www.water-alternatives.org Volume 18 | Issue 3

Panagiotopoulos, P.; Buijse, A.D.; Roozendaal, L.; Winter, H.V.;
Nagelkerke, L.A.J.; Pauwelussen, P.P. 2025. Unravelling sociomaterial complexities
in river connectivity restoration: Understanding fishways as heterogeneous networks.
Water Alternatives 18(3): 579-601

Unravelling Sociomaterial Complexities in River Connectivity Restoration: Understanding Fishways as Heterogeneous Networks

Panos Panagiotopoulos

Aquaculture biology and Fisheries ecology Group, Wageningen University & Research, Wageningen, the Netherlands; panos.panagiotopoulos@wur.nl

Anthonie D. Buijse

Aquaculture biology and Fisheries ecology Group, Wageningen University & Research, Wageningen, the Netherlands; and Department of Freshwater Ecology and Water Quality, Deltares, Wageningen, the Netherlands; tom.buijse@deltares.nl

Luc Roozendaal

Environmental Policy Group, Wageningen University and Research, Wageningen, the Netherlands; lucroozendaal@hotmail.com

Hendrik V. Winter

Aquaculture biology and Fisheries ecology Group, Wageningen University & Research, Wageningen, the Netherlands; and Wageningen Marine Research, Ijmuiden, the Netherlands; erwin.winter@wur.nl

Leopold A.J. Nagelkerke

Aquaculture biology and Fisheries ecology Group, Wageningen University & Research, Wageningen, the Netherlands; leo.nagelkerke@wur.nl

Annet P. Pauwelussen

Environmental Policy Group, Wageningen University and Research, Wageningen, the Netherlands; annet.pauwelussen@wur.nl

ABSTRACT: In the context of river connectivity restoration, fishways play a crucial role in facilitating the migration of fish past barriers, but their form and functionality are often determined by various sociomaterial complexities. This study uses the case of fishway development in the Waterschap Brabantse Delta management area of the Netherlands to explore such complexities. Taking a network approach, we investigated the implementation and management of fishways as a process of assembling heterogeneous networks that involve both human and non-human actors. Using data from interviews, field observations and document analysis, the research revealed fishways to be networks of actors that included fish, engineers and maintenance personnel. We further demonstrate that fishways are embedded as actors, or 'nodes', within broader networks that exert a reciprocal influence on their functioning. By following fishways across different phases of their development trajectory and tracing the participation or withdrawal of actors, we explore changes in the networks and their subsequent impact on fishway design and performance.

KEYWORDS: Fish migration, fishways, river restoration, sociomaterial networks, the Netherlands

INTRODUCTION

Rivers worldwide are highly fragmented, with numerous barriers having been constructed to serve human interests such as irrigation, flood control, power generation and navigation (Belletti et al., 2020; Nilsson et al., 2005). This loss of river connectivity restricts fish movement and can have detrimental effects on fish populations, especially for migratory species (Limburg and Waldman, 2009). To compensate for the connectivity loss, fishways – also known as fish ladders or fish passages – emerged as a mitigation measure, with the first recorded fishways dating as far back as the 17th century France (McLeod and Neményi, 1941). De Lachadenède (1931) mentions regulations for the construction of fishways in dams and weirs in the French province of Béarn in 1662, describing these early fishways as steep bypass channels with fascines (bundles of brushwood) placed strategically to create steps that assist migrating salmon. The construction of fishways has since spread; in recent decades, in various parts of the world, it has become a common method for helping fish overcome human-made obstacles (Hatry et al., 2013; Heath et al., 2005; Lira et al., 2017; Mallen-Cooper and Brand, 2007; Shi et al., 2015).

In the Netherlands, fishways are the predominant choice for restoring fish passageways (Panagiotopoulos et al., 2024). The Netherlands is a low-lying delta shaped by centuries of water engineering. Historically, water in the Netherlands was seen as the "hereditary enemy" threatening safety and economic prosperity (Disco, 2002). From the 19th century onwards, water engineering intensified with large-scale channelisation and the construction of embankments, weirs and sluices, aimed at controlling the country's rivers for navigation, agriculture and flood protection (van Heezik, 2008). This created a heavily altered river landscape with one of the highest barrier densities in Europe (Belletti et al., 2020). This, in turn, fragmented natural habitats and severely disrupted fish migration. Since the late 20th century, growing environmental awareness has increased pressure to develop technologies that balance the traditional goals of safety and economic prosperity with ecological restoration (Disco, 2002). The regional water authorities (*waterschappen* in Dutch) are key actors in this transition (Brevé et al., 2014). They are responsible for water management in their respective regions and are the oldest form of democratic governance in the Netherlands, dating back to the 13th century (van Steen and Pellenbarg, 2004). There are currently 21 regional water authorities in the Netherlands, and collectively, they have jurisdiction over most sites where fishways have been constructed and longitudinal connectivity has been restored.

Despite the increasing concern regarding the restoration of longitudinal connectivity and even though fishways have proliferated both in the Netherlands and globally, many barriers still remain impassable for fish. Furthermore, constructed fishways frequently do not have the intended effect of sufficiently facilitating the movement of different fish species (Bunt et al., 2012; Noonan et al., 2012). Research on fishways is dominated by the biophysical sciences (Silva et al., 2018). In general, however, social science literature on water infrastructure suggests that fishways, like other water structures, are inherently social and political (Domínguez-Guzmán et al., 2022; Jensen, 2015; Morita, 2017; White, 2011). Science and technology studies (STS) and affiliated scholarship, as well, have shown how river restoration is always embedded in historical and existing sociopolitical and multispecies relations (Eden et al., 2000; Germaine and Lespez, 2017; Woelfle-Erskine, 2019; Druschke et al., 2017; Goedeke and Rikoon, 2008). These studies emphasise the need to consider the intertwining of sociopolitical, technological and ecological factors in understanding and addressing the challenges of restoration processes. Therefore, there is a need to expand the research on fishways beyond the biophysical sciences in order to address the often-ignored political and sociomaterial dimensions. This broader perspective can help explain why, where, and how fishways are built, shedding light on why they succeed or fail, and reveal the different purposes and interests they serve.

In this paper, we combine insights from fish passage science and STS to investigate the practices and relations that shape how fishways as sociomaterial infrastructure are enacted and 'work' in different contexts. We do this with a case study that includes fishways under the jurisdiction of the Waterschap (regional water authority) Brabantse Delta, the Netherlands. Inspired by network approaches, we adopt a perspective that views fishways as heterogeneous networks made up of human and non-human actors. This perspective allows us to investigate the complex web of relationships among diverse actors that shape the form and functionality of fishways. We identify the actors that influence fishway projects, following them as they form networks that shape and condition the way fishways are implemented and managed in different situations and phases of their development. We thereby aim to extend fishway science beyond its traditional engineering and ecological focus, offering a more integrated and socially informed understanding of how and why fishways 'work', or fail to do so, in situated contexts. As we will argue, investigating fishways as networks can inform policy about where (non-technical) bottlenecks arise- at various phases in their 'life cycles'.

In the following sections, after outlining our theoretical approach and the methods used, we first describe how fishways became a matter of concern in the Waterschap Brabantse Delta. We then turn to a case study of a fishway project, discussing how fishways emerge from complex sociomaterial networks where various human and non-human actors shape their design. We then show that fishway maintenance requires building and maintaining sociomaterial relations that keep fishways clear of accumulating networks of vegetation and debris that obstruct their functioning. Finally, we turn to a case study of fishways on a small river under the jurisdiction of the Waterschap Brabantse Delta. We show that the fishways are part of overlapping networks that compete for water and demonstrate how changing environmental conditions alter network dynamics, and how changing management priorities can transform fishway functioning.

A NETWORK APPROACH TO FISHWAYS

Fishways have traditionally been studied in terms of their abiotic (hydraulic) and biotic (fish passage) effectiveness – an approach that separates them from their sociopolitical context. However, there is a growing recognition of the need to incorporate social dimensions into fishway research (Silva et al., 2018). Recent studies highlight the social side of fishways; they point out how fishways have different costs and benefits for people (Cooper et al., 2019), the important role of policies in their implementation and management (Chen et al., 2019), and the influence of stakeholder motivations on fishway development (Bond et al., 2024). While all these studies demonstrate the importance of accounting for the social dimensions in fishway research, the common conceptualisation of fishways still tends to detach the social from the material, regarding these as separate study domains.

