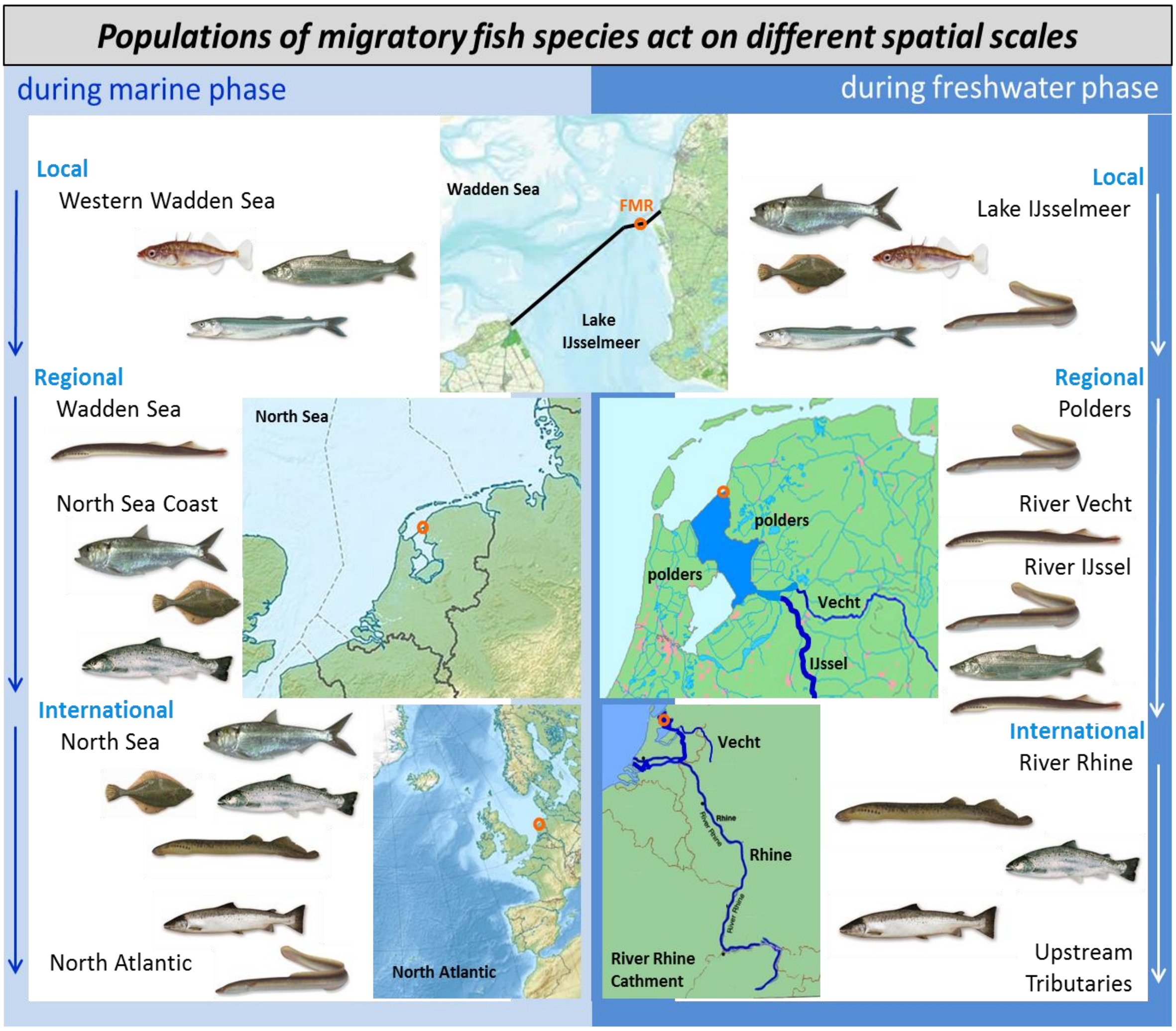

Figure 9. Overview of the different spatial scales (ranging from small local to large international scales) for the migratory fish species that use Kornwerderzand. A distinction is made for the marine phase (left panel) and the freshwater phase (right panel). The maps illustrate the matching scales.

Thus, to address the overall effects of restoring fish passage by the FMR and adjusted sluice management at Kornwerderzand, the main question:

What is the effectiveness of the FMR on fish population levels, communities and food webs
Can be further subdivided into:

a. What other marine and freshwater areas are used to complete the life cycle of the different of populations of migratory fish species that use Kornwerderzand?
b. What other migratory bottlenecks or alternative migratory pathways are present in the water systems used by these populations?
c. What are other limiting human-impacted factors that determine population size in each of these populations?
d. What trends in population abundance and species composition in marine and freshwater systems that are connected by the Afsluitdijk can be observed and how are these related to the improved migration opportunities?
e. What food web relation are found in and around the near vicinity of the FMR.

Much of the basic knowledge on population dynamics and migratory behaviour of the target species in the different water systems they use is still lacking, and these questions are therefore not easily addressed for all species. A complete coverage of this wider scope on population dynamics and population effects is very ambitious and requires a large research investment, beyond the scope of this monitoring program.

The Wadden Sea, with its tidal flats, and lake IJsselmeer are separated by the 32 km long Afsluitdijk

5 General approach and phasing of research and monitoring activities

As described in previous chapters multiple research questions arise with the goal to evaluate the current design and to potentially optimize the functioning of the FMR. To prioritize these questions, four main phases have been distinguished to optimize the functioning and to study the efficiency of the FMR. Within each phase a stepwise prioritization of the research questions has to be taken into account and there are multiple activities planned. Some activities, however, must be organized depending on progressive insights during the monitoring and research of the FMR.

1) **FMR construction phase (pre-phase)**
   During the construction phase of the FMR multiple preparatory activities are considered such as: application for permits, organize student vacancies, fisherman contracts, etc. In addition, the construction phase should also be used to optimize the detailed design of the FMR based on expert knowledge. This should be done in collaboration with contractors (builders). The construction phase is also a preparation phase to test monitoring devices specific for the FMR. For example, the design of PIT tag loops, building and testing catch facilities (driftnets) testing of fragile fish species in relation to mark recapture studies. Moreover, for large diadromous fish, the first data can already be collected when a VEMCO network is built in the discharge basin. Fish from research programs in and around the Wadden Sea can be detected at Kornwerderzand and can provide additional data to knowledge about behaviour including passage success.

2) **Adjustment phase I**
   This is the first phase in which the FMR is in operation. The FMR forms the connection between the Wadden Sea and Lake IJsselmeer and more fish are expected to be able to reach the freshwater lake. During this phase the focus is mainly on the abiotic functioning of the FMR (see Q1 in section 4.7.1). For example: *Is sand[1] transport a problem? Are there problems with high velocities? Is there a need to introduce structures into the FMR to mitigate water velocities? Are there problems with saltwater intrusion? Does the flow regimes match model calculations?* Etc.

   The aim of this phase is particular to evaluate and optimise the FMR under regular weather conditions. To do this abiotic measurement devices (Griffioen et al. 2023) need to be installed tested and used. In addition, biotic measurements can be started by testing PIT tag antennas, catch devices and specific mark recapture techniques on fragile fish species. An acoustic telemetry network can be expanded and possibly the first large diadromous fish can be implanted with transmitters.

   Testing the netting program in practice will give the first preliminary data on the efficiency of the FMR.

3) **Adjustment phase II**
   During this phase the FMR is expected to function under regular weather conditions and from this point onwards, the focus will be to further optimize the FMR on steering the gates under exceptional tidal and meteorological conditions (if applicable). Contrary to phase I, there will be more focus on the entire Kornwerderzand complex.

   This phase is used to conduct an extended netting programs to answer research questions Q2 and Q3 for small diadromous fish (tidal migrants). In addition, large diadromous fish must be caught using traps and seines to implant them with transmitters (also Q2 and Q3).
   First bottleneck analyses on the functioning of the FMR for migratory fish will be carried out based on collected data on both large and small fish, and building Individual Based Models coupled on hydrodynamic models that were developed for the FMR

[1] Sand that has been introduced into the FMR as a habitat. Sand needs to stay in the FMR

4) Optimisation phase

This an adaptive part of the research activities and will be based on the results from the Adjustment Phase I and II, bottleneck analyses will be performed.

	Construction phase Building of the FMR	**Adjustment phase I** Option to install additional objects / habitat structures into the FMR in collaboration with contractor.	**Adjustment phase II** Option to install additional objects / habitat structures into the FMR in collaboration with contractor.	**Optimisation phase** Optimization, when needed in management of the gates.
	Administration Administration e.g. fisherman contacts and contracts, construction permits (waterwet), animal testing legislation (WOD), monitoring permits (visserijwet), student vacancies and applications.			
Abiotic measurements & modelling Combi measuring and modelling	*Focus on design of FMR in relation to optimal abiotic conditions* • *Optimize design with building team* • *Install and test measurement devices*	• *Focus on steering gates under normal tidal conditions* • *Use measurements to validate model* • *Use combi model + measurements to: (1) assess optimal functioning of gates during daily / normal tidal conditions). (2) assess optimal functioning of gates in relation to Fish Friendly Sluice Management and "Visspuien".*	• *Focus on steering gates under exceptional tidal & meteorological conditions* • *Use combi model + measurements to: (1) assess optimal functioning of gates in exceptional conditions; e.g. drought, storms). (2) optimize when not only focussing on local (FMR) level but also consider the complex (Kornwerderzand) level*	• *Focus on steering gates in maintenance scenarios + long-term trends* • *Use combi model + measurements to: (1) assess optimal functioning of gates for maintenance scenarios. (2) assess optimal functioning of gates for long-term trends*
Biotic measurements and modelling – *Small diadromous fish*	• *Developing driftnets (pontoons)* • *Testing marking techniques on small diadromous fish (e.g. smelt, flounder)*	• *Developing driftnets (pontoons)* • *Testing marking techniques on small diadromous fish (e.g. smelt, flounder)*	• *Extensive monitoring using (1) liftnet monitoring at various locations in the FMR (2) lift monitoring in the discharge basin (3) dritnet monitoring in the FMR (4) Mark-recapture by releasing tagged fish in the discharge basin and in the FMR.*	• *Bottleneck analysis based upon (preliminary) results.*
Biotic measurements and modelling – *Large diadromous fish*	• *Designing PITtag loops* • *Building acoustic telemetry network. (possible detections from other tagged fish e.g. SWIMWAYS). Tag fish from monitoring (WOT).*	• *Developing PITtag loops* • *Installation of holding tanks* • *Maintaining and expand acoustic telemetry network.* • *Installation of traps, beach seine, stow net, etc.* • *implanting transmitters*	• *Installation of traps, beach seine, stow net, etc.* • *implanting transmitters*	• *depending of number of species continuation of activities*
Integration hydrodynamic modelling and fish behaviour			• *As a result of bottleneck analysis, research / lab experiments on different aspects on physical condition or migration behaviour of fish to get more insight into behaviour to optimize agent based modelling.* • *coupling hydrodynamic models-IBM/ABM*	• *Integration of results both biotic as abiotic*

Figure 10. Overview of the general phasing of the monitoring plan including the main activities.

We propose that the research and monitoring components be carried out by a consortium of science partners, a PhD-student(s) that starts in the Adjustments phase I and with groups of students especially in the intensive field campaign of spring in adjustment phase II.

Media awareness

This large-scaled FMR and the uniquely design of the FMR is relevant to use for public awareness and media attention. The design of the FMR allows to explain the need for habitat restoration, habitat connectivity (and possibly climate change), for a wide range of fish species. For example, testing methodologies, equipping fish with transmitters, or nightly visits with liftnets will be outstanding opportunities to create public awareness of the need for fish migration solutions. We think that adjustment Phase I and II are the best moment to invite journalist or other parties.

6 Abiotic monitoring FMR: hydrodynamics and design

6.1 Introduction and general approach

As part of the construction of the FMR instruments are placed in the FMR during / directly after the construction phase and continuously measure the abiotic conditions. In below figure the locations of abiotic monitoring stations is presented. As a minimum, the following abiotic measurements are performed:

- At 3 locations water levels are measured (Wadden Sea, FMR and Lake IJssel)
- At 5 locations salinity, temperature, pressure and oxygen levels are measured. The measurements are performed either at a number of heights above the bed using various instruments or an automatic winch is used which measures profiles every 10 to 15 minutes, to be decided by the contractor
- At 1 location flow velocities and discharges are measured (at the Coupure)
- At 3 locations turbidity levels are measured (Wadden Sea, FMR and Lake Ijssel
- At 1 location sediment transport measurements are performed to assess if sediment is eroded from the bed.

More details about the monitoring and rationale behind the number of devices are described in the monitoring plan in Griffioen et al 2023.

