Regional connectivity and movements of freshwater fish in the Langbroekerwetering, a weir-regulated water system with De Wit fishways

A LIFE-IP study using PIT telemetry

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Wageningen
University &
Research report
C045/22

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Wageningen Marine Research
IJmuiden, August 2022

CONFIDENTIAL no

Wageningen Marine Research report C045/22

Wageningen Marine Research, an institute within the legal entity Stichting Wageningen Research (a foundation under Dutch private law) represented by Dr. M.C.Th. Scholten, Managing Director

KvK nr. 09098104,
WMR BTW nr. NL 8113.83.696.B16.
Code BIC/SWIFT address: RABONL2U
IBAN code: NL 73 RABO 0373599285

A 4 3 2 V28

Keywords: freshwater fish, migration, dispersal, telemetry, cyprinids, percids, barriers, weirs, fishways, connectivity

This study was co-financed by LIFE IP, European Union

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Summary

Habitats fragmentation of freshwater by barriers causes serious problems for fish migration. The Water Frame Directive propagates unhampered fish migration within entire water catchments and free access to sea. To achieve this, different fish passage facilities have been developed and built in the last decennia by water boards in the Netherlands to make barriers like weirs, sluices and pumping stations passable.

In this study we evaluate connectivity and spatial use of freshwater fish in the Langbroekerwetering water system, situated in the central part of the Netherlands, that is regulated by six low-head weirs which are facilitated with De Wit Passages. It is a semi-stagnant man-made water system that drains the area and is connected to a larger network of waters through the Kromme Rijn waterway, a former river branch of the Rhine. PIT-tagging and a network of PIT-antennae at weirs and fishways, and additionally in a nature-like bypass channel and a side ditch, were used to target movement patterns of a wide range of fish species and sizes that are present in this water system. In total, during March-May 2018 and in September 2018, 1428 fish of 18 species and hybrid cyprinids were caught and tagged with PIT-tags. More abundant species were roach *Rutlilus rutilus*, bream *Abramis brama*, pike *Esox Lucius*, tench *Tinco tinca*, white bream *Blicca bjoerkna* and perch *Perca fluviatilis*. The detection network was operational until June 2020.

For the majority of fish for each species and life stage we found only limited movements at spatial scales within waterway sections (<2 km) or between adjacent stretches (~2-6 km). Only a minority of fish showed larger scale movements within the Langbroekerwetering (~8 km) or to adjacent water systems. Fishways and weirs were passed both in upstream and downstream direction by different fish species and life stages. In upstream direction, most fish used the fishways, only pike used weirs more often than fishways. In downstream direction, both fishways and weirs were used for successful passage. All of the most abundant species uses fishways also for downstream passage. Seasonal timing of detections occurred mostly in spring (April-May), or early spring for pike (February-April) for most species coinciding with the spawning period. For tench and rudd *Scardinius erythrophthalmus* detections occurred year round with more detections in the summer half year. There were also clear diurnal patterns, with much differences between species, life stages and sites.

Facilitating the weirs with De Wit fishways has substantially increased migratory opportunities for the different freshwater fish species in this study, in both upstream and downstream direction. The weirs were also used for passage, in downstream direction by most species, but in upstream direction only by a few species such as roach, bream and pike. Passage efficiency at the studied weir-fishway sites appear to be high, as was also indicated by the rapid passage of series of fishways by 29 fish from 6 different species and sizes down to 10 cm. No mass migrations or dispersal over larger scales were observed from and to the study area. It appears that none of the populations, except the diadromous eel, fully relies on this connectivity, but it will most likely enhance population size and health in the area.

Our study did not yield clear bottlenecks in connectivity, i.e. passage problems at weir-fishway sites. The relatively small scale that most fishes use the Langbroekerwetering-system is more likely a reflection of a lack of motivation to move or disperse at larger scales than that barriers are restricting these. Most species resided within the study area. Only white bream and gudgeon seem to move into the system from the Kromme Rijn System without staying in the study area for longer periods. There appears no direct need to improve fish passage facilities, rather than ensuring that good maintenance to safeguard their functioning. Whether the habitats that are connected by these sites are of sufficient quality could not be addressed in this study.

Within this study a large dataset of individual detections of a wide range of species and life stages was collected. Here we present the main results and movement patterns, but more in depth analyses, e.g. by combining the data with environmental data such as water discharge, temperature, daylength can further refine the quantification of fish passage and which factors determine this than could be addressed within the scope of this report.

Samenvatting

Habitat fragmentatie in zoete wateren is een belangrijk probleem voor vismigratie. De Habitatrichtlijn Water schrijft vrije vismigratie in complete stroomgebieden voor en vrije verbinding met zee. Om dit te bereiken zijn verschillende typen vistrappen ontwikkeld en gebouwd om de vele barrières zoals stuwen, sluizen en gemalen in de afgelopen decennia door waterbeheerders passeerbaar te maken.

In dit onderzoek evalueren we de connectiviteit en het ruimtelijk gebruik van zoetwatervis in de Langbroekerwetering, gelegen in het midden van Nederland, dat gereguleerd is met zes stuwen waarlangs De Wit vispassages zijn gebouwd. Het is een semi-stagnant kunstmatig watersysteem dat het gebied ontwaterd en is verbonden met een omliggend watersysteem via de Kromme Rijn, een voormalige zijtak van de Rijn. PIT-taggen en een netwerk van PIT-antennes bij de stuwen en vistrappen, en in aanvulling ook in een bypass-kanaal en een zijsloot, zijn gebruikt om bewegingspatronen te onderzoeken van een breed spectrum aan zoetwatervis en levensstadia die het gebied gebruiken. In totaal zijn er gedurende Maart-Mei en September 2018, 1428 vissen van 18 verschillende soorten, inclusief hybriden, gevangen en gemerkt met PIT-tags. De meest talrijke soorten waren blankvoorn *Rutlilus rutilus*, brasem *Abramis brama*, snoek *Esox Lucius*, zeelt *Tinco tinca*, kolblei *Blicca bjoerkna* en baars *Perca fluviatilis*. Het detectienetwerk was operationeel tot en met Juni 2020.

Voor de meerderheid van de gemerkte vis vonden we beperkte bewegingen op een ruimtelijke schaal van een enkel pand (<2 km) of tussen twee panden (~2-6 km). Slechts een kleine minderheid van de gemerkte vis gebruikte de gehele Langbroekerwetering (~8 km) of trok naar omliggende wateren.

De vistrappen en stuwen werden zoals in stroomopwaartse als in stroomafwaartse richting gepasseerd door de verschillende vissoorten. In stroomopwaartse richting gebruikten de meeste soorten de vistrappen, behalve snoek die merendeels via de stuwen stroomopwaarts trok. In stroomafwaartse richting werden ook zowel de vistrappen als de stuwen gepasseerd.

Migratiepatronen lieten een piek zien tijdens het voorjaar (April-Mei), of vroeger (Februari-April) voor snoek. Deze timing valt samen met de paaiperiodes voor de soorten. Zeelt en ruisvoorn *Scardinius erythrophthalmus* detecties vonden jaarrond plaats, maar vooral gedurende de zomer. Er werden grote verschillen in dag-nacht patronen voor verschillende soorten, locaties en periode gevonden.

Het bouwen van vistrappen bij de stuwen heeft geleid tot een aanzienlijke vergroting van de migratiemogelijkheden voor de verschillende zoetwatervissoorten in dit onderzoek, in zowel stroomopwaartse als stroomafwaartse richting. De stuwen werden ook stroomopwaarts gepasseerd, maar alleen door een beperkter aantal soorten als blankvoorn, brasem en snoek. De passage efficiëntie op de onderzochte locaties blijkt hoog, wat ook werd ondersteund door de snelle passage van series vistrappen door 29 vissen van 5 verschillende soorten tot zelfs kleine lengtes van 10 cm. Er is geen massale migratie van vis op grote ruimtelijke schaal waargenomen. Het lijkt dat geen van de onderzochte vispopulaties volledig afhankelijk is van deze verbindingen, afgezien van de diadrome paling, maar dat connectiviteit wel zal leiden tot grotere en gezondere vispopulaties in het studiegebied.

Dit onderzoek vond geen duidelijke knelpunten in connectiviteit, zoals passage problemen bij stuw-vistrap locaties. De relatief kleine schaal waarop de meeste vissen zich begeven in de Langbroekerwetering lijkt meer een gevolg te zijn van een geringe motivatie om te migreren dan van een sterke beperking hierin. Alleen kolblei en riviergrondel trokken vooral vanuit de Kromme Rijn de Langbroekrwetering binnen, maar werden in jaren daarna niet meer terug gezien. Er lijkt geen aanleiding te zijn om de vispassages verder te verbeteren, anders dan te zorgen dat er goed onderhoud plaatsvindt zodat ze goed blijven functioneren. Of ook de habitats die worden verbonden van voldoende kwaliteit zijn, kon niet direct worden vastgesteld binnen het bestek van dit rapportage.

Deze studie heeft een grote dataset aan detecties opgeleverd die kan worden ingezet om meer verdiepende analyses uit te voeren, zoals het koppelen aan omgevingsparameters als afvoer, temperatuur. Hiermee kunnen visgedrag en passage succes en de factoren die dit bepalen verder onderzocht worden dan binnen het bestek van deze rapportage mogelijk was.

1 Introduction

1.1 Connectivity for fish in fragmented freshwater systems

Freshwater biodiversity is declining at an alarming rate worldwide (Harrison et al. 2018, Goncalves & Hermoso 2022). For fish, habitat fragmentation is an important factor attributing to this. In Europe, more than one million man-made barriers are estimated to be present in freshwater systems (Belletti et al. 2020). In the Netherlands, the intensive water management and land reclamation, i.e. altered waterways and creation of many polders, resulted in a dense and highly fragmented network of water bodies. Most of these water systems are man-made and highly regulated, e.g. canals, ditches, artificial lakes or streams and rivers. Water level and discharge management is controlled by building many different structures such as weirs, sluices, ship locks and pumping stations for agricultural and navigational purposes. This led to a maze of potential barriers for fish, at least 18,000 in the main water systems in the Netherlands (Breve et al. 2014), that hinders movements between different sections or habitats in these water systems. The Water Frame Directive (dutch: 'Kaderrichtlijn Water') propagates unhampered fish migration within entire water catchments and free access to sea. To achieve this, different fish passage facilities have been developed and built in the last decennia by the many water boards in the Netherlands.

Traditionally, rehabilitating connectivity with fishways focused on diadromous fish species, e.g. Atlantic salmon *Salmo salar* or European Eel *Anguilla anguilla,* that need to migrate between sea and freshwater habitats to complete their life-cycle (Birnie-Gauvin et al. 2019). But non-diadromous freshwater fish show migratory behaviour as well. Movements of fish are often classified in 'migratory', 'non-migratory' or 'residency', and 'dispersal' (Lucas & Baras 2001, Clobert et al. 2004). For these classifications many different definitions are circulating. *Dispersal* is more or less undirected movement where the nett distance between individuals of the (sub)population of origin increases and ultimately can lead to gene flow between (sub)populations. For *migration* we use the definition as used by Brönmark et al. (2014): "most biologists agree that migration requires that individuals or populations (or parts of populations) move between two well-defined habitats on a temporally predictable basis. Hence, migration differs from dispersal in that individuals make a return journey to the initial habitat. The other generally accepted feature of migration is that it is to some degree temporally predictable and has a regular periodicity; for example, the daily vertical movements of pelagic fish, seasonal (spawning) migrations and also the once-a-lifetime migration of anguillid eels back to their natal marine habitat to spawn and then die."

Rapid developments in telemetric techniques in the past decades allowed to track and follow individual movements of an increasing number of species and life-stages (Cooke et al. 2013). These studies demonstrated that for most fish species, movement patterns can be very divers and differ greatly between water systems, environmental conditions and individuals within populations, showing a continuum of movement behaviours ranging from migratory, partial migratory, residency to dispersal where the borders between these classifications are not so clear (Brodersen et al. 2008, Birnie-Gauvin et al. 2017). The underlying motivation of these individual movements can be very diverse and linked to e.g. spawning, finding refuge, foraging, trade-offs between feeding and predation risk, exploring, avoiding adverse environmental conditions (Brönmark et al. 2008, Kemp 2016). Increasingly, fishways are designed and installed to facilitate movements of the entire spectrum of fish species and different life stages of freshwater fish communities and not just for diadromous migrants.

In the Netherlands, already at an early stage in the late 1980s and 1990s several type of fishways were designed to facilitate passage of a wide range of freshwater fish species and sizes (Winter 2007). One such type of fishway was developed by Wim de Wit, a former employee of Hoogheemraadschap De Stichtse Rijnlanden in 1993: the *De Wit Passage* (de Wit 1994). The De Wit Passage, a pool and orifice type fishway, was especially designed to facilitate passage of small to medium sized fish in waterways with low flow conditions and subsequently further improved thereafter (Heuts 2005). Many of these fishways have been individually monitored since their construction (mostly with fykenets) and these studies demonstrated successful passage of more than 20 fish species with sizes ranging from 6-115 cm, see Heuts (2013) for an overview. Studies on the *efficiency* of these fish passage facilities, i.e.

which fraction of the fish motivated to pass a barrier succeeds in doing so, are not yet available. In general, for most type of fishways and fish species, these studies are still relatively scarce and assessments of the *effectiveness* of fish passage facilities, i.e. did these fish passage facilities enhance populations and fish communities, are even more scarce (Silva et al. 2017, Hersey 2020). For rehabilitating fish communities, of course not only connectivity and relieving habitat fragmentation play a role. Also other bottlenecks may prevail that can obscure the positive effects of improvement in connectivity, e.g. poor habitat quality or heterogeneity in the connected water system sections.

In this research we study connectivity and spatial use of fish in a water system that is fragmented by low-head weirs which are facilitated with De Wit Passages. The chosen study area is the Langbroekerwetering water system in the central part of the Netherlands. This is a semi-stagnant man-made water system that drains the area. The Langbroekerwetering system contains six weirs that are facilitated with De Wit passages and is connected to a larger network of waters through the Kromme Rijn waterway, a former river branch of the Rhine. PIT-tagging and a network of PIT-antennae at weirs and fishways were used to target movement patterns of the wide range of fish species and sizes that are present in this water system. The field study was carried out from March 2018 to June 2020.

1.2 Aim of the study and research questions

In this report we aim to describe movement patterns of the wide range of freshwater fish species and life stages that use the Langbroekerwetering water system, which is fragmented by six weirs that are facilitated with De Wit Passages. The research questions we address in this report are:

- What is the role of movements for the different freshwater fish populations that use the study area, i.e. what type of movements (migration, partial migration, dispersal) are observed for the different fish species?
- At what spatial scale do these movements take place?
- What was the rate of these different spatial movement patterns per species (i.e. which proportion of tagged fish moved beyond single or multiple barriers)?
- What routes were taken when passing barriers (via the fishway or over the weir) in both upstream and downstream direction?
- What was the timing (seasonal, diurnal) of these movements?
- Did the measures of facilitating these weirs with De Wit Passages result in good connectivity within this study area itself and with adjacent waters via de Kromme Rijn and how important is connectivity for the different species?
- Did the movement patterns indicate bottlenecks in connectivity, and if so which additional measures might be needed to optimize connectivity?

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The study resulted in a unique and large database of fish detections from a network of detection stations (PIT-antennae) in the study area which can be used for follow-up quantitative analyses in relation to the complexity of the water system and management and in relation to different environmental parameters that could not be addressed within the scope and time budget of this project report. In the discussion we will make recommendations for what we view as most promising future analyses and directions.

2 Assignment

PIT-tagging station network and fieldwork

The construction, deployment, maintenance and read-out of the PIT-stations at the sites in the Langbroekerwetering study area and the fieldwork for catching and PIT-tagging fish was carried out by VisAdvies, RAVON and ATKB during 2018-2020 in a separate contract with the waterboard Hoogheemraadschap De Stichtse Rijnlanden (HDSR). The full datasets of this study were made available for drafting this report. Before the start of the study, Wageningen Marine Research and Wageningen University also advised on the set-up of the research.

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Analysis and reporting of the telemetry data

The data analysis and reporting was carried out by Wageningen Marine Research and Wageningen University, Aquaculture and Fisheries Group, and within the MSc-study of Maud Valkeniers at Wageningen University (Valkenaars, 2019) and the BSc-study of Maurice Kooiman at HZ University of Applied Sciences (Kooiman, 2019), summarized in Kooiman & Valkenaars (2021).

A strongly regulated section of the Langbroekerwetering waterway.

3 Materials and Methods

3.1 Study area

3.1.1 General description

The study was conducted in the Langbroekerwetering (Fig. 3.1), an artificial channel from the 12th century with a sandy bottom in the western part of the Netherlands (length: 10 km; mean width: 8 m, mean depth: 0.8 m, latitude: 52.005 and longitude: 5.347). The Langbroekerwetering is located in the eastern part of the province of Utrecht, and is confined by the Utrechtse Heuvelrug, a sandy hill on the east-side and the Amsterdam-Rhine canal on the west-side. The Langbroekerwetering is connected with a regulated former river branch de Kromme Rijn, which is the largest watercourse in this area, starting at the Nederrijn and flowing via Wijk bij Duurstede in the north-western direction to the city of Utrecht. The water in the Langbroekerwetering flows in north-western direction into de Kromme Rijn, via the final weir Langbroekerwetering. Since 1993, seven fishways have been installed in the Langbroekerwetering, initially to connect the Langbroekerwetering with de Kromme Rijn (Heuts, 2013). The general physical chemistry of the Langbroekerwetering is considered to be good (as measured in 2016) (HDSR, 2016).

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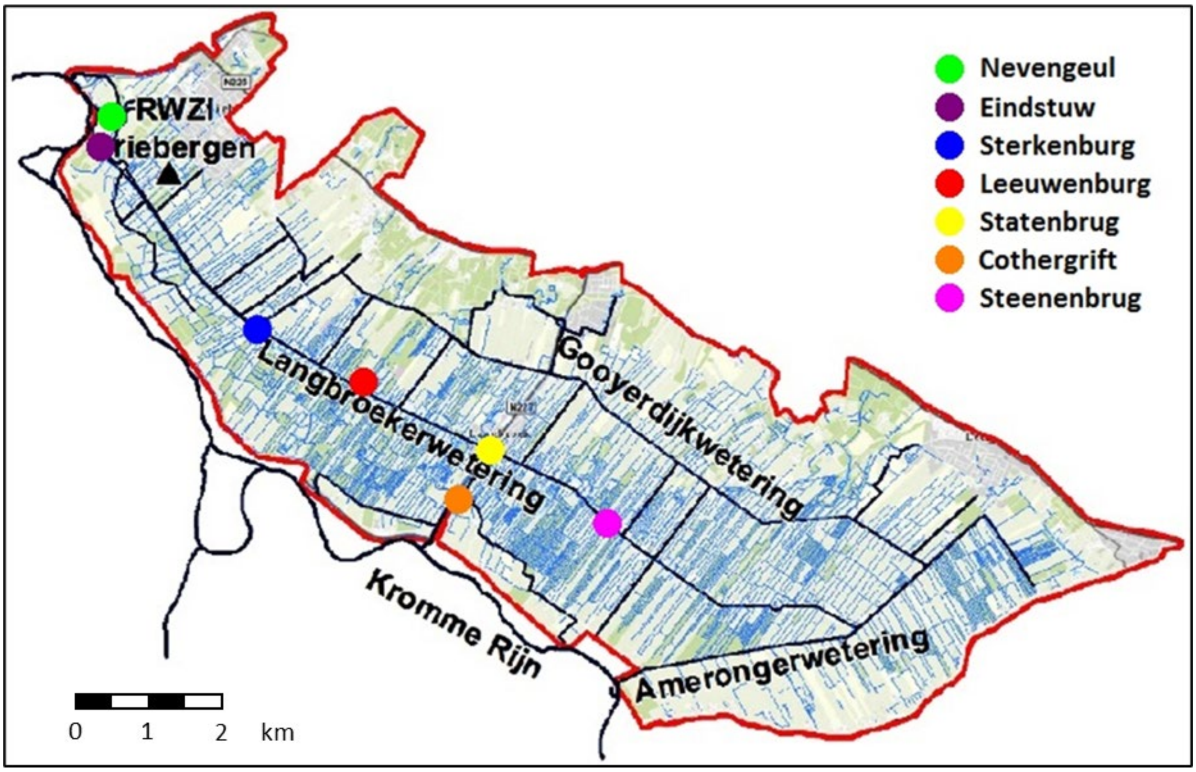


***Figure 3.1**. Map of the study area and sites with weirs and fishways in the Langbroekerwetering system.*

3.1.2 Weirs and fish passages

The study area that encompasses the Langbroekwetering water system and adjacent waters contains many weirs (Fig. 3.2 and 3.3). Six of the larger weirs in the main watercourse of the Langbroekerwetering are facilitated with fish passages ('De Wit' type fishways, see Fig. 3.4 and Tab. 3.1). This type of fishway was developed by Wim de Wit, a former employee of Hoogheemraadschap De Stichtse Rijnlanden in 1993. The main design criteria were creating steps with low water velocities that would serve the full spectrum of fish species in Dutch waters, and that that it required low discharge to function. This type of fishway is since then used in many places in the Netherlands, mainly in the lower 'polder'-waters.

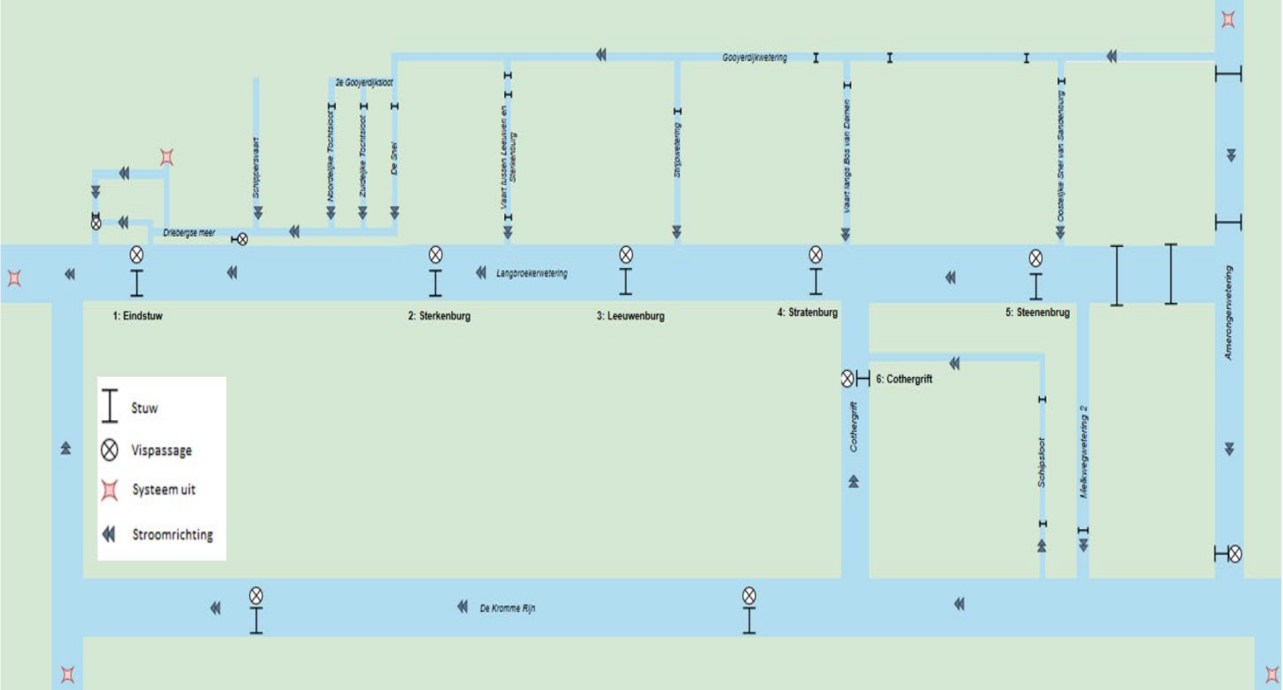


Figure 3.2. *Schematic overview of the waterways and main ditches in the study area, and the weirs and the fish passages present. The prevailing water current direction is indicated with arrows.*

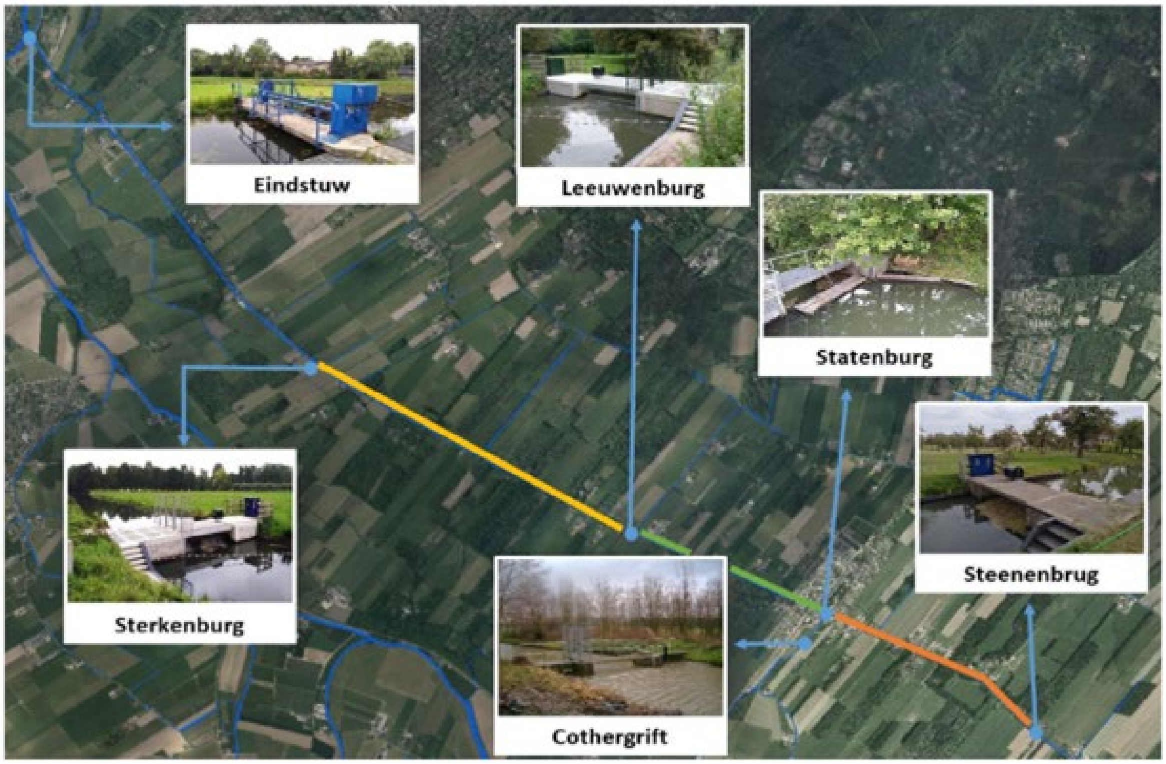


Figure 3.3. *Overview of the weirs in the Langbroekerwetering where detection stations were installed. Including the division of four compartments: blue: A:Eindstuw-Sterkenburg, yellow: B:Sterkenburg-Leeuwenburg, green: C:Leeuwenburg-Statenburg and orange: D:Statenburg-Steenenbrug-Cothergrift*.

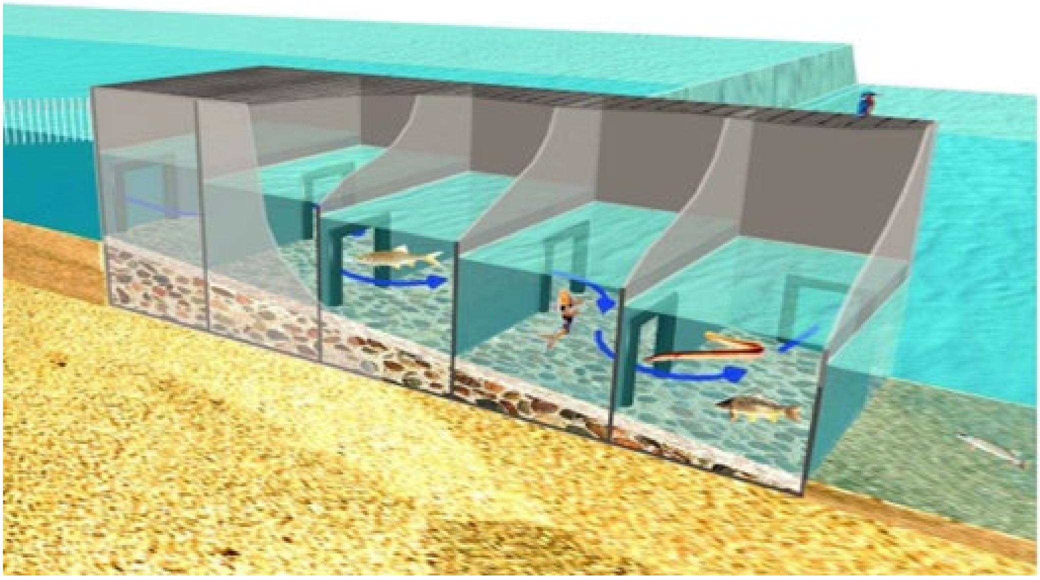


***Figure 3.4**. 3D view of a 'De Wit" fishways. Fish can swim upstream or downstream through the several chambers (here there are five chambers) Heuts (2013). Chambers vary in size from 0.6x1.2 m up to 0.89x0.3 m with openings varying in size from 0.2x0.25 m up to 0.3x0.3 m.*

***Table 3.1.** Overview weirs facilitated with fishways in the Langbroekerwetering with installed floating/stationary detection stations*

Number	1	2	3	4	5	6
Name fishway	**Eindstuw Langbroekerwetering**	**Sterkenburg**	**Leeuwenburg**	**Statenburg**	**Steenenbrug**	**Cothergrift**
Type fishway	De Wit	De Wit	De Wit	De Wit	De Wit	De Wit
Number of chambers	13	8	6	5	4	1
Measurements chambers (LxW) (m)	0.6x1.2	0.8x1.2	0.8x1.2	0.6x1.2	0.8x1	0.89x0.3
Measurements opening (WxH) (m)	0.2x0.35	0.2x0.25	0.2x0.25	0.2x0.35	0.2x0.25	0.3x0.3
Water depth at passage (m)	1.5	1.2-1.5	1.2	0.95	0.85	0.95
Water level upstream (m)	1.75	1.9	2.2	2.4	2.25	2.38
Water level downstream (m)	0.8	1.6	1.9	2.05	2.2	2.2
Year of construction	2000	2016	2016	1999	2011	1998

In the Langbroekerwetering area there are seven De Wit fishways installed to improve upstream and downstream fish movements past weirs (Fig. 3.4). Fish can swim upstream or downstream through the several chambers inside the fishway, and contains openings inside the chambers that are not aligned so that the water flow will be diminished as much as possible (Boiten et al., 2005). The chambers vary in size from 0.6x1.2 m up to 0.89x0.3 m (Tab. 3.1). Fish can enter these chambers via openings varying in size from 0.2x0.25 m up to 0.3x0.3 m. These openings are similar in all chambers, and therefore allow the water inflow speed to be the same in each chamber. The number of chambers depends on the height difference of the water level, with every 5 cm water level an extra chamber is added so that the water flow remains below 1 m/s. This velocity is required to improve movements of small sized fish through the fishways (Heuts, 2013).