In this paper, we explore fishways as heterogeneous networks of social and material relations, and as situated within contexts that themselves consist of social and ecological relations. Over the past decades, relational network approaches have emerged in STS, geography, anthropology and affiliated disciplines. The aim is to trace and describe how (water) infrastructures emerge and function as entanglements of human, non-human, material and ideological elements that carry both ecological and political meanings and effects (Helmreich, 2023; Jensen, 2015; Meesters et al., 2024; Morita, 2017). These approaches have critically addressed the nature – culture and object – subject divides in environmental science that categorise the world into "material and ecological things" (to be studied by the natural sciences) and "social constructions and meanings" (to be studied by the social sciences) (Descola, 2014; Latour, 2005). However, network approaches are instead centred on the ways in which technologies and infrastructures are enacted through, and embedded in, the ongoing and dynamic entanglement of social and material elements (Bear, 2013; De Laet and Mol, 2000; Jensen, 2015; Latour, 2005).

Such approaches have proposed various terms to capture the dynamic and relational nature of the realities they study; these include actor networks (Law, 2008), rhizomes (Deleuze and Guattari, 1987), assemblages (Bear, 2013; DeLanda, 2016), entanglements (Corsín Jiménez, 2018), and relational networks (Pauwelussen, 2015, 2016). Despite their conceptual differences, they share a common ontological perspective on the world as inherently relational, networked and enacted in practice.

Following such a relational approach, fishways can be understood as the outcomes of a process of assembling heterogeneous relations into a sociomaterial infrastructure with a specific purpose (facilitating fish migration). The stability and form of objects and infrastructures – in this case, fishways – are then an effect of the interaction of material and social elements as they assemble and stabilise into a network (Callon, 1984; Law, 2012), as well as of the negotiation of the respective priorities and interests of the actors involved. Networks are therefore political, as they may serve certain interests more than others and may follow certain visions and priorities while overruling others (Pauwelussen, 2016). Such an approach goes beyond the traditional definition of fishways as fixed hydraulic structures; it investigates them as networks of actors and relational practices that are politically conditioned.

The ontological premise of networks as being enacted in practice does not mean that the components of the networks are predefined or that the human or non-human agents steering the design and enactment of fishways are predetermined. Instead, this is an empirical question to be explored through the tracing of relations (Latour, 2005). Importantly, the concept of network here is used as a heuristic tool to focus on the relationality and contingency of fishways. In a relational approach, anything can be a 'network' and networks can be described at different scales in time and space, depending on the focus of analysis. A network, therefore, may also belong to, contain, and partially connect to other networks (Law, 2008). As our own analysis will show, while a fishway may be conceptualised as a network, it may also be seen as a part of the regional network of water infrastructures in the Brabantse Delta, potentially overlapping with other networks.

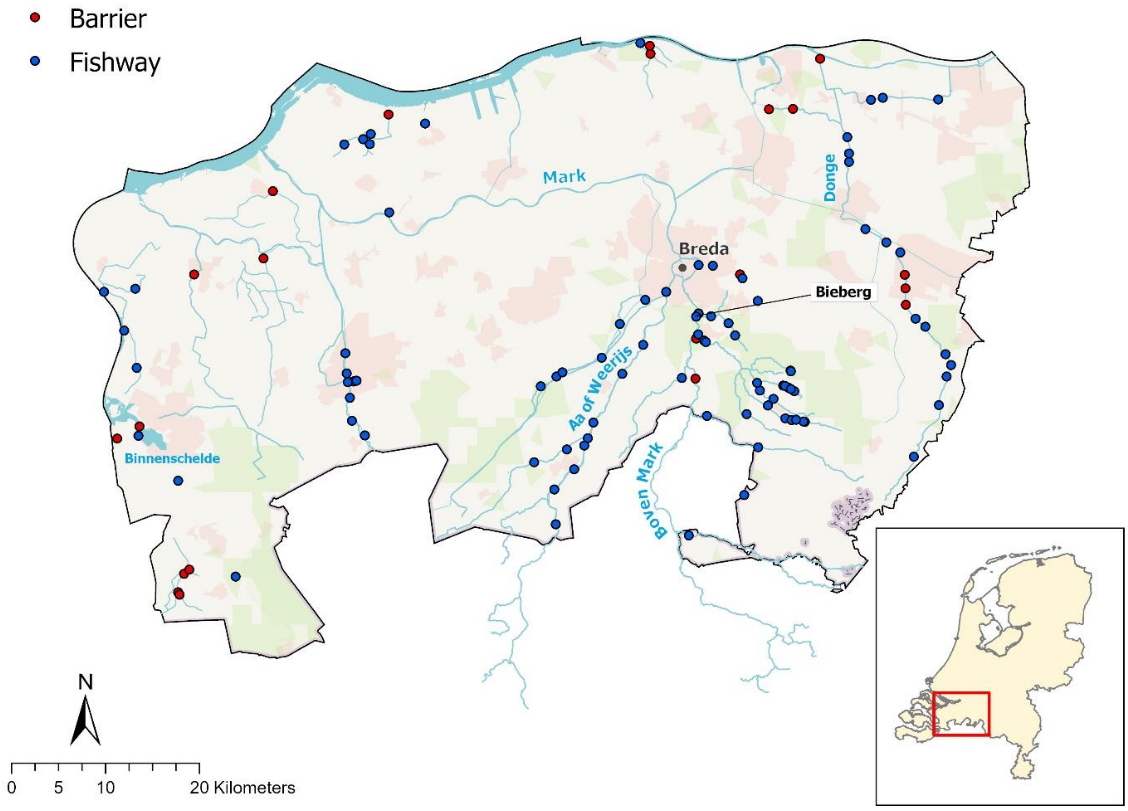
As fishways-as-networks are dynamic and continuously generated in relational practices, this also means there is a contingency and temporality to the way they take shape and function. Literature on river restoration (Angelopoulos et al., 2017) commonly refers to the way restoration projects, including fishways, are ordered along the phases of the project cycle, which unfold in the form of, for example, identification, design, implementation, monitoring and management (operation and maintenance). In this paper, we take into account this temporal aspect of fishway development while also acknowledging that the project cycle provides a rather linear and simplified depiction of the messy reality in which such projects take shape over time (Drouineau et al., 2018). However, as these more-structured, linear temporalities of fishway project cycles are dominant in the Netherlands, they affect how the design, implementation and management of fishways as networks take shape in practice. As such, the structure of this paper follows this phased approach and addresses different temporalities/timeframes within this structured fishway project cycle.

Investigating fishways as dynamic and heterogeneous networks allows for the empirical tracing of associations between various actors and elements within a network. It also reveals how such a network may dissolve when associations disassemble. Which actors associate to form a network, and how they do so, thus affects where and when fishways are realised and what they are designed to do. It also shapes both the 'functioning' and the 'non-functioning' of fishways.

RESEARCH AREA AND METHODS

The case study focuses on the Waterschap Brabantse Delta (Figure 1), which is tasked with the water management of an area of 1,710 km^2 in the southwestern part of the Netherlands. This area is characterised by a diverse range of landscapes including low-lying clay polders, riverine environments and higher sandy soils. This mosaic of landscapes accommodates a wide spectrum of land uses including agriculture, forest and nature, and urban development. The water authority is responsible for managing water in such a way that it supports these uses and developments. Amongst the responsibilities of the water authority is the restoration of connectivity for fish migration. While in other European countries complete barrier removal is gaining ground (Barraud, 2017; Mouchlianitis, 2023, 2024), the situation in the study area differs; instead, other technical solutions such as fishways are preferred. As we show in the following sections, in most cases the importance of weirs to different water users and for flood control purposes, in combination with the highly altered river systems, makes barrier removal unfeasible. The water authority thus aims to restore connectivity for fish mainly through the construction of fishways.