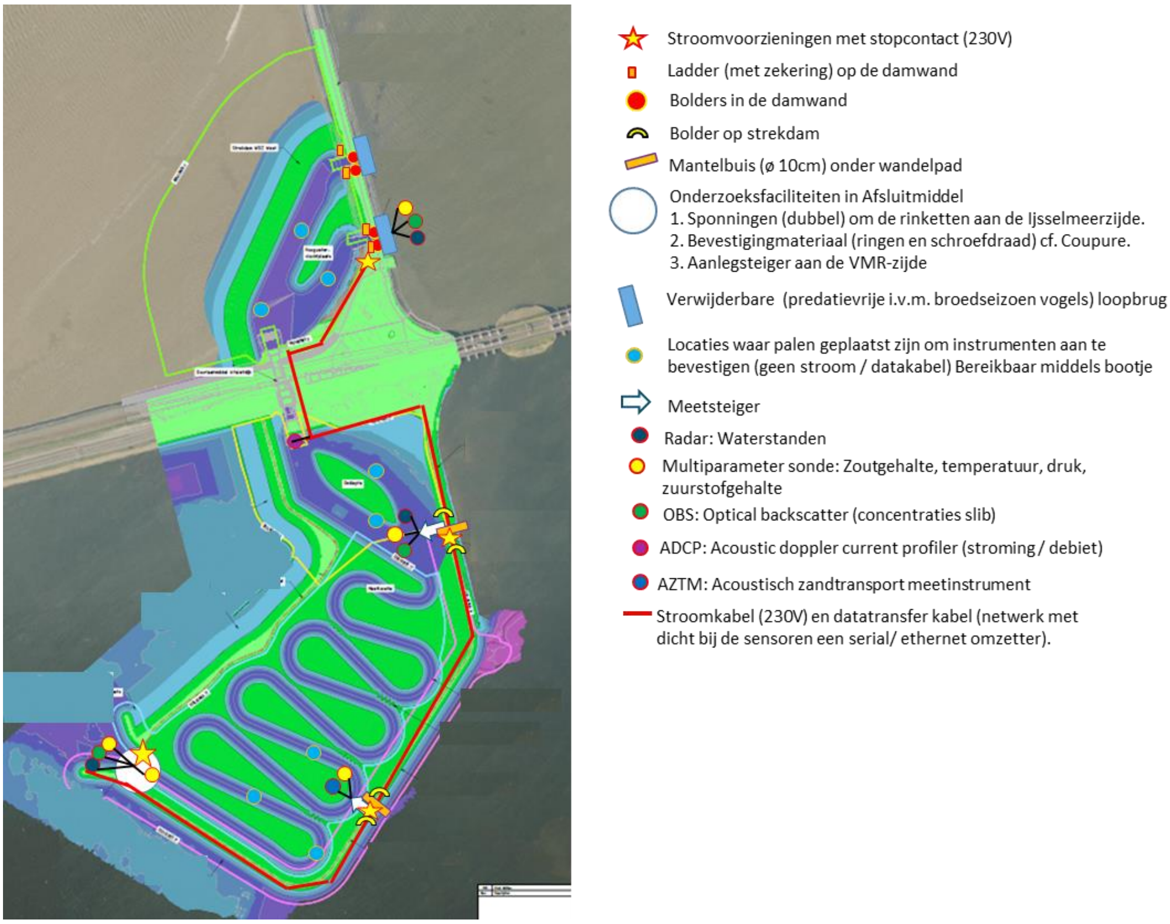

Figure 11 Map with overview of abiotic measurements

6.2 Construction phase

During the engineering and construction phase no measurements are available yet and optimizations can only be assessed using the numerical model as setup during the design phase.

During this phase the numerical model can provide valuable information to the contractor on the functioning of the FMR. The hydrodynamic modellers should inform the contractor how the system works and how adjustments to the design of the FMR might affect the abiotic flow regime. In order to further optimize the flow regime for fish an iterative approach should be followed in which the parties contribute as follows:

- Client: safeguards that the design optimizations as proposed by the contractor are in line with the set requirements and have as main purpose to provide the most optimal hydrodynamic conditions within the FMR for fish
- Contractor: the available equipment of the contractor will determine the work method statement. Moreover, the contractor has ideas how to optimize the design of the FMR and sluice gates in order to minimize both construction- and maintenance costs.
- Hydrodynamic expert: by performing numerical modelling simulations the hydrodynamic expert can advise the contractor on effects of design decisions and can propose adjustments to the design alternatives based on his knowledge on the hydrodynamic functioning.
- Fish ecologists: should be involved to safeguard that design optimizations as proposed by the contractor are beneficial for fish.

The result of the E&C phase is an improved layout of the FMR which guarantees optimal conditions for fish but is also optimal from a construction point of view. To make use of the of all disciplines present within the different parties it is proposed to have frequent meetings to discuss optimal settings of the FMR.

Under this section research question Q1-A is answered: "*How can we best further optimize the abiotic conditions within the FMR for fish during the engineering & construction phase of the FMR?"*

6.3 Adjustment phase I

Under Adjustment phase 1 the first information becomes available from the measurement instruments. Especially the measurements outside the FMR (in Lake IJssel and Wadden Sea) are of interest first because (1) they provide the boundary conditions for the numerical model, and (2) in the beginning the FMR is not functional yet and the measurements inside the FMR do not provide information of use (yet).

The numerical model is fed with these measurements and a number of simulations are made in which gates within the FMR are opened; first the smallest gates, later the larger gates and a combination of gates. The numerical model provides information on water levels, flow velocities and discharges through the FMR. When the model results show that the hydrodynamic conditions and salinity levels are acceptable for the cases considered, the next step is that the gates are opened in reality. The measurements performed are then used to verify if model and measurements are well in line. If not, the numerical model is adjusted by tuning calibration parameters like roughness or eddy viscosity until model and measurements are in line. If so, a larger gate or a combination of gates can be opened of which the measurements are again compared with the model results.

In this way the numerical model is validated step-by-step and the accuracy of the model predictions is improved. Using both the numerical model and measurement results the FMR can become operational in a controlled step-by-step approach. The process continues until the FMR is operational under normal hydrodynamic conditions.

The procedures to be followed occurring in normal tidal conditions should be described in a procedure document and should be included in the gates-steering-system which steers the functioning of the FMR.

Large advantage of this Adjustment phase I is that the contractor is still available on site. In case the hydrodynamic functioning of the FMR under certain conditions is not ideal or in case in certain areas within the FMR flow conditions occur which are non-optimal, it can be decided to perform small adjustment works inside the FMR to mitigate this.

Under this section research questions Q1-a,b,c and d1 are answered:

b. *How accurate can we calibrate the numerical model on abiotic measurements such that the numerical model can accurately predict the abiotic conditions in the FMR under all tidal and extreme conditions?*
c. *System understanding. What can we learn from the abiotic measurements and model simulations. How does the abiotic system function and do we understand the effects of opening / closing gates on the system?*
d. *How can we apply our system understanding and the calibrated numerical model to assess:*
    a. *The optimal opening- and closure regime of the gates in coupure and sluice under normal tidal conditions to obtain the optimal hydrodynamic conditions for fish*

6.4 Adjustment phase II

Also in Adjustment phase II the step-by-step approach is followed making use of the combination of measurements and model predictions. In this phase focus will be put on the more extreme conditions.

When under the normal conditions the numerical model is improved and lessons have been learned based on the analyses of the measurements, the model can be applied to the more extreme conditions like:

i. Periods of drought and limited availability of fresh water
ii. Periods with large water level gradients between Wadden Sea and Lake IJssel
iii. Periods of storms (very high or very low water levels at Wadden Sea or Lake Ijssel)

Comparable to the approach followed under the normal conditions, the optimal opening- and closure regime of the gates in coupure and sluice is obtained under extreme conditions.

The procedures to be followed for the various extreme conditions should be described in a procedure document and included in the gates-steering-system which steers the functioning of the FMR.

When the more extreme conditions occur in reality, the measurements and model simulations should be compared again with each other to know how well the model performs and if adjustments need to be made for future situations.

Under this section research question Q1-d2 is answered:

d. *How can we apply our system understanding and the calibrated numerical model to assess:*
    ii. *The optimal opening- and closure regime of the gates in coupure and sluice under extreme conditions to obtain the optimal hydrodynamic conditions for fish*

6.5 Optimisation phase

On the longer term the FMR will adjust itself due to the acting hydrodynamic forcings but also because of growth of vegetation (e.g., reed and other shoreline vegetation in the FMR). Vegetation will change the hydrodynamics. In order to preserve the most ideal hydrodynamic conditions for fish it is periodically verified if the steering of the gates should be adjusted such that the ideal abiotic conditions in the FMR remain, also when vegetation has grown or the bathymetry of the FMR has changed.

Apart from above under this phase the results from the biotic monitoring become available which are performed in the first years after FMR construction. It could be that biotic monitoring results indicate that certain hydrodynamic conditions are optimal for fish. Based on these results the steering of the gates and sluices should be adjusted.

Under this section research question Q1-e is answered:

e. *As under bullet d but now including long term trends inside the FMR (local scale):*
   I. *changing bathymetry within the FMR*
   II. *growth of vegetation within the FMR*

f. *Is it possible to adjust the steering of the FMR when, based on the biotic monitoring results performed in the first years after FMR construction, it is expected that the hydrodynamic functioning of the FMR can be further improved for fish?*

Hydrodynamic modelling of the entire Kornwerderzand sluice-complex: similar to what Deltares has modelled for Den Oever (Reijmerink and Bijlsma, 2016), could be carried out for coupling hydrodynamics to fish behaviour on the sluice-complex scale (Figure 12).

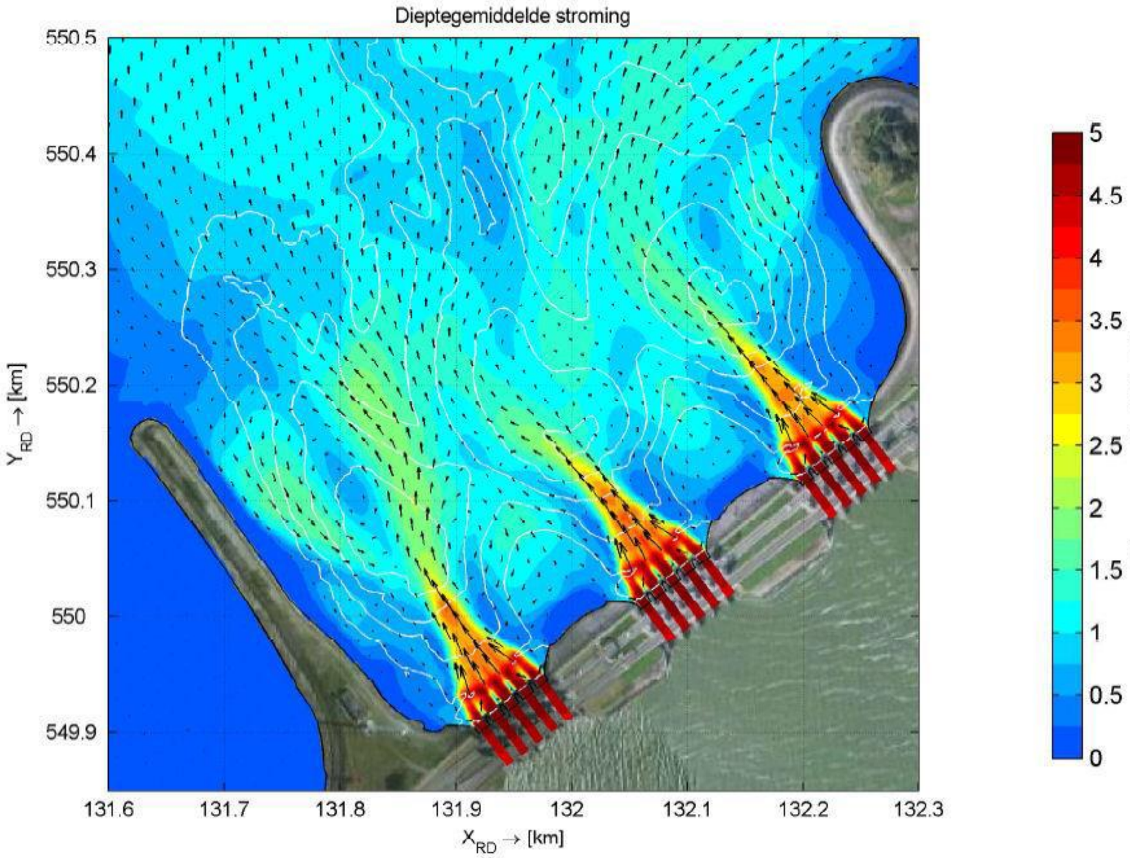

Figure 12 Hydrodynamic modelling of the Kornwerderzand sluice-complex: similar as to what Deltares has modelled for Den Oever (Reijmerink and Bijlsma, 2016), for coupling hydrodynamics to IBM-models.

7 Research and monitoring of small diadromous fish (tidal migrants)

7.1 Introduction and general approach

To investigate the use of the FMR by small diadromous migrants we will use a set of different research tools. We propose to concentrate the research activities during a one-year campaign preferably during adjustment phase II, with necessary preparatory activities in phase I. Since the program may be expensive it is better to concentrate all effort in one year when the FMR is tested and adjusted based on abiotic measurements (adjustments phase II).

Indirect measurements on delay, abundance, passage efficiency for small fish (tidal migrants)
Contrary to large diadromous fish where sophisticated transmitters are preferred (direct and individual measurements), to follow groups of small fish throughout the FMR and Kornwerderzand batch mark techniques and density measurements (fluxes) are needed (*Figure 13*). Tidal migrants are too small or too fragile to use larger transmitters and other research approaches and techniques are needed to measure the total numbers of fish arriving at the complex and passing through the different routes and sections of the Kornwerderzand complex (Figure 6). The most basic approach is to measure densities and fluxes of fish in the different connected sections that make up the complex. These measurements should be in line with species specific migration period and preferably executed during peak periods. It is preferred to measure for multiple (3-5) periods and consecutive (3-5) days period. This will cover data collected under different circumstances. However, to unravel underlying behavioural patterns, mark recapture experiments are needed to determine: passage success (Q2), delay or duration of passage (Q2/3), 'recurrence behaviour' or 'loop' movements (Q3, see Figure 7).