3.2 PIT-telemetry setup

To study movements alongside weirs and fish passages between the different stretches/compartments of the Langbroekerwetering water system PIT-tag telemetry was used. PIT stands for Passive Integrated Transponders, and are tracking tags that do not require power. Instead, they have an internal microchip that is activated when it passes close to a special antenna. The implication of the term passive is that the tag is dormant until activated by an antenna or a handheld reader. If a PIT tag is present, the antenna generates a close-range, electromagnetic field that immediately activates the tag, which transmits its number. This unique alphanumeric code permits a tagged individual to be distinguished from every other one, whether on a population or global scale. The antenna is connected to a computer that records the identity of the tag and the time that it passed by the antenna. PIT tags are used in a wide range of animals and pets. A PIT tag is an electronic microchip encased in biocompatible glass that varies in size. In this study sizes of 12, 23 and 32 mm long and 2.1-3.6 mm in diameter were used for different size classes of fish. The glass casing protects the electronic components and prevents tissue irritation. PIT tags were injected with a 12-gauge needle into the body cavity. The biggest advantage of PIT-tags is that it does not need a battery, so it can last for the entire time that a fish is carrying it. Because of their small size they can be used in small fish as well. These tags are also very inexpensive, which mean that larger amounts of fish can be tagged. The main drawback is that is has to be very close to the antenna to transmit data, typically just 30-80 cm away. In this study PIT-antenna were deployed in fish passages covering 1-3 orifices between compartments (Tab. 3.2, Fig. 3.5a-b), floating on the overflow at weirs (Tab. 3.2, Fig. 3.5c-d, Fig. 3.6) from February 2018 to June 2020. Two more antennae were added in early autumn 2018 (nature-like bypass channel near Eindstuw) and early spring 2019 (side-ditch in the stretch between the weirs Sterkenburg and Leeuwenburg). to cover an alternative route alongside Eindstuw and indicate within compartment habitat use of side ditches.

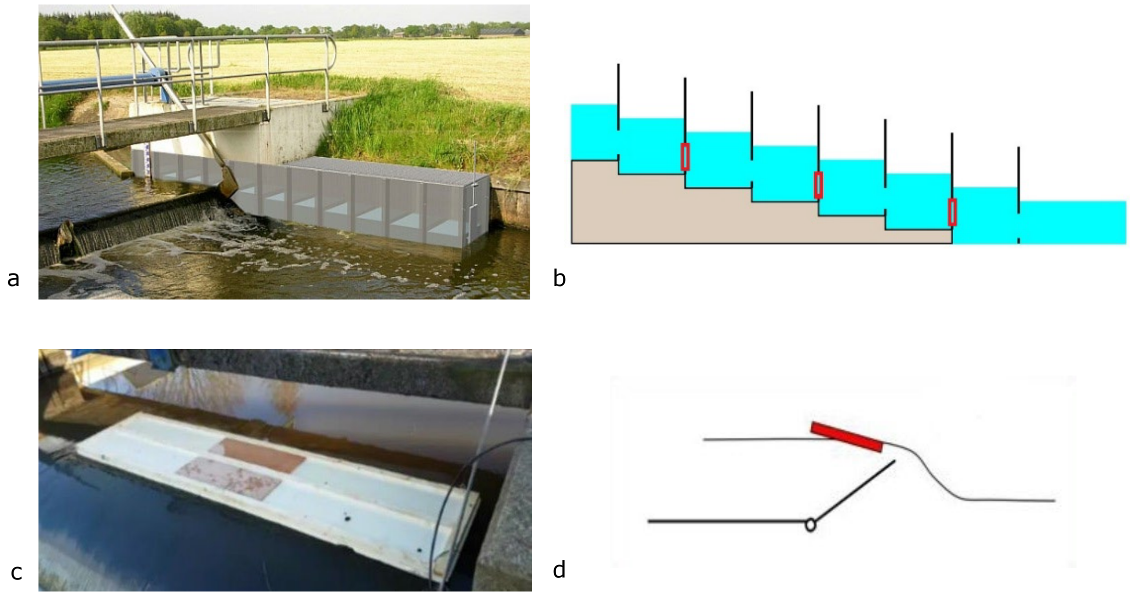


__Figure 3.5__. Overview of the de Wit fish passages (a); side scheme on location of the PIT-loops within the passages (b); the floating PIT-loop at the weir (c) and side scheme of the PIT-loop at a weir (d).

Table 3.2. *Overview detection stations installed near the fishways.*

Location	Name fishway	Number of chambers	Number antennas	Location in chambers	Weir covered
1	Eindstuw Langbroekerwetering	13	3	1,7,14	yes
2	Sterkenburg	8	3	2,3,8	yes
3	Leeuwenburg	6	3	2,3,6	yes
4	Statenburg	5	3	2,3,5	yes
5	Steenenbrug	4	2	n.a.	no
6	Cothergrift	1	2	1,2.	no

Figure 3.6*. Photo of a floating PIT-loop at a weir site.*

3.3 Tagging of fish

In March-May 2018 and in September 2018, 1428 fish of 18 species and hybrid cyprinids were caught and tagged. Electrofishing was conducted during the day from 6-9 March and on 27-28 September by researchers from RAVON. Furthermore, in mid-May additional fish were tagged when caught using a fish trap (fyke) located at the inflow opening of the fishway at Eindstuw Langbroekerwetering (Tab. 3.3).

After being anesthetised (3-4 minutes in tank with 2 g Benzocaine for 40 L water), the total body length (cm) was measured and a Passive Integrated Transponder-tag (PIT-tag) was injected into the abdominal cavity of every fish, which was done by researchers from VisAdvies (ecological and research consultancy firm in the Netherlands). The fish were tagged with different Oregon RFID® PIT-tags of 12 mm (HDX, ISO 11784/11785 compliant ICAR-registered animal tag, 0.1 g, diameter of 2.12 mm), a tag of 23 mm (HDX, ISO 11784/11785 compatible, 0.6 g, diameter of 3.65 mm) or a tag of 32 mm (HDX, ISO 11784/11785 compatible, 0.8 g, diameter of 3.65 mm), depending on the size of the fish (12 mm tag: 15-20 cm; 23 mm: 21-30 cm; 32 mm: >31cm). Due to the size of the transmitter, only fish larger than 15 cm were tagged. After tagging and recovery from anaesthesia, the fish were released into the same area from where they were caught (Table 3.3). The fish caught with the fish trap in May were released upstream near Eindstuw Langbroekerwetering.

Numbers of fish caught with different gear type (electro-fishing, fyke-net) and period (spring, autumn 2018), are given for each species in Fig. 3.7. Numbers per size class for each species are given in Fig. 3.8.

***Table 3.3**: Number of individual fish tagged in Spring (March-May) and September 2018 per species, released in the different compartments of the Langbroekerwetering after tagging.*

Species English (Dutch)	Species Latin name	Tag size	Spring			Autumn	Total
		(mm)	March	April	May	Sept	
Bleak (alver)	*Alburnus alburnus*	12	2				2
Perch (baars)	*Perca fluviatilis*	12	66	3	11	36	116
		23	3		1	9	13
		32	1				1
Stone loach (bermpje)	*Barbulata barbulata*	12	1				1
Roach (blankvoorn)	*Rutilus rutilus*	12	147	3	11	163	324
		23	5	8		52	65
Bream (brasem)	*Abramis brama*	12	3		1	7	11
		23	3		3	3	9
		32	189		5		194
Weatherfish (grote modderkruiper	*Misgurnis fossilis*	12	3				3
		23			1		1
Hydrid (hybride)	*Cyprinid hybrid*	13			2		2
		23			1	1	2
White bream (kolblei)	*Blicca bjoerkna*	12	7		66	31	104
		23			23	10	33
		32		1	4		5
Crussian carp (kroeskarper)	*Carassius carassius*	12	10			1	11
European eel (aal/paling)	*Anguilla anguilla*	23			1		1
		32	3	1	5		9
Ruffe (pos)	*Gymnocephalus cernua*	12	5				5
Gudgeon (riviergrondel)	*Gobio gobio*	12	27	10	24		61
Asp (roofblei)	*Aspius aspius*	12				1	1
Rudd (ruisvoorn)	*Scardinius erythrophthalmus*	12	41		3	26	70
		23	7			10	17
Carp (karper)	*Cyprinus carpio*	32	6				6
Pike (snoek)	*Esox lucius*	12	10			23	33
		23	24			30	54
		32	98			2	2
Pikeperch (snoekbaars)	*Sander lucioperca*	12				1	1
Ide (winde)	*Leuciscus idus*	12	6	1	1	5	13
		23	1	1		13	15
		32	1				1
Tench (zeelt)	*Tinca tinca*	12	44			4	44
		23	22		1	6	29
		32	66		1		67

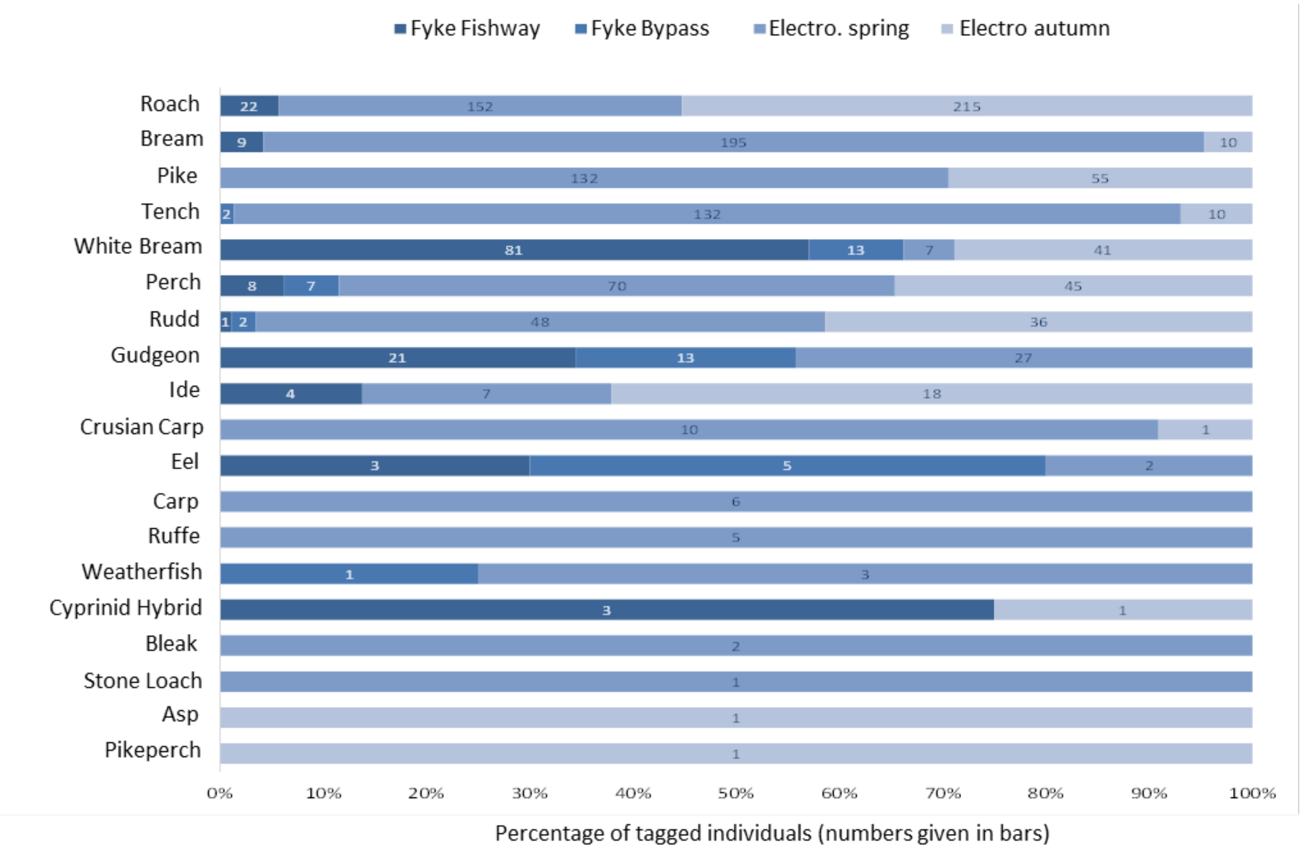


Figure 3.7. *Number and percentage of tagged individuals per catch method (gear type) and period (spring and autumn). The number in each stacked bar gives the number of individuals per species.*

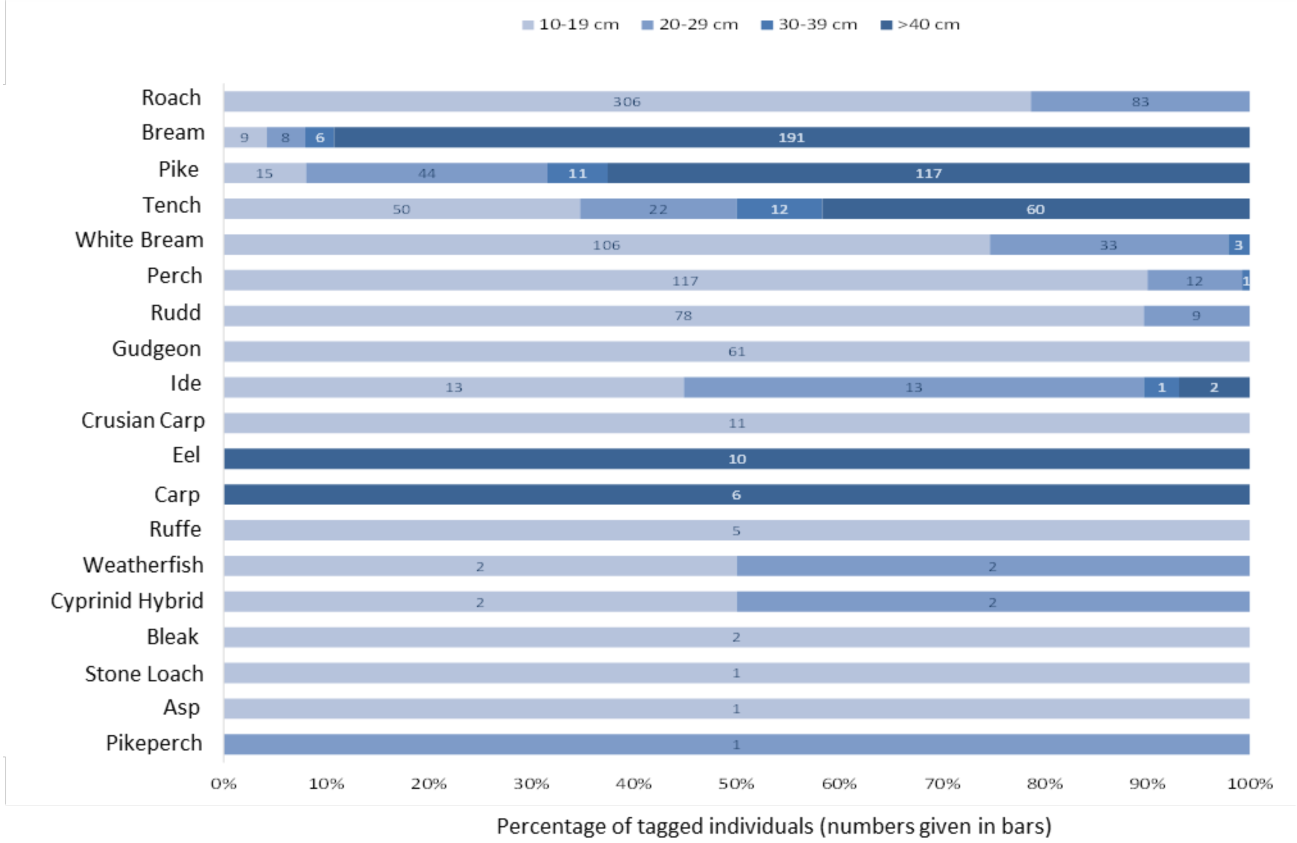


Figure 3.8. *Number and percentage of tagged individuals per length class per species. The number in each stacked bar gives the number of individuals per species.*

3.4 Data analysis of fish movements and passage

From the individual detection datasets, the following was derived:

Individual movement patterns were considered to be '**migratory**' when there was a repetitive seasonal pattern over a period spanning more than one year

Individual movement patterns were considered to be '**dispersal**' when there was a non-repetitive seasonal pattern in movements encompassing at least 2 compartments of the water system studies over a period spanning more than one year

Only the sites Eindstuw, Sterkenburg, Leeuwenburg and Statenburg were analyzed for upstream and downstream passage via the fishways and weirs, because for these sites both the fishways (with 3 detection antennae) and the weir (one detection antenna) were covered.

For **upstream and downstream appearance** at a weir-fishway site; the first detection with in the fishway was used, or the weir when directed from previous position (i.e. release or earlier detections at other sites) was known. For each individual fish per site per half year of the study period (January-June 2018; July-December 2018; January-June 2019; July-December 2019; January-June 2020) it was determined if and from what direction (upstream or downstream) an appearance was made at a site. The first half of a year (January-June) encompasses spring movements and the second half of a year (July-December) encompasses autumn migrations. Detection patterns greatly varied between individual fish and could often not be clearly classified as directed attempts (Kooiman 2019). Moreover, some fish moved up and down fishways passing them many times in short periods or appeared to stay within the fishway for longer periods where is was not always clear if they left the fishway in between fishway visits.

To indicate **upstream and downstream passage**, we determined for each individual fish that made an upstream or downstream 'appearance' at a given site and migration period, whether these appearances were followed by successful passage in upstream or downstream direction for this individual fish per migration period.

For, a similar approach was used per individual, per site and per half year period as described for appearance above. A fishway was considered to be passed successful when the first detection was on the downstream loop and the last of a series on the upstream loop (successful upstream passage via the fishway), or vice versa (successful downstream passage via the fishway). Passage over the weir was only considered to be successful if this was indicated by a previous upstream position followed by a consecutive downstream position (successful downstream passage via a weir) or vice versa (successful upstream passage via a weir). If a fish was detected at a weir and not thereafter, it was considered an unsuccessful passage, which is a conservative approach.

In addition, for each species the number of individuals that showed '**fast passage of series of fishways: in upstream direction**' i.e. passing a series of more than two fishways in less than 7 days, was determined.

4 Results of the PIT-telemetry study

4.1 Overview of tagging results and detections per species

In total 1,428 fish of 18 different species, and 2 hybrids (cyprinid), were tagged. Of these, 510 tagged fish were detected by antennae during the course of this study (Table 4.1). Roach was the most abundantly caught species, followed by bream, pike, tench, white bream and perch. The percentage of tagged individuals that were detected after tag-release varies between species. For species where more than 10 individuals were tagged, eel showed the highest detection rate (90% detected) and Crussian carp the lowest (9% detected). Of the species that were tagged in numbers larger than 50, tench (16%), rudd (20%) and perch (29%) showed relatively low detection percentages, whereas white bream (51%), gudgeon (41%), roach (40%), bream (39%) and pike (39%) showed relatively higher detection percentages. However, a substantial part of the tagged fish (ranging from 49-84% for the different species) was never detected after release for these more abundant species.

***Table 4.1**. Overview of all tagged fish, length, number of detected fish.*

Species English (Dutch)	Species Latin name	Tagged	Detected	Detected
		n	n	%
Roach (blankvoorn)	*Rutilus rutilus*	389	155	40%
Bream (brasem)	*Abramis brama*	214	84	39%
Pike (snoek)	*Esox lucius*	187	72	39%
Tench (zeelt)	*Tinca tinca*	144	23	16%
White bream (kolblei)	*Blicca bjoerkna*	142	72	51%
Perch (baars)	*Perca fluviatilis*	130	38	29%
Rudd (ruisvoorn)	*Scardinius erythrophthalmus*	87	17	20%
Gudgeon (riviergrondel)	*Gobio gobio*	61	25	41%
Ide (winde)	*Leuciscus idus*	29	11	38%
Crussian carp (kroeskarper)	*Carassius carassius*	11	1	9%
European eel (aal/paling)	*Anguilla anguilla*	10	9	90%
Carp (karper)	*Cyprinus carpio*	6	1	17%
Ruffe (pos)	*Gymnocephalus cernua*	5	1	20%
Weatherfish (grote modderkruiper)	*Misgurnis fossilis*	4	1	25%
Hydrid (hybride)	*Cyprinid hybrid*	4	2	50%
Bleak (alver)	*Alburnus alburnus*	2	2	100%
Stone loach (bermpje)	*Barbulata barbulata*	1	0	0%
Asp (roofblei)	*Aspius aspius*	1	0	0%
Pikeperch (snoekbaars)	*Sander lucioperca*	1	0	0%
Total	*Sander lucioperca*	1428	514	36%

In the following paragraphs movement patterns of the 10 species for which more than 10 individual fish were tagged and more than 5 were detected are presented. A schematic overview of the detection data for each of these 10 species is given in Annex 1.

4.1.1 Roach (*Blankvoorn*)

Roach was the most numerously caught species in the PIT-tagging experiments. Batches were tagged in each of the four stretches (although only 2 in stretch 3, Annex 1 Fig. A1.2). Tagged roach were detected in the entire system and used all weirs and fishways that had PIT-loops. In each batch (except stretch 3, where only 2 were tagged), there were individuals that moved through multiple fishways. The majority, however, was not detected after tagging and most tagged roach that were detected moved for relatively short distances to adjacent weir-fishways locations and more in upstream than in downstream direction (Annex 1 Fig. A1.2).

Some of the roach from the different batches tagged in 2018 were detected throughout the study period until June 2020 (Fig. 4.1). In each of the years (2018, 2019 and 2020), numbers of individuals that were detected peaked in April, most likely associated with spawning movements. The peak in October 2018 may be associated with a short distance redistribution of roach following the catch-tag-release of batches in September, given that this peak in detections was not observed in autumn 2019.

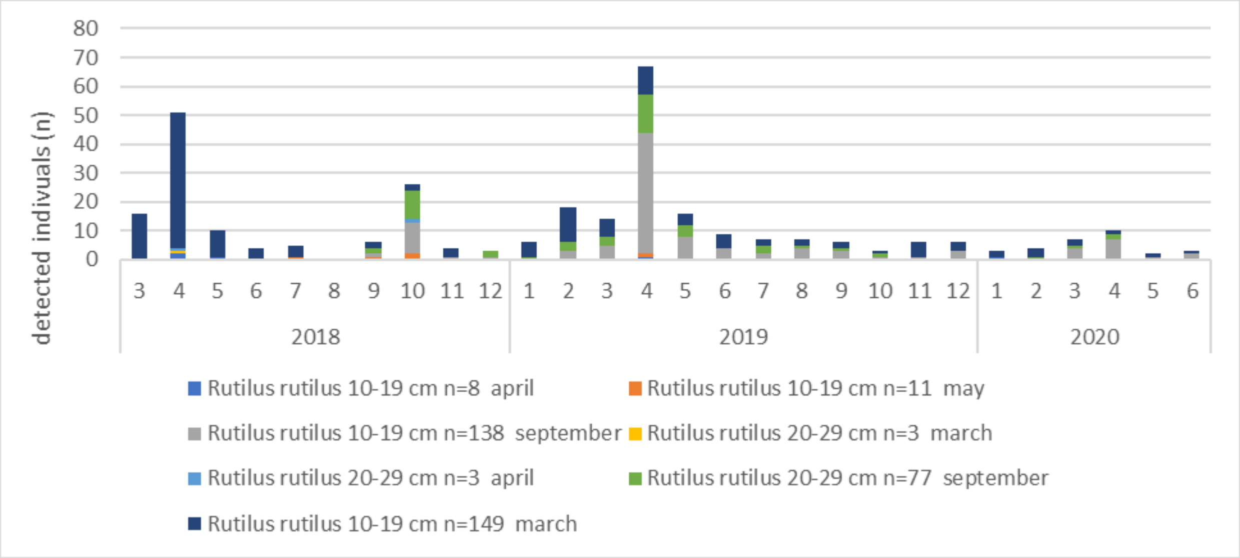
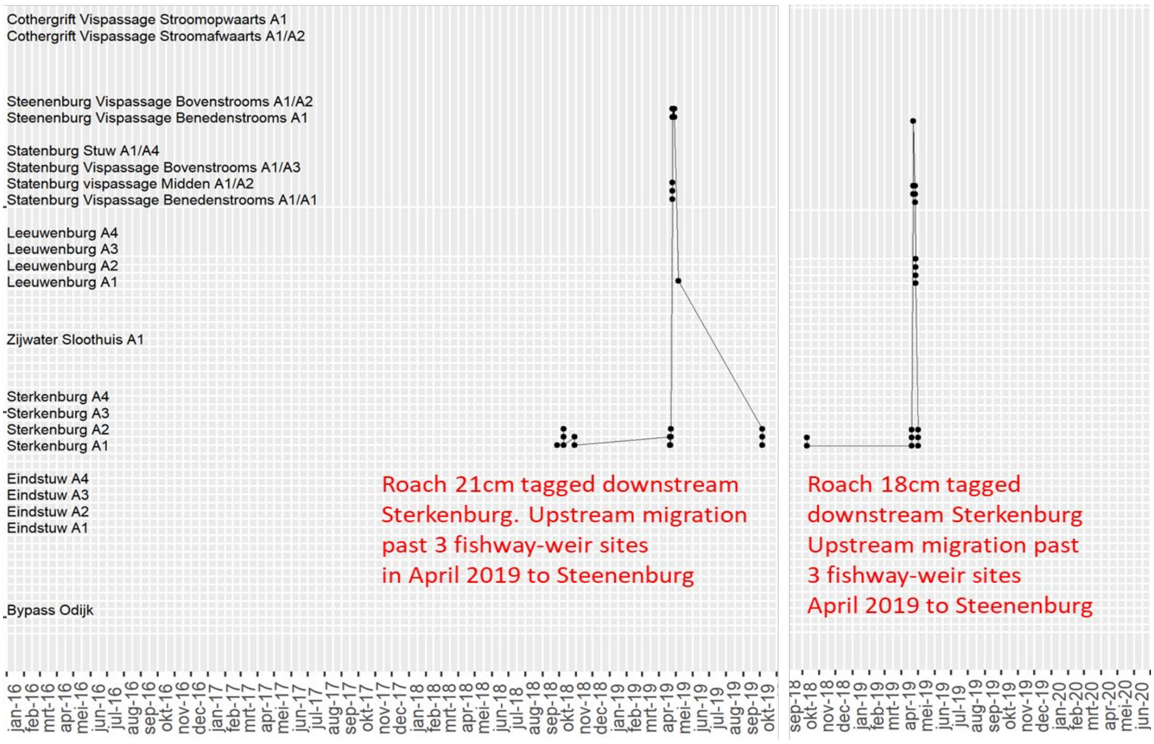


***Figure 4.1**. Number of tagged individual roach per month that were detected for each of the batches.*

Timing of tagged roach (Fig. 4.2) showed that detections outside the spring spawning period are mainly during daylight. During spring movements occur day and night, but predominantly during day. Individual patterns varied from detected at only one station to individuals that were detected at multiple sites throughout the study period. Some individuals were detected in different seasons near the place where they were released with a short upstream migration past several fishways during April-May which coincides with the spawning period of roach.

***Figure 4.2**. Individual detections plotted for time of day (0-24 hour, y-axis) and date. Top left: different colours per individual. Top right: timing of detections at weir loops, bottom left: timing of detections in fishway loops. Bottom right: timing of detections in bypass channel (red) and side ditch (blue).*

In Fig. 4.3, two individuals are shown that made short lasting migrations upstream and downstream, returning to the same area where they resided before, indicating spawning migrations and site fidelity to home ranges. One roach swam up and down fishway Sterkenburg continuously for three days (18.653 detections) in late April 2019 without passing to the upstream stretch.