Figure 1. Map of the area under the jurisdiction of the Waterschap Brabantse Delta showing the implemented fishways (as of 2022), including the Bieberg fishway (implemented in 2003).



In this study, data collection was based on semi-structured interviews, document analysis and field observations. Interviews were conducted in English or Dutch and took place between September 2022 and January 2025. Using snowball sampling, we interviewed 37 people who were stakeholders in fishway projects. In-person or online interviewees included: water authority employees from different departments (15), engineers and consultants (6), staff from forestry and nature conservation organisations (2), contractors (2), representatives of local citizens' organisations (3), local and national government officials (5), and individuals engaged in recreational fisheries (2) and agriculture (2). All interviews were transcribed and imported into the ATLAS.ti software for coding and analysis. The interviews were complemented by field observations and document analysis. During October and November 2022, the first and third authors visited and documented 28 fishways, taking photographs and making detailed notes. The field visits aimed to better understand the local context in which fishways were situated, their design, and their maintenance and operation status. This documentation of observations allowed us to trace, describe and compare the material components and dynamics of fishways in different places and relate them to the insights derived from the interviews. Document analysis was used to identify the policies and guidelines of the Waterschap Brabantse Delta regarding fishways, assess the importance of fishways to the local fish species through monitoring reports, and explore the current and historical context of different rivers and brooks that may have influenced fishway development. The present study is part of an interdisciplinary research project on fish migration and fishways in the Netherlands.

THE EMERGENCE OF FISH MIGRATION AS A MATTER OF CONCERN

For decades, water management in the Waterschap Brabantse Delta served mainly agricultural and flood control purposes. Rivers and brooks were channelised and weirs were constructed. These modifications aimed to retain water during low discharge and release excess water quickly during wet periods to avoid flooding. However, the constructed weirs posed obstacles to fish migration. From the mid-1990s onwards, fish migration gradually became a matter of concern in the Waterschap Brabantse Delta. The first fishway was constructed in 1994 in the Binnenschelde, a recreational lake in the town of Bergen op Zoom. This fishway was designed as a so-called 'pool and weir' fishway whereby pools are arranged in a stepped pattern and separated by small overflowing weirs. The fishway's main goal was to provide access to a newly created spawning and nursery area for pike (*Esox lucius*).[1] From 1995 until 2008, fishway implementation in the area gradually increased. In 2009, fishway construction accelerated and most fishways were built thereafter. While the first fishway in the Binnenschelde was a special case and had only one target species, subsequent fishways were constructed mainly to improve overall river connectivity; this followed a multi-species design approach that was intended to support the unobstructed movement of all native fish species.

In 2006, the document "Policy Vision on Fishes" ("Beleidsvisie Voor Vissen") (Kroes and van Nispen, 2006) was published. It established a baseline for the role of fish migration in future water management plans and presented prioritised migration routes, bottlenecks to migration, and proposed solutions. The document's development was the result of a broader trend towards restoring freshwater fish populations, rooted in the European Water Framework Directive (WFD) (European Commission, 2000). Coming into force in 2000, the WFD obliges European member states to achieve good status in all bodies of surface water and groundwater by 2027 – 'good status' in this context refers to both good chemical and ecological status. The presence and health of fish populations are one element of biological quality used to assess the ecological status of surface waters. Member states are responsible for preparing their River Basin Management Plans (RBMPs). These include stipulated approaches and measures for protecting and preventing further deterioration and, where necessary, restoring water bodies in order to reach 'good' status. The document "Policy Vision on Fishes" was incorporated into the first RBMPs (2009-2015) and became the official policy of the water authority for fish migration.

The introduction of the WFD stimulated the Waterschap Brabantse Delta to transition towards a more ecocentric water management policy. As stated in "Policy Vision on Fishes": "Within the current water authority policy, measures are formulated to improve morphology, water quality, and water management. With the WFD, also fish become part of the assessment of all waters" (Kroes and van Nispen, 2006: 4).

Fish thus gained a more central role in the management policies of the water authority. As stated by an ecologist who serves as the water authority's internal advisor on fish migration: "The WFD ensured greater ecological awareness also for the role of fish in water management" (Interview, 10 October 2022). The water authority saw fishways as essential to helping fulfil its legal obligations to the EU by enabling the movement of fish and thereby contributing to the rehabilitation of fish communities. As the ecologist of the water authority further explains:

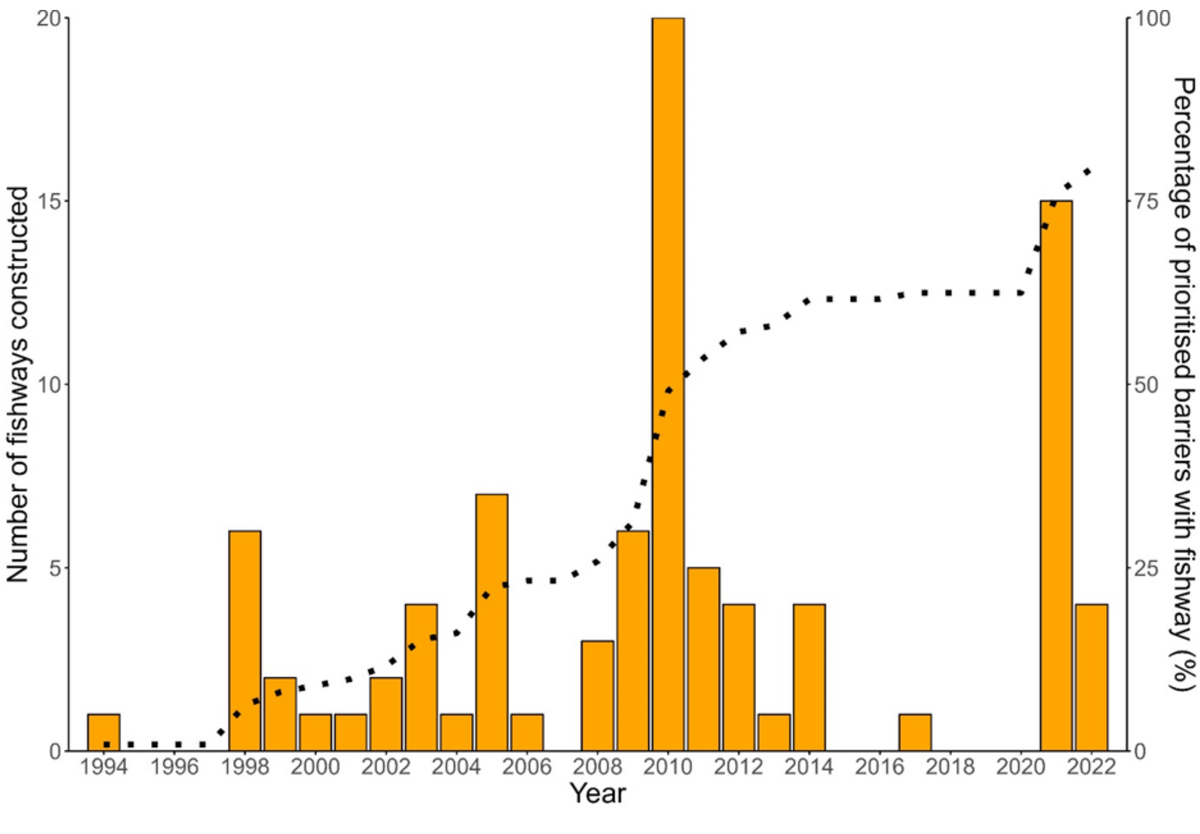
> We need to reach ecological goals, and fishways are a measure that can help us reach them. Therefore, as a water authority, we stated that we will construct fishways to achieve those goals. Then, of course, we must implement that. If we do not do that, we can be held accountable by the EU. (…). What I noticed at the water board in 2008, when there was a kind of financial crisis, and the years after that, it was sometimes a bit difficult with the available money. Agreements had then been made for the WFD, and they were not

[1] The Binnenschelde lacked suitable spawning grounds for pike. Maintaining a healthy pike population was deemed essential by the water authority in order to reduce benthivorous bottom-disturbing cyprinid (carp-like) fish populations (especially bream *Abramis brama*). The aim was to improve water clarity in the Binnenschelde, which in turn would promote a more diverse aquatic plant community. This newly created spawning area is situated at a higher elevation than the Binnenschelde, so a fishway was necessary for pike to reach it (Dekker, 2022).