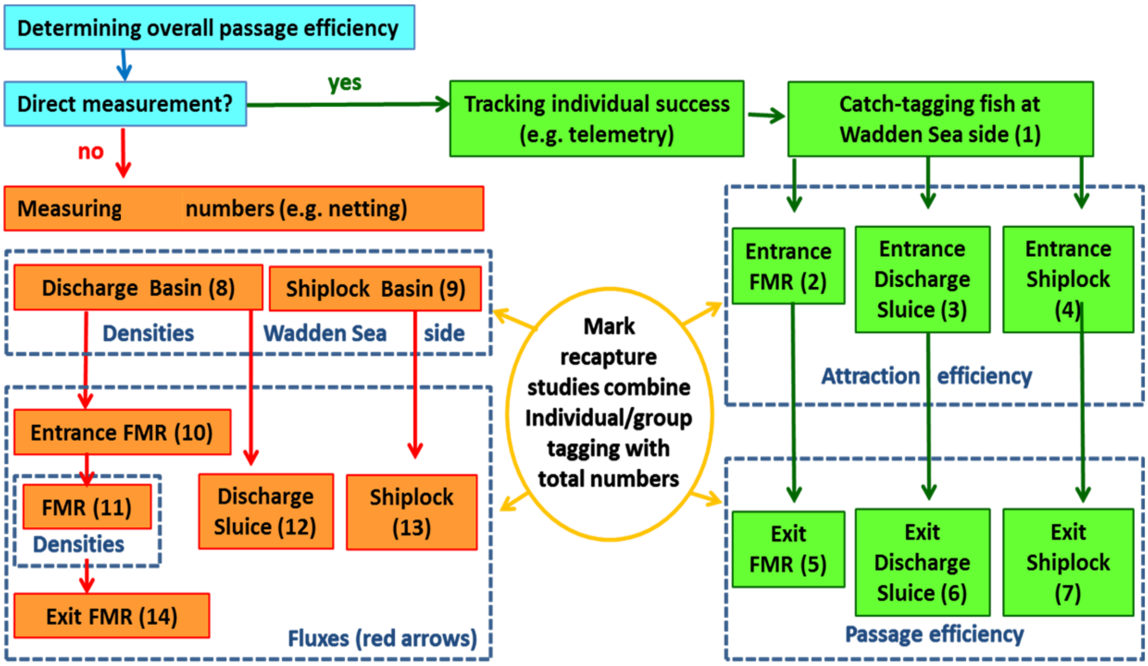

Figure 13. A schematic flow-chart of determining overall passage efficiency by using direct techniques for species for which these are applicable (green boxes and pathways) and with indirect assessments based on total numbers, densities and flux measurements for fish species or life stages where individual tracking techniques are not available (orange boxes and pathways) and where possible combined with mark-recapture experiments to determine duration, recurrence behaviour and provide independent estimates for total numbers.

Mark recapture techniques

Mark-recapture techniques are present in various forms and differences among these methods include group (mass) or individual marking, tag retention and the necessity to kill glass eels to identify recaptures. Examples are methods such as alizarin red S (Kullmann et al. 2017, Kullmann et al. 2018, Diekmann et al. 2019), oxytetracycline (Simon and Dörner 2005), vital dyes (Briand et al. 2005), coded wire tags (Simon and Dörner 2005), PIT tags (Griffioen and Winter 2014b) and visible implant elastomer (VIE) tags (Imbert et al. 2007, Griffioen et al. 2022a) are all used in the field for various purposes. To answer the research questions of passage success (Q2) and bottleneck analysis (Q3), marking method that can discriminate between groups, affecting neither behaviour nor survival, are preferred. VIE tags (groups), vital dyes (groups) and PIT tags (individual ID) are all methods that do not require killing to identify markings. Vital dyes (e.g. Bismarck Brown) are especially useful for pilot experiments due to low effort. Depending on the fish species the best methods must be chosen (Table 2).

Table 2 *Overview of catching and marking techniques per target species (tidal migrants). VIE = Visible Implanted Elastomers, PIT = Passive Integrated Tags and BB = vital dye Bismarck Brown (other colours are present and treated similar).*

		Catch method						Mark method*			
Species name		**Traps (large mesh)**	**Traps (fine mesh)**	**Driftnets (various design)**	**Liftnets (small e.g. 1x1m)**	**Liftnet (large e.g. 3x3m)**	**Elverfinder**	**VIE**	**PIT**	**BB**	**Ref**
Anguilla anguilla	Glass eel (juvenile)	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	1
Gasterosteus aculeatus	three spined stickleback	Only large individuals	Yes	Yes, but less effective (to be tested)	Yes, but less effective	Yes	No	Yes	Yes, only large individuals	No	2
Platichthys flesus	Flounder Larvae (<1cm)	No	Yes	Yes	Yes	Yes	No	No, to be explored in larger individuals (>5cm)	No		3
Osmerus eperlanus	Smelt	Only large individuals. High mortality in small individuals	Yes	Yes, but less effective (to be tested)	Yes, but less effective	Yes	No	No, to be explored	No, to be explored		4

*more methods are available, but these are chosen since markings are visible without killing the fish.

1) (Griffioen et al. 2014b, ARCADIS 2015, Griffioen and Winter 2018, Griffioen et al. 2019b, Schiphouwer et al. 2019)
2) (Griffioen et al. 2014b, ARCADIS 2015, Griffioen et al. 2019b, Ramesh et al. 2023)
3) (Bos 1999, Jager 2001, Griffioen et al. 2014b, Krijnsen and Rondeel 2019)
4) (Griffioen et al. 2014b) (Pers. Comm. PP Schollema Hunze & Aa's)

For glass eels and three spined sticklebacks, VIE tags can be used to follow groups of fish (Table 2, and Photo 1 and 2). Large three spined stickleback can also be equipped with PIT tags (Ramesh et al. 2023). However, for small flounder these techniques are not useful since they are only 5-7mm in length when they arrive at Kornwerderzand (Griffioen et al. 2014b, Krijnsen and Rondeel 2019). For smelt, these techniques may be applicable but need to be tested in the field. Griffioen et al. (2014b) used a lift net program to get insight in the behaviour and abundance of small migratory fish: glass eel, flounder larvae, smelt and three spined stickleback. However, this study lacked mark recapture analyses. Slijkerman (2018) and Dekker (1997 and 2000) both used lift nets in combination with group dyeing to examine residence time of glass eel in the vicinity of tidal barriers, but where only able to use a single colour (Dekker and van Willigen 1997, Dekker and VanWilligen 2000, Slijkerman et al. 2018). Therefore similar, but optimized, approaches using VIE tags (and PIT) are needed at Kornwerderzand to evaluate the functioning of the FMR as used elsewhere along the Dutch coast in more recent years (Griffioen et al. 2018 , Griffioen et al. 2019b, Schiphouwer and Kooiman 2021, Griffioen et al. 2022c). Recent studies have shown that 1000's of glass eel can be tagged efficiently when using VIE tags using different colours combinations for different groups (Schiphouwer and Kooiman 2021, Griffioen et al. 2022c). Moreover, some individuals are recaptured after one year (unpublished results WMR) indicating that this technique is useful for studies taking longer than several week-months. Therefore, this technique is a preferable method for studying small diadromous fish such as glass eel and three spined stickleback.

Photo 1 and 2. Glass eel and three spined stickleback tagged with VIE tags.

Netting program and mark recapture experiments

To answer the research questions Q2 (passage success) and Q3 (bottleneck analysis) an extensive netting program is proposed in addition to mark recapture techniques for all species (Figure 14).

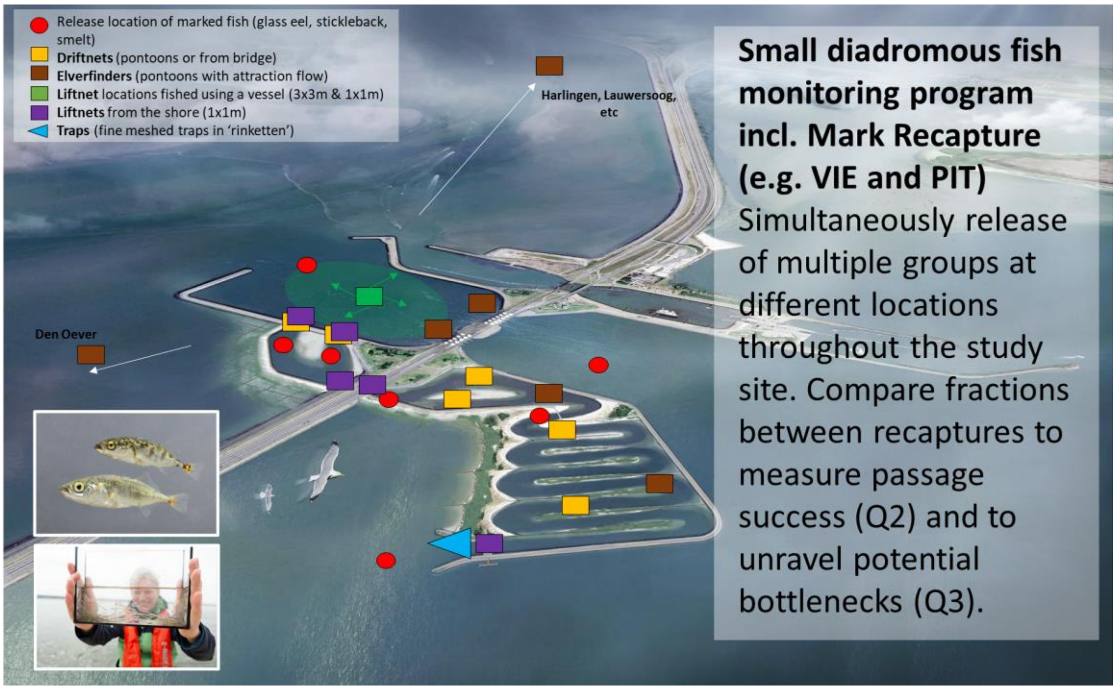

Figure 14. An overview of the proposed netting program to evaluate passage success and collect data for a potential bottleneck analysis for tidal migrants (small diadromous fish). In addition to the netting program a mark recapture program is needed (release of multiple groups throughout the season) to unravel underlying patterns of behaviour. ***Note.*** *Lift-netting throughout the discharge basin (indicated by the 'green circle') is done with both small and large nets operated from a boat similar to previous studies (Griffioen et al. 2014b).*

Locations and number of nets are based on expert judgement and experience. Depending on the species one or multiple nets are needed to catch the fish in order to estimate fluxes/densities and to find potential recaptures (Table 2). The program consists of driftnets, elverfinders (glass eel monitoring devices: www.elverfinder.com), small and large lift nets and traps (fine meshed and large meshed). All are needed to catch small tidal migrants within the FMR. Liftnets are positioned in the discharge basin,at the entrance points and in the FMR (coupure and sluice gates). Driftnets are positioned at the entrance points and inside the FMR. As described in the previous paragraph, this program is extended with a mark recapture program (Figure 15). Fish are therefore caught (preferably in the basin, green area in Figure 14), tagged and released again at various locations before the entrance of the FMR to determine passage success, but also within the FMR to determine recurrence behaviour, accumulation within the FMR, passage success at various potential bottlenecks in the FMR, or loop movements (Figure 15).

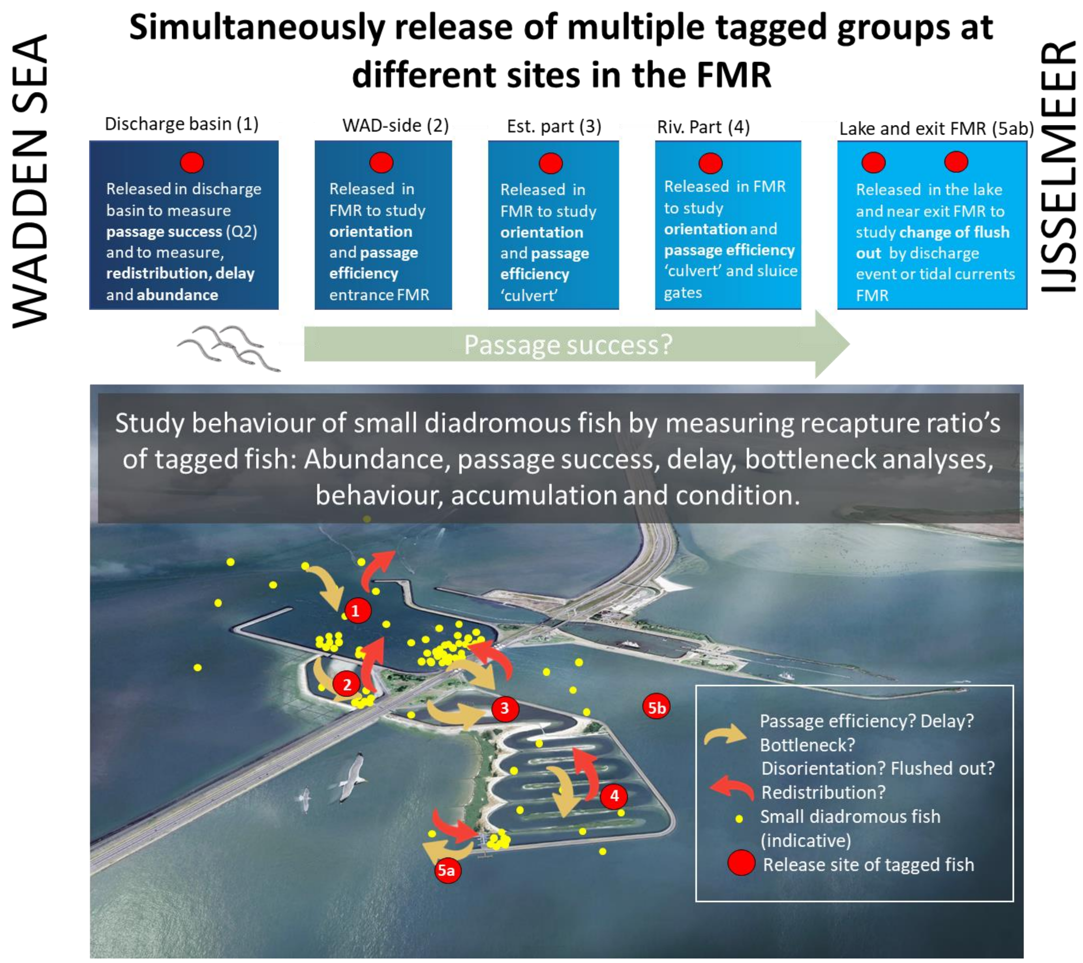

Figure 15. Mark recapture of small diadromous fish to observe and study behaviour in the Kornwerderzand complex. The approach is to simultaneously release multiple groups at difference sites within the complex and throughout the season.