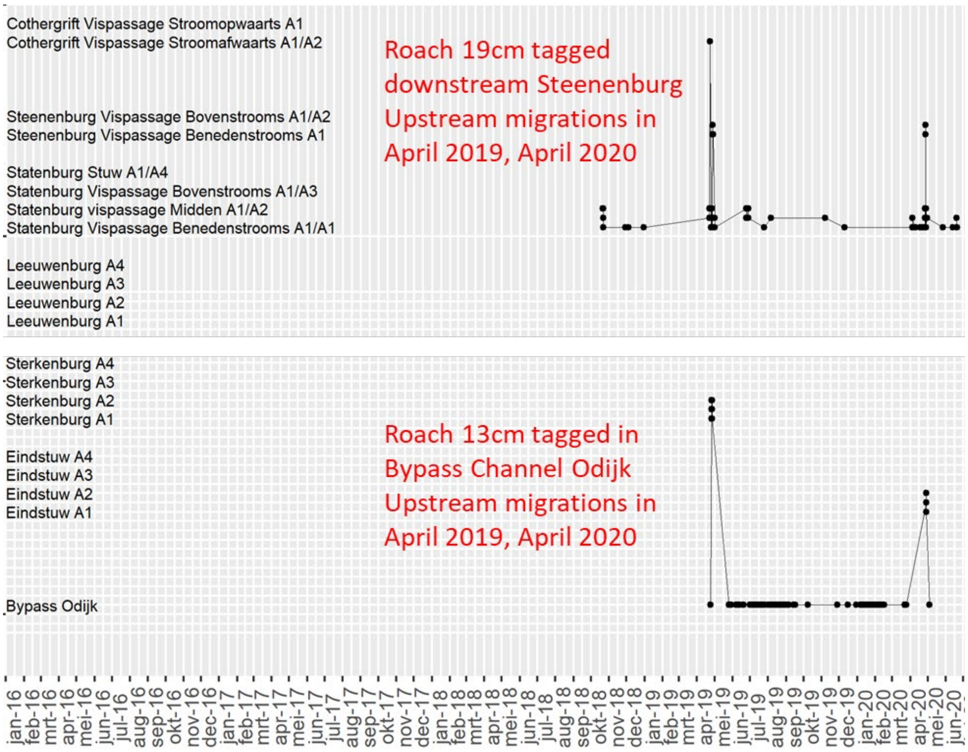


Roach 21cm tagged downstream Sterkenburg. Upstream migration past 3 fishway-weir sites in April 2019 to Steenenburg

Roach 18cm tagged downstream Sterkenburg Upstream migration past 3 fishway-weir sites April 2019 to Steenenburg

Figure 4.3. *Individual patterns of two roaches showing short lasting upstream migrations with a returning downstream migration to the same area where they were tagged. A1-A2-A3 refers to the downstream, middle and upstream loop in a fishway, A4 refers to a weir loop.*

Some roaches also showed short lasting upstream and downstream migrations during the spawning period is subsequent years, with similar returning behaviour to the same area where they were tagged, indicating a cyclic migratory pattern (Fig. 4.4).



Roach 19cm tagged downstream Steenenburg Upstream migrations in April 2019, April 2020

Roach 13cm tagged in Bypass Channel Odijk Upstream migrations in April 2019, April 2020

Figure 4.4. *Individual patterns of two roaches showing spawning migrations each year. A1-A2-A3 refers to the downstream, middle and upstream loop in a fishway, A4 refers to a weir loop.*

4.1.2 Bream (*brasem*)

Most bream were tagged near Eindstuw and at stretch 1 (Annex Fig. A1.3). Bream were detected at all antenna loops, except in the Bypass channel alongside the Eindstuw. All fishways were passed successfully at some point for some individuals. During downstream migration a substantial part was detected at the weirs.

There is a clear seasonal pattern in the detections of bream throughout the study period (Fig. 4.5) peaking in April-May each year, which coincides with the spawning period. Many of the individuals (almost all 40+cm and adult) were also detected in following years throughout the study period.

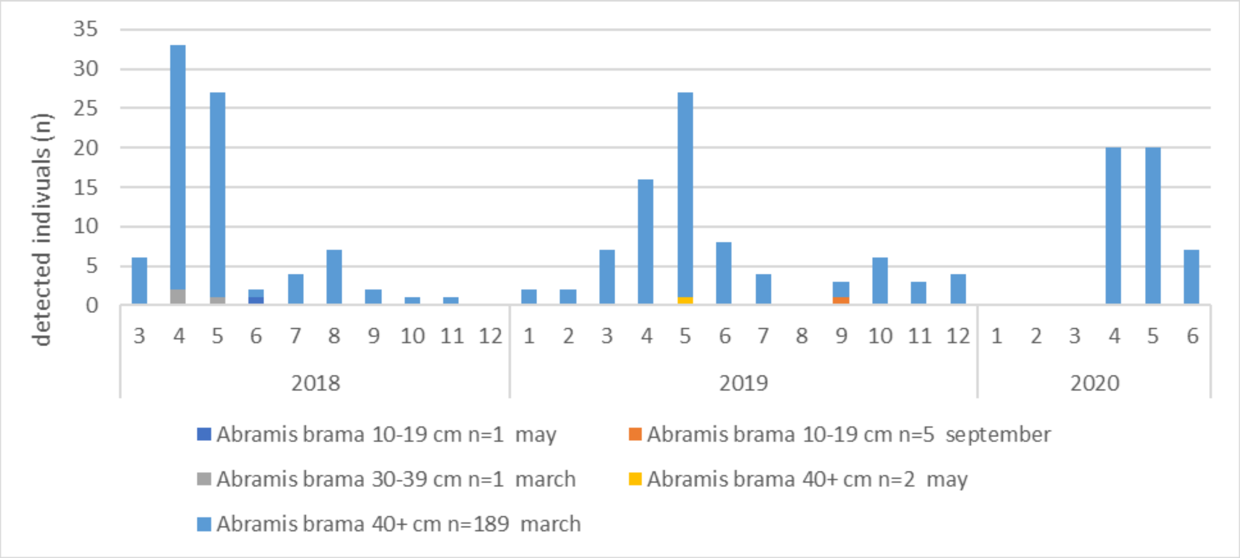


Figure 4.5. *Number of tagged individual bream per month that were detected for each of the batches.*

The timing of daily patterns over the seasons (Fig. 4.6), clearly show the spawning seasons in April-May where detections occurred both during night and day, with somewhat more at night. Outside the spawning period, most detections occurred at night, especially in the side ditch.

Variation in individual movement patterns for bream was large, but most bream showed more detections during spring time. In Fig. 4.7 two examples of individual patterns for adult bream are given. Each of these breams was mostly detected during April-June of each of the subsequent three springs that were covered during the study period. The male of 50 cm in the lower panel of Fig. 4.7 was detected directly upstream the weir of Leeuwenburg weir almost continuously for weeks during the spawning period in each of the three study years. Male breams maintain small territories during spawning (Poncin et al. 1996), which would be a good explanation for the pattern in detections observed. One bream left the Langbrokerwetering via Cothergrift to the Kromme Rijn and showed up at the Eindstuw 5 days later, thus most likely having passed two fishway-weir sites in the Kromme Rijn in these 5 days (Fig. 4.8).

Figure 4.6. *Individual detections plotted for time of day (0-24 hour, y-axis) and date. Top left: different colours per individual. Top right: timing of detections at weir loops, bottom left: timing of detections in fishway loops. Bottom right: timing of detections in bypass channel (red) and side ditch (blue).*

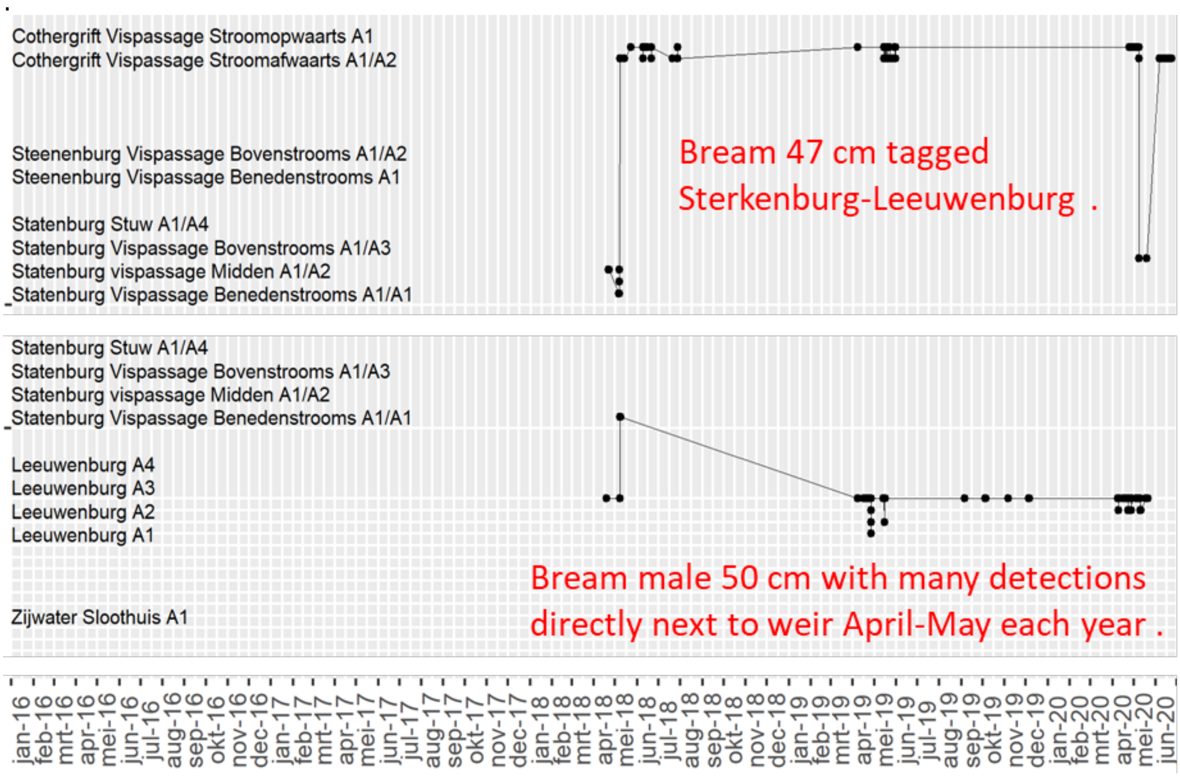
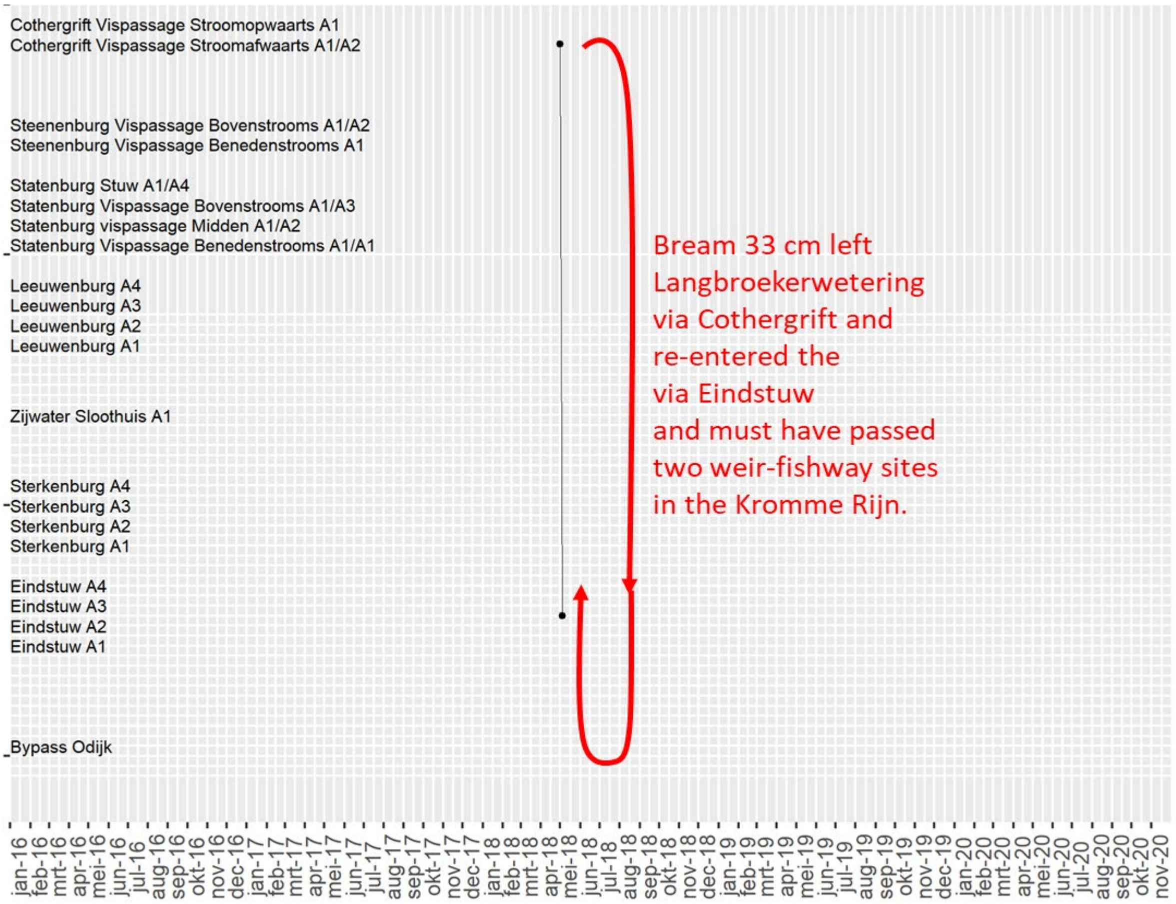


Figure 4.7. *Individual movement pattern of two individual adult breams (top and bottom panel). A1-A2-A3 refers to the downstream, middle and upstream loop in a fishway, A4 refers to a weir loop.*



Bream 33 cm left Langbroekerwetering via Cothergrift and re-entered the via Eindstuw and must have passed two weir-fishway sites in the Kromme Rijn.

***Figure 4.8**. Individual movement pattern of a bream of 33 cm. A1-A2-A3 refers to the downstream, middle and upstream loop in a fishway, A4 refers to a weir loop.*

4.1.3 Pike (*snoek*)

Pike was detected at all detection antenna in the study area. Some individuals passed series of fishways or series of weirs. Pike used weirs for passage in both upstream and downstream direction. It also used fishways, but relatively to a less degree (Annex Fig. A1.4).

Detections peaked during March-April for pike, which is an early spring spawner, in each of the years. Some pikes were detected for the full study period, but in general, numbers of detected individuals decreased steadily (Fig. 4.9).

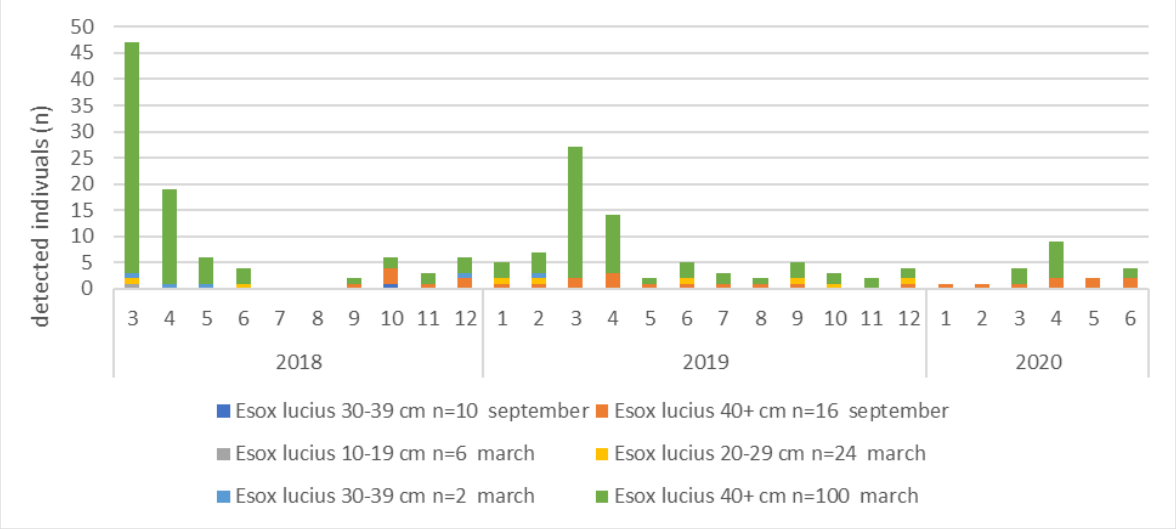


***Figure 4.9**. Number of tagged individual pike per month that were detected for each of the batches.*

Daily and seasonal patterns were very diverse for pike, showing more movements at night for some periods and individuals and more at day in other individuals and periods. This occurred within the detections at weirs, fish passages, in the Side Ditch and the bypass channel (Fig. 4.10).

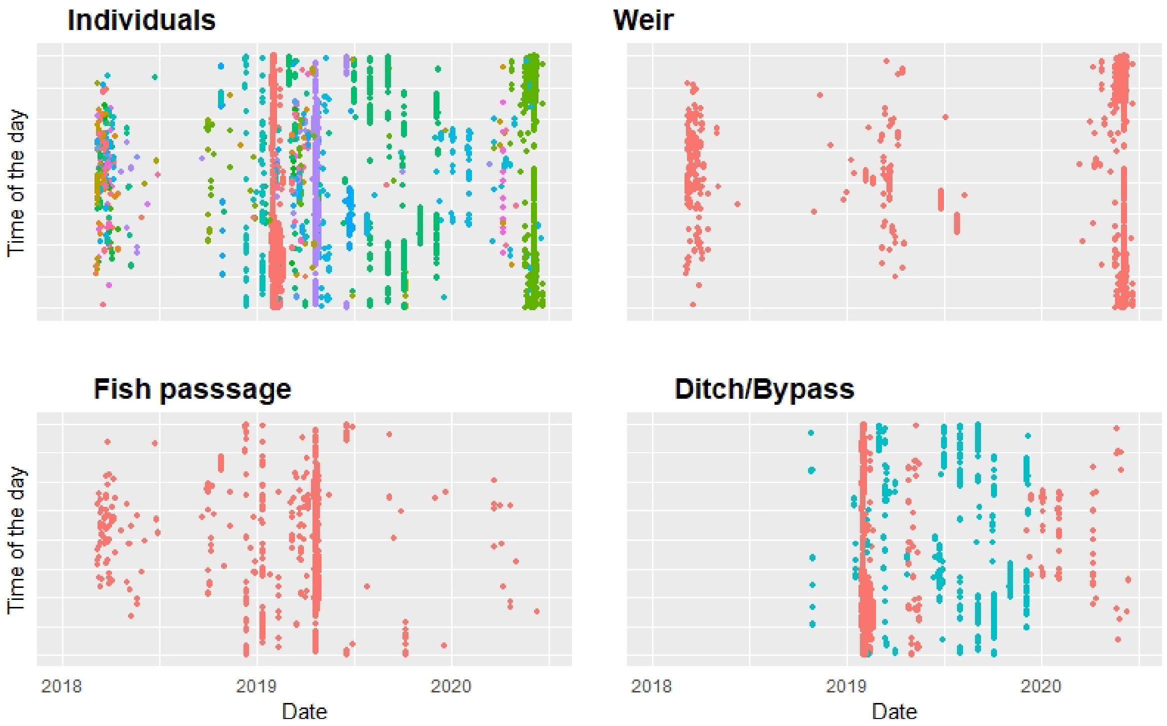


Figure 4.10. *Individual detections plotted for time of day (0-24 hour, y-axis) and date. Top left: different colours per individual. Top right: timing of detections at weir loops, bottom left: timing of detections in fishway loops. Bottom right: timing of detections in bypass channel (red) and side ditch (blue).*

Individual movement patterns greatly varied from only a few detections at one site to recurring detections over longer periods. In Fig. 4.11 three examples of individual patterns are given. A pike of 62 cm passed fishway Steenenburg during February-March in 2018 and in 2019 in both directions and appeared to reside upstream from Statenburg during periods in between (Fig. 4.11 top left panel). A pike of 66 cm was detected at irregular intervals at the Eindstuw and the bypass channel alongside the Eindstuw at Odijk (Fig. 4.11 bottom left panel). A pike 69 cm was observed to pass fishway Sterkenburg and Leeuwenburg within a few days (Fig. 4.11 right panel).

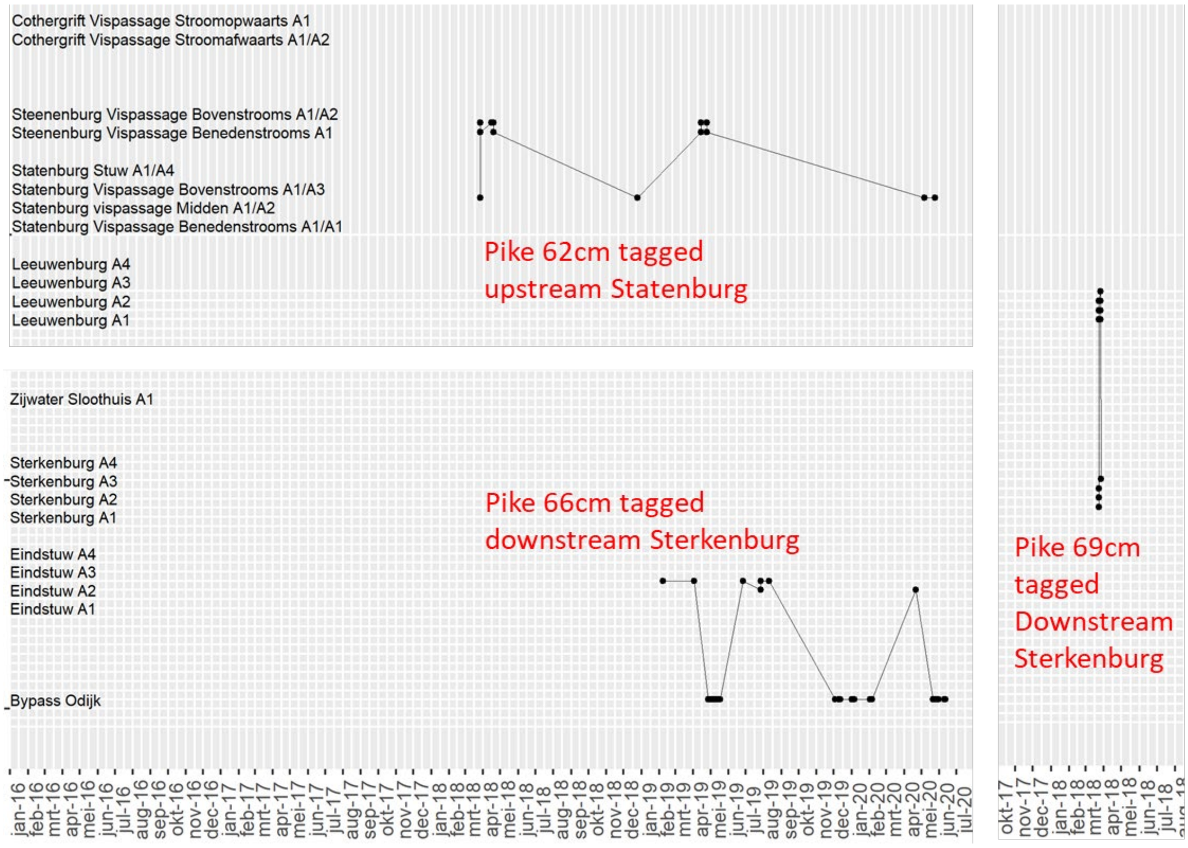


***Figure 4.11**. Individual movement patterns of three pikes. A1-A2-A3 refers to the downstream, middle and upstream loop in a fishway, A4 refers to a weir loop.*

4.1.4 Tench (*zeelt*)

Relatively few tagged Tench were detected during the study period (only 18% of all tagged tench in total) and these detections mainly occurred at stations directly adjacent to the stretch where they were tagged. No individual Tench passed more than one fishway in a row (Annex Fig. A1.5).

Even though a relatively small fraction of the tagged tench was detected, they remained detected throughout the study period, with most detections during April-July (Fig. 4.12). Tench is a fractional spawner that lays batches of eggs throughout the summer.

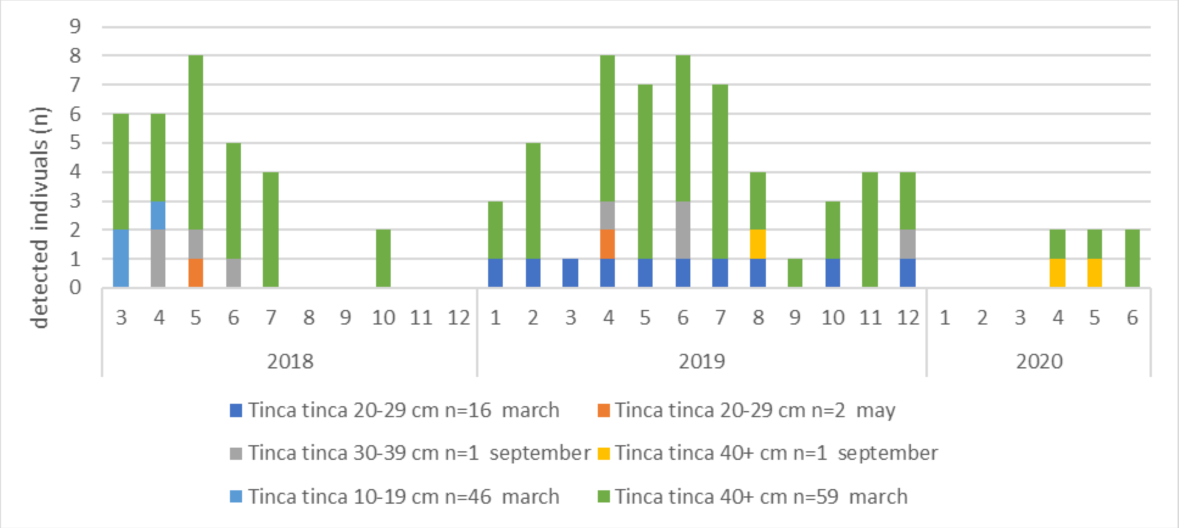


***Figure 4.12**. Number of tagged individual tench per month that were detected for each of the batches.*

Most detections for tench were made at the antenna loops (either at a weir, fishway or in the bypass channel or ditch) that directly border the stretch where a tench was tagged and released. Detections occurred during day and night, but relatively more at night (Fig. 4.13).

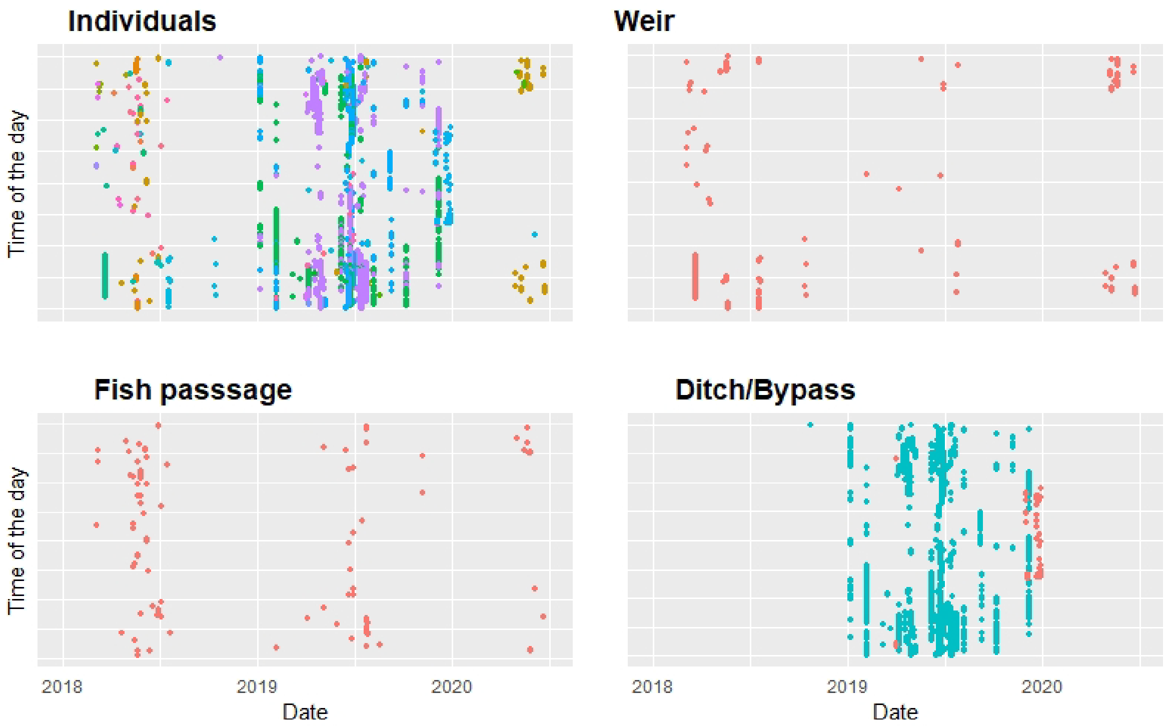


***Figure 4.13**. Individual detections plotted for time of day (0-24 hr, y-axis) and date. Top left: different colours per individual. Top right: timing of detections at weir loops, bottom left: timing of detections in fishway loops. Bottom right: timing of detections in bypass channel (red) and side ditch (blue).*

Of the small number of tenches that were detected, most showed only few detections at single sites. One adult tench of 44 cm was observed to move between Statenburg and Cothergrift where it was detected both within the two fishways and directly at the two weirs (Fig. 4.14). Fishway Statenburg was passed multiple times in both directions in April-May 2018 and 2020, but it was only briefly seen upstream from Statenburg during May-June 2019.