> challenged. We have committed ourselves to the EU. It applies to all WFD measures that were laid down (Interview, 10 October 2022).

This demonstrates how fishways do not exist in a political-economic vacuum, but are instead challenged and influenced by economic phenomena such as the 2008 financial crisis. Political commitment in periods of economic uncertainty is therefore important for fishway implementation. By 2015, after the completion of the RBMP's first phase (2009-2015) and nine years after the document "Policy Vision on Fishes" was published, the number of fishways in the area had nearly tripled since 2006 (Figure 2). This highlights that the implementation of the majority of fishways was not an isolated regional intervention, but rather a more concerted response to the European-level problematisation of the ecological status of freshwater systems translated into the WFD legislation. Agricultural interests and safety concerns have long dominated the goals of water management in the Brabantse Delta, reflecting water management politics in the Netherlands more broadly (Ravesteijn and Kroesen, 2007). The acceleration of fishway development thus marked a shift towards considering more ecocentric values in decision-making around how and where water can flow and for what purpose. This provided the institutional conditions for fish migration to receive attention and funding, which then enabled the development of fishways as environmental infrastructures. The water authority's creation of a policy document on the future of fish migration in its jurisdiction further inscribed ecocentric values and concerns about fish migration as a key element of 'good' water governance.

Figure 2. The implementation of fishways in the Waterschap Brabantse Delta (1994-2022).



Note: Bars show the number of fishways constructed per year; the dashed line indicates the percentage of prioritised barriers that have already been equipped with a fishway.

FISHWAY DESIGN AS CONFLICT RESOLUTION

Increasing interest in fishways enabled their past and current development in the Waterschap Brabantse Delta. However, their actual implementation was not a done deal. Developing a fishway requires relational work that is contingent on social and ecological conditions in situ. Technical and ecological accounts of fishway development have already shown how interventions are the outcome of designing and planning practices that tie together technical and material relations. However, considering fishways as networks made up of both social and material elements brings into view how the development of fishways requires a process of aligning sociomaterial relations into a (temporarily) stabilised network that fulfils the purpose of enhancing fish mobility and river connectivity. The case of restoring river connectivity in the Boven-Mark exemplifies such a process.

The Boven-Mark refers to the upper section of the Mark River. It extends from its source in Zandvenheide in the eastern part of the municipality of Merksplas in Belgium to the Dutch city of Breda. The Dutch part of the Boven-Mark has a total length of 14 km. In the 1960s, large parts of the river between the Dutch-Belgian border and Breda were heavily modified. Meanders were cut off, the river channel was deepened and widened, and three weirs were installed to accelerate the drainage of excess rainfall, optimise water management for agriculture, and reduce flood risk (Beers et al., 2017). In 2003, one of the three weirs, the Bieberg weir, became passable for fish as part of a broader nature development project for the Mark valley. Led and funded by the Department of Rural Areas (a subdivision of the Ministry of Economic Affairs), the fish passage project was executed in close collaboration with the regional water authority, the province, the municipality of Breda and the Dutch state forestry service (Staatsbosbeheer). Yet, as we show below, the Bieberg weir was not only an obstacle to fish migration but also a crucial node in keeping together existing sociomaterial relations in the Boven-Mark, which conditioned the way that the fish passage project took shape.

The need for unobstructed fish migration in the Boven-Mark had been recognised years earlier. A 1994 monitoring study in the Dutch section of the Boven-Mark showed that certain fish species that were typically found in flowing rivers were observed in low numbers; these included ide (*Leuciscus idus*), bleak (*Alburnus alburnus*), and gudgeon (*Gobio gobio*), while other species, such as chub (*Squalius cephalus*) were completely absent (see Table A1 in the Appendix) (Quak et al., 1996). This poor showing notably contrasted with the reference image in the same study, which described what the fish communities in the Boven-Mark would ideally look like in a more natural state (Table A1). According to Quak et al. (1996), "Hundreds of ides migrate from the downstream section (Beneden-Mark) to the Boven-Mark every spring to reproduce in the tributaries. There is also a permanent population of fish that finds summer and winter habitat in the Boven-Mark. The same picture applies to the bleak".

One of the key causes of the degraded state of the Boven-Mark was the presence of weirs, which not only posed bottlenecks to fish migration but also obstructed the natural flow of the river through impoundment. The location of the Bieberg weir was crucial as it was the most downstream barrier, separating the Boven-Mark from the lower parts of the river. For the water authority, therefore, addressing the Bieberg weir was the first step towards restoring the Boven-Mark for fish migration and thereby promoting the recovery of fish communities.

Initially, the water authority ecologist proposed the complete removal of the weir and its replacement with a fishway – an option that was immediately opposed by the board of the water authority. As the water authority ecologist at the time stated:

> There was a brief consideration to remove the entire weir and place the fishway in the main stem, but the board of the water authority was very clear about this. They wanted to retain a last flood control measure for water discharge and water levels (Personal communication, 4 February 2025).

One of the water authority's main responsibilities is to prevent flooding in the city of Breda, which has 180,000 inhabitants. The Bieberg weir, located just upstream of Breda, is the final flood control structure before water reaches the city and thus is key to protecting it from extreme high-water levels. Its removal was therefore non-negotiable. The weir's importance to networked flood safety infrastructures caused the water authority to instead consider making it passable for fish via a fishway.

Consensus was reached on the appropriateness of building a fishway next to the weir; however, ideas and interests still differed among the involved parties regarding what the fishway should look like and what it should do. At first, the water authority had its mind set on a more 'natural' solution. In a personal communication on 4 February 2025, a water authority ecologist stated that, "We then clearly wanted a bypass channel, as it also offers spawning, nursery area and habitat for rheophilic species". Such a 'nature-like' bypass is designed to mimic a natural river channel. The land northeast of the weir would be provided by Staatsbosbeheer and was a suitable location. This type of fishway would provide a continuously flowing channel that would combine fish migration with the partial restoration of the flowing character and habitat diversity of the Boven-Mark – something that had been lost through the weir's impoundments and the river's channelisation.

The Bieberg weir, however, is also entangled in a wetland conservation network. Thus, while the 'nature-like' bypass option would overlap and support the network of habitat restoration, it would also intervene and possibly conflict with that of wetland conservation. The province of Noord-Brabant has designated the area upstream of the weir as wetland nature, which is managed by Staatsbosbeheer. The weir plays a key role here by maintaining adequate (ground) water levels and ensuring suitable hydrological conditions for the management of the wetland. A bypass channel would require a substantial part of Boven-Mark's discharge. Therefore, there was a risk that during drier periods, the discharge required for the fishway would drain the wetland upstream by lowering the (ground) water level. This conflicted with the provincial goals for the area and the management objectives of Staatsbosbeheer. As the water authority ecologist remarked, "There was also a significant trade-off between water for fish migration versus water for wetland nature (high groundwater levels)" (Personal communication, 12 December 2023).

Given these conflicting priorities, the challenge was how to design a fishway that could accommodate the weir's function in the network of wetland conservation while also supporting fish migration and habitat restoration. A Staatsbosbeheer representative explains their broader stance towards fishways when hydrological conditions can pose a constraint:

> Staatsbosbeheer is a landowner, and we implement goals of the province. In cases where we encounter a situation where the implementation of a fishway may lead to excessive drainage in a particular area, our approach is not to simply abandon the idea of a fishway. Then you think about the *type* of fishway. Maybe you don't have the ideal one, but you try to think of a middle ground (Interview, 10 November 2022).