Netting program: Driftnets

The upstream migration in tidal gates, of small diadromous fish can be determined using so-called tapered driftnets (ARCADIS 2015). It should be taken into account that these nets where only used during the adapted sluice management regime, which lasted for 15 minutes (ARCADIS 2015). This technique has practical limitations for longer lasting studies. The nets can be installed in the tidal gates, but they do not fully cover the wet surface of a tidal gate. In previous studies, five nets where used: three nets on the bottom, one in the middle and one at the surface (ARCADIS 2015, Griffioen and Winter 2019). All nets together, covered 7.5% of the full wet surface of one tidal gate. An alternative method is a large and long net (atoomkuil) that fully covers the wet surface of a tidal gate, but mesh size (40mm – 8mm) must be wider compared to the tapered driftnets. Using the latter method, small and or elongated diadromous fish such as flounder larvae (5-7mm in length) and glass eel will probably be missed. In the ship locks large fine meshed nets can be applied when there is no ship traffic (ARCADIS 2015).

A new preliminary design, however, may be used in the FMR itself to capture small diadromous fish in the FMR (Figure 16), since water velocities do not exceed 0.5m/s. Although the nets do not fully cover the river cross section, it may be complementary to the conventional traps (fykes) that catch larger fish and can be used to study behaviour of fish in relation to tidal currents. Though, nets have to be tested and optimized in collaboration with experienced fisherman/technicians (Figure 16).

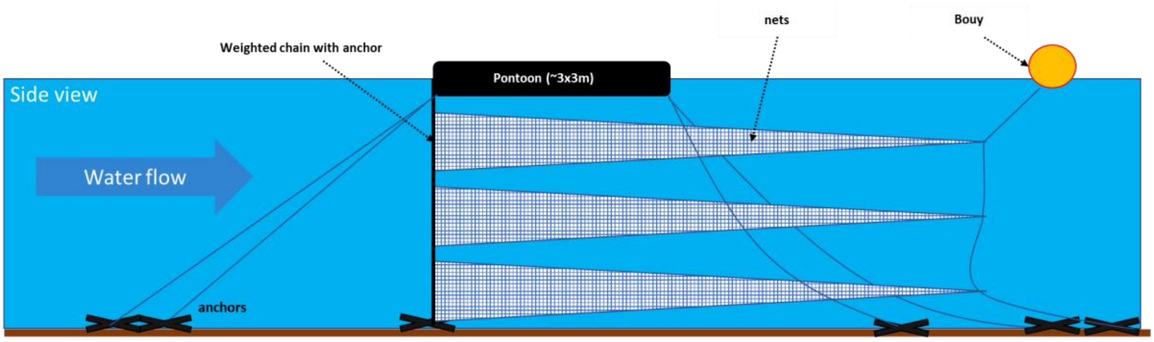

Figure 16. Proposed driftnet setup to catch small diadromous fish within the FMR or at the entrance and exit. Contrary to the discharge sluices (water velocities up to 4-5m/s), water velocity in the FMR is below 0.5m/s. This proposed netting design allows to catch fish during specific tide frames at locations within the FMR independent to structures or bollards. This setup needs to be optimised and tested in collaboration with professional fishermen in the field. To test for positioning of the fish in the watercolumn, three nets are proposed to fish at the bottom, mid column, and surface area.

Netting program: Lift nets and fine meshed traps
Liftnets both small (1x1m) and large (e.g. 3x3m) are used to collect fish from the water column (Photo 3). Liftnets are used along the Dutch coast and at instream barriers for index monitoring of small diadromous fish (Wintermans 2015, Griffioen et al. 2017a, Goverse 2018, Schiphouwer et al. 2019). Catch efficiency varies between species and larger nets have higher efficiency per m^2 (Griffioen et al. 2014b).

Fine meshed traps (Photo 4) are proposed at the sluice gates (#6, Figure 2). The challenge with these nets is that the flow direction may vary in relation to tidal flows. In addition, the operation of the doors may also vary according to the flows. Therefore, the operation of these nets needs to be tested during the Adjustment Phase I in order to use them properly in the extensive netting camping during Adjustment Phase II.

Photo 3. The use of large (3x3m) lift nets and small lift nets (1x1m) in the discharge basin at Kornwerderzand.

Photo 4. The use of fine meshed traps near fish passages. In this case pumping station Schiegemaal.

Netting program: Elverfinders

In addition to netting (e.g. lift nets or drift nets), specialized traps for glass eels and young yellow eels are also useful to (re)capture (tagged) eel (Figure 17). Since 2017/2018 multiple studies have been executed along the Dutch coast using elverfinders along the coast as at instream barriers. Since 2020, each spring, elverfinders are installed in the discharge basin of Kornwerderzand as part of the Dutch national glass eel monitoring program (Keeken et al. 2022). For the FMR a separate report is written that further describes installation requirements for elverfinders to be successfully used in the FMR (Griffioen et al. 2023).

Figure 17. An elverfinder (www.elverfinder.com) installed near the Haringvliet sluices to measure abundance and delay of glass eel. The monitoring is used in addition to mark recapture technique (e.g. VIE-tagging, Bismarck Brown and PIT telemetry).

Mark recapture: PIT tag

In addition to the netting program and the use of marking techniques, PIT tags are also useful to mark individual fish (instead of groups). This can also be used in small (yet larger individual) tidal migrants. PIT tags can be used for both large and smaller fish, but because individual 'tracking' is possible, therefore this technique is briefly described in section 8.

Data analysis mark recapture
Beside presence absence data and recapture rate comparisons among various locations, data can also be used to estimate abundance. Since sites such as discharge basins are 'open systems', instead of ' closed systems, models should take into account fluxes of fish that leave and enter the area during the season. Methods to use VIE tags / vital dyes (batch mark) or PIT tags (individual marks) in abundance estimates are described in other studies (Briand et al. 2005, Skalski et al. 2009, van Keeken et al. 2023, Griffioen et al. 2024).

7.2 Construction phase

During the construction phase preparations for an extensive netting program should be made. Due to the challenging environment (tidal characters with varying depths and flow directions) multiple techniques must be designed and tested in the field (Figure 10). Questions must be answered in order to successfully make progress in following actions and the following phases. This phase is especially useful to thoroughly prepare the extensive netting program carried out in Adjustment Phase II. The following question arise:

Technical questions to be answered in order to prepare for the netting campaign including mark recapture experiments:

1. *What is an optimal design for driftnets to capture small diadromous fish within the FMR?*
2. *Where can these prototype nets be tested in the field?*
3. *How efficient are drift nets catching larger tidal migrants such as smelt and three spined stickleback?*
4. *Are the nets applicable (safely and easily) and efficient in catching tidal migrants?*
5. *What dimensions of the nets are needed to cover as much wet surface as possible while remaining efficiently in practice (handling of the nets)?*
6. *What mark recapture techniques are possible for smelt and flounder larvae, and at what sizes?*
7. *Are all procedures to apply permits clear?* or *What (additional) permits are needed to organize an extensive netting program?*
8. *Which fishermen are available to help during the netting program? And do they need additional equipment in order to catch small fish (e.g. fine meshed nets).*
9. *Develop efficient monitoring devices for three spined stickleback and smelt (low efficiency in lift net monitoring)?*

7.3 Adjustment phase I

Following the questions stated in the construction phase, the 'Adjustment phase I' is especially useful to further test and expand the activities using specialized drift nets in the FMR itself. In addition, traps in the sluice gates (see #6 Figure 2) can be installed and tested (in addition to PIT tag antennas, see section 8). Also, fishing activities in the discharge basin as part of the Dutch statutory work (WOT research program) can be used to tag the first groups of small fish and (further test and optimize) marking techniques for smelt and flounder larvae.

The following questions must be answered during this phase:

1. *Are the designed driftnets applicable in the FMR considering the velocity rates in the FMR?*
2. *Are the (fine mesh) traps applicable in the sluice gates (see #6 Figure 2)?* And: *How do these nets (and operation of these nets) needs to be optimised?*
3. *Can traps and driftnets be attached easily and safely at the structures of the FMR (e.g. at both entrances, open culvert and 'Afsluitmiddel'/sluice gates)?*
4. *How efficient are the (drift, fykes and lift)nets for the different target species?*
5. *Are all (or most of the) locations covered to perform data analyses in the future (e.g. fluxes of densities)?*
6. *Does the collected data already show accumulation of fish in the FMR?*

7. *Are there already indications for optimisation to optimize the functioning of the FMR?*
8. The final questions of this phase are: *What is the optimal design for an extended netting program throughout the FMR? How many persons are needed to fully execute the extended netting program? Are all nets and equipment ready to use in the following phase? Are all fisherman prepared? Etc.*

7.4 Adjustment phase II

Adjustment phase II is the phase to conduct a large netting campaign including a large mark recapture program to understand passage success (Q2) and collect data for a bottleneck analyses (Q3).

By releasing multiple groups of tagged fish besides an extensive netting program, the following questions can be answered during this phase (see section **Error! Reference source not found.** and REF _Ref140140154 \r \h 4.7.3 for further detailed questions):

1. *(Q2) What is the attraction/passage efficiency of the FMR?*
2. *(Q2/Q3) What is the delay of successfully passing fish?*
3. *(Q3) Is there a need for optimizing the functioning of the FMR and how can this be achieved?*

To answer these questions an overview of activities is given in Table 3. Activities are depending on weather conditions. A high frequency of liftings and hauls in the field helps to give as much detailed information as possible. Moreover, driftnets and fine meshed traps are handled depending on tidal flow directions. Therefore, the frequency of activities highly determines required manpower. Moreover, since all of the fish species migrate during dark period, activities mostly occur during the evenings and nights except for the visits of the elverfinders.

After the netting program there is still a half year left for the tidal migrants where the contracters (builders) are able to make adjustments to the FMR (e.g. introduce rip rap stones, dead trees, etc). Therefore, once the extensive netting program is finished, data should be analysed to prioritize interior design adjustments in the FMR.

Table 3. Main activities for the netting program and mark recapture experiments for tidal migrants including the expected migration season (dark green = peak period).

		Expected migration season														
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Flounder Larvae																
Three spined stickleback																
European eel (glass eel)																
Smelt																

Activity	Frequency	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Administration																
Request permits ethical committee																
Contracts fisherman																
Buy marking methods (VIE and PIT)																
Prepare and checks nets																
Install elverfinders Dicharge sluices																
Install elverfinders FMR																
Install driftnets entrances FMR																
Install driftnets in FMR																
Install driftnets in sluice gates FMR (exit)																
Tagging fish (depending on catch)																
Visit driftnets	Daily according tides															
Conduct elverfinder visits	Daily during peaks but at least twice a week															
Conduct netting program (1x1 and 3x3m)	Once or twice a week															
Conduct netting program (1x1m) from shore	Daily during peaks but at least twice a week															
Analyses results																
Period to make adjustments to the design FMR (in collobaration with contracters)																

7.5 Optimisation phase

During the optimisation phase there is a possibility to optimise the FMR in collaboration with the contractor (builder). However, contrary to the previous phase (when relatively large adjustments can be made eg., introduction of additional habitat / rip-rap, adjustment to the entrances, etc), in the following phases it is more difficult to do large adjustments. Therefore, following phases should concentrate on when operational adjustments such as the the valves and gates to adjust velocity rate, turbulence, attraction flows, etc. To test these adjustments a stripped-down netting program can be carried out to monitor or study the adjustments. Moreover, a stripped-down netting program can identify differences among years and circumstances and may include the following activities:

1. **Elverfinders near the tidal gates** of the discharge sluices
   (part of the Dutch statutory program to monitor glass eel).
2. **Mark recapture of glass eels** and release them in the basin to compare passage success and potential delay / residence time.
3. **Elverfinder in the FMR** to compare catches and to monitor recaptures
4. **Liftnet monitoring** at the sluices gate of the FMR (location needs to be decided)
   (in collaboration with students and volunteers similar to lift net monitoring programs along the coast).
5. **Drift net and trap (fine meshed) monitoring** but in a lower frequency (e.g. once a week) and monitor less locations.

8 Research and monitoring of larger diadromous fish

8.1 Introduction and general approach

Direct measurements on delay, abundance and passage efficiency for large diadromous fish: general approach and techniques.
For the larger fish species, direct measurements, using rapidly developing telemetry techniques, are available to get detailed passage success per route (FMR, sluices and locks) within the complex (Figure 13). A representative group of fish per target species will be tagged and released near or at the complex. Using telemetry techniques to follow the fish will give an estimate of the number of fish that tried to pass the complex in proportion to number that actually passed. As seen by Griffioen et al. (2022), not all fish will pass the barrier once released. Therefore, an estimate of the passage efficiency is always based on the number of tagged fish, the number of fish that made migration attempts after release and the fish that passed the complex. Preferably, the telemetry technique must be able to distinguish between an approach (attempt), an entry and passage of an individual. Depending on the species a technique or a combination of techniques must be chosen. VEMCO (acoustic tags) for example is a flexible method giving high resolution data to study questions related to, behaviour, attempts and passage success. To study passage success in combination with success of the migration further upstream, receivers must be installed at river tributaries upstream and will also give information on passage success on a larger level (e.g. passage at Den Oever). PIT-tag is especially useful to use for smaller fish such as stickleback and smelt[2] and can be used in addition to the netting program for those species. However, it is better to tag all migratory fish that qualify for this method with PIT-tags since these tags are relatively cheap, the lifespan of the tags are 'eternal', and upstream tributaries may have also PIT-tags stations. Mark recapture studies will also benefit from fish that are equipped with PIT-tags. Some fish will be equipped with both an acoustic as a PIT-tag.