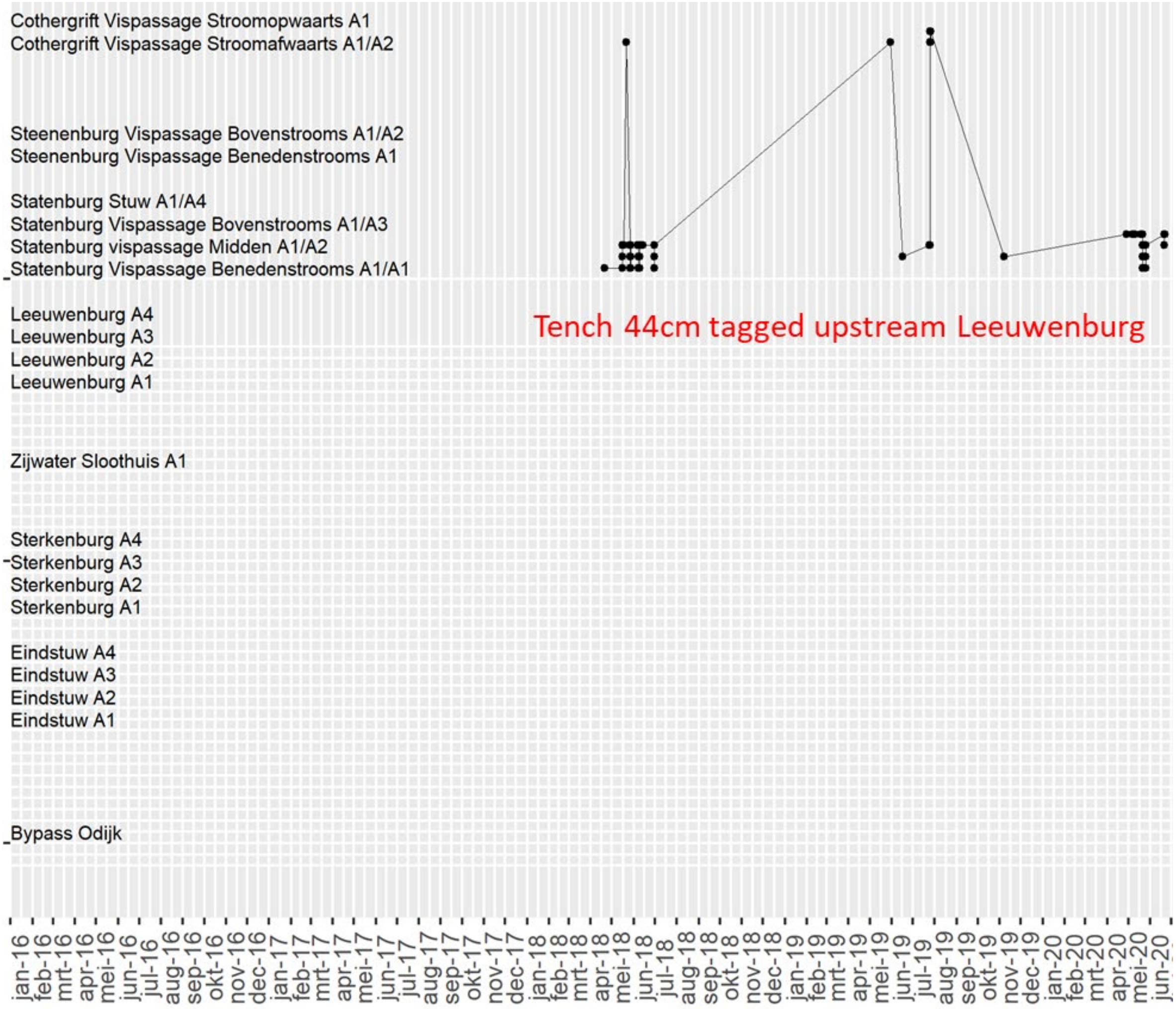


***Figure 4.14**. Individual movement pattern of a Tench of 44 cm. A1-A2-A3 refers to the downstream, middle and upstream loop in a fishway, A4 refers to a weir loop.*

4.1.5 White bream (*kolblei*)

Most white bream were caught and tagged when entering stretch 1 from the Kromme Rijn through the fishway (Fig. 3.7). Part of this group moved along series of fishways deeper into the Langbroekerwetering system (Annex Fig. A1.6). Also some individuals from the batches caught and tagged in stretch 3 and 4 moved past several fishway-weir locations in both directions.

Tagged white bream were mainly detected during the first year during the spawning period, peaking in May 2018. Detections thereafter were much less and hardly any white bream was detected in the last study year (Fig. 4.15). Although in 2019 most detections were during March-June, no peak in detections as in 2018 occurred.

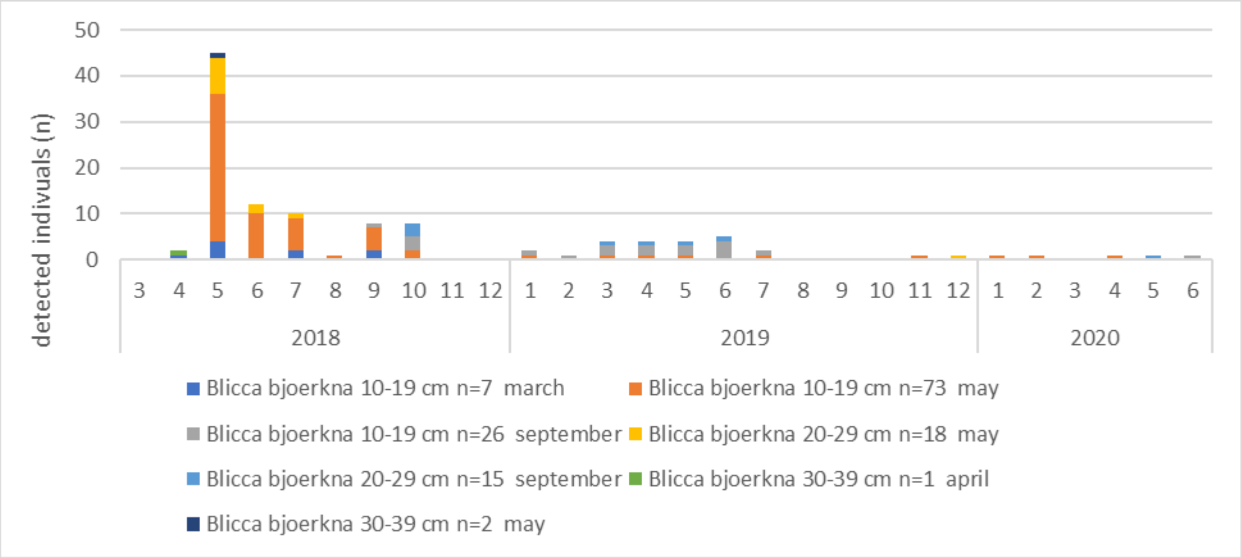


Figure 4.15*. Number of tagged individual white bream per month that were detected for each of the batches.*

White bream was mostly detected in fishways during upstream movements, and relatively few were detected moving downstream over the weirs. There was no clear difference between day and night in the timing of the detections throughout the study period (Fig. 4.16).

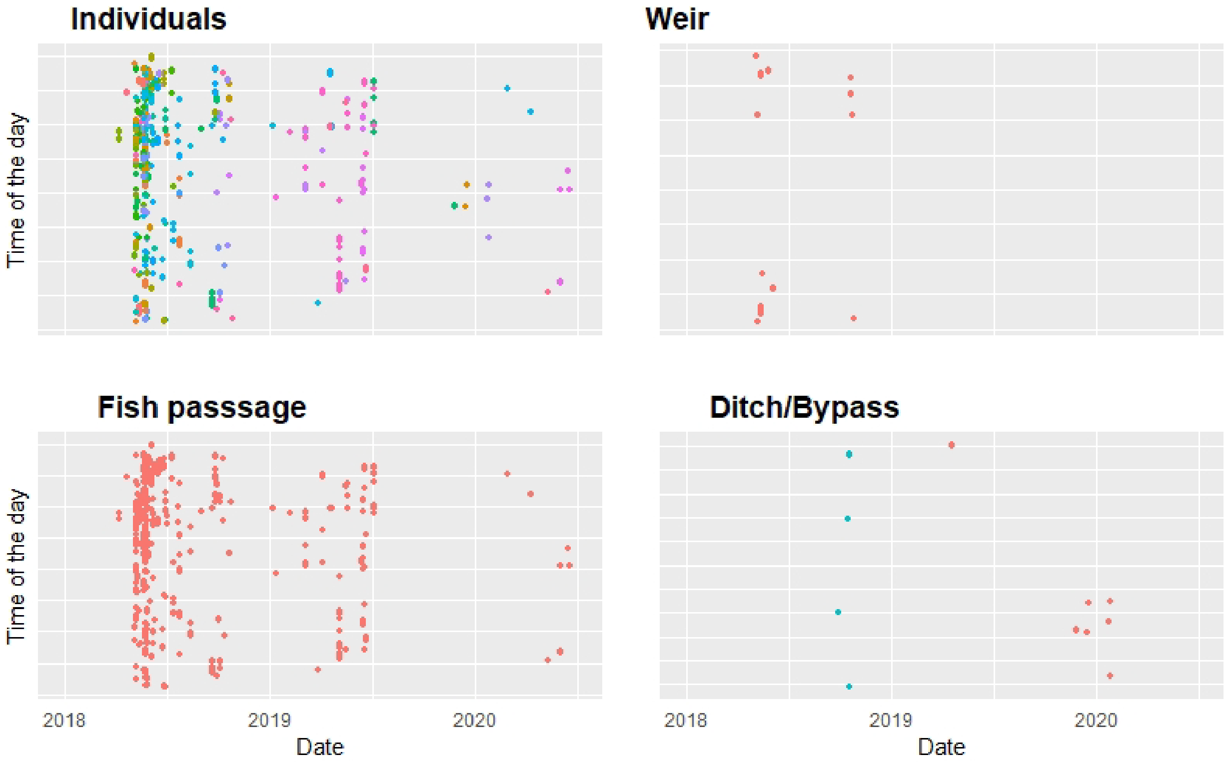


Figure 4.16*. Individual detections plotted for time of day (0-24 hr, y-axis) and date. Top left: different colours per individual. Top right: timing of detections at weir loops, bottom left: timing of detections in fishway loops. Bottom right: timing of detections in bypass channel (red) and side ditch (blue).*

A substantial part of the White Bream tagged at Eindstuw from the fykenet fishing in the fishway showed fast upstream movements from Eindstuw past multiple upstream fishways (see Fig. 4.17 for five examples). Some of the fish appear to have left the Langbroekerwetering-system via Cothergrift to return to the Kromme Rijn (Fig. 4.17 three left panels), while others showed return downstream migrations to the Kromme Rijn directly following upstream passage of the fishways (Fig. 4.17 three right panels). Upstream passage of series of fishways could occur within a short time span, with the fastest White bream passing 3 fishways and the stretches in between within 8.5 hours, after already having passed the fishway at Eindstuw before it was caught in the fykenet (Fig. 4.17 left panel). Only few of the white breams were detected in a subsequent year as well.

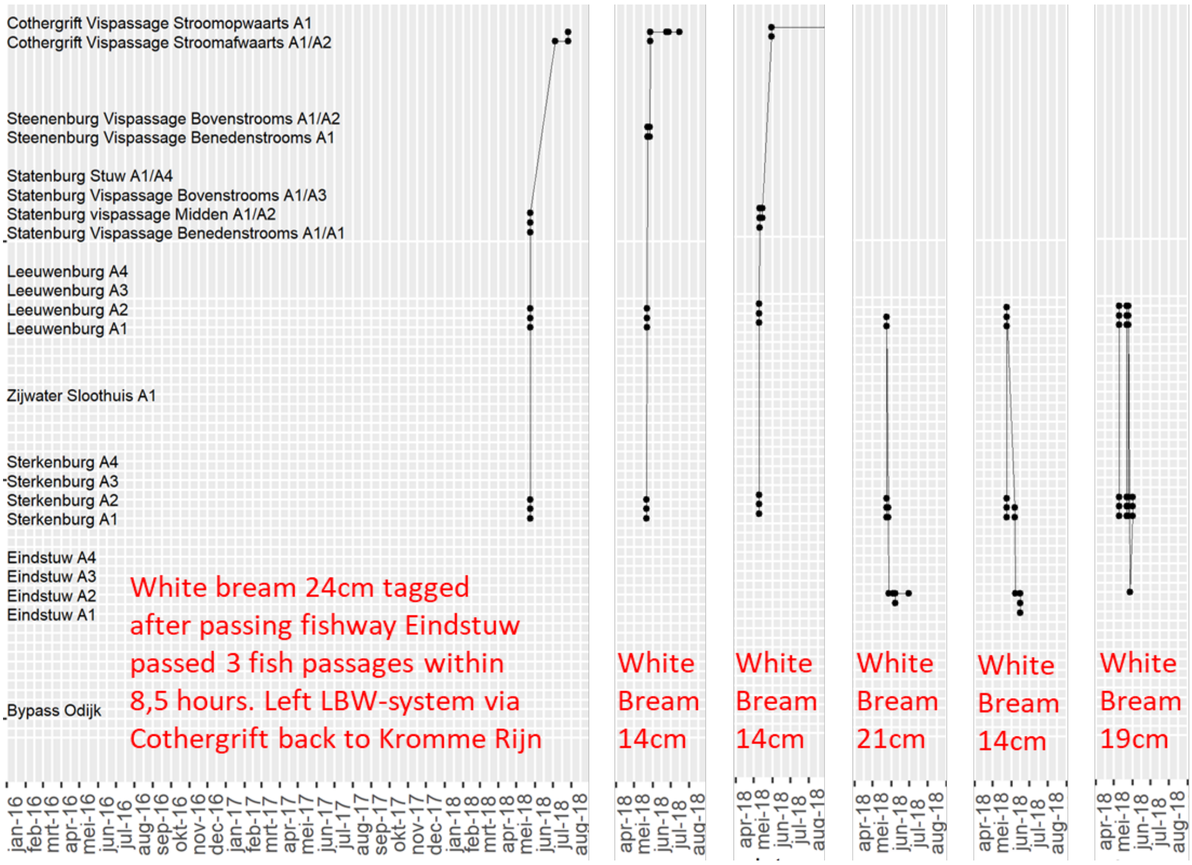


__Figure 4.17__. Individual movement pattern of six white breams, caught and tagged in the fykenet at fishway Eindstuw. A1-A2-A3 refers to the downstream, middle and upstream loop in a fishway, A4 refers to a weir loop.

4.1.6 Perch (baars)

Detections of almost all tagged perch were restricted to antenna loops directly adjacent to the stretch they were caught and released, with only two exceptions that passed multiple fishways (Annex Fig. A1.7).

Almost all perch were only detected within one year after tagging. The two peaks in 2018 in April and October directly followed up on when the tagging batches of perch were caught and released (Fig. 4.18). The peak in April 2019 might be related to spawning movements (perch is a relatively early spring spawner).

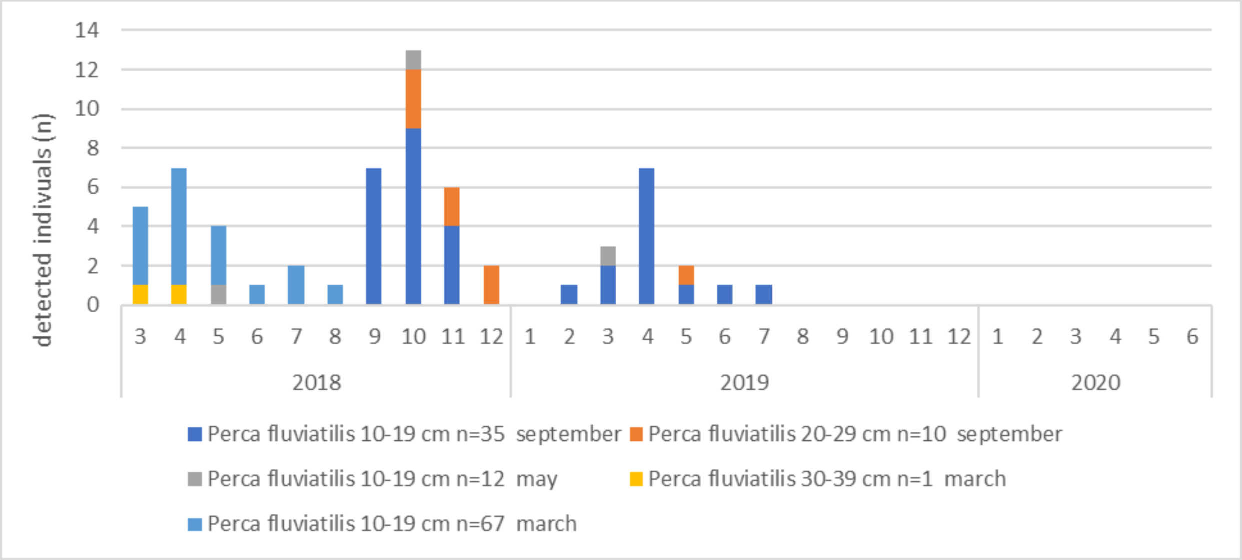


***Figure 4.18**. Number of tagged individual perch per month that were detected for each of the batches.*

Detections occurred more often during day than at night, except for one individual that was continuously present directly near the weir (presumably upstream) for several days (Fig. 4.19). The cluster of detections during the day by several perch in autumn 2018 might be related to resettling movements after being caught and tagged.

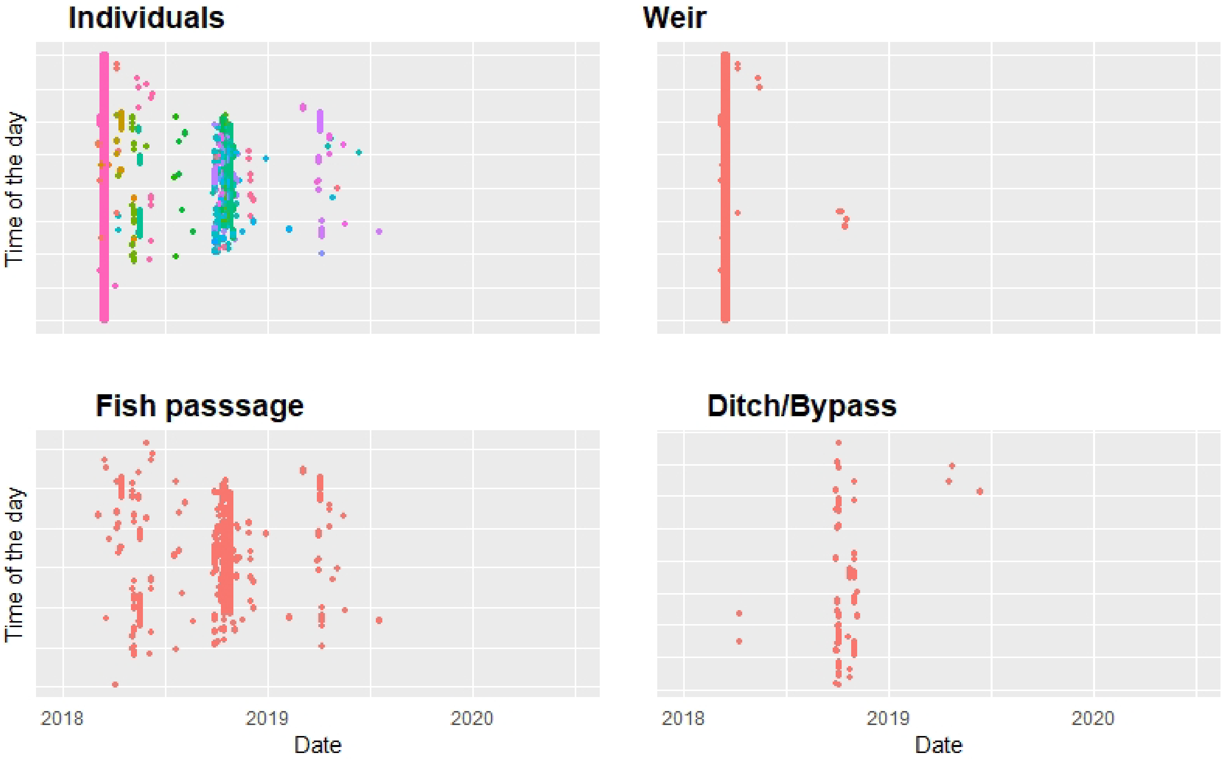


***Figure 4.19**. Individual detections plotted for time of day (0-24 hr, y-axis) and date. Top left: different colours per individual. Top right: timing of detections at weir loops, bottom left: timing of detections in fishway loops. Bottom right: timing of detections in bypass channel (red) and side ditch (blue).*

Of the perch that were detected, most were seen for only up to a few times at single sites adjacent to the stretch they were tagged, often entering fishways for either downstream or upstream direction without passing it. Some perch did pass fishways, however, one small perch of 12 cm passed three fishways (Sterkenburg, Leeuwenborg and Steenburg) in only 38 hours, and must have passed Statenburg in between as well, although it remained undetected there (perhaps it passed over the weir, where the small PIT-tag of 13 mm might be missed by the Weir-loop, Fig. 4.20 left panel). Another perch was seen to move up and down fishway Sterkenburg many times during September-October 2018 (Fig. 4.20 right panel).

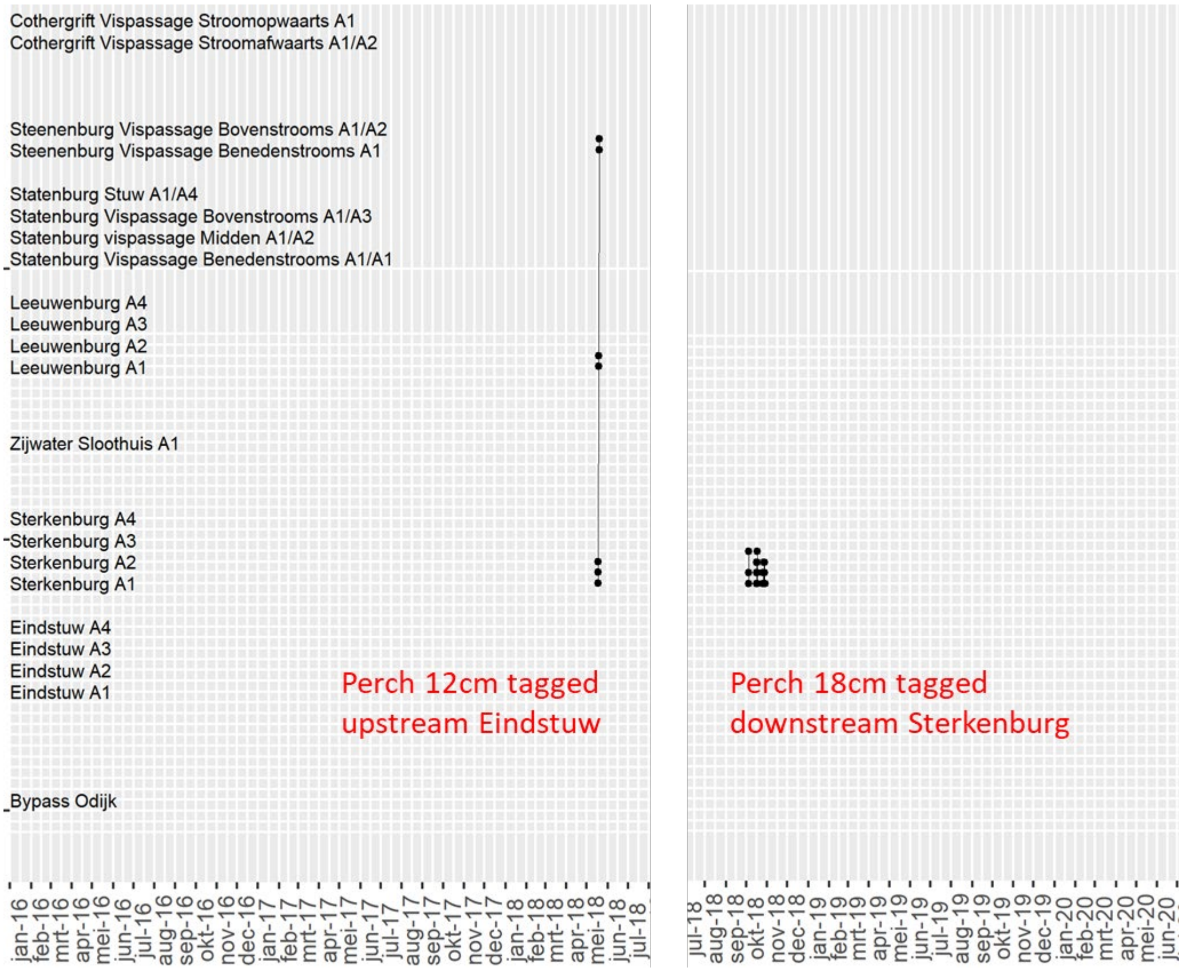


***Figure 4.20**. Individual movement patterns of two perch. A1-A2-A3 refers to the downstream, middle and upstream loop in a fishway, A4 refers to a weir loop.*

4.1.7 Rudd (ruisvoorn/rietvoorn)

Rudd were almost exclusively detected at stations directly adjacent to the stretch they were tagged and released. Only one tagged rudd passed two weir/fishway locations in a row (Annex Fig. A1.8).

Tagged rudd were detected up to 20 months after tagging (Fig. 4.21). There was no clear seasonal pattern, with October 2018, April and June 2019 relatively showing highest detection rates. In 2020, no rudd were detected anymore.

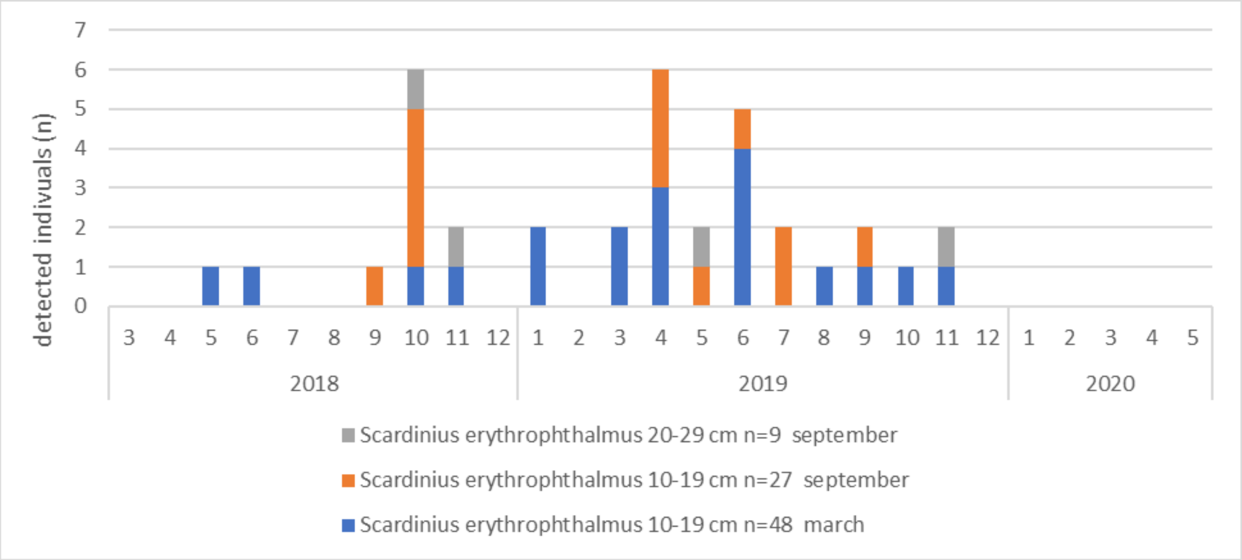


Figure 4.21*. Number of tagged individual rudd per month that were detected for each of the batches.*

In addition to two individuals that were detected relatively often in a fishway during autumn 2018, Most detected movements were scattered over the seasons during 2019 in either a fishway or the ditch site (Fig. 4.22). Detections at weirs were scarce and none was detected in the bypass channel alongside the Eindstuw.

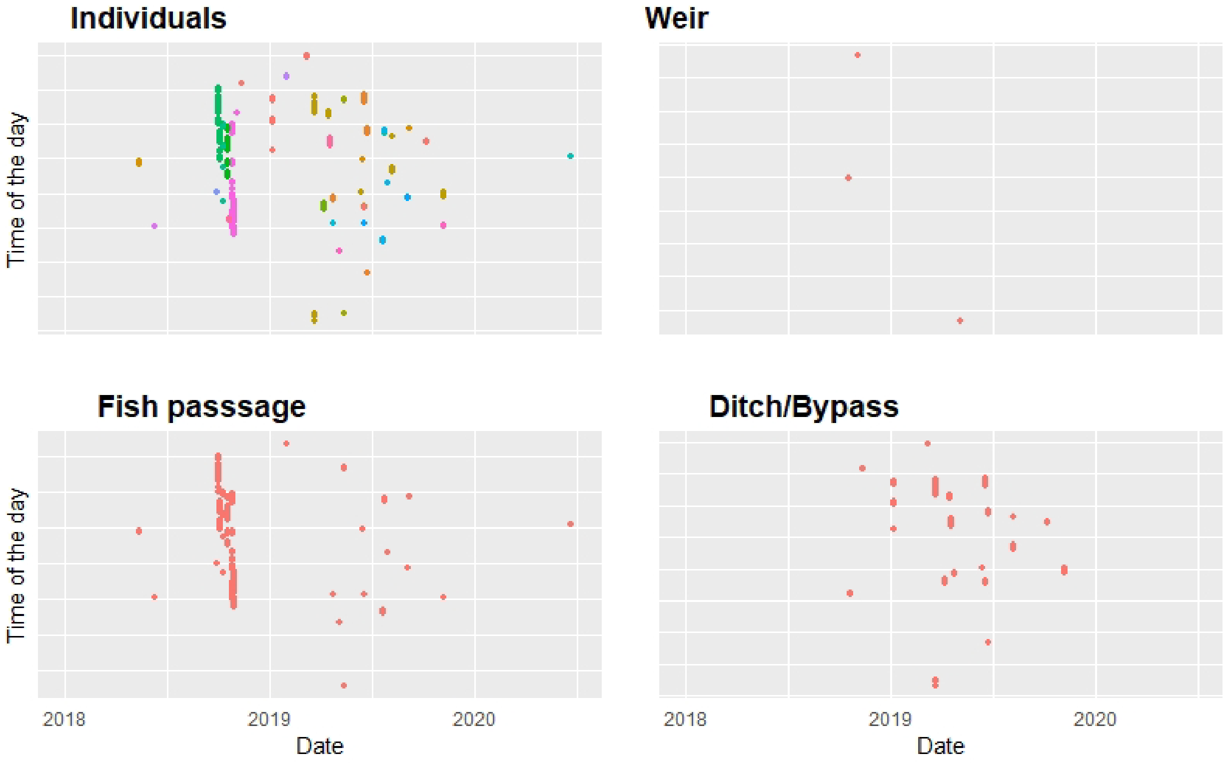


Figure 4.22*. Individual detections plotted for time of day (0-24 hr, y-axis) and date. Top left: different colours per individual. Top right: timing of detections at weir loops, bottom left: timing of detections in fishway loops. Bottom right: timing of detections in bypass channel (red) and side ditch (blue).*

Only a small fraction of the tagged rudd were detected and most of these were seen for only up to a few times at single sites adjacent to the stretch they were tagged. Two individuals were detected multiple times in a fishway during autumn 2019 (Fig. 4.23). Some rudd passed fishways over longer periods (Fig. 4.23 top panel). One rudd was detected 731 times over a 7 month period in the side-ditch (‘zijwater Sloothuis’) but nowhere else (Fig. 4.23 bottom panel).