This need for a middle ground to accommodate conflicting interests shaped the design process of the fishway at the Bieberg weir. An engineer from Arcadis, a consultancy firm, was contracted by the Department of Rural Areas and collaborated with the water authority's ecologist in exploring whether all interests could be successfully aligned in the design of a nature-like fishway. Describing his task, the engineer explains that,

> I was asked to do the hydraulic modelling. In the Boven-Mark, there was not enough discharge throughout the year to maintain the water level upstream. (…). If we were to design a regular bypass with V-shaped weirs we would have a problem with the water level upstream. So, I was asked by the water authority: *Can we design it in a different way?* (Interview, 24 January 2025).

With a nature-like bypass appearing feasible, the engineer and the ecologist had to balance the concerns and different requirements of the material and technical components of the fishway. As the ecologist further explains,

> Together with the engineer from Arcadis, we did a lot of calculations to achieve an optimal solution between: a) maximising the discharge through the bypass to create a strong attraction flow for fish, because its downstream entrance was relatively far from the weir b) keeping the fishway open for as long as possible; c) preventing negative effects on the wetland upstream (groundwater levels) (Personal communication, 4 February 2025).

The designers also had to consider the passage requirements of the different fish species. Although no document could be found about the target species of the fishway, the water authority ecologist indicated that, in line with common Dutch practice, it had likely been designed for all native fish species that would seek passage. In the end, a solution was found through designing a 500-meter-long nature-like bypass (Figure 3). Each element in the design played a role in aligning the different interests and needs of human and non-human groups involved in or affected by the fishway.

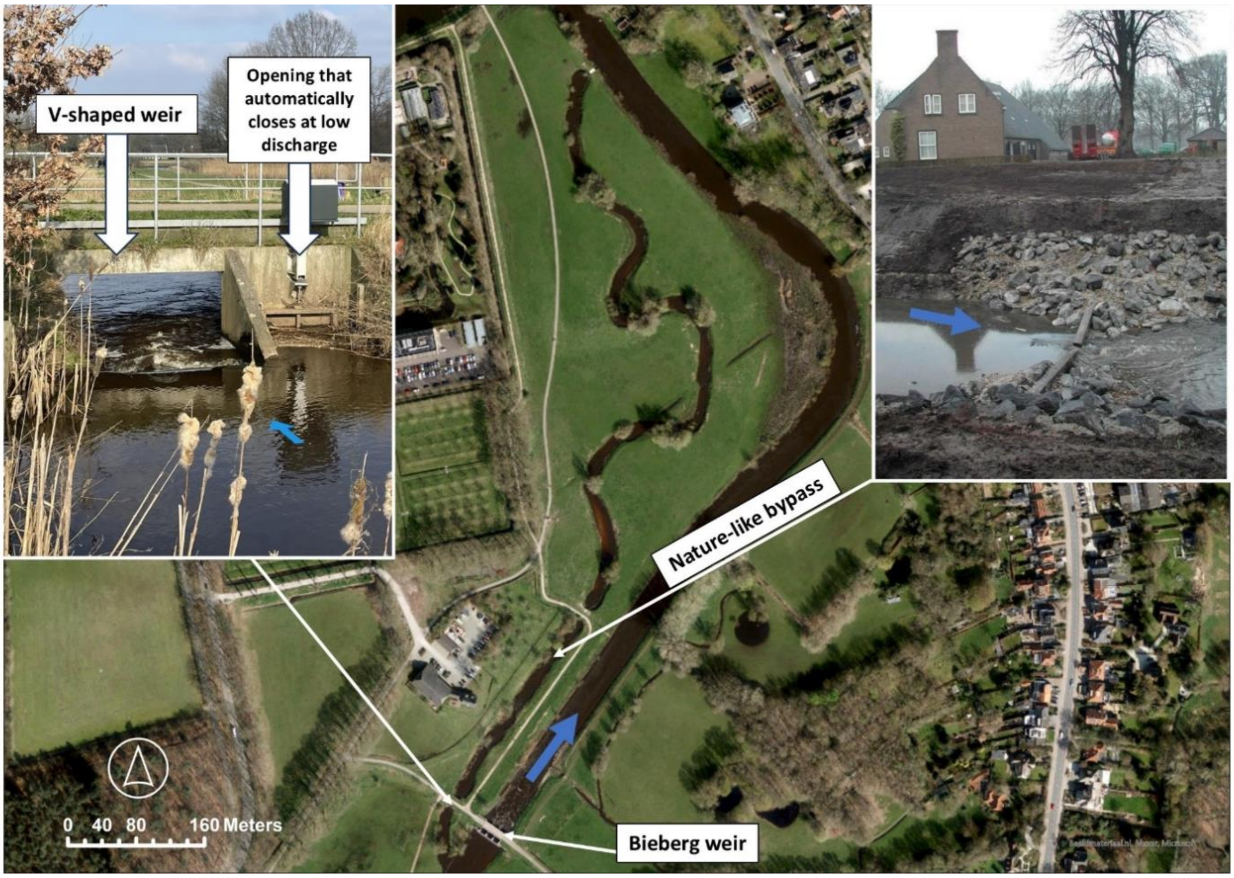
First, the Boven-Mark bypass featured eight steps separated by V-shaped weirs with vertical slots, with water flowing downward from step to step through the slots and over the weirs' crest (Figure 3 and Figure A1 in the Appendix). A vertical slot design was chosen in order to accommodate the various passage behaviours of the respective fish species, particularly bottom-dwellers.

Second, for the upstream side, two openings were designed (Figure 3). During average and high discharge conditions, fish could pass through both openings. During low discharge and when the water level upstream would drop below a set threshold, an automatic slide would seal the one opening, allowing migration only through the second opening, which consisted of a V-shaped weir without a vertical slot. The upstream water level could not drop below the lowest point of the 'V', in contrast to weirs with vertical slots, where the water level could drop to the bottom of the slot. The designers proposed this configuration to balance the interests of wetland conservation, fish migration and river restoration. The openings ensured that sufficient water would flow through the fishway to attract fish at the downstream entrance while also keeping the fishway open as long as possible. In this design, the water flow through the fishway would cease when the water level dropped below the lowest point of the V-shaped weir, preventing the wetland upstream from being drained.

The fishway design was materialised a few months later. Despite the careful deliberations on its form and design to make the fishway function well in different overlapping networks, the result still came with trade-offs. For example, bottom-dwelling fish species need a connection to the bottom to swim through barriers. Even small barriers (<5-17 cm) can block their upstream passage (Jones et al., 2021). Yet, in the chosen design, when discharge is low, fish migration is only possible through the V-shaped weir that has no vertical slot. Thus, during low discharge, bottom-dwelling fish such as gudgeon and spined loach (*Cobitis taenia*) remain marginalised.

The case of the Bieberg fishway highlights how fishways are a work of assembling relations that include both human and non-human actors. While often presented as material structures designed to accommodate the migration needs of fish, the Bieberg case shows that fishways' design and functioning are conditioned by the sociomaterial networks in which they are situated. As we showed, the design and implementation of the Bieberg fishway were shaped by the compromises and alliances formed among diverse actors. These included the water authority, different fish species and the city of Breda, all of which have different needs and purposes in terms of how the water flows. As both the weir and the fishway are also part of different networks of wetland conservation and Breda's flood safety, the process of designing the fishway also became a process of aligning these different networks (Figure 6a). In the two following sections, we further explore how fishways as networks can destabilise or even stop functioning in later phases of their 'life cycle'.

Figure 3. The Bieberg fishway; left: upstream side of the fishway showing two openings; centre: nature-like bypass fishway; right: details of a V-shaped weir with a vertical slot, just after construction.



Source: Left photo: authors; right photo: Waterschap Brabantse Delta.

Note: Blue arrows indicate the direction of flow.

FISHWAY MAINTENANCE AS NET-WORK

During our field visits to fishways in the area of the Waterschap Brabantse Delta in October and November 2022, we observed that many fishways were not functioning as intended. The vertical slots of a fishway in the Donge River, for example, were clogged with branches and leaves, obstructing the water flow and creating obstacles for fish (Figure 4). In another case, the nature-like bypass at the Bieberg weir was overgrown with vegetation, which was altering the water flow and making passage more difficult for fish (Figure 4). Despite their differences, these cases had in common that debris and vegetation were obstructing water flow through fishways, hampering their function.