Telemetry techniques give insight in individual searching behaviour, attraction and passage success of tagged fish as well as the duration of passage (delay / residence time) through different sections and indicate number of passage attempts and success and failure rates in time. These techniques yield *direct* measurements (%) of passage success and behavioural patterns as seen at Kornwerderzand (De Vaate et al. 2003, Griffioen et al. 2014b, Griffioen et al. 2022d). With all telemetry techniques (as for VIE tags), an approval of the animal ethical commission is needed since surgery to the fish is needed when implanting tags in the body cavity. E.g. fish need to be anaesthetised (e.g. with 2-phenoxyethanol 0.2-1.0 ml/L depending on species and complexity of the surgery) to implant tags in the body cavity. Usually a mid-ventral incision in the posterior quarter of the body cavity is made. The incision can be closed with resorbable sutures or glue. In many cases surgery lasts 3–5 min. After surgery fish need to be observed in a recovery tank until swimming behaviour is normal and released to continue migration. Preferably, translocation of fish should be as minimum as possible.

Radio Frequency Identification telemetry: PIT-tag
In addition to acoustic telemetry techniques (with costly transmitters), PIT tags can also be used both for mark recapture using manual readers as for tracking using antennas. This telemetry system is based on Radio Frequency Identification (RFID) technology and needs transmitters and fixed detection stations. The transponders do not have an internal power supply (passive), and tags are much smaller (12, 23 and 32mm in length) compared to most acoustic techniques. Another difference is that the tags will operate indefinitely. The transponders are glass encapsulated electronic circuits powered by magnetic fields from a reader. In general, there are two types of tags: half duplex (HDX) and full duplex (FDX). HDX is the most commonly used technique in the Netherlands and known as a more robust and reliable type for fish pass evaluation (Castro-Santos et al. 1996). The longer the tags the larger the

[2] Need to be tested in a pilot study whether larger smelt are suitable to implant PIT-tags

detection range. The detection range will be smaller in salt water. With detection station design, at least three phases are distinguished:

1) design detection station
2) build a prototype to test loops and detection range
3) build final detection station

The alternating salinity inside the FMR will affect the performance of the antennas, but it should be possible to construct arrays of antennas that will detect most fish. Especially when auto-tuning electronics are applied. Fish have to be in the immediate vicinity of an antenna to be recorded and identified and it can be used on all tagged fish passing close enough to the antennas within the FMR. This technique can be used to tag a large number of individuals, considering the low price per tag, and fish can also be detected further inland when they enter rivers and creeks if detection station are installed over there.

PIT-tags stations are difficult, if not impossible, to install in the full cross section of the FMR, at the discharge sluices (high water velocity and large wet surface) and the shiplocks (high intensity of ship traffic). In the coupure, including the vertical slot, however there are rabbets to install temporary frames which needs to be explored further in the Adjustment phase I. Considering the dimensions of the antenna's, they must be carefully designed to prevent noise or reduced detection range. Moreover, they need to be resistant to debris and water velocities up to 0.5m/s. Large arrays (~5x5m) have been built at the outflow of pumping stations (Griffioen et al. 2022b) or at ship locks around the levelling gates in salt water conditions (~2x2m) (Griffioen et al. 2019a). Considering the large dimensions of the FMR however, arrays may be restricted to smaller sections. Arrays of antennas could be installed in the FMR to cover the vertical slots in the coupure and the sluice gates at the exit of the FMR. It must be explored in the field whether arrays can be built to cover the cross section of the larger structures of the FMR using the facilities to attach the antennas (Griffioen et al. 2023). Large arrays need multiple synchronised loggers that may introduce noise or reduced detection range. Such large antenna constructions need to be designed carefully and tested in the field once the FMR is ready for monitoring. In addition to fixed frames in the structures of the FMR, flexible PIT arrays can also be installed on pontoons together with drift net or traps or used as horizontal (floating or submersed) antennas to cover the upper and lower parts of the water column. Although these antennas do not cover the full cross section of the FMR they do collect additional data of behaviour of fish. Fisherman in the area should ideally be equipped with a manual PIT-tag readers to scan their catch on tagged fish. Recaptures should be reported (size fish, date catch, trap information etc.).

Target species of the PIT-tag monitoring program are especially three spined stickleback and smelt. Whether this technique is applicable on smelt needs to be tested. In addition to sophisticated transmitters, all relevant diadromous fish (including the larger specimens) can be implanted with PIT-tags to increase sample size and for potential inland detection at river tributaries and mark recapture purposes. Considering the marine environment causing reduced PIT tag detection, it is better to use large 23 or preferably 32mm tags instead of 12mm if physiological characteristics of the species allows.

8.2 Construction phase

Acoustic telemetry

During the construction phase it is proposed to already install receivers in and around the discharge basin. Other programs (e.g. Waddentools Swimway, Ruim Baan voor Vis, Eems Vissen in Beeld) have tagged multiple species in the Wadden Sea. Those fish (e.g. North Sea houting and Sea Trout) may approach Lake IJsselmeer and contribute to knowledge about the current passage success or attraction/feeding behaviour of Kornwerderzand (Table 1). By building the core network of acoustic receivers early, opportunistic data from fish tagged in other studies can be collected as well.

Reference tags in addition to receivers in the discharge basin should be used in order to track acoustic noise due to discharge water (Griffioen et al. 2022d). As opposed to Griffioen et al. 2022d, we suggest using the VEMCO VR2Tx receiver with integrated tag in the discharge basin, but developments are going fast and with the transition to open-source-code in acoustic telemetry and full compatibility, more manufacturers can be taken into account.

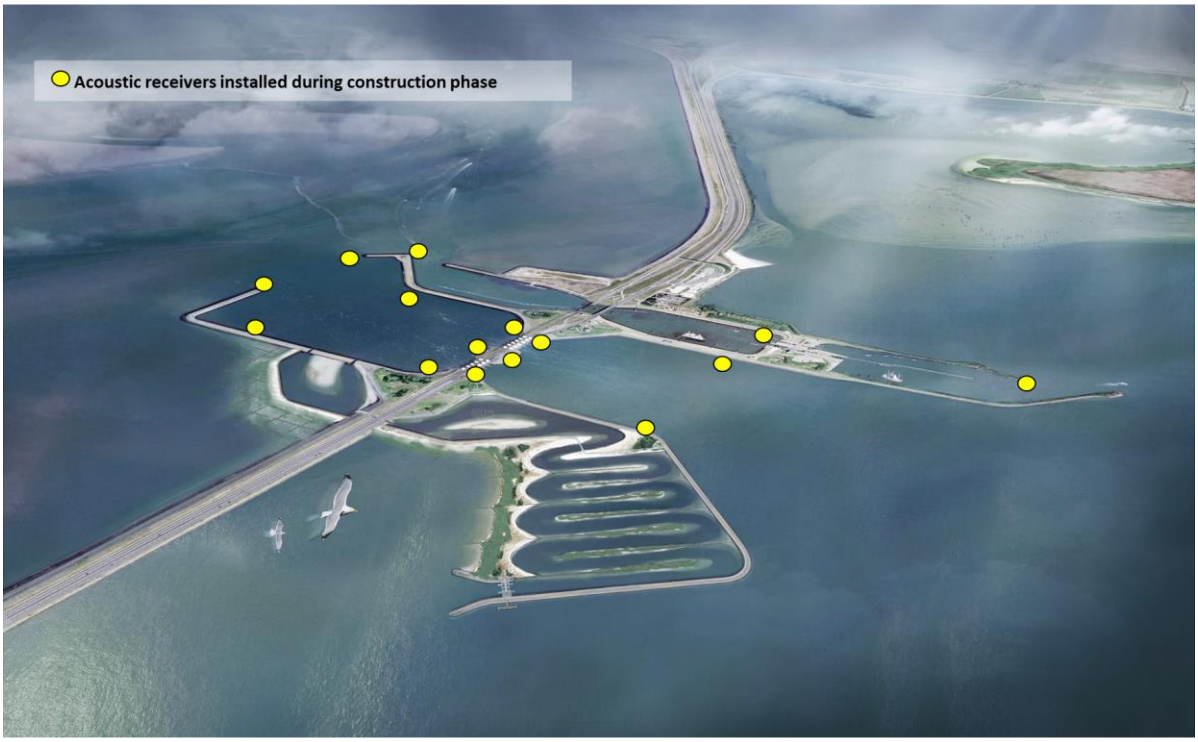

Figure 18. Basic setup for an acoustic telemetry setup during the construction phase of the FMR. Tagged fish used for other programs can reach Kornwerderzand and provide additional data for the current state of passage success or feeding behaviour in the discharge basin.

The following questions must be answered during this phase:

1) *Are all permit requests being handled/ready?*
    a. *'Waterwet' permit (water authority)*
    b. *WOD permit (animal welfare)*
    c. *Fisheries permit (is requested via the Dutch statutory tasks)*
2) *Where can holding tanks be placed to temporarily store the target species?*
3) *Are the receivers being ordered and ready for use?*
4) *Which fisherman are able to help to install the receivers?*

It has to be explored whether during this phase PIT arrays can already be designed and tested in the field.

8.3 Adjustment phase I

Acoustic telemetry setup

During this phase, additional receivers can already be installed (Figure 19) and fish that are tagged in other programs (e.d. Waddentools Swimway, Eems Dollard, etc) can potentially be detected in the FMR. However, a large campaign to catch and equip large diadromous fish is not recommended during this phase. Hydrodynamic optimisation is still in progress and fish behaviour can therefore be altered depending on waterflows. Nevertheless, a small set of transmitters should already be present in the case of a catch of a rare species in the annual netting program covered in the Dutch Statutory tasks. Species like salmon, sea trout, etc are only occasionally caught and should be carefully treated to equip them with transmitters once they are caught. Those fish form a valuable baseline in the following phase. In addition, it is also useful to explore tagging procedures of larger individuals of smelt and twaite shad[3].

[3] Both are fragile fish of which the smelt is a relevant target species for the FMR. It is doubtful whether twaite shad should be a target species since there is no suitable spawning habitat present as described in winter et al. 2014.

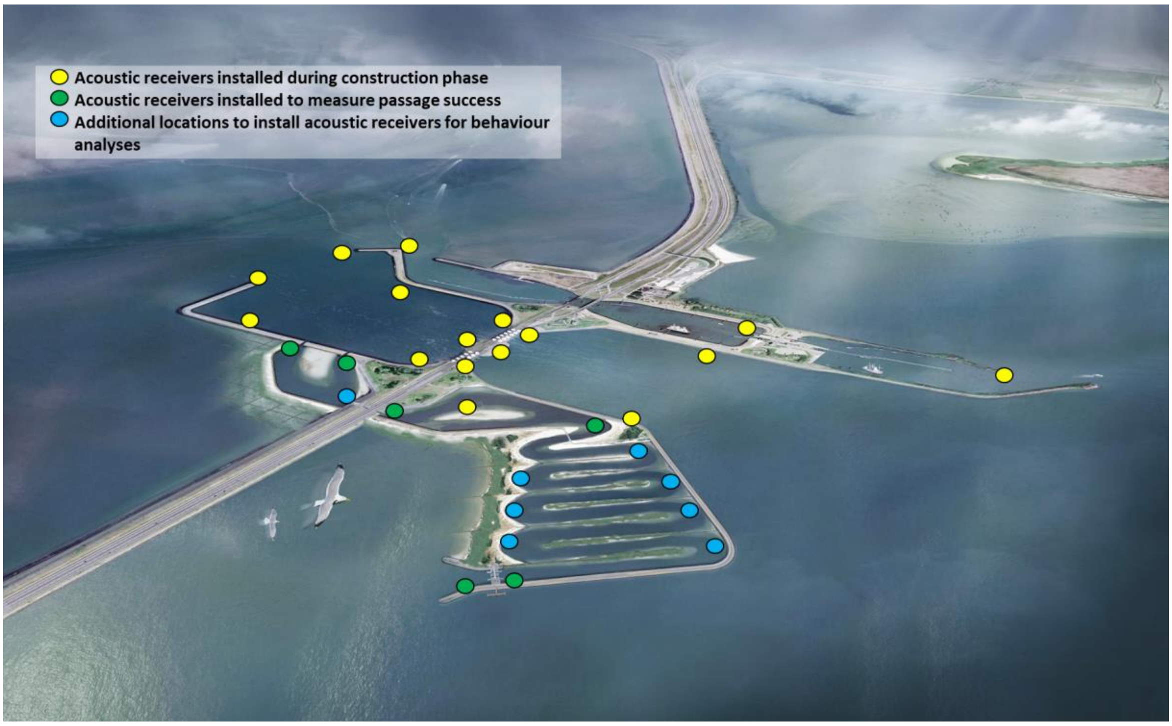

Figure 19. Full acoustic telemetry set up to study passage success but also to observe delay and other behaviour. Note: blue and green position need to be evaluated once the project is running. Overlap in detection range may be present.

PIT arrays
Pit arrays need to be designed, tested and installed in the vertical slots and in the sluice gates (Griffioen and Winter 2017, Griffioen et al. 2023). These arrays should be built and tested under high salinity circumstances considering the reduced detection ranges compared to freshwater conditions. Comparable designs and dimensions are used at large pumping stations in the North Sea Canal (Griffioen et al. 2022b), although other, more durable, material is recommended (synthetic/fibre glass) instead of aluminium frames.

8.4 Adjustment phase II

During this phase a full-scale netting program (both active as passive techniques) must be conducted to catch large diadromous fish (Table 4). Most of these species are caught only occasionally in the general netting program of WMR. Therefore, additional effort is needed to ensure catches of large diadromous fish. Different types of nets, depending on fish species and period of the year, should be used to ensure the numbers of target species are met to collect sufficient data. Traps can be installed in and around the FMR depending on progressive insights (Figure 20) and additional seining and stow netting is carried out in the discharge basin conform previous research programs (Griffioen et al. 2014b). Additional rod fishing (in cooperation with Sportvisserij Nederland) can help to catch sea trout, although from experience we know that getting sufficient numbers of this species remains a challenge.

Table 4 Main activities for the acoustic telemetry program including PIT tag. Three spined stickleback and smelt are potentially caught in the netting program of small diadromous fish (see section 6.2).