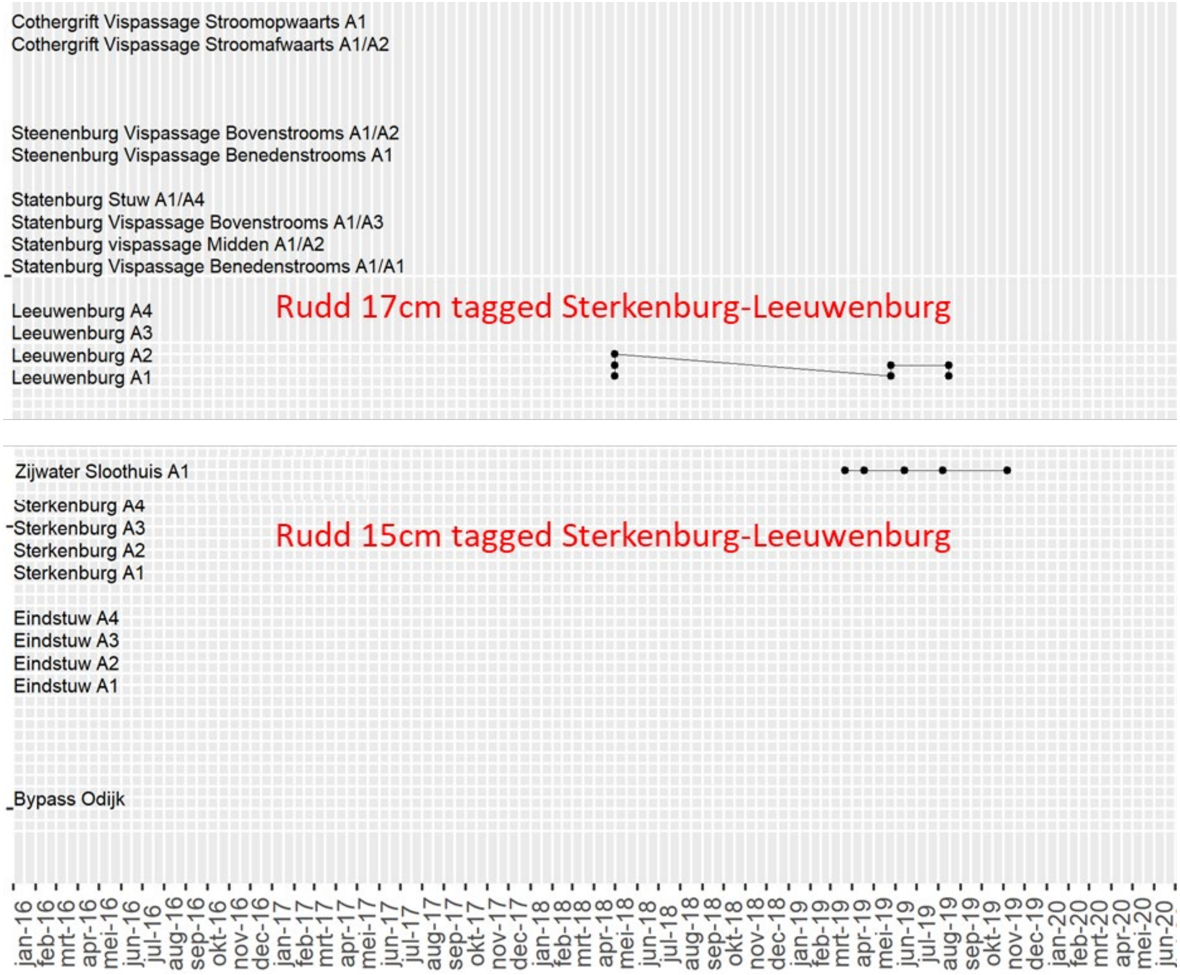


***Figure 4.23**.individual detection pattern of two rudd. A1-A2-A3 refers to the downstream, middle and upstream loop in a fishway, A4 refers to a weir loop.*

4.1.8 Gudgeon (riviergrondel)

This small-bodied cyprinid was mostly caught in the fykes in the fishway and in the bypass channel at Eindstuw (Fig. 3.7), presumably entering the study area from the Kromme Rijn, and detected mostly in the stations at Eindstuw and Sterkenburg (Annex Fig. A1.9). Only few gudgeons moved beyond Sterkenburg via the fish passage (5). Both the fishway and the weir at Eindstuw were used for downstream passage.

Tagged gudgeons were only observed during spring 2018. None of the tagged gudgeons was detected in the years thereafter (Fig. 4.24). Detections peaked in April-May coinciding with their spawning period.

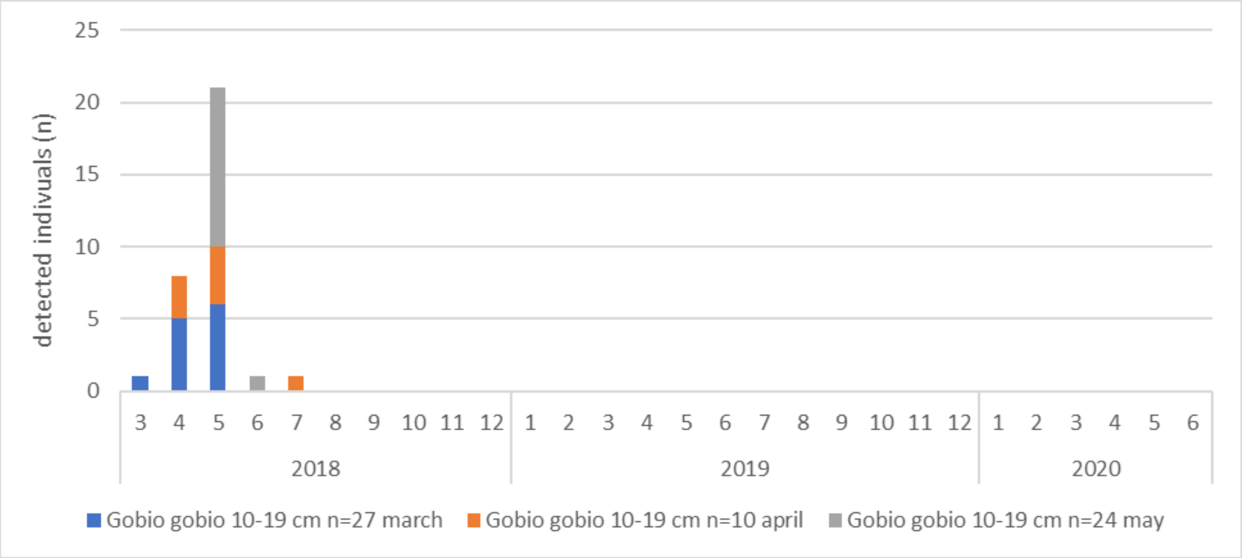


Figure 4.24. *Number of tagged individual gudgeon per month that were detected for each of the batches.*

Detections occurred mainly during night, which was very strongly apparent at the weir station, and also visible in the fishway detections, although some individuals were also detected for prolonged periods during day (Fig. 4.25). The latter might reflect gudgeons using the fishway as a habitat, rather than as a corridor. Even though a substantial part of the gudgeons were caught in the bypass channel with fykes (Fig. 3.7), none of the tagged gudgeons was detected in the bypass channel thereafter.

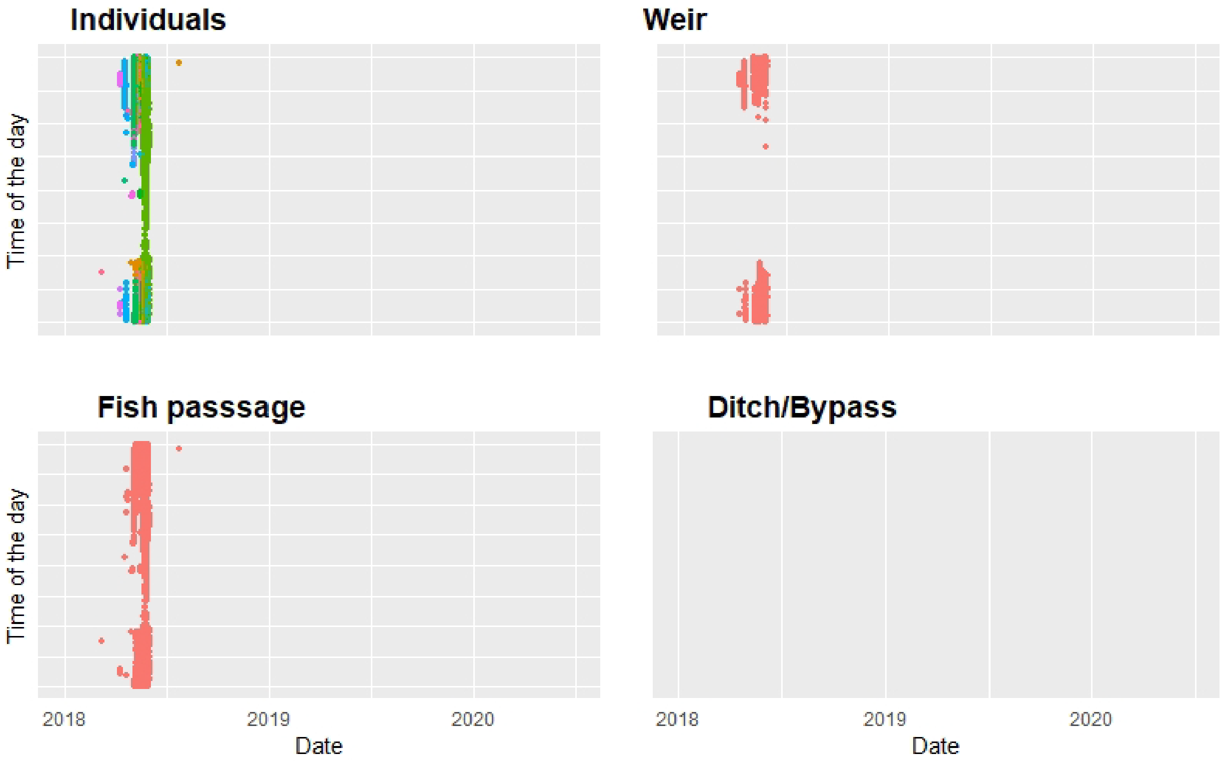


Figure 4.25. *Individual detections plotted for time of day (0-24 hr, y-axis) and date. Top left: different colours per individual. Top right: timing of detections at weir loops, bottom left: timing of detections in fishway loops. Bottom right: timing of detections in bypass channel (red) and side ditch (blue).*

Some gudgeons swim up and down the fishways and spend prolonged periods up to 16 days in the fishways (one individual was detected 635 times in the Eindstuw fishway from 18-24 May 2018). Gudgeons that were caught and tagged at the Eindstuw site either moved upstream to reside in and around the fishway and weir Sterkenburg, resided in and around the weir and fishway at Eindstuw or moved downstream past the Eindstuw, both via the fishway or via the weir (see Fig. 4.26 for three examples).

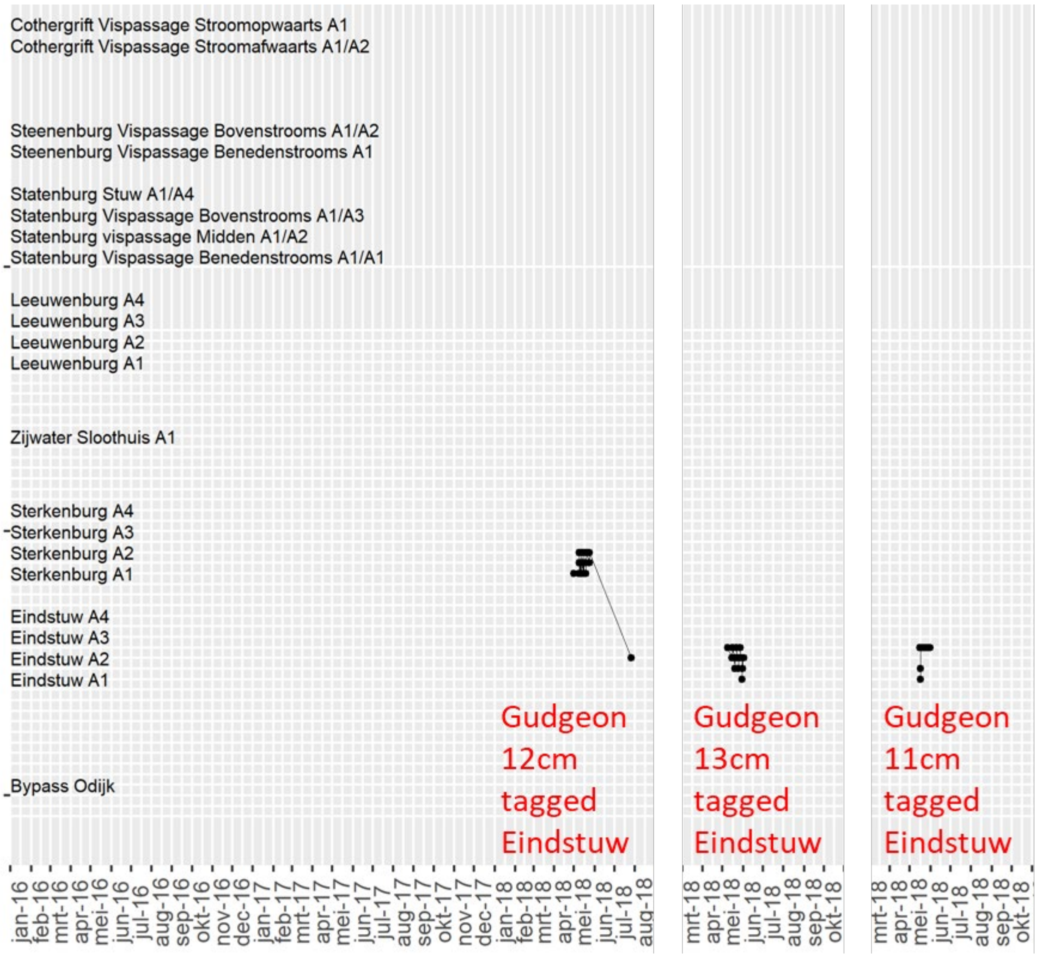


***Fig. 4.26**. individual detection patterns of three gudgeons caught, tagged and released at Eindstuw. A1-A2-A3 refers to the downstream, middle and upstream loop in a fishway, A4 refers to a weir loop.*

4.1.9 Ide (winde)

Most of the tagged ide were juvenile (<30 cm, Fig. 3.8). Only 9 out of 26 were detected of which 5 were detected at multiple fishway-weir locations. Only one passed a series of 4 fishway-weir locations (Annex Fig. A1.10).

Even though the number of tagged individual ide that were detected was relatively low, especially for a species considered to be more migratory (Winter & Fredrich 2003), the number of detections throughout the study period remained relatively constant (Fig. 4.27). Numbers of detected individuals were highest in April-June for each of the three years, but numbers are too low to detect a clear seasonal pattern.

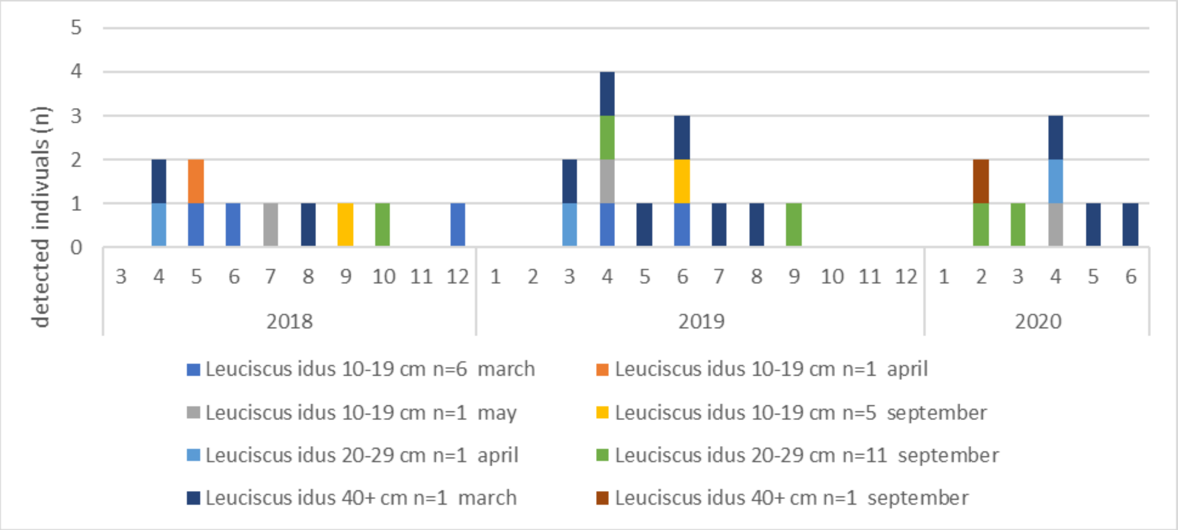


***Figure 4.27**. Number of tagged individual ide per month that were detected for each of the batches.*

Ide were detected at fishway and weir stations, however not in the bypass channel alongside the Eindstuw, nor in the ditch site (Fig.4.28). One individual spend much time in the vicinity of a weir before and after the spawning season in 2020. No clear pattern in day-night movements was observed.

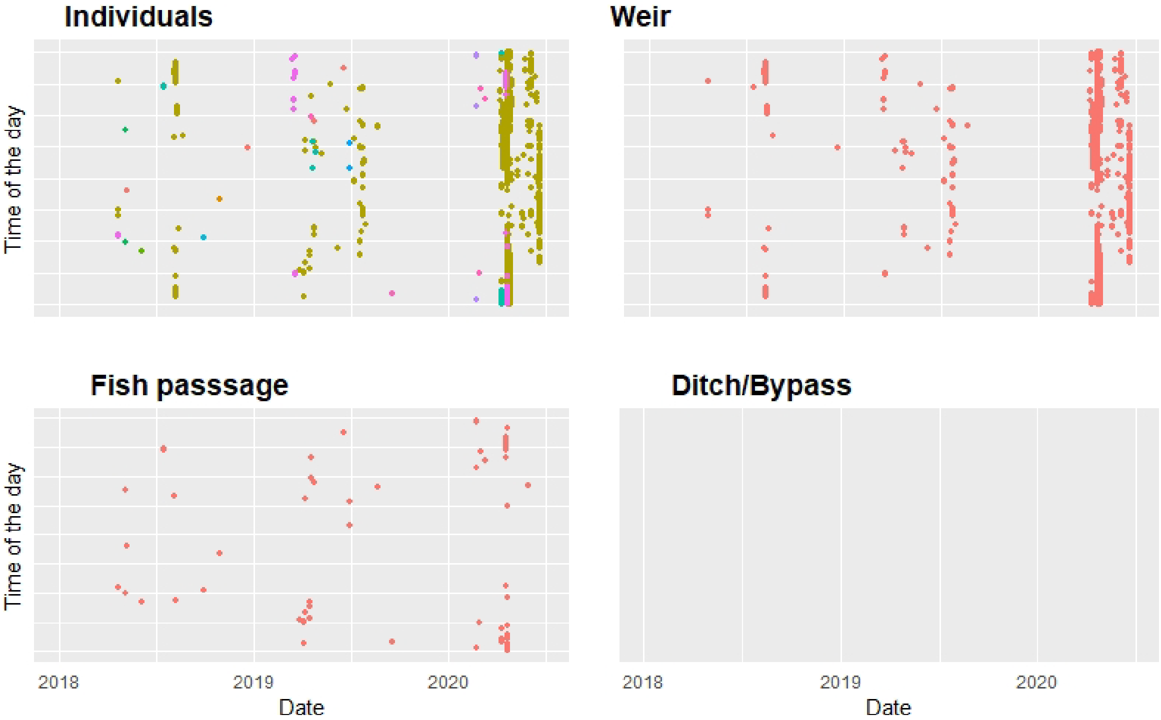


***Figure 4.28**. Individual detections plotted for time of day (0-24 hr, y-axis) and date. Top left: different colours per individual. Top right: timing of detections at weir loops, bottom left: timing of detections in fishway loops. Bottom right: timing of detections in bypass channel (red) and side ditch (blue).*

Individual patterns were divers. In Fig. 4.29 the movement pattern of an adult ide (left panel) and a juvenile ide is given (right panel). The adult ide of 44 cm appears to reside in the stretch in between Leeuwenburg and Statenburg showing up at the downstream side of Statenburg in early spring of 2019 and 2020, but did not pass the fishway or weir at Statenburg nor the fishway or weir at Leeuwenburg. The right panel shows the pattern of a juvenile ide of 17 cm. This ide moved upstream past the fishway Leeuwenburg and upstream via the weir at Statenburg, then most likely via the weir at Steenenburg (where no detection station was placed) and finally reaching Cothergrift (where it was detected in the fishway). It then swam back to the Steenenburg and was detected in the fishway there.

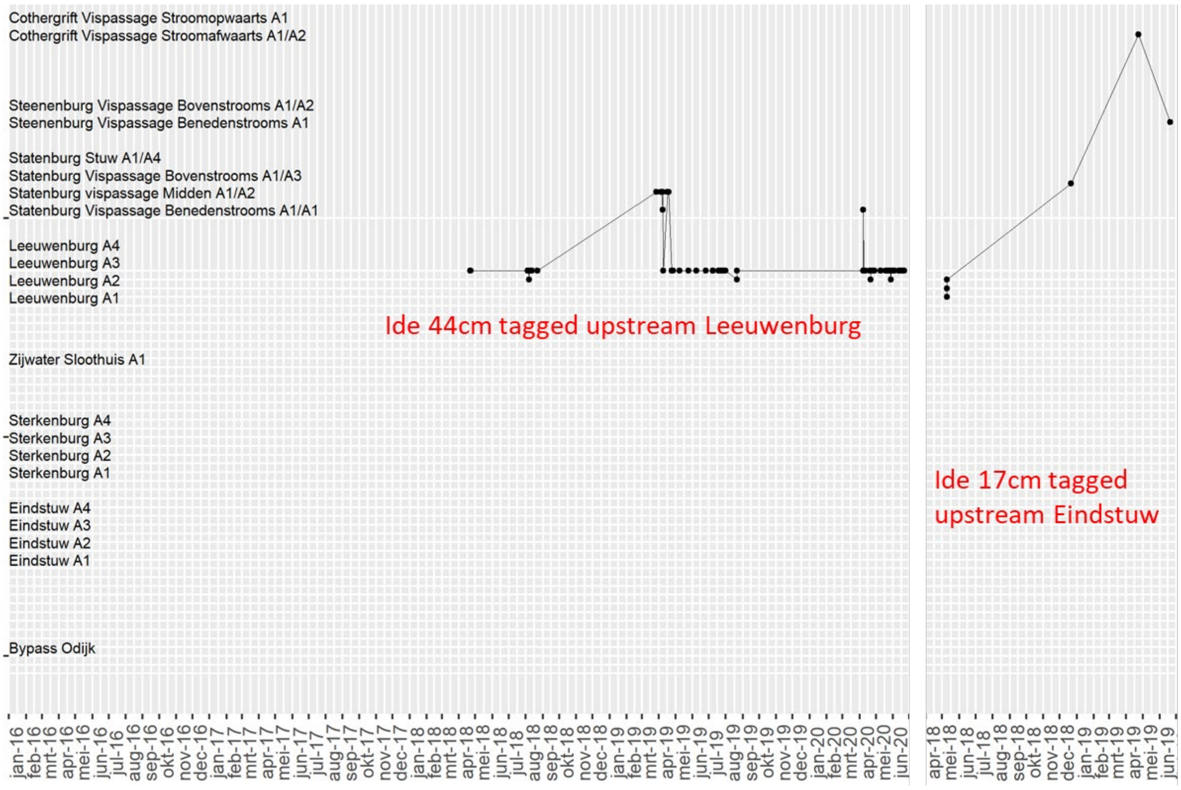


Fig. 4.29. *Individual movement patterns of an adult ide (left) and juvenile ide (right). A1-A2-A3 refers to the downstream, middle and upstream loop in a fishway, A4 refers to a weir loop.*

4.1.10 Eel (aal/paling)

Only a small number of eel was caught and tagged (9 at Eindstuw and 1 at Sterkenburg-Leeuwenburg stretch). All of these eels were in the non-migratory yellow eel phase, in between the migratory glass eel and silver eel phases. All eel near the Eindstuw were detected at the different stations around the stretch Eindstuw-Sterkenburg (Annex Fig. A1.11). Two eels passed two fishways in a row up to Leeuwenburg.

No clear seasonal pattern was observed. Detections occurred throughout the entire study period (Fig. 4.30), even though numbers of tagged individuals was low.

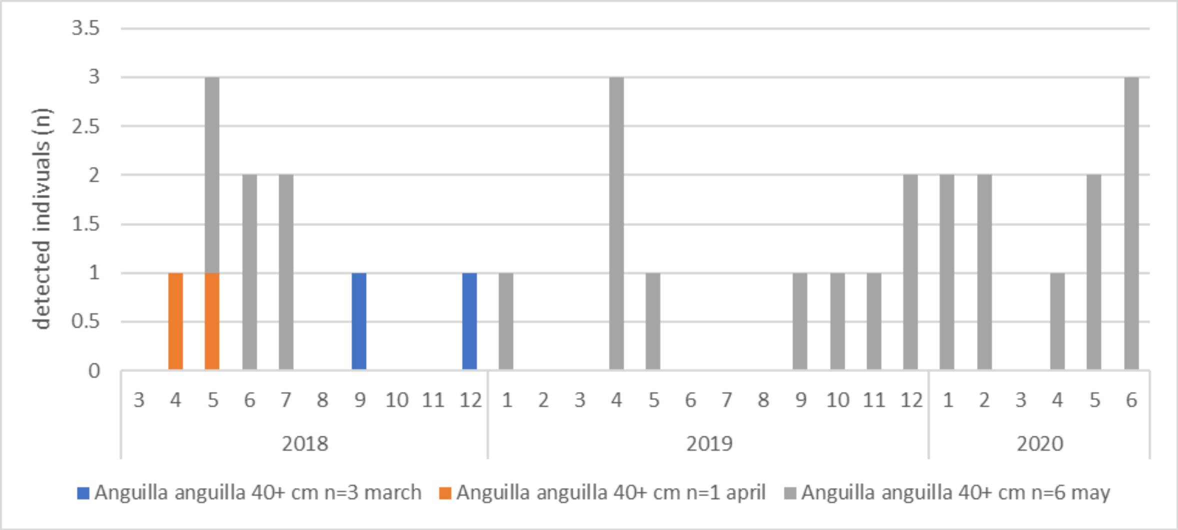


Figure 4.30. *Number of tagged individual eel per month that were detected for each of the batches.*

The weir and fishway detections occurred almost exclusively at night (Fig. 4.31), whereas activity in the bypass channel alongside the Eindstuw showed a more diverse pattern, with detections in all hours during spring 2019, a periods of mainly detections during the daylight (winter 2019/2020) and a period of only night-time detections in spring 2020.

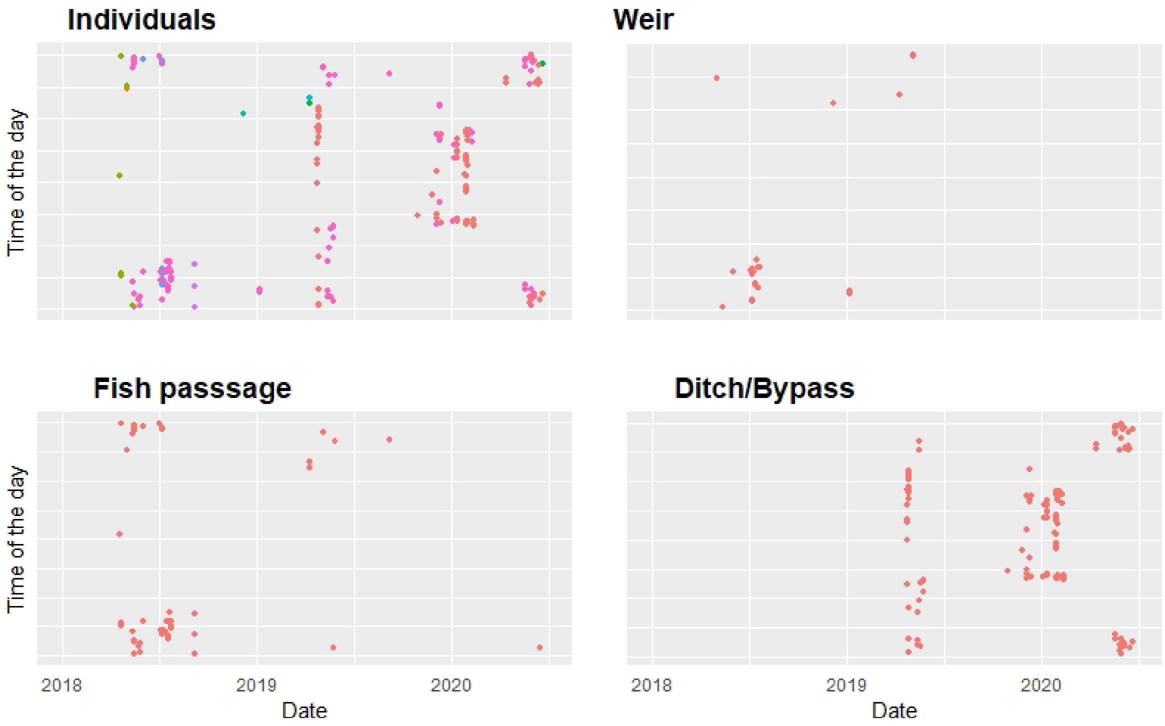


***Figure 4.31**. Individual eel detections plotted for time of day (0-24 hr, y-axis) and date. Top left: different colours per individual. Top right: timing of detections at weir loops, bottom left: timing of detections in fishway loops. Bottom right: timing of detections in bypass channel (red) and side ditch (blue).*

Most eels were detected, at various sites (weirs, fishways, bypass channel). One large eel of 71 cm was observed to perform upstream and downstream movements during April-May in both 2018 and 2019 (Fig. 4.32). It passed fishway Sterkenburg and fishway Eindstuw multiple times in both directions, but did not pass the fishway at Leeuwenburg even though it was detected in the fishway (no detection at A3). It has passed Sterkenburg two times without being detected (once in upstream direction directly after tagging, and one downstream direction in July 2019), perhaps due to misdetection at the weir. It also spend time in the bypass channel. The motivation for these spring movements are unclear but might be related to favourable feeding conditions since it coincides with the spawning period of many cyprinid and percid species, perhaps foraging on deposited eggs or larvae.