Once a fishway is constructed, its continued functioning is not guaranteed. Its role in overlapping networks may shift or, as we observed in the Donge River, its ability to support fish migration may be undermined by encroaching vegetation and/or accumulating debris (Larinier, 2008; Moore and Rutherfurd, 2017; Valbuena-Castro et al., 2020). Because fishways can deteriorate structurally and because their role in networks is subject to change, keeping them functional requires regular physical maintenance. As we show below, however, if we consider fishways as sociomaterial networks, such maintenance requirements can also pertain to maintaining social relations.

During interviews, ecologists and other water authority employees frequently raised concerns about the maintenance of fishways. As a senior programme manager complained,

> I saw a photo from an ecologist a couple of weeks ago when he was taking all the debris away by hand from fishways because there was no way that fish could pass. Maybe somebody from the maintenance department must face the consequences of their actions. It is not difficult work (Interview, 31 October 2022).

The water authority's ecologists are its main advocates during the development phase; after implementation, however, fishway maintenance is no longer their responsibility. Instead, the responsibility shifts to the water authority's maintenance department, whose employees must conduct regular inspections and carry out any required upkeep. As the quote above suggests, maintenance employees may not always fulfil their responsibilities and may allow debris or vegetation to encroach and entangle with the fishway network, thereby destabilising its functioning. Thus, while the shift in responsibility formally brings new actors into the fishway network to maintain its relations, in practice, they may fail to enact this role.

Figure 4. Obstructed fishways; top: a vertical slot fishway at Donge (Groenendijk) clogged with debris; bottom: the bypass fishway at Bieberg overgrown with vegetation.

Source: Authors.

Fishways are one of many networks for which the maintenance department is responsible. It also maintains other networks such as pumps, weirs and dykes, all of which require attention and resources. As one maintenance employee put it, "We are responsible for the maintenance of so many different structures; fishways are just one of them" (Interview, 22 November 2022). Therefore, maintenance employees are actors in several overlapping infrastructural networks within the wider area of the water authority, of which fishways are only one. This overlapping of responsibilities, in combination with the limited personnel available, constrains the time and energy that employees are able to devote to maintaining the various aspects of a functioning fishway. For maintenance employees, fishways usually become a low-priority node in a broader network of maintenance. As a former maintenance employee described it,

> I stopped trying to keep those fishways functioning. The maintenance department already has a lot on its plate and has been better at saying no in recent years. The importance of fishways is not widely recognised in that department either, and this is a pity (Interview, 14 November 2022).

Fishway maintenance is typically the responsibility of experienced maintenance employees; however, shortages of personnel often necessitate engaging external actors. As one maintenance employee put it, "Because we can't always do everything ourselves, we sometimes hire contractors who go on the road with us" (Interview, 22 November 2022). These contractors have limited knowledge about how fishways are designed, the relations that constitute them, and how they are supposed to function. This can expose the network to different logics, as the contractors come with their own interpretations of what a good fishway is supposed to do and look like. For example, a maintenance employee described his experience with external contractors during the maintenance of fishways in the Chaamse brooks (tributaries of the Boven-Mark):

> A contractor had skipped a few fishways around Chaam, and then I went back to tell them to do those too. They [the fishways] were completely overgrown with vegetation. Then the contractor said: 'But there are all kinds of stones underneath'. 'Yes, *these [stones]* are the *fishways*!' I replied (Interview, 22 November 2022).

Another complication in the maintenance of fishways lies with the maintenance guidelines. The internal document entitled *Green Elements and Peripheral Facilities Management and Maintenance* provides instructions for employees on how to maintain fishways. However, the document covers only *certain types* of fishways. As one ecologist mentioned, "There is a guideline, but only for one particular fishway type, only for nature-like fishways" (Interview, 9 June 2023). The guidelines do not cover the maintenance needs of other fishway types present in the area, which exemplifies a disconnect between maintenance protocols – meant to guide maintenance practices – and the material needs of the actual fishways in place. The maintenance guidelines also prescribe fishway inspections for only *certain periods*: before the start of the spring fish migration period and monthly inspections during it; maintaining connectivity is thus prioritised for this part of the year only. This is reflected in the words of a maintenance employee, who told us that, "Maintaining the fishways, yes, in the spring, the early spring, we pay quite some attention to that. The rest of the year it's a bit of an afterthought" (Interview, 22 November 2022).

To effectively enable the life cycle of different mobile fish species, fishways need to provide fish passage year-round. Without year-round maintenance, debris and vegetation may obstruct the fishway's water flow and hamper the movement of fish. Even so, and as we also observed during our field visits, in the guideline document that prescribes fishway maintenance, fishways become an afterthought outside of the specified maintenance period.

The case of fishway maintenance in the Brabantse Delta showcases how enrolling new actors in the network throughout the different phases of fishway projects is essential for keeping fishways functioning and fulfilling their purpose. Maintenance personnel, contractors and guideline documents become actors in the network (Figure 6b); however, the connections (or lack thereof) between actors condition how and when fishways function. Debris or vegetation obstructs fishways' functioning only if the connections within the network are weak or poor; these can include limited personnel, untrained contractors, or inadequate guidelines. While fishway maintenance is often perceived as a technical task focused on the physical upkeep and cleaning of fishways, a sociomaterial network perspective reveals that it is essentially also about building and maintaining the relations that keep fishways *as networks* functioning.

FISHWAYS AS LEAKAGE IN A CHANGING ENVIRONMENT

In the summers of 2018, 2019, 2020 and 2022, the Netherlands was hit by prolonged and unprecedented droughts (KNMI, 2023). The combination of high temperatures with very low precipitation reduced water availability across the country. One of the most affected regions was the southern part of the Netherlands (Brakkee et al., 2021), where the jurisdictional area of the water authority is also located. The increasingly dry spring and summer seasons intensified competition for water in the area, with consequences for the performance of fishways. The effect of drought shows how fishways as networks are embedded in an environment that is changing. As we will show in this section, changing conditions such as drought can affect or alter the sociomaterial relations that constitute fishways. As a consequence, the fishway network may change shape, function or meaning to those involved in it.

This process is exemplified by the case of the Aa of Weerijs River. The Aa of Weerijs originates in Belgium and flows northwards towards the city of Breda. Originally, the river's source was located in a vast swamp area. The peat bogs had a sponge effect that made the discharge much more constant than it is today. From the 14th century, marshland areas around the Aa of Weerijs were reclaimed for peat extraction. During the 19th century, the demand for agricultural land led to large-scale heathland reclamation in the catchment area (Beers et al., 2018). In the 1960s, the Aa of Weerijs was channelised to accelerate the drainage of excess rainfall, thereby reducing flood risk and improving agricultural conditions, while weirs were installed to ensure sufficient water retention during dry periods. Today, agriculture is still the main land use in the catchment (73%); this includes a tree cultivation sector of high commercial export value (Jonoski et al., 2025), which relies on the river for irrigation.

The Aa of Weerijs has also been designated by the water authority as a fish migration priority route (Beers et al., 2018). Between 2003 and 2006, six vertical slot fishways were constructed alongside the weirs to allow fish migration. These fishways consist of a concrete channel divided into stepped pools, each connected by a baffle with a narrow vertical opening from the bottom to the top (Figure 5). The most downstream weir was replaced by V-shaped weirs with vertical slots. Fourteen target species have been identified for the water course, including the critically endangered European eel (*Anguilla anguilla*) (Table A1 in the Appendix) (Kroes and van Giels, 2009). However, similar to the Bieberg case, the constructed fishways aimed to facilitate the passage of all native fish species, rather than only the identified target species. In 2009, monitoring of four of the vertical slot fishways showed that a total of 20 different fish species were found to be using them to move upstream (ibid).

In the case of the Aa of Weerijs, a network of agricultural production meets a network that prioritises fish migration for the area. While the former requires weirs to manage water for irrigation, the latter requires these weirs to be passable for fish. The water authority has sought to accommodate these respective interests through the construction of fishways next to the weirs; this allows for both irrigation and fish migration, thereby making the water flow part of both networks and thus resolving the potential conflict. However, this solution worked only as long as the discharge was sufficient to allocate water to both fish migration and irrigation. When the Aa of Weerijs was affected by drought, water became scarce, and its allocation became a point of contention.