	PIT tag	Acoustic	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
			Expected migration season														
Atlantic Salmon	X	X															
Three spined stickleback	X																
Twaite shad	X	X															
Houting	X	X															
River lamprey	X	X															
Smelt	X?	X?															
Sea trout	X	X															
Sea lamprey	X	X															

Activity	Frequecy	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Administration																
Request permits (e.g. ethical committee)	yearly	depending on progress														
Organize equiopments (e.g. sugery material)	yearly															
Contracts fisherman																
Buy transmitters																
Buy/organize receivers																
Install receivers																
Design and built PIT arrays																
Install / maintain PIT arrays																
Check data PIT arrays																
Install traps/fykes (sea lamprey, houting)	Daily during peaks but at least twice a week															
Beach seining (seatrout, houting, shad, salmon)	Upon request															
Netting (kuilen voor rivierprik en grote spiering)	Upon request															
Check receivers (collect data, change batteries)	yearly (batteries) collect data (twice a year)															

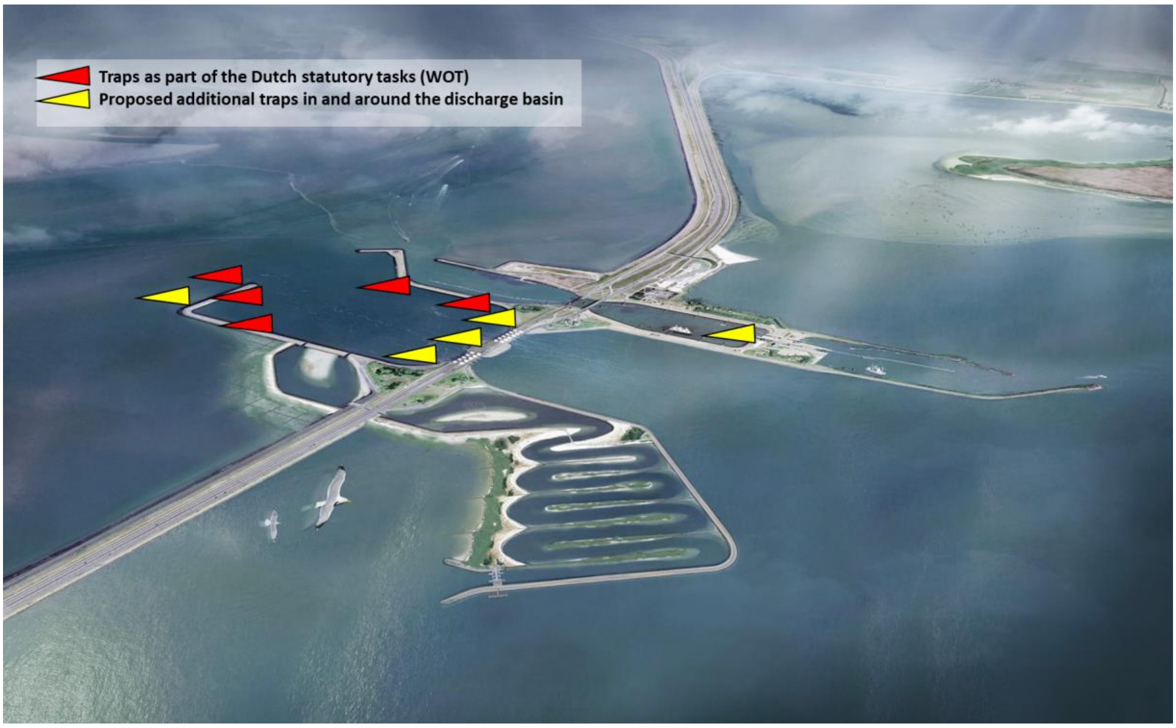

Figure 20. Current (red) and proposed (yellow) netting (trap) set up to catch larger diadromous fish. Note: yellow positions need to be evaluated once the project is running. Traps in the FMR are presumably not necessary, but optional for the optimisation phase.

Acoustic telemetry:
Different types of transmitters are needed to answer the research question as discussed in section 3. Depending on the catch composition in the traps and seine fishing, fish are equipped with a specific transmitter depending on fish size and research goal. River lampreys are relatively small and elongated fish that will be equipped with the smaller V7 transmitters. North Sea Houting can possibly be tracked for longer periods (foraging behaviour) and larger V9 or V13 with a longer battery life span are recommended to cover multiple years of migration behaviour. However, to prevent overlap in detection

range, V7 transmitters with a lower detection range, are recommended to ensure (relatively) the determination of small scale behaviour in the basin and in the FMR as previously used in sea lamprey (T0 study, Griffioen et al. 2022).

In principal, to also simultaneously study predation losses and potential predators, all river lamprey, sea lampreys, houting and sea trout will be tagged with acoustic transmitters with predation-sensors (acid solvable coating on the sensor that emits another ID after the predation event) and temperature sensor (to potentially determine from Vemco/InnovaSea (Boulêtreau et al. 2020). Predation transmitters will transmit the ambient temperature up to the predation event and the temperature measured at the time of predation will then be transmitted for the remainder of the tag's life after the predation event (Innovasea.com). As such these tags can provide an idea of the type of predator, e.g. seals, larger piscivorous fish or cormorants, who all differ in their body temperatures.

It is recommended to have a minimum set of transmitters ready in order to use when (rare) fish are caught. Also, a holding tank to temporarily store the fish is needed to effectively use occasional catches of rare species and to use the operational effort as efficiently as possible.

Fish that are expected to be caught in sufficient numbers are river lamprey and presumably North Sea houting and sea lamprey. Other fish are expected to be caught only occasionally such as sea trout. We propose to start with a batch of 25 individuals for each of these 4 species (or as close to it as is possible based on the catches) during the Adjustment phase II. This number is based on experience in previous studies: a trade-off between what is practically achievable and yielding enough information to answer the questions.

All fish will be also tagged with a 32 mm PIT tag and additional catches (e.g. when more than 75 of one species are caught) will be equipped with a PIT tag to enlarge the PIT-tagged group.

8.5 Optimalisation phase

Based on the results of the Adjustment phase II, additional batches of river lamprey, sea lamprey or houting can be tagged after alteration is FMR management or inventions that were taken and additional or reallocated receivers can be placed to zoom in on areas where bottlenecks for successful passage were determined during Adjustment Phase I and II Choice of sensors (e.g. depth, acceleration, predation) on the transmitters can be fine-tuned to the measuring of the behaviour in related tot the identified bottlenecks.

The current set-up and available equipment will also allow to study passage behaviour of facultative migrants such as sea bass, mullets, or study the return of 'washed out' freshwater fish. These can be caught using the ongoing monitoring fykes, or additional fykes as have been used in Adjustment Phase I and II.

9 FMR functioning as habitat for fish and predators

9.1 Introduction and general approach

In addition to using the FMR as a corridor during migrations between sea and freshwater, the FMR can also be used as habitat. The habitat functioning of the FMR in relation to fish can range from:

- Acclimatisation, when using the FMR as corridor moving from salt to freshwater (adjusting osmoregulation).
- Sheltering from predation (by piscivorous fish, birds or marine mammals) or adverse conditions (e.g. strong wind and wave action), near habitat structures or in vegetation.
- Foraging, some target species and estuarine residents may use the FMR as feeding habitat.

A variety of habitats and structures will be available in the FMR: rip-rap, or other hard substrates, along the shores and on the bottom of the seaside entrances, coupure and freshwater inlet. The majority of the bottom and shore substates will be soft sediments, mainly sand. Developments in vegetation will be monitored. To what degree maintenance is needed to control vegetation or remove debris that hampers the functioning of the FMR, is unknown and will be determined during adjustment phase I and II. Additional habitat features can be added or implanted during the construction phase or later, depending on the habitat development and prevailing bottlenecks that emerge from the results of the fish research and monitoring programs during the adjustment phase I and II. Currently it is considered to level the height of the levees and 'islands' in the more natural sections of the FMR so that they will be flooded during part of the tidal cycle. Therefore these will not serve as breeding sites for fish-eating birds, and provide less resting sites for birds in the direct vicinity of the FMR.

Predation by piscivorous birds, fish and seals in and around the FMR can have serious detrimental effects of passage rates of migratory fish moving from the Wadden Sea into lake IJsselmeer. Seal predation on migratory fish will be from the Wadden Sea side. To what degree they will also use the FMR is unknown. Potential fish-eating avian predators include cormorants, terns, gulls, grebes and merganser. Predatory fish that can enter the FMR can be both marine piscivorous species with high freshwater tolerance, e.g. sea bass, or freshwater fish entering from Lake IJsselmeer to feed on fish in the FMR, such as pikeperch, pike and perch. Providing shelter in the FMR may minimize these predation risks. The development of the habitat features in the FMR after construction, e.g. the development of vegetation along the shorelines and shallower parts of the FMR are unknown and will be closely monitored during Adjustment phase I and II. It can be decided to place additional shelter and structures in the FMR before we gain knowledge on how serious species-specific predation risks are ('no-regret' or 'precautionary approach'). Or these shelter providing structures can be placed during the 'Optimisation phase, only in case predation proves to be a serious problem in Adjustment Phase I and II. Within Waddentool Wadden Mosaic different hard structures have been tested in the Wadden Sea and these might also be applied in the FMR. However, these were mainly applied to enhance reef structures. Also, in rivers experiments with reintroducing large woody structures are conducted. Natural estuaries contain large quantities of woody debris and driftwood (Wohl & Iskin 2021). Structures like the pear tree-units are well-studied, reference to these original wooden structures in estuaries, yet are controllable and plug and play at any time of the different phases in the study. In parts of the FMR that are deep enough, they ideally need to be fully submerged throughout the tide to not serve as perches for piscivorous birds, and should not hamper flow conditions needed for a well-functioning of the FMR. Nor should they be exposed to adverse extreme conditions and subject to severe damage or displacement. The lake IJsselmeer side seems to be suited to provide with 'pear-tree' shelter-like habitat features.

Figure 21. Introducing shelter structures like 'pear trees' in and near the FMR, can potentially provide shelter to reduce predation risk.

9.2 Construction phase

During this phase a debate can take place on placing shelter structures in the FMR, and if so, how many and where and assess how this might affect the sediment- and hydrodynamics of the FMR. These can be explored with the models that are available. Based on this a decision can be made if, where and when shelter structures can be placed.

9.3 Adjustment phase I and II

Based on the above, the introduction of woody reef-like structures, and structures along the shore (rip-rap or other types of hard substrates) could provide reduced predation risk and provide habitat for foraging or more resident fish. Als vegetation development will need to be carefully monitored. In addition, the structure of the FMR, together with the availability of monitoring and sampling equipment gives opportunities to test more fundamental research questions. For example (Oscar Franken pers. comm.):

- The relative contribution of the three main drivers of the attractiveness of the reef structures for fish (food availability, reduction in predation pressure and reduction in flow velocity) could be experimentally tested.
- Using ADCPs to test the direct effect of the structures on local flow velocity.
- Testing the effect of placing weathered (with food) versus unweathered (no food) reef structures on fish abundances and community composition.
- Test how the development of communities of sessile organisms differs based on the abiotic conditions (i.e. salinity and fluctuations on salinity) along the gradient created by the FMR. Stations in the marine side, estuarine part freshwater side and in the river part as well as in Lake IJssel (full fresh water) and in the Wadden Sea (full marine water) will create a full estuarine gradient on very small spatial scales.

During the most intense field campaigns for tidal migrants and larger diadromous fish in the Adjustment phase II, frequent counts of piscivorous birds and mammals in and around the FMR should be carried out, to link predator presence and abundance to fish species-specific losses during FMR passage. Presence of piscivorous fish is more challenging, but the fykenet fishing for large diadromous fish species for tagging purposes may yield data on this as well.

9.4 Optimalisation phase

If it is decided to provide additional shelter for fish during the optimalisation phase, there are some aspects that need then to be considered:

- Constructing and placing artificial reef structures will need regular (annual?) checkups and possibly maintenance or replacement of the structures.
- Migratory fish could stay longer in the FMR, increasing their residence time, which may increase overall predation pressure in the FMR.
- Longer, or even permanent, residence of fish in the FMR while conditions further inland are even more favourable, may lead to an ecological trap in which the individuals do not reach their ecological optimal conditions.
- Structures might obstruct the passage or capture of floating material and larger debris or drifting plant material.

Overall, these risks or potential drawbacks should be compared to the possible benefits of placing the structures but can be further evaluated during the optimalisation phase when needed.

10 Coupling abiotic dynamics and fish behaviour using modelling methods

To study attraction and passage behaviour of the different target species in relation to abiotic dynamics, different model approaches can be combined.

Multiple modelling techniques are available to analyse movement and environmental data. These can roughly be divided into statistical descriptive models using empirical data and mechanistic models such as Individual Based Models (IBMs), more geared toward explaining the behavior in relation to the hydrodynamics.

The simplest of these are correlative statistical techniques, such as generalised linear models (GLMs) and their derivatives. These modelling techniques can link movement parameters, to environmental variables such as flow velocity or food availability. These modelling techniques can also be adapted to include individual variability. When working with presence/absence data one should be careful in interpreting absences. A lack of detections might indeed be a true absence, but might also be the result of reduced detection probability (Payne et al., 2010).

Individual-based modelling is a well-suited method to couple individual fish movements to a hydrodynamic models that is developed for the FMR and the Kornwerderzand complex and validated models have high predictive power. Several studies have showed that IBMs are useful tools for investigating responses of fish to hydrodynamics (Kerr et al. 2023, Goodwin et al. 2006, Mawer et al. 2023). IBMs can capture individual processes, behaviours, and responses to parameters under changing conditions, and simulate the fine-scale movement of individual fish within a population as they attempt to find for example a passage (Mawer et al. 2023). Coupling acoustic telemetry data with hydraulic modelling will even provide more insight in fish behaviour – e.g. what environmental cues are the fish responding to (Mawer et al. 2023). For example Goodwin et al. (2006) developed an Eulerian–Lagrangian–agent-based method (ELAM) that is well suited for describing large-scale patterns in hydrodynamics as well as the much smaller scales where individual fish make movement decisions.