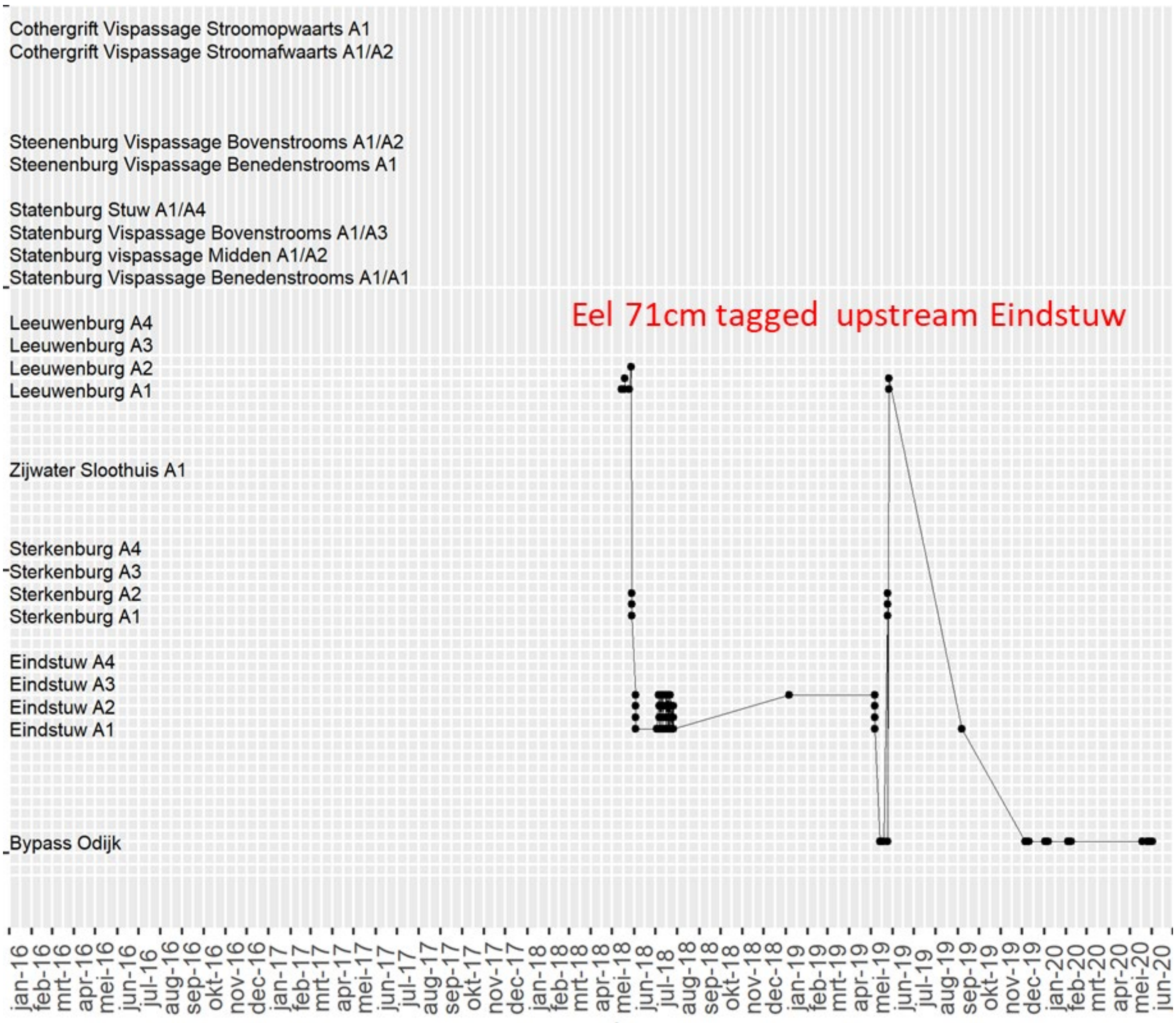


***Fig. 4.32**. Individual pattern of a large yellow eel. A1-A2-A3 refers to the downstream, middle and upstream loop in a fishway, A4 refers to a weir loop.*

4.2 Passage of weirs and De Wit fishways

For the four sites where both the De Wit fishways and the weirs were covered with PIT-antennae (Eindstuw, Sterkenburg, Leeuwenburg, Statenburg), upstream and downstream passage has been analysed in this paragraph.

First, upstream individual passage of all detected species are presented for the different site and routes per site, i.e. via fishway or via weir (Table 4.2). Roach, bream, pike and white bream had the highest number of upstream directed appearances at the four weir and fishway sites. In total, of the 15 species and hybrid cyprinids that were detected at a site in an upstream direction (appearance), 11 species and 2 hybrid cyprinids successfully passed the weir and fishway sites. For the 10 most abundant species, overall percentage of successful passage ranged from 46% (for ide) to 90% (for white bream). Both fishways and weirs were used as routes to successfully pass the sites in an upstream direction. 29 individual fish of 6 different species and a hybrid cyprinid, were able to successfully pass series of fishways in an upstream direction within short periods less than 7 days, (see examples presented in 4.1, e.g. white bream in fig. 4.17).

Table 4.2. *Overview of upstream passage via fishways and weirs; Number of upstream directed detected appearances per species for the sites with fishway and weir detection stations (Eindstuw, Sterkenburg, Leeuwenburg, Statenburg); number of upstream successful passages per species and route (fishway FP, weir W); percentages of successful passage (fishway and weir combined) per species and site and total (all 4 sites combined); number of fast passages of series of fishways, i.e. passing multiple fishways within 7 days). See 3.4 how these parameters were determined.*

Species	Upstream directed appearance				Upstream directed passage								Upstream directed passage					Fast
	Einds.	Sterk.	Leeuw.	Staten.	Einds.		Sterk.		Leeuw.		Staten.		Einds.	Sterk.	Leeuw.	Staten.	Total	passage
	n	n	n	n	FP	W	FP	W	FP	W	FP	W	%	%	%	%	%	series FP
Roach		62	32	13			26		17	2	10	1		42%	59%	85%	52%	7
Bream		23	15	17			12	1	6	1	8	2		57%	47%	59%	55%	
Pike		26	28	18		1	8	9	6	7	3	6		65%	46%	50%	56%	2
Tench		2	3	4			1		3		3			50%	100%	75%	78%	
White bream		35	23	9			34		19		7			97%	83%	78%	90%	14
Perch	2	8	6	3			6		3		2		0%	75%	50%	67%	58%	2
Rudd		5	4				4		1					80%	25%		56%	
Gudgeon	5	4	1		4		2		1				80%	50%	100%		70%	
Ide		4	7	2			3		2		1			75%	29%	50%	46%	
Eel	3	4	3	1	2		4		2				67%	100%	67%	0%	73%	1
Hybrid		1	1				1		1					100%	100%		100%	1
Weatherfish																		
Carp			1	1											0%	0%	0%	
Bleak		2	3	2			2		1	2		2		100%	100%	100%	100%	2
Pikeperch		1												0%			0%	
Ruffe		1												0%			0%	
Total	10	178	127	70	6	1	103	10	62	12	34	11	70%	63%	58%	64%	62%	29

Second, downstream individual passage of all detected species are presented for the different site and routes per site, i.e. via fishway or via weir (Table 4.4). Roach, bream, pike, tench, white bream and gudgeon had the highest number of downstream directed appearances at the four weir and fishway sites. In total, of the 13 species and hybrid cyprinids that were detected at a site in a downstream direction (appearance), 11 species and 2 hybrid cyprinids successfully passed weir and fishway sites. For the ten most abundant species, overall percentage of successful passage ranged from 0% (for ide) to 71% (for white bream). Both fishways and weirs were used as routes to successfully pass the sites in an downstream direction.

Table 4.4. *Overview of downstream passage via fishways and weirs; Number of upstream directed detected appearances per species for the sites with fishway and weir detection stations (Eindstuw, Sterkenburg, Leeuwenburg, Statenburg); number of upstream successful passages per species and route (fishway FP, weir W); percentages of successful passage (fishway and weir combined) per species and site and total (all 4 sites combined). See 3.4 how these parameters were determined.*

Species	Downstream directed appearance				Downstream directed passage								Downstream directed passage				
	Einds.	Sterk.	Leeuw.	Staten.	Einds.		Sterk.		Leeuw.		Staten.		Einds.	Sterk.	Leeuw	Staten.	Total
	n	n	n	n	FP	W	FP	W	FP	W	FP	W	%	%	%	%	%
Roach	14	13	5	33	4		10	1	3	1	6	2	29%	85%	80%	24%	42%
Bream	32	5	19	14	1	1	3	2	4	4	5	3	6%	100%	42%	57%	33%
Pike	13	7	23	15		1	3	1	4	1	1	3	8%	57%	22%	27%	24%
Tench	11	5	7	8			1	1	2	3	3	1	0%	40%	71%	50%	35%
White bream	35	20	7	4	16		14	4	5	1	3		46%	90%	86%	75%	65%
Perch	1	5	2	6			5		2		2		0%	100%	100%	33%	64%
Rudd	4	1		3	1		1						25%	100%		0%	25%
Gudgeon	19	2	1		5	1	2		1				32%	100%	100%		41%
Ide	1		5	2									0%		0%	0%	0%
Eel	8	4	2		4	1		3	1	1			63%	75%	100%		71%
Hybrid	2	1			2		1						100%	100%			100%
Weatherfish	1				1								100%				100%
Carp		1												0%			0%
Bleak		2	2	2			2			2		2		100%	100%	100%	100%
Pikeperch																	
Ruffe																	
Total	141	66	73	87	34	4	42	12	22	13	20	11	27%	82%	48%	36%	43%

Fish successfully passed the weirs and fishways in both upstream and downstream direction. In upstream direction a higher percentage used the fishways, than in a downstream direction (table 4.5). Keep in mind that for fish that were last detected at a weir station, with no follow-up position it could not be determined whether these successfully passed the weir or just turned around a the weir. These last detections were not classified as successful, which is a conservative estimate, especially in a downstream direction. The percentage of successful passage in a downstream direction can therefore be considered as a minimum fraction, where the true percentage will most likely be higher. For fishways, successful passage could be determined from the sequence of detection at loops from upstream to downstream or vice versa and will therefore more closely reflect all successful passages.

In upstream direction, most species predominantly used the fishways (87%-100%), except pike, that used the weir for upstream passage (58%) more often than the fishway (43%). Also in downstream direction fishways were often used for successful passage by all species, although the downstream passage of weirs might be underestimated as stated above.

Table 4.5. *Ratio between the two different routes, i.e. via the fishway and via the weir, used for successfull passage in upstream and in downstream direction, for all four sites (Eindstuw, Sterkenburg, Leeuwenburg, Statenburg) combined, for each of the 10 most abundant species*.

Successful	Upstream passage		Downstream passage	
	Via fishway	Via weir	Via fishway	Via weir
Roach	95%	5%	85%	15%
Bream	87%	13%	57%	43%
Pike	43%	58%	57%	43%
Tench	100%	0%	55%	45%
White bream	100%	0%	88%	12%
Perch	100%	0%	100%	0%
Rudd	100%	0%	100%	0%
Gudgeon	100%	0%	89%	11%
Ide	100%	0%		
Eel	100%	0%	50%	50%

Variation in the division of successful passage via the fishways or via the weirs did not vary much between the four sites (Tab. 4.6). Again, downstream passage via the weirs can be considered a minimum fraction, especially for the Eindstuw weir which is the last in the series weirs in downstream direction.

Table 4.6. *Ratio between the two different routes, i.e. via the fishway and via the weir, used for successfull passage in upstream and in downstream direction for all fish species combined, for each of the 4 sites (Eindstuw, Sterkenburg, Leeuwenburg, Statenburg)*.

Successful	Upstream passage		Downstream passage	
	Via fishway	Via weir	Via fishway	Via weir
Eindstuw	86%	14%	89%	11%
Sterkenburg	91%	9%	78%	22%
Leeuwenburg	84%	16%	63%	37%
Statenburg	76%	24%	65%	35%
Total	86%	14%	75%	25%

Passage times in upstream and downstream direction as analysed by Kooiman (2019) showed short passage times for all species, with faster passage in downstream direction than in upstream direction (Fig. 4.33). For more details on passage behaviour see Kooiman (2019) and Valkenaars (2019).

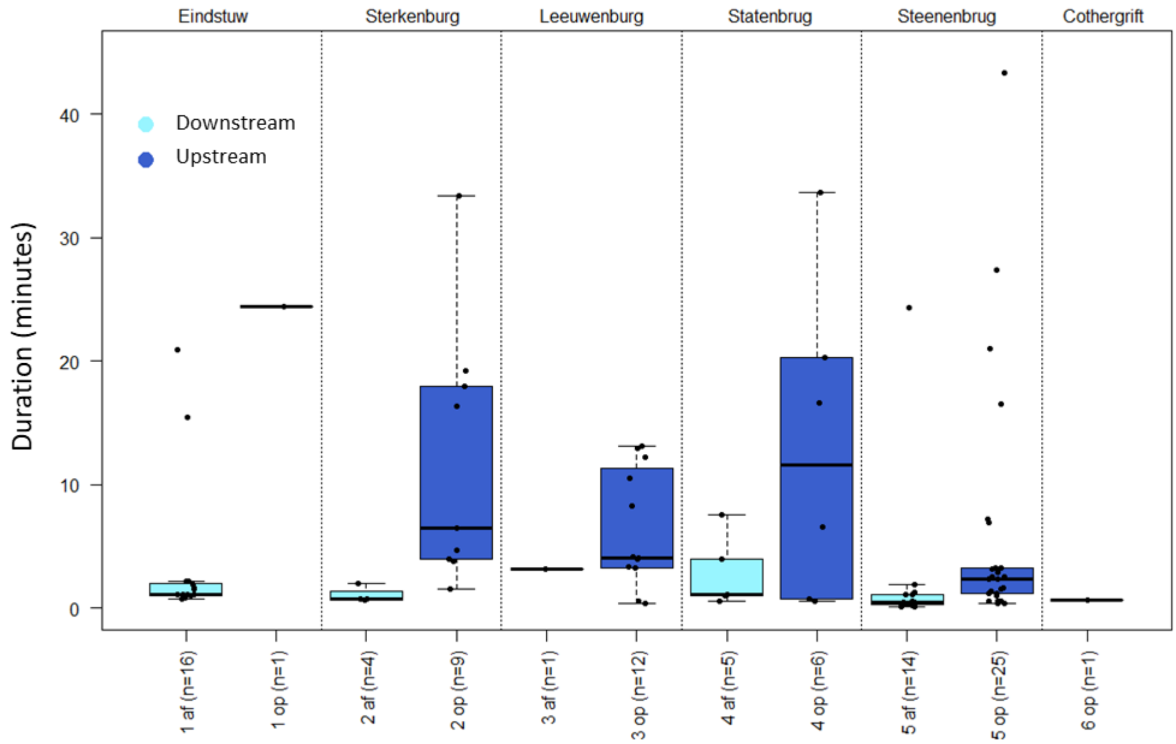


Fig. 4.33. *Passage duration for successful upstream and downstream passage per weir-fishway location for all species pooled (see Kooiman, 2019).*

4.3 Comparison between species

The network of detections stations was in operation during 2.5 years (28 months) and all of the tagging took place in the first 7 months (March-September 2018). There was a marked difference between species in the duration that individuals were detected (i.e. timespan between tagging and last detection per individual fish, Fig. 4.34). Gudgeon, white bream and perch showed the lowest average of individual duration of detection. Gudgeon was only detected in the two months directly after tagging. Perch and White Bream were detected mostly during the first four months, with only some white bream being detected in the second study year 2019 as well. Longest average duration of detection for individual tagged fish were bream and ide. Also Pike and Eel were detected for relatively long periods in multiple years. Tench, rudd and roach had average detection durations that lie in between these other species.

To explore the spatial scale of individual movements, and how this varied between en within species, we determined for each species the fraction of detected individuals, to distinguish between individuals that moved at a spatial scale up to the length of a single stretch, the fraction detected for 2 weir/fishways away from release and fraction detected for 3 or more weir/fishways away from release ,to distinguish which part of the tagged fish used larger spatial scales of 2, 3 or more stretches (Fig. 4.35).

The highest fraction of tagged fish that was detected was found for eel with 90%. 51% of the White Bream were detected, and 38-41% of the tagged Gudgeon, Roach, Bream, Pike and Ide. Tench (16%), Rudd (20%) and Perch (29%) showed the smallest fraction of tagged fish that were detected (Fig. 4.35).

For each of the species, the fraction of tagged fish that were detected at two or more different weir-fishway sites was small (<20%). Eel, White Bream, Ide and Pike showed 10-20% of tagged fish that moved over larger distances within the study area. Numbers of tagged fish that passed three or more fishway-weir sites were relatively low, e.g. White bream 6%, Roach and Ide 3% and less than 3% for the other species.

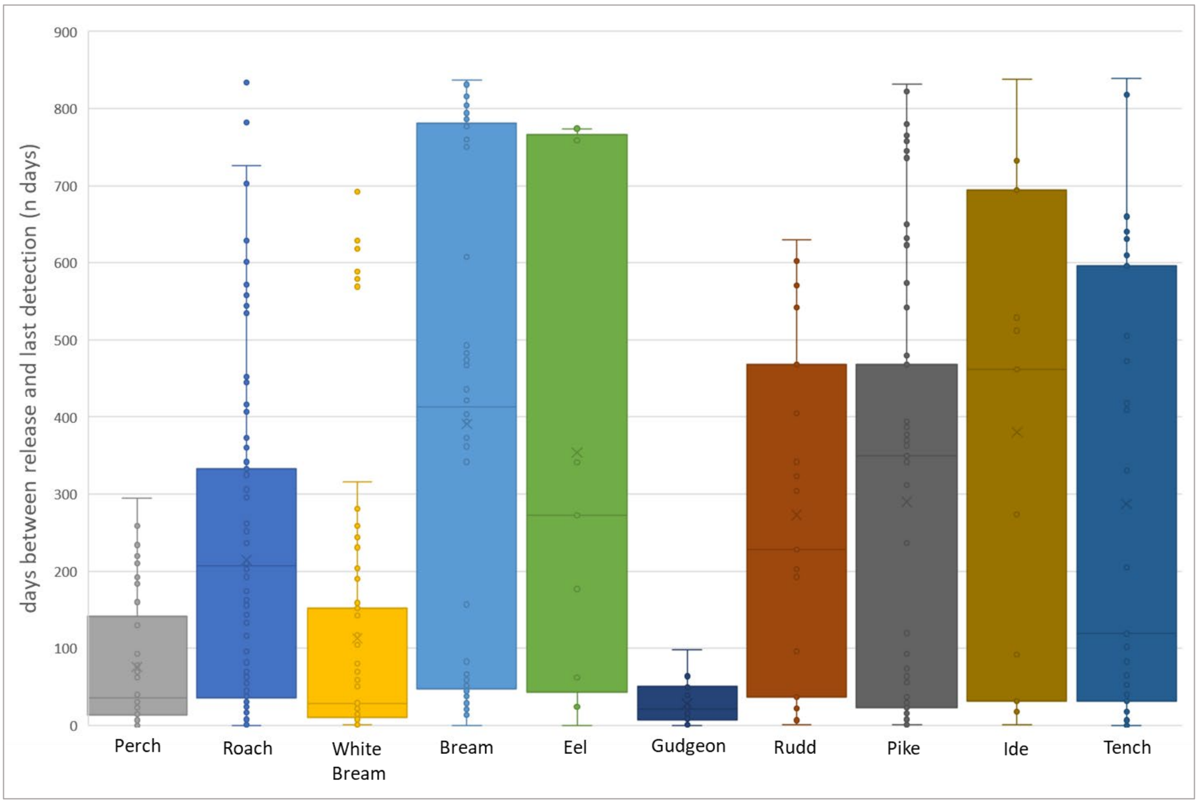


***Figure 4.34**. Boxplots of individual timespan between tagging and last detection for each species.*

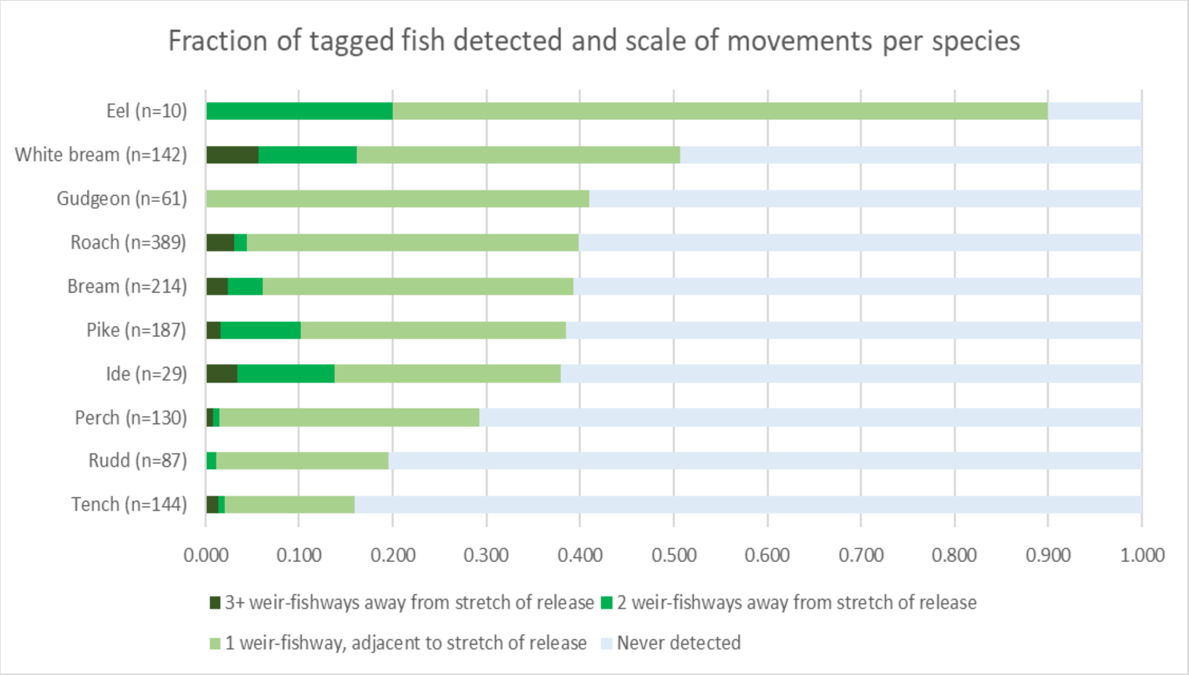


***Figure 4.35**. Fraction of tagged fish detected and indication for scale of movement by using numbers of weirs in between tagging location and detection at the longest distance (number of weirs) for each individual as a proxy for this.*

Percentages of tagged fish that were detected were tested for four length classes (10-19 cm, 20-29 cm, 30-39cm and >40 cm) for each species using a Fisher's exact test (two-sided), see Kooiman (2019) for a detailed description and full results of these analyses. No significant differences between length classes were found for most species, except for Pike and Tench where significantly higher percentages were found for the larger length classes in comparison to the smaller length classes and for Roach significantly lower percentages for larger size class (Fig. 4.36). It should be noted, however, that for most fish species caught and tagged were so unevenly distributed over the different size classes, e.g. Gudgeon, Roach, Perch and Rudd predominantly 10-19cm fish, and Bream predominantly >40 cm fish, that a good comparison between different length classes was not feasible.

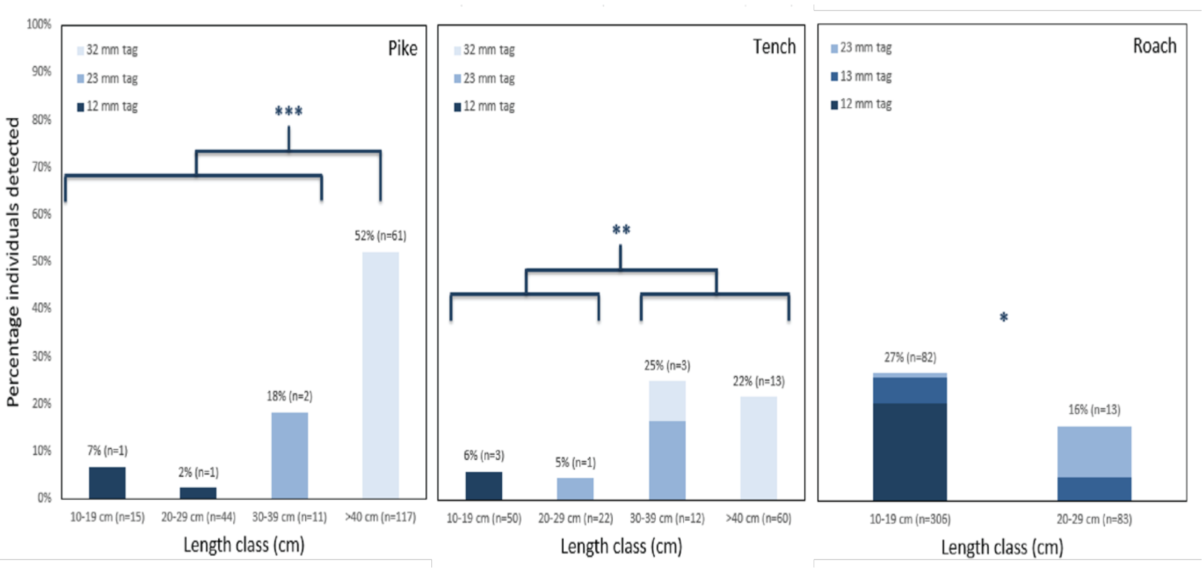


Figure 4.36*. Percentage of tagged fish that were detected per size class (total number of tagged fish n is given in brackets per size class). For pike (left), tench (middle) (right) significant differences were found between size classes using Fisher's exact test (two-sided: *=p<0.05; ***= p<0.001). The different PIT-tags (12, 23, 32 mm) that were used are given for each size class. For other species no significant differences in percentage of tagged fish were found between different size classes.*

For each of the individual movement patterns, it was determined which performed 'migratory' behaviour and which 'dispersal' behaviour (see 3.4 for the approach used). As a proxy for residency, percentage of non-detected fish could be used, though this will be maximum estimate since mortality and residency cannot be disentangles within these datasets. In Tab. 4.7, an overview of the results for each of the 10 most abundant freshwater species is given.

Table 4.7*. Overview of the main results for the 10 most abundant freshwater fish species.*

	Tagged	Detected		Residency	Migratory		Dispersal		Upstream	Downstream
	n	n	%	(Max. %)	n	%	n	%	passage %	passage %
Roach (blankvoorn)	389	155	40%	60%	5	1%	3	1%	52%	42%
Bream (brasem)	214	84	39%	61%	9	4%	7	3%	55%	33%
Pike (snoek)	187	72	39%	61%	13	7%	7	4%	56%	24%
Tench (zeelt)	144	23	16%	84%	0	0%	0	0%	78%	35%
White bream (kolblei)	142	72	51%	49%	2	1%	1	1%	90%	65%
Perch (baars)	130	38	29%	71%	0	0%	0	0%	58%	64%
Rudd (ruisvoorn)	87	17	20%	80%	0	0%	0	0%	56%	25%
Gudgeon (riviergrondel)	61	25	41%	59%	0	0%	0	0%	70%	41%
Ide (winde)	29	11	38%	62%	2	7%	2	7%	46%	0%
Eel (aal/paling)	10	9	90%	10%	1	10%	0	0%	73%	71%

5 Discussion

5.1 Connectivity and movement patterns of fish

Scale of movements of freshwater fish
This field study of 2.5 years on regional movements of tagged freshwater fish species in Langbroekerwetering water system showed that only a small proportion of the studied freshwater fish, had movements of a scale that covered the entire study area (~8 km). Also within the study area the scale of most movements were limited. More than half of the individuals were not detected at the borders of each stretch where fish were caught, tagged and released, where distance between sites with PIT stations were on average a few km (0.8-3.8 km). A minority of tagged fish showed movements beyond these stretches of several kilometres where they were released. Only a small fraction showed movements over more stretches (ranging from 0% for gudgeon to 20% for yellow eel). Some used the entire Langbroekerwetering system, e.g. several white bream entering via fishway Eindstuw (Fig. 4.17).

Because mortality (e.g. predation by fish eating fish and birds), and residency of fish (remaining on stretches in between detections stations), cannot be disentangled within the current datasets, it is likely that the proportion of fish that moves at (somewhat) larger scales is higher than the percentage of non-detected indicates (Fig. 4.35). However, because many fish that were detected did show movements at a relatively small scale, i.e. mostly only one more stretch, the conclusion that the majority of fish tagged show movements smaller than a few kilometres appears justified.

Because adjacent water systems were not covered by detection stations, individuals that left the study area might have performed larger scale movements, as was indicated by some tagged fish such as a bream of 33 cm that left the study area via Eindstuw and re-entered the study area at Steenenburg, and must have passed two weir-fishway sites in the adjacent water system Kromme Rijn (Fig. 4.8).