Figure 5. A vertical slot fishway (under the metal frame) in the Aa of Weerijs River near Wernhout, with agricultural land on both sides of the river.

Source: Authors.

For the Waterschap Brabantse Delta, the process of water allocation involves the water-level management department and the *centrale regiekamer* (central control room). The latter is a control room from which the operation and management of water infrastructure are coordinated, based on real-time information from the area including data on water quantity. Water-level managers oversee and operate weirs and fishways in the field. Based on water levels, the control room gives the official order to the water-level managers to adjust the infrastructure accordingly. When enough water is flowing in the Aa of Weerijs, the overlapping networks of fish migration and agriculture can coexist; sufficient water flows through fishways for fish and farmers have enough river water to irrigate their crops. On the other hand, when water levels drop due to decreased precipitation and high evaporation, it becomes more challenging for water-level managers and control room decision-makers to allocate water between these two networks. The water-level manager in the Aa of Weerijs describes the difficulty of decision-making regarding water allocation during drought:

> You must weigh everything at some point. I'll give you an example: imagine that you are a farmer and you have hundreds of thousands [of euros] worth of plants, and then someone from the water authority comes and says that you can no longer irrigate because the fish come first. What would you do? (Interview, 30 November 2022).

Water scarcity puts a strain on the relations between the networks and the actors of which they consist, which generates tension. Drought may cause an intensification of the differences between what fishways mean to the respective actors. For fish and the ecologists speaking on their behalf, for example, fishways are essential to the facilitation of movement and, as fish species migrate unevenly throughout the year (Kroes and Monden, 2005), keeping fishways in operation year-round is in the interest of both fish and ecologists. During drought, operational fishways can also play an important role in fish survival as they provide fish access to refugia – habitats where fish can seek shelter during extreme environmental conditions (Interview with water authority hydrologist, 14 October 2022). In contrast, for farmers and water-level managers who may favour agricultural interests, drought conditions turn fishways into a 'leakage'. This is where they are seen to compromise the function of the weirs in retaining sufficient water levels for agricultural interests. A hydrologist, describing the conflict in the control room, told us that:

> You can see that there is a conflict between our water level managers, who want to maintain high water levels, and our ecologists, who want to ensure that fish migration can take place. (…). With us, fish are mainly defended by the ecologist in the control room (Interview, 14 October 2022).

During drought, these two alliances of actors – fish and ecologists, and water-level managers and farmers – are in a tug of war, with the fishway's functioning at the centre. As an ecologist commented, "Then it is a discussion about which one is more important, the ecology or the economy", to which he then added, "It's already an unfair balance, I think" (Interview, 9 June 2023). Indeed, during drought the needs of irrigators are usually prioritised over those of fish, which results in fishways being closed by the water-level manager. As the water-level manager of the Aa of Weerijs explained:

> It is very nice that these fish can move towards Belgium, and if possible, that fishways are open. But from my point of view, letting the farmers irrigate is my number one priority. (…). The water is free draining. Water leaves and does not come back. I try to retain the water as long as possible. Well, that includes closing fishways. Then, there are smaller brooks from which little or no irrigation takes place. There, the fishways will stay open for a long time. In the large water bodies, like the Aa of Weerijs, the fishways close first, and this is a trade-off, and every year [there is] a battle between the water level managers and the ecologists (Interview, 30 November 2022).

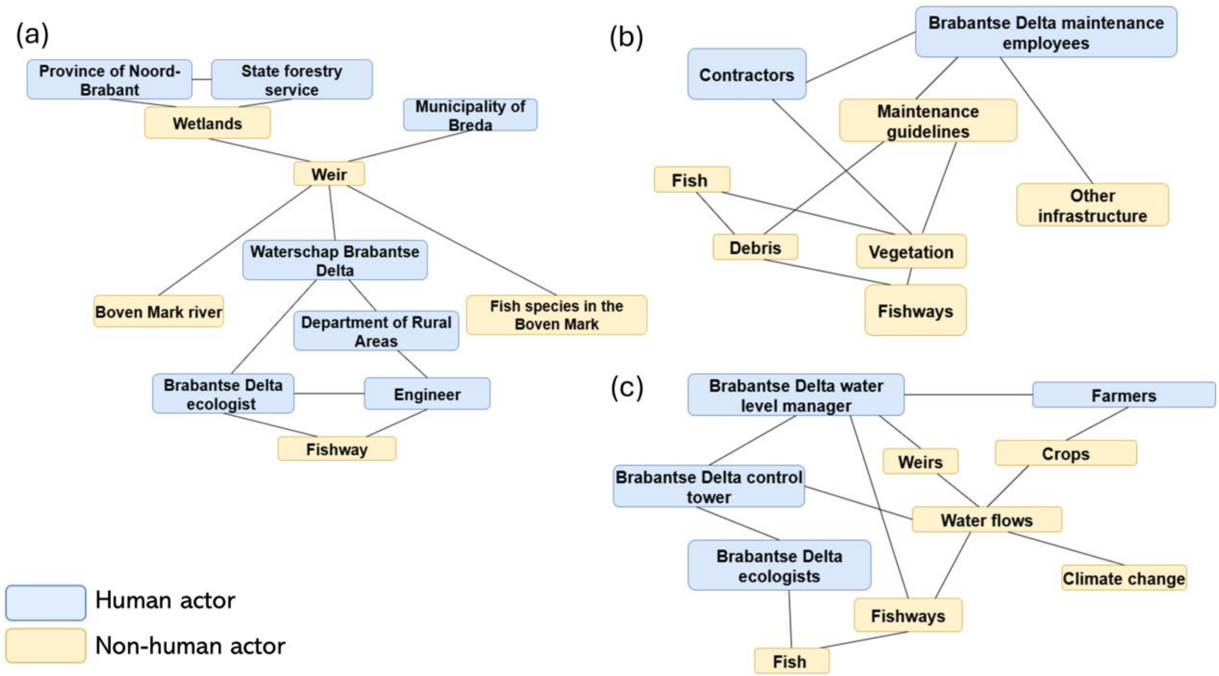
Under conditions of water scarcity, tensions between different interests and claims to water may no longer be resolved through technical design. Water allocation then becomes a matter of deciding which alliance gains priority with regard to how, and how much, water is allocated, and where and when it is allocated. This, in turn determines if, where, and when fishways remain operational for fish migration, thus illustrating how the different sociomaterial contexts in which fishways are situated influence their operation. As the quote above indicates, economic pressure from agricultural interests can have a considerable influence on the making of these decisions and may even cause fishways to stop functioning as a passage for fish. For example, this happened during the spring fish migration in mid-April 2020, when the vertical slot fishways in the Aa of Weerijs were closed by the water-level manager to enhance the water available for agricultural needs.

According to official procedure, water-level managers can close fishways after the decision has been taken by the central control room; however, water-level managers often act independently and allocate water according to their own perceptions of need. In 2022, a water-level manager closed the fishways in the Aa of Weerijs earlier than the official order. As he put it, "This year I closed them 3 weeks earlier than I was ordered to. (…). If I had to wait, then my water would be gone and it would no longer be of any use to the fish either" (Interview, 30 November 2022).

However, these autonomous decisions were critiqued by an ecologist, who pointed out that water-level managers often close fishways while water resources are sufficient to sustain both fish migration and other water demands (Personal communication, 28 August 2024). This shows how, in times of water scarcity, tensions may arise not only around the distribution of water but also around the procedure, that is, who gets to make the decision and whose interests are considered.

The case of the Aa of Weerijs highlights not only how fishways are part of overlapping networks that compete for water allocation for their respective purposes, but also how changing environmental conditions can alter these dynamics. During drought, tensions intensify and priorities may shift; in the case of the Aa of Weerijs, this resulted in agricultural interests taking precedence over those of fish migration (Figure 6c). Despite the official authority of the control room, water-level managers also decide and act relatively independently and can close fishways according to their perceptions of what is a priority at that place and time, making them powerful actors in the operation of fishway networks. In situations of water scarcity, it becomes clear that decisions on water allocation are not taken impartially; rather, they are embedded in historically developed asymmetries in political representation and decision-making in Dutch water management, where agriculture has long taken precedence.