These models will be fed with data on behaviour as derived for the mark-recapture experiments for small migrants and from the telemetric studies on large diadromous fish. When well validated, these IBM models can then also be used for scenario-studies to optimize different FMR management strategies. Data collection for hydrodynamic modelling are collected as described in (Griffioen et al. 2023) and can be carried out on different spatial levels from inside the FMR to the entire sluice-complex of Kornwerderzand.

IBM models that will be developed within the PhD-project of Melanie Meijer zu Schlochtern in the 'Haringvliet-Kier' studies, can act as a basis for adjusting and applying these for the FMR as well. Internationally, the ecological engineering group of prof. dr. Paul Kemp from University of Southampton has large expertise on developing IBM models for diadromous fish. These models are potential powerful and predictive models that can help exploring scenarios and aid decision-making in drafting and fine-tuning management protocols to optimise species-specific and seasonal functioning of the FMR.

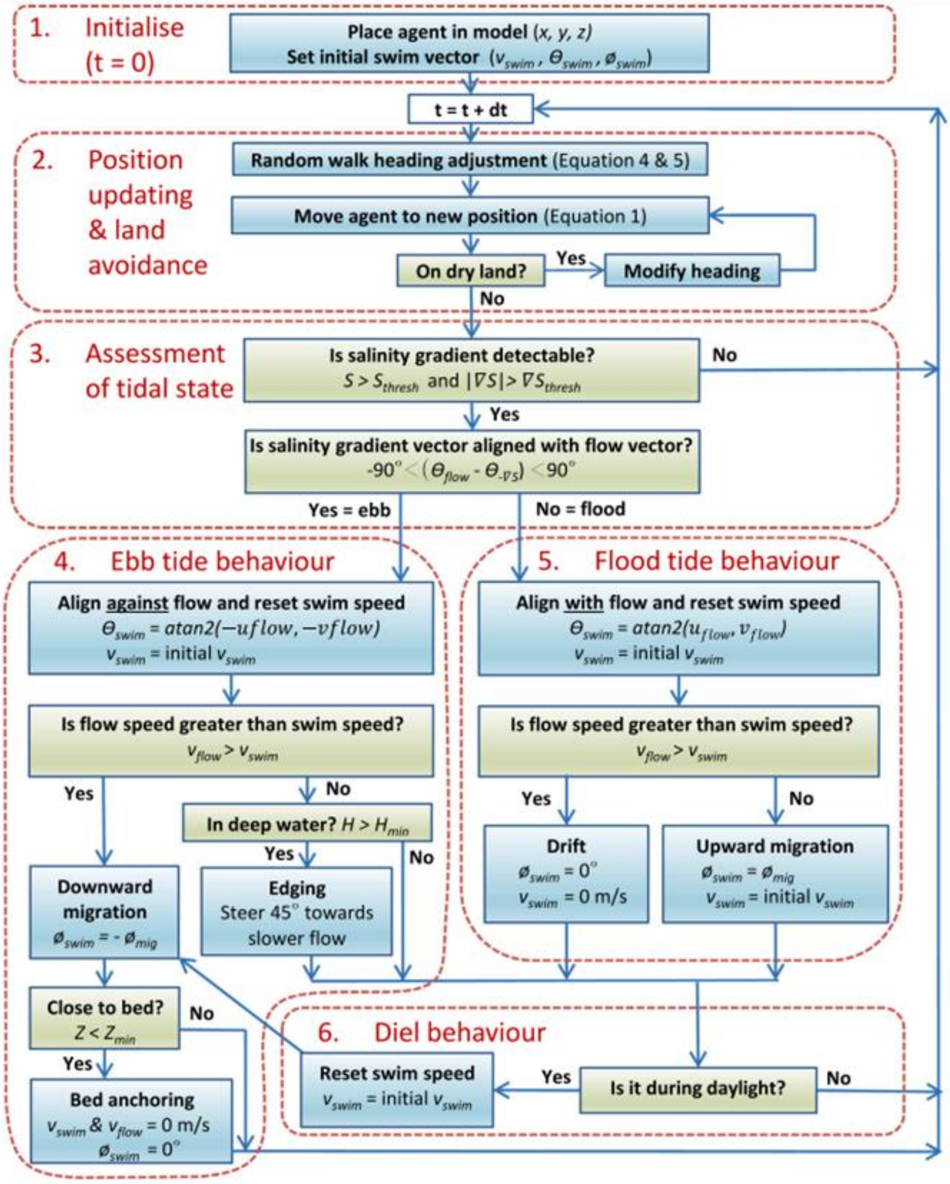

Figure 22. Schematic overview of an IBM for diadromous fish behaviour (Benson et al. 2021)

11 Links to other ongoing and future research projects

To understand passage success, habitat use and seasonal patterns of fish migration, but also to evaluate the functioning of the FMR from a wide perspective, it is important to ensure cross-pollination between ongoing and future projects. To increase data collection and to ensure knowledge exchange on a national (Figure 23) and an international (Figure 24) level, communication between projects is key for an ecosystem approach. For example, fish, equipped with transmitters, will swim along the coast or in upstream areas out of the scope of the FMR, but will give additional data on behaviour and passage success from a wider perspective than the FMR when data is exchanged. It is also important to keep track of population trends and population dynamics considering the future evaluation of the FMR and the effects on a population level (chapter 12). Therefore, a long list of ongoing and future (larger) projects in the Netherlands is presented below to keep track of the up-to-date knowledge and experiences in the field. The plans for the FMR may benefit from these projects or vice versa. In addition, it is important to keep track of international studies and experiences with similar fish species or sites (e.g., Elbe).

Cross-pollination between projects and keeping track on technical developments is important to:

- increase data exchange of acoustic transmitters and data collection (e.g. European Tracking Network ETN).
- design or to adjust protocols for tagging fragile fish species. Knowledge exchange of fragile fish species is needed to fully use all available experiences considering fragile fish species, such as smelt or twaite shade which are difficult to equip with transmitters.
- adjust or refine methodologies or research approaches (e.g., netting, timing, data processing, modelling) based on other experiences ('lessons learned') such as the Haringvlietdam Kier, Nieuwe Waterweg, North Sea Canal, Eems Dollard.
- increase data input for IB modelling. For example, what are location specific behavioural patterns of fish in relation to environmental cues and what are more generic processes that can be used interchangeably. Information exchange will also clarify knowledge gaps which may need to be further studied. During the Adjustments Phase additional and specific experimental laboratory experiments will help to further optimise modelling to further understand fish behaviour in relation to environmental cues.
- fully use the technical potentials of current technical possibilities such as: video monitoring including artificial intelligence, eDNA, specific transmitters (e.g., predation or acceleration tags), sonar acoustics, but also modelling techniques or software.

Swimway Wadden Sea

Within the Waddentools Swimway program (running until mid-2025), a large acoustic network is available for tracking fish in the western Wadden Sea (PhD Jena Edwards). This network is especially useful for the FMR to track fish that leave the Kornwerderzand area and explore the Wadden Sea itself. Tagged fish that are used for passage success of the FMR/Kornwerderzand can also be picked up in the Wadden Sea. In previous studies for example, most of the sea lamprey released near Kornwerderzand left the site and were never seen thereafter (Griffioen et al. 2022d). With a large network in the Wadden Sea the behaviour of these fish can be understand better. However the Waddentools Swimway program is coming to an end and currently routes towards prolongation of the network are investigated together with RWS.

In addition to the acoustic network, fish are sampled in a number of salt marsh creeks along the Groningen and Frisian coasts and on Schiermonnikoog. The artificially created salt marshes along the Dollard were also sampled for two years. This is part of the PhD project of Hannah Sharan-Dixon from the RUG. The results of this research will be available before the end of 2024.

In the sub-project on pelagic fish in the Waddentools Swimway program (PhD Margot Maathuis, WMR), stownet sampling was carried out year-round for pelagic fish and zooplankton at four places in the Wadden Sea. The results of this research will be available at the end of 2024. In addition, continuous acoustic measurements of pelagic fish have been carried out in the Marsdiep and the Eems near Borkum using a Wide Band Acoustic Transceiver (WBAT). These results have been partly published (Maathuis et al. 2023). Currently routes towards prolongation of the WBAT observations at the Eems location are explored together with RWS.

Haringvliet Kier
Multiple projects are ongoing near the Haringvlietdam. Knowledge of these project are of use for the FMR. One of these projects is the passage behaviour of large anadromous fish in relation to the consequences for sluice management and population rehabilitation (PhD Melanie Meijer zu Schlochtern). In addition, projects are running near the dam for small tidal migrant (Griffioen et al. 2017b, Bergsma et al. 2020, Bleile and Vriese 2021, Bleile and Vriese 2023). Similar to the Haringvlietdam (the Kier) and the FMR is to restore connectivity between sea and freshwater and both large as small diadromous fish will benefit from this connectivity. The FMR will benefit from the experiences and knowledge gained at the Haringvlietdam.

Ruim Baan voor Vissen (2)
The Ruim aan voor vissen project is a collaboration between four northern water boards, Van Hall Larenstein and the Waddenfonds. The aim of this project is a collaboration between parties that study the Wadden Sea in relation to the connection between freshwater areas. For example, a large part of this project is a PhD thesis (Donne Mathijssen) aiming to determine how improved connectivity and restored habitats benefit migratory fish species, as well as which bottlenecks still obstruct fish migration in the restored Westerwoldse Aa stream basin.

Vissen voor verbinding
Vissen voor verbinding studies the connectivity between Wadden Sea, Lauwersmeer and hinterland areas. It is an initiative of various water managers, authorities, and NGO's. Main target species is the sea trout, but also European eel, ide and three spined stickleback are target species.

Eems vissen in beeld
The Eems vissen in beeld project is part of the Ruim Baan voor Vissen 2 project, which focuses on improving fish migration between the Wadden Sea and the hinterland including creating a habitat for fish. Eems vissen in beeld is an initiative of the waterboard Waterschap Hunze en Aa's and Van Hall Larenstein University of Applied Sciences. The project is carried out in collaboration with various partners, including two German angling federations, the Niedersächsische Landesamt für Wasserwirtschaft, Küsten und Naturschütz and the Wasser- und Schifffahrtsamt. Part of this project is an acoustic telemetry network (similar as the network in the Wadden Sea as part of the Swimway projects). This network allows to track the presence and absence of tagged fish from Eemshaven to Bourtange and Lingen (Germany). However, also other methods are used to study small fish. Target species within the project are twaite shad, European eel, river lamprey, flounder, three spined stickleback and ide.

Wieringerhoek and PGAW (Programmatische Aanpak Grote Wateren)
The PGAW (including the Wieringerhoek) aims to maintain or improve nature and water quality including biodiversity in the lake IJssel and surrounding habitats. It aims to create a robust ecosystem that is adapted to climate change. Part of these areas are close by the FMR such as the Wieringerhoek (other side of the Afsluitdijk) and parts of the surrounding areas of the FMR (e.g., Frisian coastal areas). The FMR restores connectivity and the PGAW areas may benefit from the FMR or vice versa.

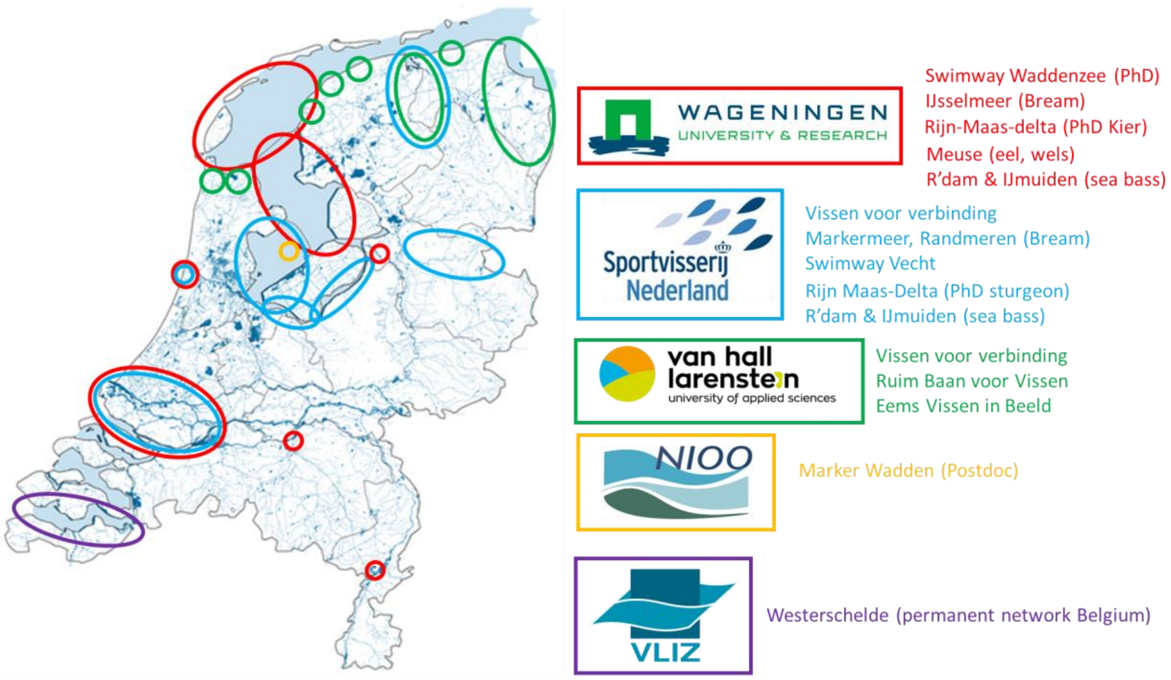

Figure 23. Examples of various ongoing projects in the Netherlands using telemetry and catching techniques (acoustic, netting, RFID, etc).