Upstream passage via fishways and weirs
The fishways and weirs were successfully passed by 13 freshwater fish species in upstream direction. Upstream passage predominantly occurred via the fishways for most species, except for pike that more often used pathways via the weirs. These low-head weirs enabled upstream passage for at least roach, bream, pike and bleak. Flow conditions over the weirs are an important factor in this (Winter & van Densen 2001), which will vary with the discharge of the draining water system. Most species and individuals used the fishways as a pathway for upstream passage. These included small bodied fish of 10-15 cm of different species. Fish smaller than 10 cm were not tagged. These findings confirm earlier fykenet studies that the De Wit fishway is suitable for a wide range of species and sizes (Heuts 2013).

Downstream passage via fishways and weirs
Most species that were tagged used both fishways and weirs for downstream passage of the studied weir-fishway sites. Fishways were often used for downstream passage for the tagged species. Because for fish that were last detected at a weir station, where no follow-up position was present, it could not be determined whether these successfully passed the weir or just turned around at the weir, and therefore not classified as successful. This will be a conservative estimate, especially in a downstream direction, since attempting to pass a weir with overflow from an upstream direction will likely result in fewer successful passages than swimming with the current over the weir in a downstream direction. The percentage of successful passage over weirs in a downstream direction will therefore most likely be higher, because at least a part of these last detections will be passage of weirs, especially in downstream direction.

Passage efficiency
Facilitating the weirs with fishways have improved migratory opportunities in both directions to a level that this does not seem to hamper movements past these small barriers and ensure good connectivity within the Langbroekerwetering and to adjacent water systems. As a proxy for passage success we used the number of confirmed successful passages relative to the number of appearances per tagged individual fish for each subsequent migration period (set at half year periods January-June, encompassing spring migrations, and July-December, encompassing autumn migrations). Ideally, passage efficiency would be determined as the fraction of individuals that successfully pass of all

individuals approach a weir-fishway site and are motivated to pass. Efficiency can then be derived on an individual basis or on an attempt basis (Winter 2007, Hersey 2020). Determining the number of attempts from the highly variable detection patterns and sequences for the tagged individual fish proved very difficult and left a considerable part undetermined (Valkenaars 2019, Kooiman 2019). And when determining efficiency on an attempt basis, some individuals that passed the sites multiple times in both directions would largely effect the end result. There were no stations present that covered the full width of the waterway directly downstream or upstream the barriers. Therefore, not all fish that were motivated to pass that approached the weir-fishway sites might be detected at the PIT-loops in the fishway or above the weir. These undetected fish would mean that the number of appearances would then be higher and the true passage efficiency be lower than suggested by the data presented. On the other hand, however, also not all fish that appeared at the PIT-loops on the different sites might have been motivated to pass a weir-fishway site. This would then lead to an higher efficiency for the fish motivated to pass than presented. The nett result of this on passage efficiency is not clear. We observed that 29 fish (ranging from very small 10 cm fish to larger adults) of 6 species and 1 hybrid cyprinid passed series of fishways within short timespans of less than 7 days. One white bream of 24 cm even passed 3 fishways and 6 km waterway within 8.5 hours. It was caught after passing the Eindstuw fishway and later on also passed the Steenenburg Fishway and thus have passed a series of 5 fishways in total. These fast passages of series of fishways with hardly no delay, suggests that finding the entrance ('attraction efficiency') and passing the fishways are hardly hampered, at least during most conditions (see also Bravo-Córdoba et al. 2021). And therefore it is likely that using detected appearance at the weir-fishway site as a proxy for approaching the site, would not be very far off. With the note that in some infrequently occurring flow conditions, i.e. during severe draughts as in summer 2018 when there will be no flow over the weirs and very little via the fishways, or very high floods when water velocities over and directly downstream the lowered weirs are very high, this might be different.

We found high passage percentages for each of the species and observed relatively small spatial scale that the majority of freshwater fish use in the study area. This suggests that at least part of the fish that appear at weir-fishway sites were not motivated to pass, and that the already high passage efficiency might be even higher for the fish motivated to pass.

Movements versus habitat aspects

The Langroekerwetering system is a highly regulated water system with 6 weirs and De Wit passages and a main waterway with many connecting side ditches. Improving connectivity by providing fishways in fragmented water systems will only lead to higher fish populations and more healthy fish communities when the connecting habitats are of required quality as well (Silva et al. 2017). Even though only one side ditch was covered with an PIT-loop, 33 fish used this side ditch, sometimes for prolonged period up to months. This indicates that these side ditches make up an integral part of the habitats fish use in the Langbroekerwetering. Fishways can also be used as habitats rather than as corridors (Sánchez-Pérez 2022). In this study we found intensive use of the fishways for periods up to 17 days for especially gudgeons. In a relatively stagnant water system, the fishways and conditions directly around the weirs may act as small 'islands' habitats with flowing water conditions that might be attractive for spawning, feeding, sheltering for predators or provide good oxygen conditions in periods with very low flow and high water temperatures. Detection of patterns at fishway-weir sites of several species suggest that these are used as habitats as well (see species sections in 4.2).

We could not disentangle residency and mortality for the non-detected fish, which was the majority of all tagged fish. There could be several patterns underlying these findings. If the main reason for this result is a high degree of residency, then this implies that the habitat quality is good enough to stay year-round in relatively small stretches less than a few kilometres. If the main reason for this is high mortality rates for these freshwater species or some of these (the smaller individuals) by predation by fish-eating fish or birds, then habitat quality, e.g. complexity and heterogeneity providing shelter might be a constraint for healthy fish communities. The balance between these different underlying reasons for the high degree of non-detected tagged fish might be different for the different species, but could not be tackled within the scope of this report. Long-term fragmentation can also lead to increased residency by selection (Branco et al. 2017), but whether that plays a role in our study area is not known, because no pre-fishway data on this exists.

Role of migration of the different species in relation to connectivity

None of the studied species showed large scale movements that encompassed the majority of the population. For some species, roach, bream, pike, white bream, ide and yellow eel, for some individuals seasonal migratory (cyclic repetitive detection) patterns were observed. This is comparable with another recent PIT-tag study in regional connectivity around the Noordzeekanaal region (North-West

Netherlands), where partial migration was found in some species like bream, but no mass migrations alongside pumping station fishway barriers were observed (Griffioen et al. 2022). Eel is the only diadromous species in our study and needs upstream connectivity from sea for the glass eel stages and downstream connectivity to sea for the silver eel stages. In our study only yellow eel were tagged. Whether these have originated from natural immigration from sea, i.e. passed all barriers between Langbroekerwetering and the North Sea cannot be determined with certainty since also stocking of glass eel or small yellow in the Netherlands takes place. Of these yellow eels one showed a migratory pattern during the 'resident' stage. The migratory patterns for these different species shows that these are partly migratory, and because this could only be assessed for individuals that were detected for periods longer than one year, due to mortality, the actual occurrence of partial migration might be higher than presented here. The underlying reasons why some individuals show migratory patterns and others do not, or at a smaller spatial scale, can be very diverse and dependant on individual context (e.g. condition, personality traits) or trade-offs between foraging opportunities and predator avoidance (Brodersen et al. 2008, Brönmark et al. 2008, Brönmark et al. 2014, Chapman et al. 2013, Kemp 2016, Birnie-Gauvin et al. 2019).

Larger non-repetitive movement patterns over a period longer than a year, classified as dispersal, were relatively rare with 20 individuals and 5 fish species. Here, the actual number of individuals that show dispersal behaviours will be higher, especially because fish remaining for only a short period in the study area without returning could have suffered mortality or show dispersal movement in adjacent waters that were not covered by PIT-loops. Influx of fish from the Kromme Rijn into the Langbroekerwetering occurs for several species, especially for white bream and gudgeon (remarkably these two species were not or hardly recurring in later years after tagging), and to a lesser degree also for roach, pike and bream, but does not seem to be a dominant factor for the fish communities that use the Langbroekerwetering, since the majority of fish here appear to be present year-round with only limited local movement patterns within and between stretches in the Langbroekerwetering water system. It might be that the relative stagnant character of this regulated water system, which is very comparable to the adjacent connecting relatively stagnant water systems, make it less attractive for rheophilic fish species, such as ide (Winter & Fredrich) that move between streams and stagnant waters.

Overall, connectivity does not seem to be compromised in the Langbroekerwetering, and the current weir-fishway sites provide good migratory opportunities for a wide range of fish species and life-stages and poses little restrictions to movements of fish. The fishway-weir sites provide suitable and effective pathways for movement of fish that show migratory behaviour and undertake dispersal movements between the different sections within the Langbroekerwetering and to adjacent waters. Except for the diadromous eel, that is fully dependent on large scale connectivity to sea, most other species are only partly dependant on this connectivity for partial migration and dispersal between different water systems. It is important to consider both connectivity and habitat quality at different scales for different fish species (Tummers et al. 2016).

5.2 Methodological considerations

Using PIT-tag telemetry as a method, has the benefit that a wide range of species and life-stages could be included in the study. PIT-tags are small and implanting these in fish is successfully used worldwide with very low mortality rates (Gibbons & Andrews 2004, Cooke et al. 2013). Though some mortality due to catching, handling and implanting tags in fish (especially small fish) cannot be ruled out, the organizations (under supervision of Visadvies) that carried out the tagging fieldwork are very experienced in PIT-tagging and method-induced mortality is estimated to be low.

The detection range that can be achieved with PIT-tag telemetry is, however, small (from 20-80 cm to the antenna loop depending on the conditions and tag size). As a result, some misdetection will occur as observed from sequential detection patterns concerning fishway passage, e.g. certainly passing a fishway with not being detected at one of the loops in a fishway, or certainly passing a weir-fishway site without being detected and most likely to be misdetected when passing a weir. Especially at high flow conditions when much water overflows the lowered weir, misdetections of tagged fish passing are probably high. Because for weirs we had only single detection loops and in fishways we had series of 3, sometimes 2 loops, misdetections at weirs have a higher chance of not being notices when assessing sequences of detections than misdetections in fishways. As discussed in 4.2 and 5.1, misdetections will lead to an underestimation of passage efficiency and scale of movement (e.g. migratory, dispersal). Another source of misdetection is temporary malfunctioning of PIT-loops. Visadvies has an online check system to enables them to quickly respond to malfunctioning loops thus minimizing its effect. A full analysis of the effect of misdetections and quantification of it was not feasible within the scope of this report, but it is unlikely that this will affect the conclusions presented.

Not all fish were caught and released on the exact same spot, and as a result, some movements directly after releasing might be related to the catching and releasing, rather than reflecting natural movements. This appeared to be true especially for the fish caught and released in autumn 2018, given that these movements were not observed in subsequent years in individuals we detected for longer periods.

5.3 Conclusions

The main conclusions for the different research questions as listed in 1.2 are given below:

What type of movements are observed for the different fish species?
For most species and life stages appears to be relatively resident, remaining in the waterway stretch where they were caught and released. It should be noted that residency could not be disentangled from mortality, and that if mortality rates, e.g. by predation, are high, the degree of residency might be lower than the presented detection patterns suggest. The more mobile individuals showed migratory as well as dispersal patterns.

At what spatial scale do these movements take place?
For the majority of fish for each species and life stages we found only limited movements at spatial scales within waterway sections (<2 km) or between adjacent stretches (~2-6 km). Only a minority of fish showed larger scale movements within the study area (~8 km) or to adjacent water systems. The spatial scale that fish used outside the study area could not be determined.

What was the rate of these different spatial movement patterns per species?
The highest fraction of tagged fish that was detected at single barriers was for yellow eel (90%) and white bream (51%). For gudgeon, roach, bream, kike and ide 38-41%, and lowest for Tench (16%), Rudd (20%) and Perch (29%). For each of the species, the fraction of tagged fish that were detected at two or more different weir-fishway sites was small (<20%). Eel, White Bream, Ide and Pike showed 10-20% of tagged fish that moved over larger distances within the study area. De numbers of fish that showed large scale migratory or dispersal movements were small in all species.

What routes were taken when passing barriers in both upstream and downstream direction?
Fishways and weirs were passed both in upstream and downstream direction by different fish species and life stages. In upstream direction, most fish used the fishways, only pike used weirs more often than fishways. In downstream direction, both fishways and weirs were used for successful passage. All of the most abundant species uses fishways also for downstream passage. The successful passage of weirs in a downstream direction will be even higher than presented in this study due to the conservative approach how last detections were interpreted (when the last detection occurs at a weir it is uncertain that this was successfully passed, but in many cases especially in a downstream direction this will be the case).

What was the timing of these movements?
Seasonal timing of detections occurred mostly in spring (April-May), or early spring for pike (February-April) for most species coinciding with the spawning period. For tench and rudd detections occurred year round with more detections in the summer half year. There were also clear diurnal patterns in movements, with much differences between species, life stages and sites. For instance mainly at night for weir and fishway passage in gudgeons, mainly during day for fishway use in perch, mainly during day for the side ditch for rudd. Or day and night without a specific preference.

Did the measures of facilitating these weirs with De Wit Passages result in good connectivity within this study area itself and with adjacent waters via de Kromme Rijn and how important is connectivity for the different species?
Facilitating the weirs with De Wit fishways has substantially increased migratory opportunities for the different freshwater fish species in this study, in both upstream and downstream direction. The weirs were also used for passage, but in upstream direction only by a few species such as roach, bream and pike. Passage efficiency at the studied weir-fishway sites appear to be high, both when using

appearance-passage percentage as a proxy for efficiency, and as indicated by the rapid passage of series of fishways by 29 fish from different species and sizes. No mass migrations or dispersal over larger scales were observed from and to the study area, but for each of the species part of the individuals used weir-fishway passage, for migration or dispersal. It appears that none of the populations, except the diadromous eel, fully relies on this connectivity, but it will most likely enhance population size and health in the area.

Did the movement patterns indicate bottlenecks in connectivity, and if so which additional measures might be needed to optimize connectivity?
Our study did not yield clear bottlenecks in connectivity, i.e. passage problems at weir-fishway sites. The relatively small scale that most fishes use the Langbroekerwetering-system is more likely a reflection of a lack of motivation to move or disperse at larger scales than that barriers are restricting these. Most species resided within the study area. Only white bream and gudgeon seem to move into the system from the Kromme Rijn System without staying in the study area for longer periods. There appears no direct need to improve fish passage facilities, rather than ensuring that with maintenance their functioning is regularly checked for (Heuts 2013). Whether the habitats that are connected by these sites are of sufficient quality could not be addressed in this study. The high degree of non-detected fish can suggest high residency, which means that local habitat quality is sufficient good to ensure year-round use of the small sections. But this high degree of non-detected fish can also be caused by a higher degree of mortality, which means that habitat heterogeneity or sheltering for predators might be insufficient. The balance between these two underlying mechanisms might be different for each species.

5.4 Implications for management and recommendations

The De Wit fishways have clearly improved connectivity and the fishway function well for a wide range of species and life-stages. In this PIT-tag study fish could pass unhampered, whereas in many earlier fykenet studies passage of larger fish appeared to be hampered by the monitoring method (Heuts 2013). The De Wit fishways are suitable fish passage facilities that can be widely used in water systems, especially smaller systems with on average low flow conditions.

Within this study a large dataset of individual detections of a wide range of species and life stages was collected. We presented the main results and patterns, but we recommend more follow-up in-depth analyses, e.g. by combining the data with environmental data such as water discharge, temperature, daylength, to further quantify fish passage efficiency and determine which factors contribute to this on different scales in an integral approach (e.g. see Kemp 2016, Tummers et al. 2016).

The interplay between habitat quality, residency and mortality rates, e.g. by predation, within the different waterway sections remained unclear. To further explore and quantify this, we recommend to include surveying tagged fish within the stretches year-round in combination with monitoring predatory fish and birds, and habitat mapping (as already started by Valkenaars 2019). This can improve our understanding of the movement ecology of the freshwater fish that use these water systems, and determine whether some bottlenecks in the functioning of these water systems still prevail.

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Acknowledgements

For this study many persons made a contribution. We would like to thank VisAdvies, RAVON and ATKB for carrying out the fieldwork on catching and tagging the fish, and especially Hendry Vis from Visadvies, who carried out the construction, design, deployment and data retrieval of the PIT-stations and co-workers at HDSR for their operational support.

Quality Assurance

Wageningen Marine Research utilises an ISO 9001:2015 certified quality management system. This certificate is valid until 15 December 2018. The organisation has been certified since 27 February 2001. The certification was issued by DNV GL.

Furthermore, the chemical laboratory at IJmuiden has NEN-EN-ISO/IEC 17025:2005 accreditation for test laboratories with number L097. This accreditation is valid until 1th of April 2021 and was first issued on 27 March 1997. Accreditation was granted by the Council for Accreditation. The chemical laboratory at IJmuiden has thus demonstrated its ability to provide valid results according a technically competent manner and to work according to the ISO 17025 standard. The scope (L097) of de accredited analytical methods can be found at the website of the Council for Accreditation (www.rva.nl).

On the basis of this accreditation, the quality characteristic Q is awarded to the results of those components which are incorporated in the scope, provided they comply with all quality requirements. The quality characteristic Q is stated in the tables with the results. If, the quality characteristic Q is not mentioned, the reason why is explained.

The quality of the test methods is ensured in various ways. The accuracy of the analysis is regularly assessed by participation in inter-laboratory performance studies including those organized by QUASIMEME. If no inter-laboratory study is available, a second-level control is performed. In addition, a first-level control is performed for each series of measurements.
In addition to the line controls the following general quality controls are carried out:

- Blank research.
- Recovery.
- Internal standard
- Injection standard.
- Sensitivity.

The above controls are described in Wageningen Marine Research working instruction ISW 2.10.2.105. If desired, information regarding the performance characteristics of the analytical methods is available at the chemical laboratory at IJmuiden.

If the quality cannot be guaranteed, appropriate measures are taken.

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Justification

Report C045/22
Project Number: 4315100050

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

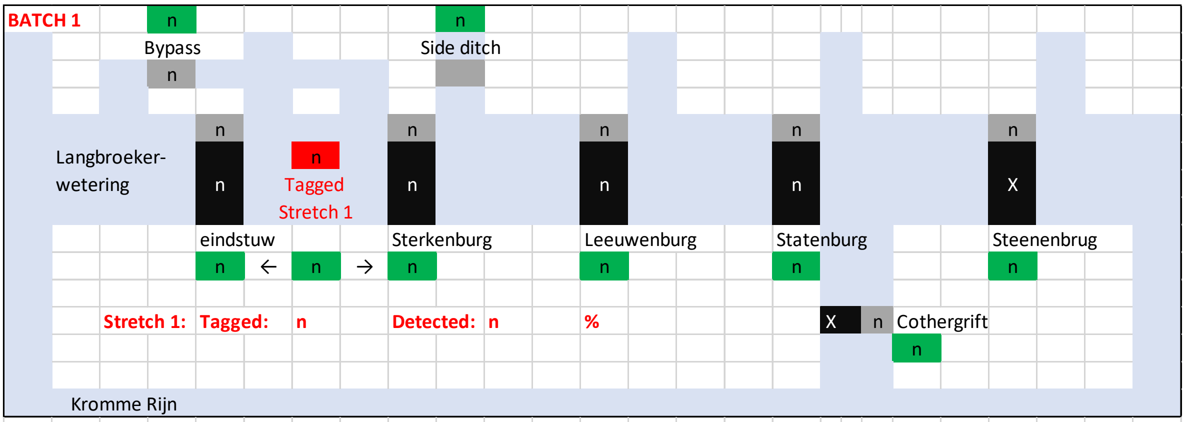
Approved:	Dr. P. de Bruijn Researcher
Signature:	
Date:	31-8-2022

Approved:	Drs. J. Asjes Management Team
Signature:	
Date:	31-8-2022

Annex 1 Schematic overview PIT tagging data per species

In this Annex, we give summary of all the detection data for the 10 species of which more than 10 individuals were tagged, and more than 5 individuals were detected for the different study sites plotted in a schematic view of the study area. Species are listed in the order of decreasing number of tagged fish, i.e. starting with the most abundant species. The legend and setup of the schematic overview per species is given below (Fig. A1.1).

LEGEND FOR FIGURES IN THE FOLLOWING SPECIES SECTIONS



🟥 n	Number of fish tagged in the stretch of which the results are shown in this panel
▨ n	Number of individual fish detected in fish passage/bypass for this batch
■ n	Number of individual fish detected over a weir for this batch
🟩 n	Number of unique individuals that were detected at a site (e.g. weir+fish passage combined) for this batch
■ X	Weirs where no detection antenna was present

Figure A1.1. *Legend to the figures for each of the species sections below. In this diagram, a schematic overview is given of:*

- *the waterways (light grey), weirs (black), fish passages (dark grey) of the study area.*
- *for each species, the number of fish that are tagged for the stretch where they were caught and released (red square) and in red a summary of total number, detected number and percentage of detected number per batch*
- *the numbers of detected individuals from this tagged/release batch that have passed the different detection stations in the entire study area. Detection stations are all denoted with 'n' (i.e. a number of fish that has been detected for each of the species will be shown there in the following sections) at the fish passages (in dark grey) and at the weirs (in black) and for the bypass and side ditch separately.*
- *The total number of unique individuals that have been detected of the tagged batch is given in the green squares below the 'tagged batch number in Stretch' and below each of the 'barrier' locations (e.g. weir and/or fish passage per location).*
- *Weirs that were not fitted with antennae (Steenenburg and Cothergrift) are denoted with an 'X', indicating that fish may have passed these weirs undetected.*

Roach (*Rutilus rutilus*, Dutch: Blankvoorn)

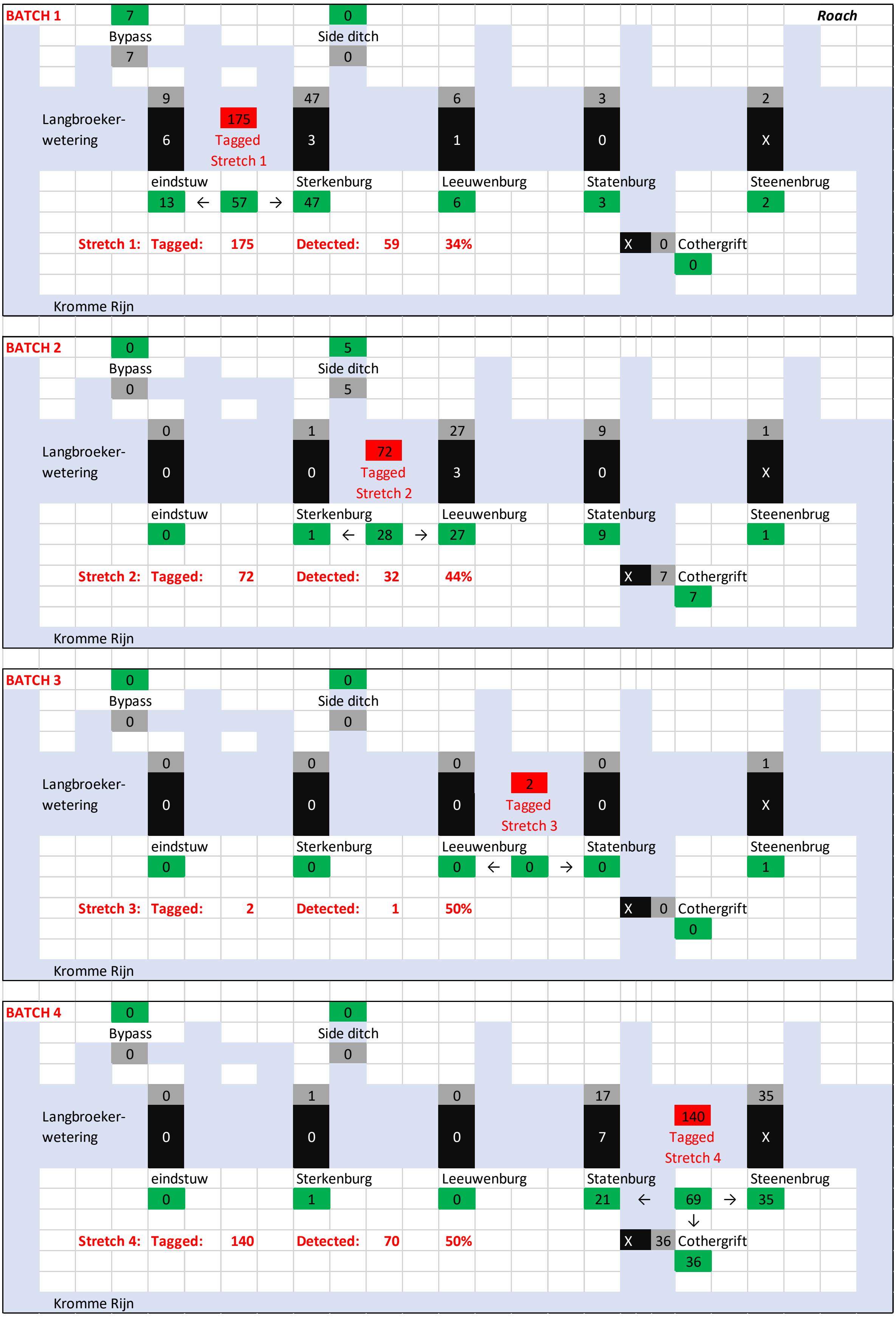


Figure A1.2. *Numbers of roach tagged and detected for each batch (see Fig. A1.1 for legend).*

Bream (*Abramis brama*, Dutch: brasem)

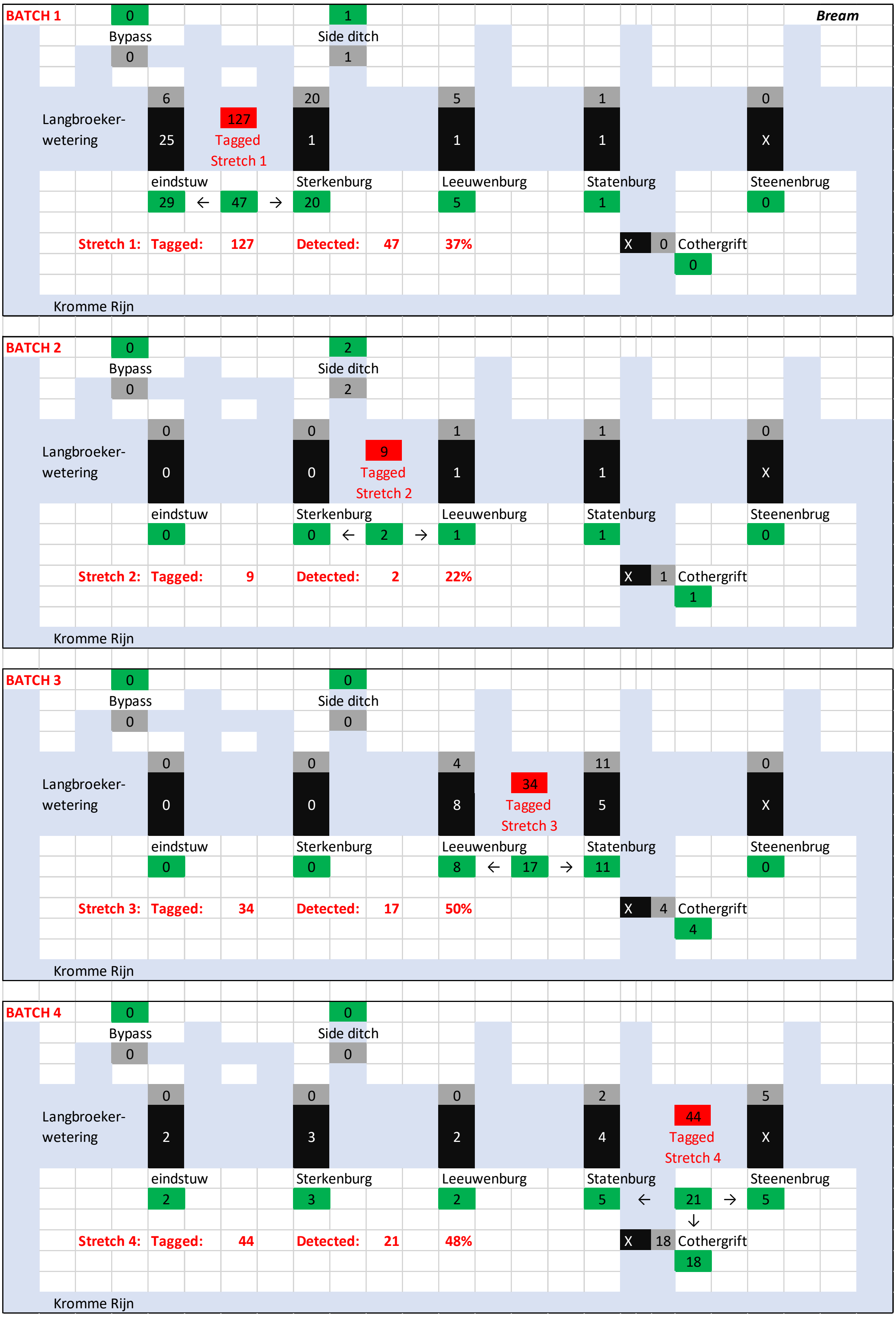


***Figure A1.3**. Numbers of bream tagged and detected for each batch (see Fig. A1.1 for legend).*

Pike (*Esox lucius, Dutch: Snoek*)