Figure 6. The heterogeneous networks (simplified) of (a) fishway design and implementation at the Bieberg weir, (b) fishway maintenance in the area under the jurisdiction of Waterschap Brabantse Delta, and (c) fishway operation in the Aa of Weerijs River.



DISCUSSION AND CONCLUSIONS

In this paper, we drew inspiration from network approaches in STS and affiliated scholarship to explore the sociomateriality of fishways under the jurisdiction of the Waterschap Brabantse Delta in the Netherlands. Conceptualising fishways as heterogeneous networks allowed us to trace how they evolve through different parts of their 'life cycle' and how this process involves different kinds of actors. Fishway design, implementation, maintenance and operation are shaped by sociomaterial relations that make up dynamic networks that may overlap and interact. Through the case study of fishways in the Brabantse Delta, we showed that an integrated understanding of fishways as complex infrastructures requires going beyond the technical and ecological domains to also consider how fishways are made up of, and embedded in, social and material relations. Instead of seeing the social and the material as separate, our analysis aimed to trace the interaction and entanglement between them through the relations that enact – or destabilise – fishways in practice. Such a network approach sheds light on the complex sociomaterial conditions that influence the functioning of fishways as infrastructures that enhance the movement of fish.

Our case study in the Waterschap Brabantse Delta exemplifies the growing attention in Dutch policy-making to fish migration in recent decades and how this has translated into the ambitions of, and projects by, the water authorities to restore the connectivity of the rivers under their jurisdiction. This proliferation of fishway implementation was boosted by the European political setting, particularly by the EU Water Framework Directive. The WFD shows that fishway development itself is embedded in wider policy settings and funding bodies. Despite the importance of such policies as a driver of fishway implementation, our analysis showed that this is just a first step towards restoring river connectivity. For fishways to become functional networks, the alignment of the Waterschap Brabantse Delta's policies with the EU's WFD is required; so also is the navigation of sociomaterial complexities at the scales of fishway implementation, maintenance and operation, all of which must take into consideration changing environmental conditions.

Fishway implementation is often entangled in networks with competing interests (Le Pichon et al., 2020). As we showed through the case of the Bieberg fishway, the overlapping networks of flood control and wetland conservation at the Bieberg weir ultimately influenced the choice of type and design of the fishway. Similar dynamics were observed in rivers characterised by a Mediterranean climate where water scarcity is a recurring concern (Romão et al., 2021), and at hydropower stations where allocating water for fishways is seen as a loss of energy generation (Wolter and Schomaker, 2019). Efforts to mitigate and solve such contradictions between goals, visions and interests have often led to adjustments to fishways' technical design. Through these design adjustments, the goal is to balance the different passage behaviours of fish species with the demands of overlapping networks such as flood safety and hydropower production. Thus, fishway design is not only a technical issue but also a sociomaterial and political process that conditions how fishways are designed and engineered, with what materials they are built, and with which and whose priorities they align.

Our analysis shows that fishways as networks can become destabilised under changing environmental conditions. In the small river Aa of Weerijs, water-level managers closed fishways – even before receiving an official order – in order to conserve water for farmers during periods of water scarcity. This reflects a broader trend in the Netherlands, where priorities shifted during recent droughts and fishways were closed to retain as much water as possible, often for the benefit of agriculture (van de Ven and Koole, 2019). Similar tensions occur worldwide, such as in Montana, USA, where irrigators block fishways during low flows to divert water (Plymesser et al., 2024). These cases illustrate how nature and society often behave unexpectedly; in this process, sociomaterial networks can be disrupted and even carefully designed expert solutions like fishways can be challenged. This highlights the fragility of our belief that we can control nature.

With the growing global demand for increased food production (van Dijk et al., 2021) and hydropower expansion (Chowdhury et al., 2024), and with projections of more frequent severe droughts worldwide due to climate change (Ault, 2020), the water demand of fishways will likely overlap more often with networks of competing interests. This will happen in the context of a continuing decline in freshwater fish populations (Deinet et al., 2024) that are vital to the well-being, cultural identity and subsistence of people (Noble et al., 2016). To better understand the different tensions, bottlenecks and consequences for fishway performance at different scales and timeframes/temporalities of the fishway development process, it will be necessary to incorporate the social sciences into fish passage research and rethink fishways as networks made up of sociomaterial relations rather than as isolated structures. Such insights into the complexities of fishways are an important step towards developing more integrated and socially informed strategies and policies for enhancing fish passage.

ACKNOWLEDGEMENTS

This study was financed by Rijkswaterstaat, the Dutch Foundation for Applied Water Research (STOWA), and Sportvisserij Nederland. We are grateful to all the interview participants for their time and willingness. We especially thank Marco Beers (Waterschap Brabantse Delta) for helping us get in contact with actors involved in fishway networks, providing us with data on fishway implementation (Figure 2) and the photo in Figure 3. Finally, we thank Tom Critchley (Department of Design, Goldsmiths University of London) for his feedback on the manuscript and assistance with proofreading.

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APPENDIX

Figure A7. Schematic drawing of a fishway with V-shaped weirs and vertical slots

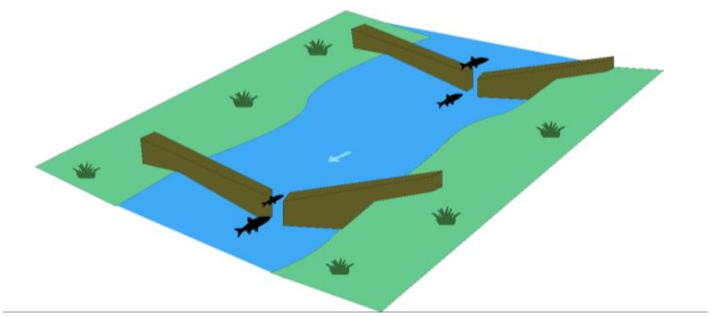

Table A1. List of observed (excluding exotic) and target species (x) in the Boven-Mark (Quak et al., 1996), target species (x) in the Aa of Weerijs River (Kroes and van Giels, 2009), and their migration type according to Kroes and Monden (2005)

Common name	Scientific name	Boven-Mark Total (N)	Boven-Mark	Aa and Weerijs	Migration type
Bleak	*Alburnus alburnus*	1	X	X	Regional
Perch	*Perca fluviatilis*	76	X		Local/regional
Roach	*Rutilus rutilus*	2448	X	X	Local/regional
Bream	*Abramis brama*	131			Local/regional
Three-spined stickleback	*Gasterosteus aculeatus*	3			Anadromous/local
Carp	*Cyprinus carpio*	6			Local/regional
White bream	*Blicca bjoerkna*	4	X	X	Local
Eel	*Anguilla anguilla*	17	X	X	Catadromous
Ruffe	*Gymnocephalus cernuus*	8			Local
Rudd	*Scardinius erythrophthalmus*	524	X	X	Local
Gudgeon	*Gobio gobio*	12	X	X	Local
Pike	*Esox lucius*	8	X		Local/regional
Pike perch	*Sander lucioperca*	1		X	Local/regional
Sunbleak	*Leucaspius delineatus*	120	X	X	Local
Tench	*Tinca tinca*	24	X	X	Local
Ide	*Leuciscus idus*	17	X	X	Local/regional
Burbot	*Lota lota*	-	X		Local/regional
Chub	*Squalius cephalus*	-	X	X	Local/regional
Dace	*Leuciscus leuciscus*	-	X		Local/regional
Crucian carp	*Carassius carassius*	-	X	X	Local
Bitterling	*Rhodeus amarus*	-	X		Local
Weatherfish	*Misgurnus fossilis*	-	X		Local
Spined loach	*Cobitis taenia*	-	X	X	Local
Stone loach	*Barbatula barbatula*	-		X	Local