Waddenmozaïek

Wadden Mosaic is a project that focuses on a better understanding of the underwater nature in the Dutch Wadden Sea. Specific attention is paid to the deeper parts that are permanently submerged, even at low tide: the subtidal Wadden Sea. Part of the project is to study the effects of potential management measures for the protection and reinforcement of the subtidal area. The project ends in 2025.

Basismonitoring Wadden Sea

To better evaluate the Wadden Sea policy, the Basic Monitoring Core Team draws up analysis documents. In these analyses it is evaluated whether the current monitoring is sufficient to evaluate the policy goals. For fish the analysis has been carried out up to the phase where additional monitoring will be formulated (Tulp 2020). Several monitoring caveats have been identified, that might be filled up in the coming years.

International: European tracking network

The use of acoustic telemetry and building of networks rapidly increases. This means that fish tagged in FMR studies can be followed in other water systems or deeper into the upstream areas of the FMR. And vice versa, tagged fish from other studies might be detected at the FMR (opportunistic gain of data for FMR evaluations). Initiatives such as the European tracking network are important networks to increase the knowledge and data exchange. It aims to close the gap from a loosely coordinated set of existing regional telemetry initiatives to a sustainable, efficient, and integrated pan-European biotelemetry network embedded in the international context of already existing initiatives (https://europeantrackingnetwork.org). The network achieves this through meetings & collaborations, the maintenance & development of a centralised database, promote and support technological advancements, workshops and training, concerted actions for funding, communication & dissemination, and feeding the data and findings into policy and management frameworks. After installing acoustic receivers in and around the FMR, the network and transmitters need to be part of this pan-European biotelemetry network to get additional data when fish are leaving the FMR or the Wadden Sea. Potentially signals are picked up in other international acoustic networks for a better understanding of (international) fishways, use of habitats and seasonal migration routes.

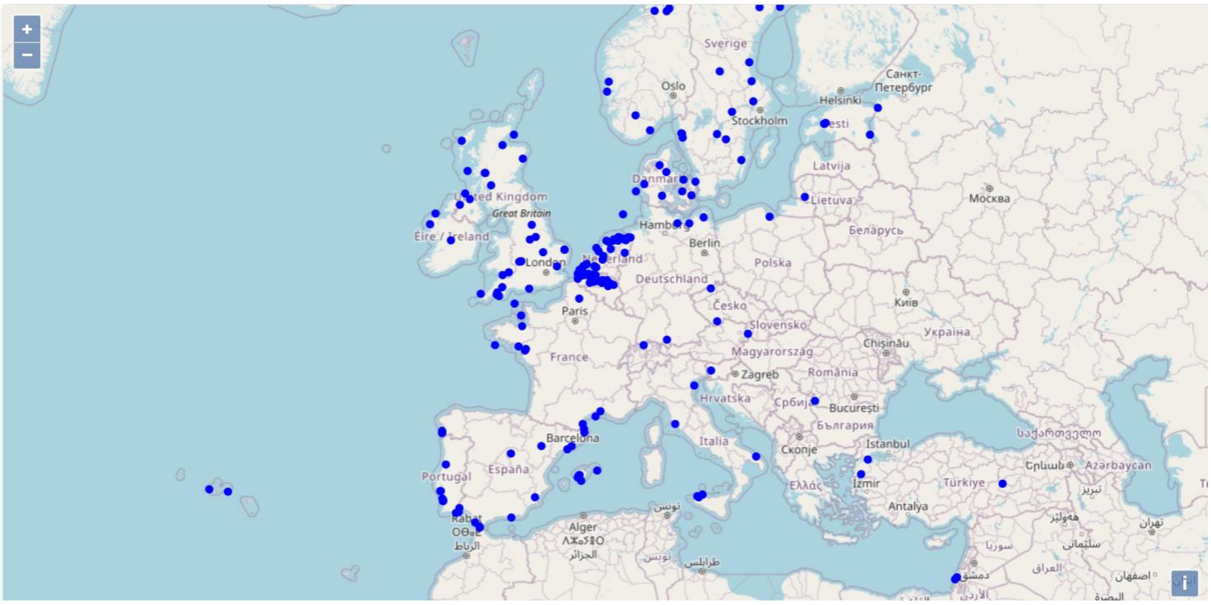

Figure 24. An overview of all ETN network projects with receiver arrays in Europe covered by the central database of ETN (https://www.europeantrackingnetwork.org).

For modelling behaviour of diadromous fish in relation to abiotic conditions and cues, the research group on ecological engineering of Prof. Dr. Paul Kemp from the University of Southampton (UK) has extensive expertise on developing agent- and individual based models for migratory fish. Specific applications they studied and modelled relate to how understanding of the behavioural ecology of fish can help solve challenges in sustainable water and energy engineering, particularly on how the physical environment influences the behaviour and physiological performance of fish, and how manipulation of that environment by engineering means can be used to mitigate for negative impacts of water and energy resource development.

12 Evaluation of the FMR on population, fish community and food web levels

The research and monitoring studies addressing Q5 'Effect of the FMR on population, fish community and food web' are not covered by the reserved budget for carrying out the research and monitoring plan. Effects of the FMR on a fish population level and fish communities are to be evaluated on the long term (>10 years after construction), while the research and monitoring plan as proposed in Q1-4 aims to evaluate and to optimize the FMR on the short term (<3-5 years after construction). The proposed research program aims to design an integrated operating protocol for the FMR based on fish behaviour as studied in Q1-4. Yet we sketch here some options and opportunities to address research question Q5 for future purposes.

Species-specific trends in long-term fish monitoring programs
A comparison of species-specific trends in long-term fish monitoring programs in adjacent waters (Wadden Sea, IJsselmeer, Rhine basin) is a way to analyse whether densities show an increase after construction of the FMR. In a previous study, a similar approach was used to indicatively assess the effects on sluice management and small diadromous fish such as flounder larvae (Winter 2009). If connectivity is the only bottleneck for some of the diadromous populations and passage success of the Afsluitdijk is improved with the FMR than a positive response in trends is expected. There is a number of long-term monitoring programs that can be used to evaluate such trends (e.g., Dutch Statutory work and other international monitoring programs, Table 5). However, for data interpretation and to understand the trends from a wider perspective, it is also important to study more in depth processes and include studies on food availability, diet, habitat connectivity, spawning ground status, etc.

Table 5. Main national (Dutch) and international monitoring programs.

Area	Specific area	Program	Method	Period
Wadden Sea	Western Wadden Sea, Eastern Wadden Sea, Ems-Dollard	DFS (Demersal Fish Survey)	beam trawl	Aug-Oct
Wadden Sea	East Frisia, Jade + Weser, Elbe, Dithmarschen, North Frisia	DYFS (demersal Young Fish Survey)	beam trawl	Aug-Oct
Wadden Sea	Western Dutch Wadden Sea	NIOZ fyke	fyke	Mar-Jun, Sep-Nov
Wadden Sea	Western Dutch Wadden Sea	WMR fykes	fyke	Apr-Jun Sep-Nov
Wadden Sea	Jade-Weser	Jade stow net	stow net	Apr-Jun, Aug
Wadden Sea	Dithmarschen, North Frisia	Schleswig-Holstein stow net	stow net	Aug
Wadden Sea	Ems-Dollard, Elbe	German estuaries stow net	stow net	Apr-May, Sep-Oct
Wadden Sea	Danish Wadden Sea	Danish rivers tagging studies	tag-recapture	Oct-Dec
Wadden Sea	Western Dutch Wadden Sea	NLeel	lift net	Mar-May
Wadden Sea	Western Dutch Wadden Sea	NLeel	elverfinder	Mar-Jun
Wadden Sea	North Frisia	WGeel	trapping ladder	n.a.
Wadden Sea	Danish Wadden Sea	WGeel	Electro fishing	3x/year
Lake IJssel	Dutch lake IJssel area, Dutch rivers	WMR fykes	fyke	Mar-May Sep-Nov (Dec)
Lake IJssel	Dutch lake IJssel area	FYMA Open Water monitoring	beam trawl	Okt-Nov
Lake IJssel	Dutch lake IJssel area	FYMA Open Water monitoring	electro trawl	Okt-Nov
Lake IJssel	Dutch lake IJssel area	Shore monitoring	seine, electro fishing	Aug-Sep
River Rhine	Dutch branches of the Rhine (Waal, Nederijn/Lek, IJssel)	Diadromous Fish Monitoring	Fykenet ('zalmsteek')	Spring-autumn
River Rhine	German Rhine and tributaries (e.g. Sieg, Iffezheim), compiled by ICPR	Fishway monitoring	trap, video	Year-round

Analysing species-specific trends, could result in a negative result but does not automatically lead to a negative evaluation of the FMR. Passage efficiency of the Afsluitdijk might by high(er) due the presence of migration measures including the FMR. However, other bottlenecks such as loss of spawning grounds, reduced food availability, other factors further upstream or climate change might negatively affect trends. Vice versa, a positive trend might indicate an improved connectivity between the Wadden Sea and the lake/rivers, but better food availability or improved spawning grounds might also contribute to species-specific trends of fish. Comparing species-specific trends as previously done for the Wadden Sea (Tulp et al. 2022) needs long term data (>10 years), but to interpretate observed trends additional information is needed. Changes in trends are difficult to explain and assign to specific measures taken. To evaluate the effect of the FMR in isolation from to other changing factors is a daunting task because so many factors are changing simultaneously (e.g. fisheries at Lake IJsselmeer, temperature, nutrients).

Food web

However an ecosystem wide approach including food web analyses can shed more light on the ecosystem functioning, though this is challenging to achieve and requires data-rich study areas. The effect of the FMR on a food web level requires more in depth studies. Food web analysis on both Wadden Sea and IJsselmeer sides should include a multitude of trophic levels and taxa to evaluate foodweb functioning and interpretate differences in population trends (Christianen et al. 2017, Tack et al. 2024) and modelling approaches.

Population structure

The quantification of the effect of the FMR on population structure is more feasible. Tools like micro-chemistry analyses and genetics can give insight into which (sub)populations are able to reach Lake IJsselmeer and their contribution tot the total population within Lake IJsselmeer. For instance whether the contribution of diadromous smelt to the IJsselmeer spawning population has increased, can be investigated using microchemistry analyses of otoliths (Tulp et al. 2013). Genetic tools to separate populations are also particularly useful to identify fish of which origin is able to cross the Afsluitdijk barrier (Farrell et al. 2022, Kroes et al. 2023).

Fish community on both sides of the Afsluitdijk

As a result of the increased migration possibilities the entire fish community and food web of surrounding water systems may be affected. In addition to species-specific trends in long-term fish monitoring programs, multivariate approaches including not only migratory fish are needed to study potential changes in the fish community. Also effects on the size structure of the fish community can be expected (eg as the result of changed predation). These analyses can be carried out using the long term monitoring programs. Clear shifts in trends, for example if the abundance of founder on Lake IJsselmeer significantly increases after the construction of the FMR, can be attributed to a direct effect of increased migratory opportunities. However such analyses are purely descriptive and can yield only correlative relations with the FMR. A more mechanistic understanding of the effect of the FMR on community or food web levels need a theoretical modelling approach combined with extensive field datasets on different trophic levels. This is beyond the scope of this report, but important to establish with the insights and data gathered within the FMR monitoring and research program and programmes and studies listed in Ch. 11 and in the sections above.

Climate change

With rising sea levels and increased occurrence of summer droughts due to climate change, the number of barriers and levees in estuaries may further increase worldwide. The need to mitigate connectivity problems for diadromous fish may even become more urgent in the future (Little et al. 2022). Losing tidal dynamics, diminished freshwater discharge and dealing with subsequent series of barriers from sea to hinterland (Bice et al. 2023) further emphasize the need for solutions such as the FMR. In addition, climate change may also alter species composition and specifically change target species for the FMR. Some of these target species are especially susceptible to climate change. Smelt on lake IJsselmeer is already hampered by peak temperatures in some summers, and with further rising temperatures conditions may become unsuitable for this species to maintain viable populations (Keller et al. 2020). Also for Atlantic salmon and sea trout rising peak temperatures during summer may cause increasing problems and are already scarce in the monitoring programs including at the Afsluitdijk at

Kornwerderzand (WMROpenData 2024). This may override potential beneficial effects of the FMR in the future.

Finally, the design of the FMR is expected to allow for a more robust future perspective in contrast to measures which are dependent on river discharge (e.g., fish friendly sluice management or the Kier). In addition, the risk of freshwater fish that potentially will be flushed out is also expected to be reduced in the FMR as compared to measures taken with sluice management (tidal gates).

13 Quality Assurance

Wageningen Marine Research utilises an ISO 9001:2015 certified quality management system. The organisation has been certified since 27 February 2001. The certification was issued by DNV.

Acknowledgements

We would like to thank Theo Gerkema from NIOZ for constructive discussions on (his main contribution on measuring abiotic parameters is given in the first report: Griffioen, Perk, Gerkema, Röell, Winter (2023). 'Beschrijving onderzoeksfaciliteiten Vismigratierivier.' Wageningen Marine Research report C019/23. We would also like to thank Oscar Franken for his contribution to chapter 9, habitat functioning of the FMR.

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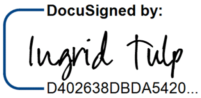
Justification

Report C020/24
Project Number: 4316100317

The scientific quality of this report has been peer reviewed by a colleague scientist and a member of the Management Team of Wageningen Marine Research

Approved: Dr. Ingrid Tulp
Senior Researcher WMR

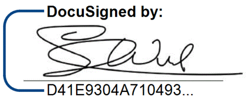
Signature:



Date: April 4th, 2024

Approved: Dr. Cas Wiebinga
Management Team WMR

Signature:



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With knowledge, independent scientific research and advice, **Wageningen Marine Research** substantially contributes to more sustainable and more careful management, use and protection of natural riches in marine, coastal and freshwater areas.

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