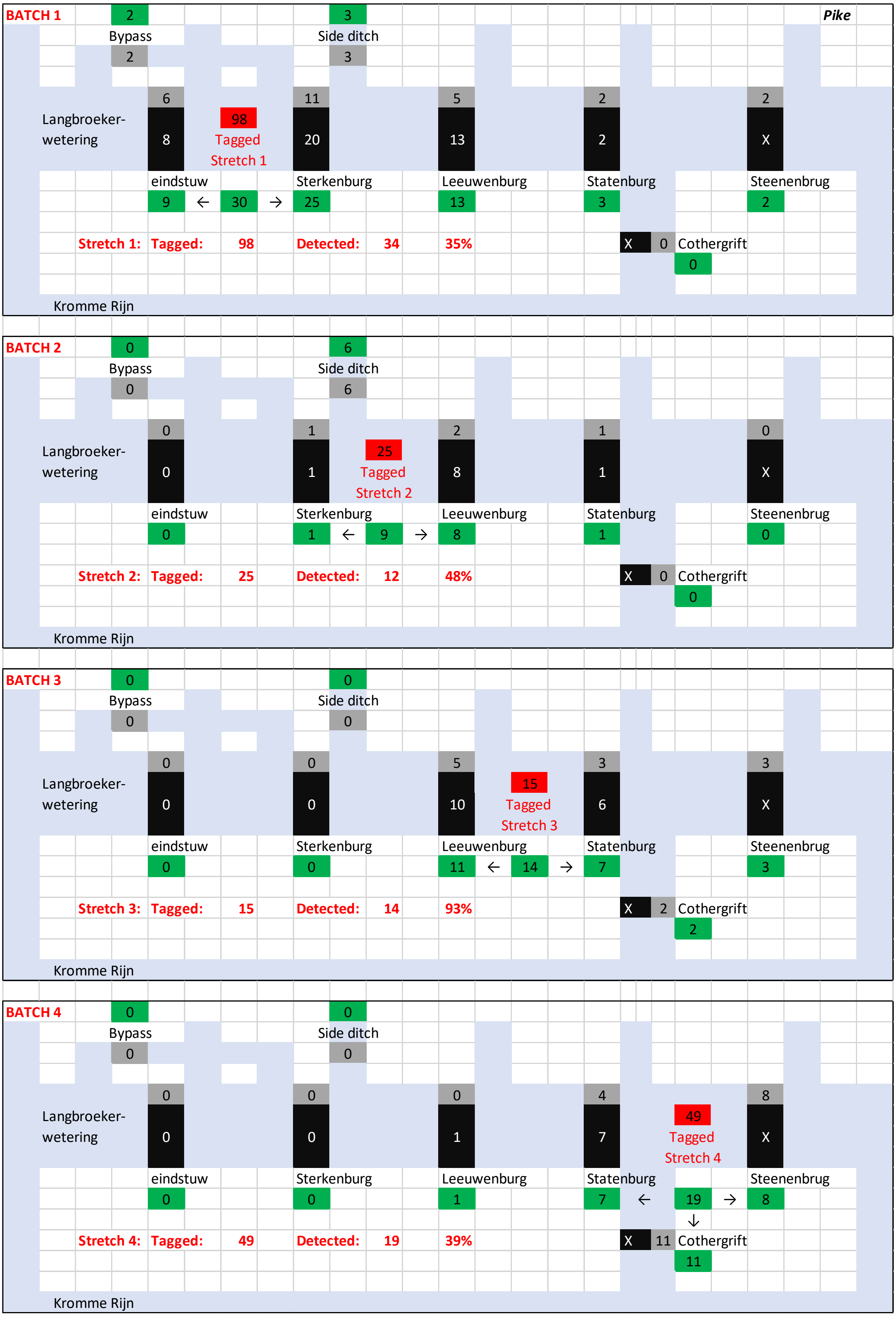


Figure A1.4. *Numbers of pike tagged and detected for each batch (see Fig. A1.1 for legend).*

Tench (*Tinca tinca, Dutch: Zeelt*)

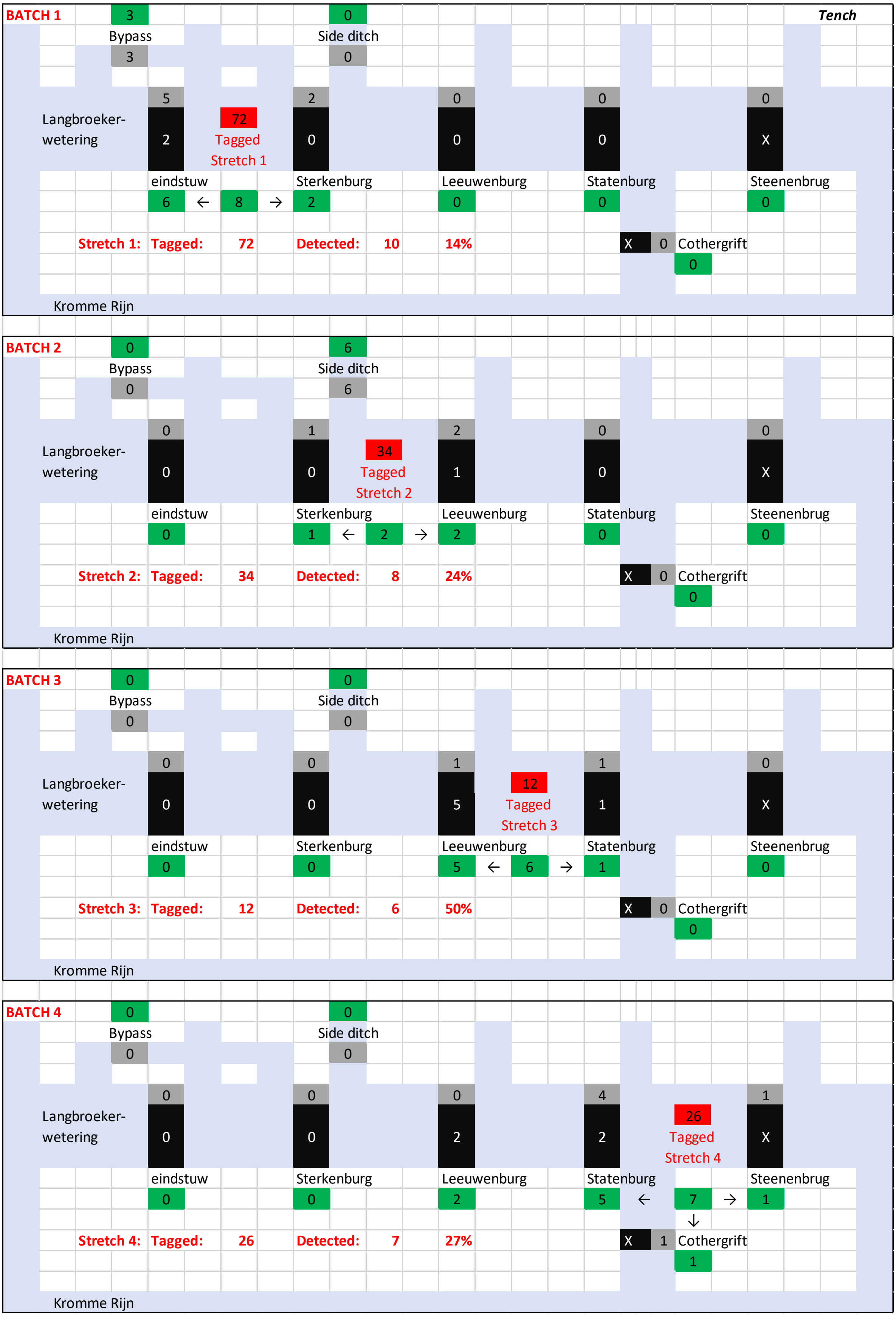


***Figure A1.5**. Numbers of Tench tagged and detected for each batch (see Fig. A1.1 for legend).*

White bream (*Blicca bjoerkna, Dutch: Kolblei*)

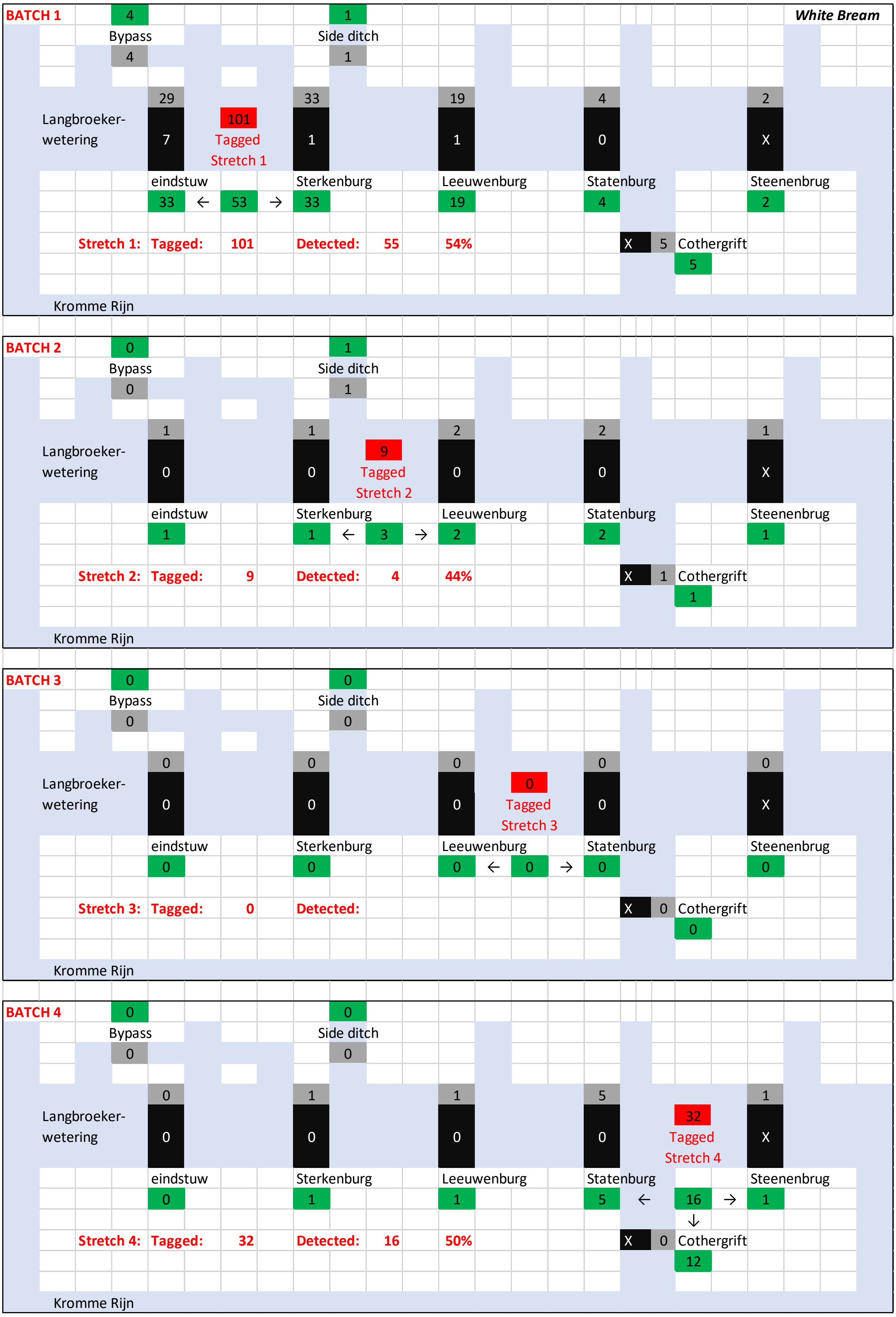


Figure A1.6. *Numbers of white bream tagged and detected for each batch (see Fig. A1.1 for legend).*

Perch (*Perca fluviatilis, Dutch: Baars*)

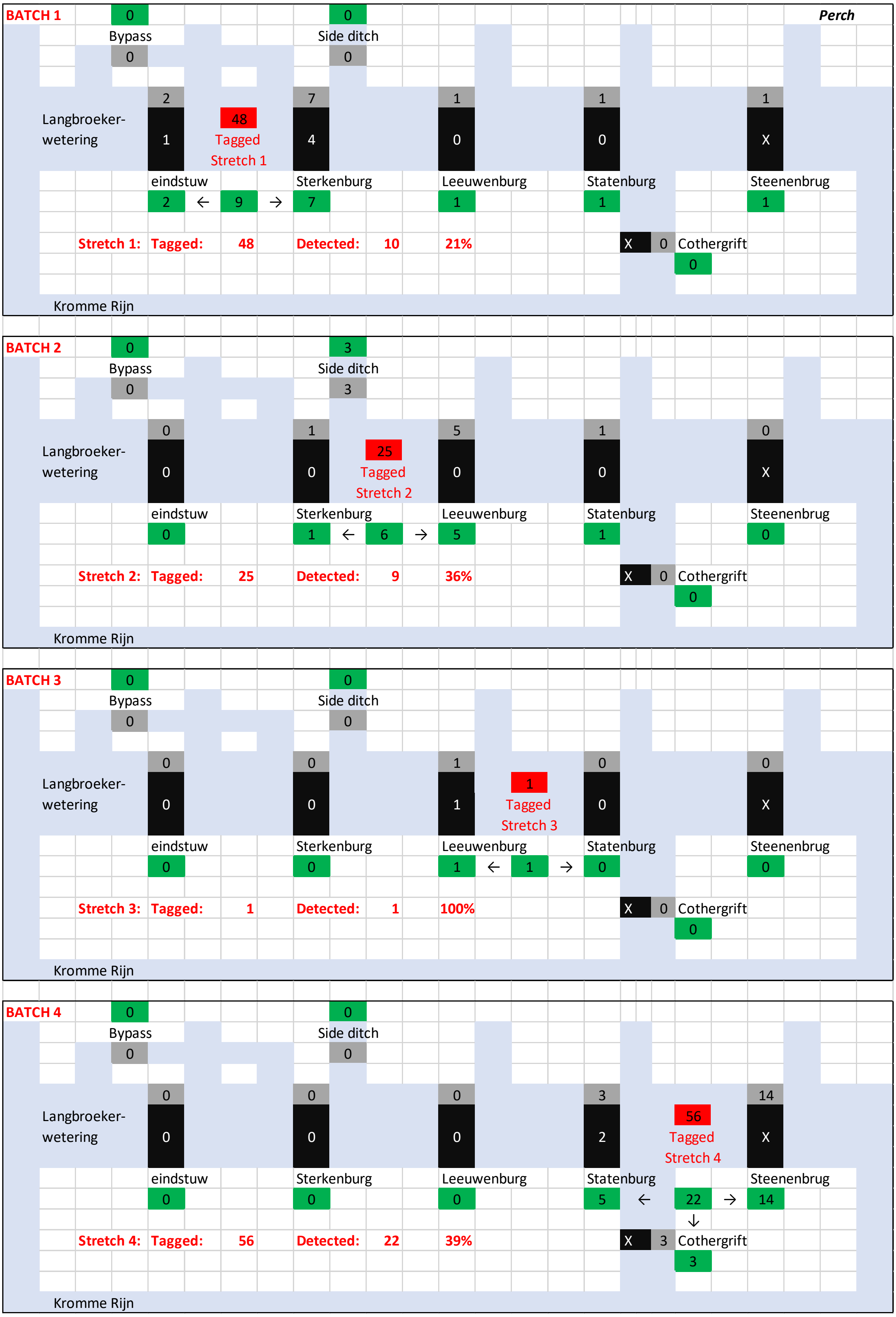


Figure A1.7. *Numbers of perch tagged and detected for each batch (see Fig. A1.1 for legend).*

Rudd (*Scardinius erythrophthalmus, Dutch: Ruisvoorn/Rietvoorn*)

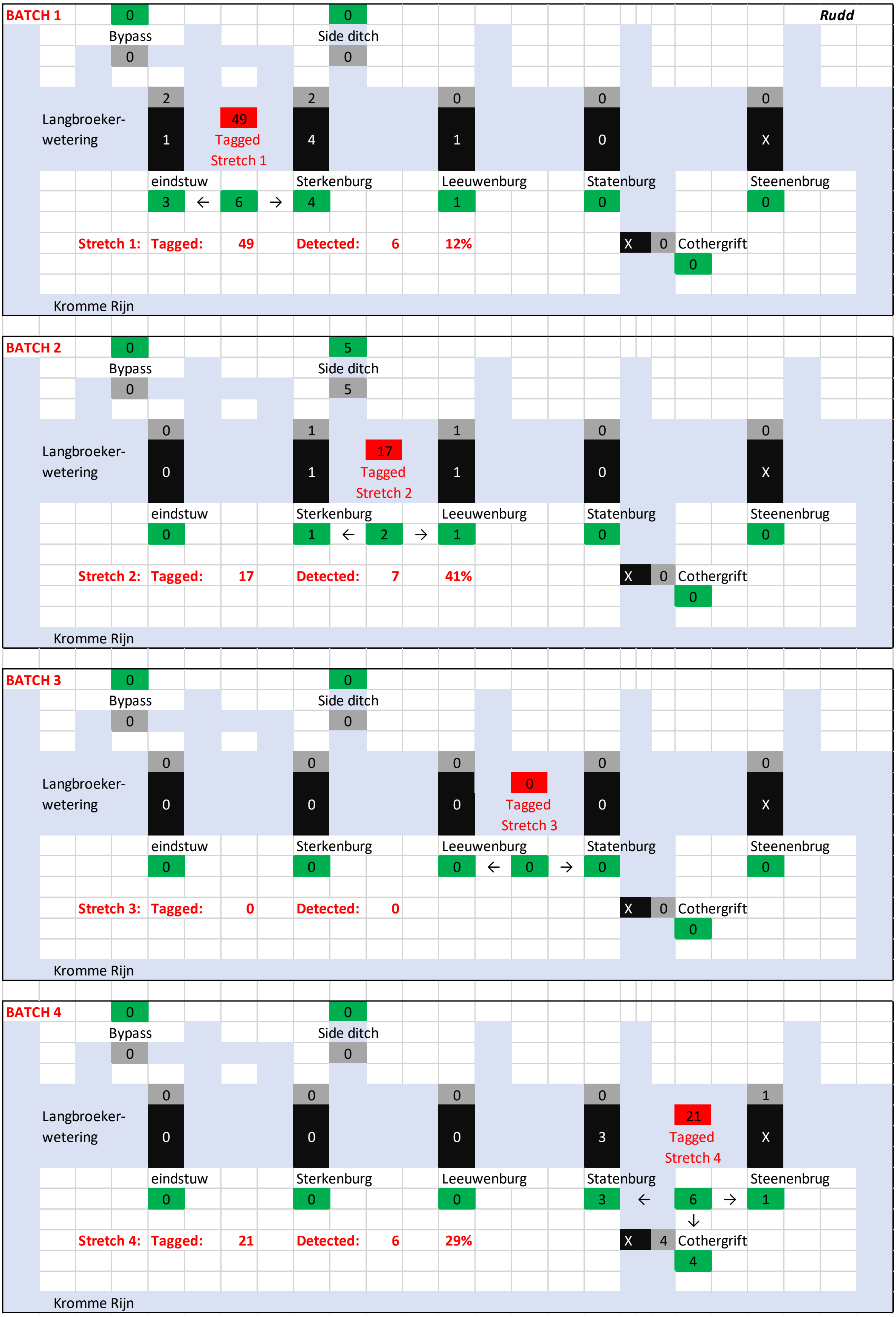


Figure A1.8*. Numbers of rudd tagged and detected for each batch (see Fig. A1.1 for legend).*

Gudgeon (*Gobio gobio, Dutch: Riviergrondel*)

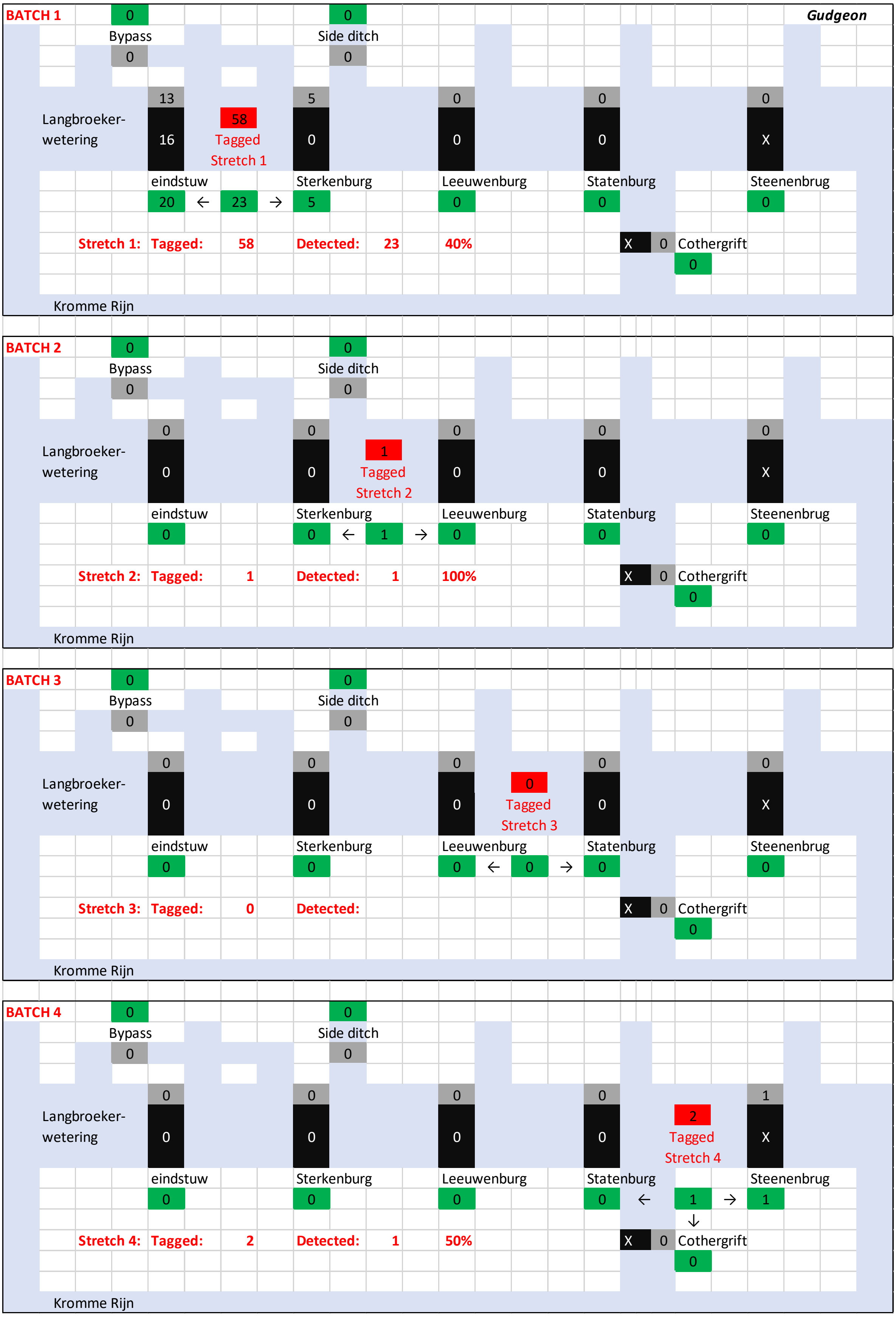


Figure A1.9*. Numbers of gudgeon tagged and detected for each batch (see Fig. A1.1 for legend).*

Ide (*Leuciscus idus, Dutch: Winde*)

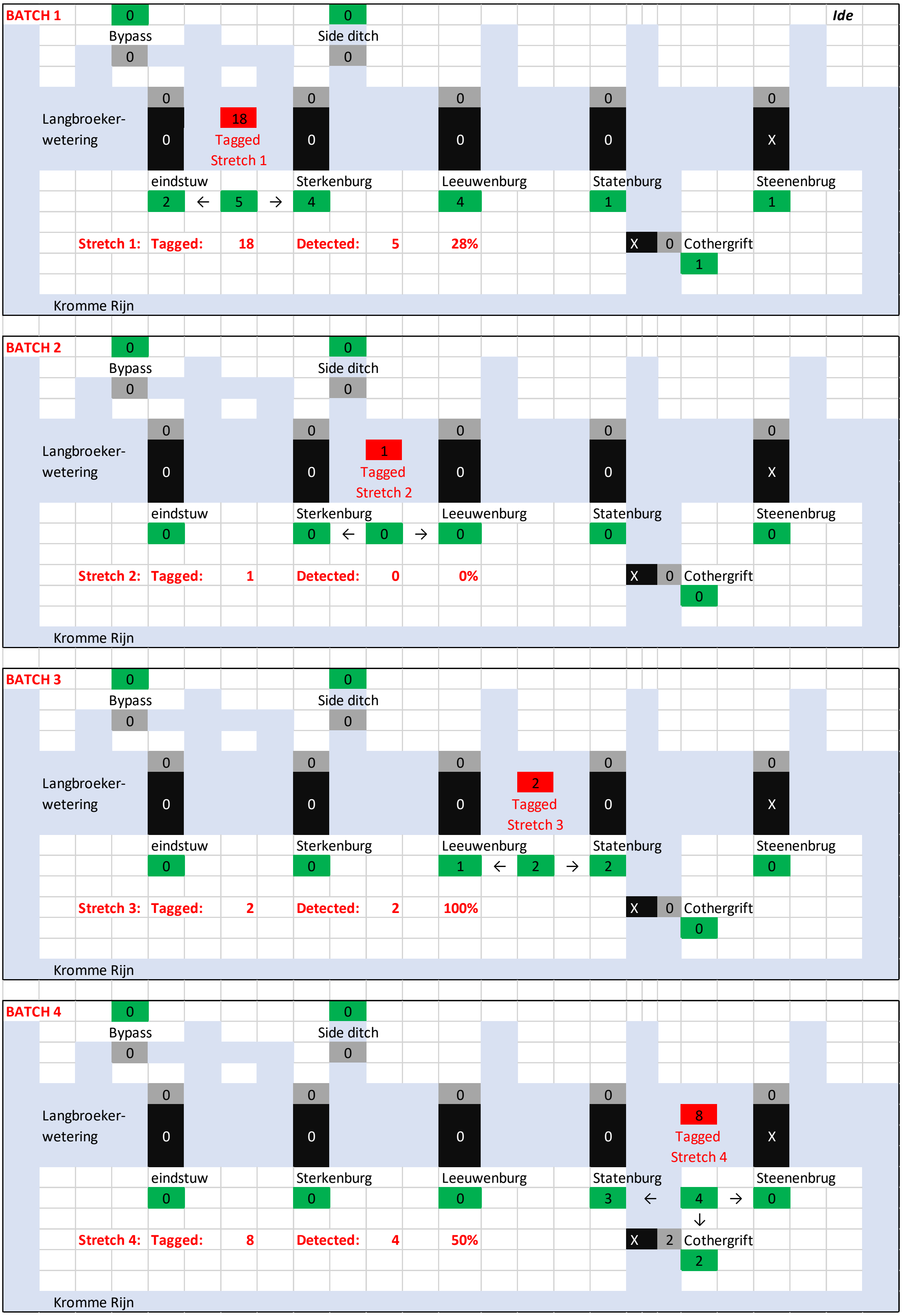


Figure A1.10*. Numbers of ide tagged and detected for each batch (see Fig. A1.1 for legend).*

Eel (*Anguilla anguilla, Dutch: paling/aal*)

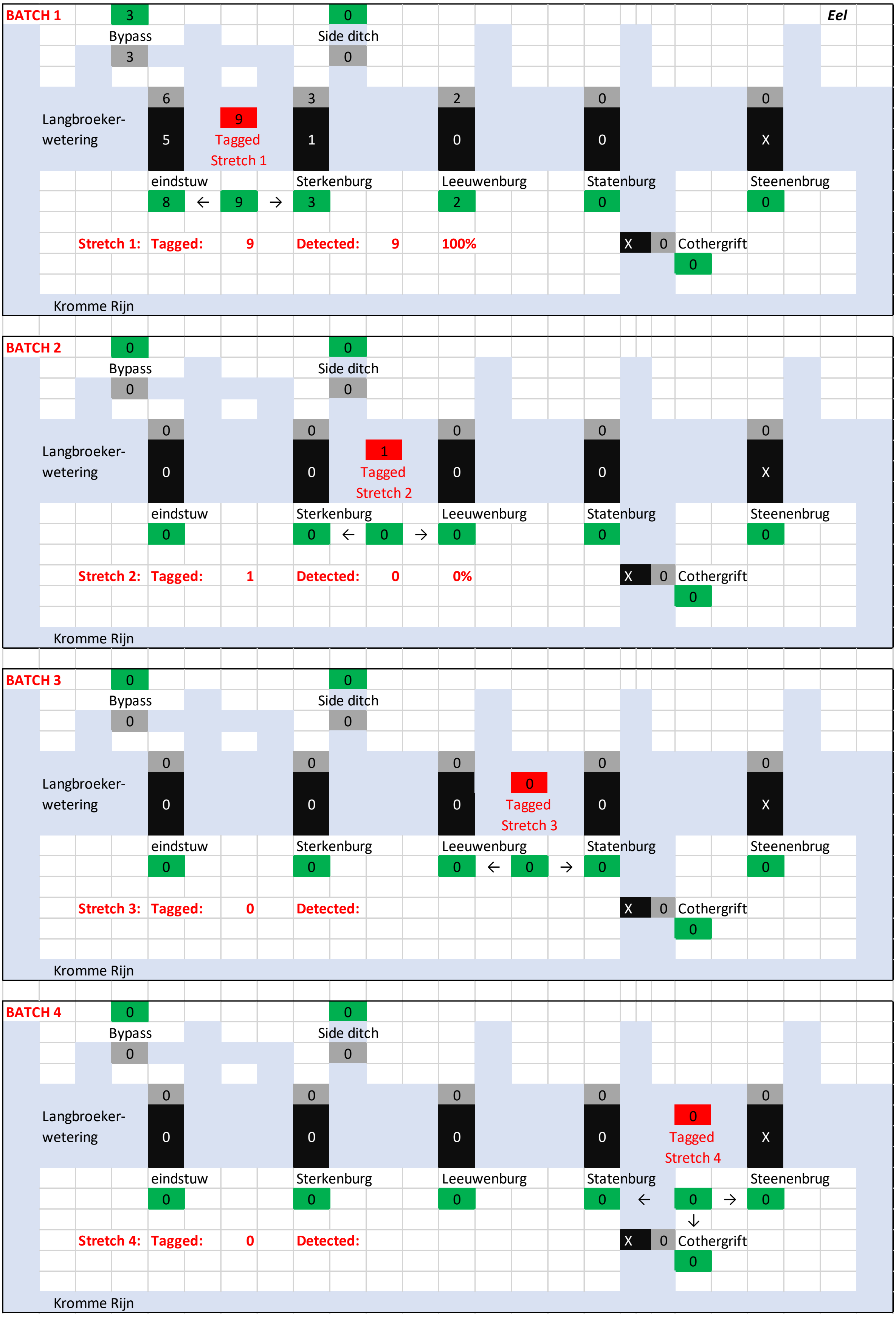


Figure A1.11. *Numbers of eel tagged and detected for each batch (see Fig. A1.1 for legend).*

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