Silver eel behaviour in the vicinity of pumping stations: a telemetry study in Friesland

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Uitgebreide Nederlandse samenvatting

1. Inleiding

In Nederland staan duizenden kleinere en grotere gemalen om te zorgen voor een veilige waterhuishouding. Voor de migratie van schieraal is het belangrijk dat de vissen de gemalen veilig kunnen passeren. Kunst *et al.* (2008) heeft in een studie een schatting gegeven van 91 ton vis dat in Nederland beschadigd raakt of gedood wordt door gemalen; hiervan is één-derde aal en twee-derde schubvis. Het aandeel van de schieraalpopulatie dat veilig door gemalen naar zee migreert, is afhankelijk van het aandeel aal dat vanuit de polders wegtrekt naar zee en van de overleving bij het passeren van de gemalen. Migrerende aal kan door diverse oorzaken aarzelen om een gemaal te passeren. Hierdoor kan naast sterfte in het gemaal ook barrièrewerking van een gemaal uitgaan. De barrièrewerking door deze aarzeling kan variëren van beperkt blijven tot geringe vertraging in de migratie tot zelfs blokkering van de migratie. In deze studie onderzoeken we in hoeverre barrièrewerking bij gemalen optreedt tijdens de migratie van schieralen.

2. Onderzoeksvragen

1. Als een gemaal blokkerend werkt:
   - Welk percentage van schieralen die voor een gemaal is gedetecteerd migreert uiteindelijk via de gemalen richting zee?
2. Als een gemaal de migratie vertraagd:
   - Wat is de tijdsduur tussen uitzet en passage door het gemaal?
   - Wat is de tijdsduur dat alen voor het gemaal verblijven voor passage door het gemaal?
   - Wat is de tijdsduur dat alen achter het gemaal blijven na passage?
   - Wat is de tijdsduur tussen passage en detectie bij uittrekpunten naar zee?
3. Bestaan relaties tussen het moment van migratie via de gemalen en de hoeveelheid verpompt water door de gemalen of het tijdstip van de dag?

3. Materiaal en Methode

Vier gemalen in de provincie Friesland zijn tussen september 2011 en april 2012 voorzien van VEMCO VR2W ontvangers (receivers):

- H.G. Miedema en Ropta: monden uit op de Waddenzee,
- Schalsum en Offerhaus: monden uit op de Friese Boezem en alen kunnen gedetecteerd worden bij uittrekpunten Harlingen, Dokkumer Nieuwe Zijlen en Zoutkamp.

Per gemaal werden drie receivers geplaatst:

- receiver A: één receiver op 200-300 meter voor het gemaal voor detectie van aal die vanuit de polder richting gemaal zwom,
- receiver B: één receiver vlak voor het gemaal (7-35 meter) en
- receiver C: één receiver achter het gemaal (45-105 meter).

Daarnaast zijn ook bij enkele andere uittrekpunten (boezem naar kustwater) bij Harlingen, Dokkumer Nieuwe Zijlen en Zoutkamp een receiver geplaatst.
In totaal zijn in 2011 125 alen uitgerust met VEMCO V9 zenders (transmitters) en uitgezet in de polders. Bij de gemalen H.G. Miedema, Ropta en Schalsum zijn alen uitgezet op 5 oktober (15 alen per gemaal) en 19 oktober (16 alen per gemaal), bij gemaal Offerhaus zijn alen uitgezet op 28 september (8 alen) en 25 oktober (24 alen).

4. Resultaten

4.1 Aantal gedetecteerde alen

Van de 125 uitgezette alen zijn 119 alen in de achterliggende polder gedetecteerd door een receiver. Van deze alen zijn 87% door de gemalen heengegaan (Tabel 4.2.1). Per gemaal lagen de percentages van alen die door het gemaal zijn gegaan op 73% voor Miedema, 94% voor Ropta, 100% voor Schalsum en

71% (gecorrigeerd) voor Offerhaus. Voor Offerhaus is de groep uitgezet op 28 september (batch 1) uit de berekeningen gehouden, aangezien vijf van de acht alen uit deze groep enkel bij de achterste receiver gezien is en één aal geheel niet gezien is. Deze groep alen is sterk afwijkend van de overige resultaten en twijfel bestaat of bij deze groep bij het operatie- en uitzetproces mogelijk iets niet goed gegaan is. Van de alen bij Schalsum zijn 17 alen gedetecteerd bij Harlingen en één bij Dokkumer Nieuwe Zijlen, terwijl één aal van Offerhaus ook bij Dokkumer Nieuwe Zijlen gedetecteerd is (Tabel 4.2.2).

4.2 Verblijftijden

Sommige alen verbleven langere tijd in de polder voor het gemaal, maar de meeste alen (60%-86% per uitzetdatum) passeerden de gemalen binnen een dag nadat ze de eerste keer gedetecteerd waren bij de receiver voor het gemaal (Figuur 4.3.1). Sommige alen gingen na enkele minuten door het gemaal heen, terwijl andere alen ook een langere periode voor het gemaal verbleven voordat ze het gemaal passeerden (Figuur 4.3.2). Van de 19 alen die waargenomen zijn bij de uittrekpunten deden 11 alen hier 1-3 dagen over om van de gemalen naar de uittrekpunten te zwemmen, terwijl drie alen hier langer dan 10 dagen over deden (Figuur 4.2.4).

Bij gemalen Miedema, Ropta en Schalsum werden de meeste alen maar hoogstens één dag gedetecteerd achter het gemaal na passage, terwijl voor gemaal Offerhaus 66% van de alen die door het gemaal gegaan zijn over langere periode gedetecteerd zijn, met vier alen langer dan 15 dagen tussen eerste en laatste detectie achter het gemaal (Figuur 4.2.3). Deze lange verblijftijd kan veroorzaakt zijn doordat alen gewond dan wel dood achter het gemaal hebben gelegen, maar het kon ook zijn dat ze zich lokaal hadden gesetteld na de passage van het gemaal. De huidige studie kan hier geen onderscheid in maken.

4.3 Migratiefactoren

De migratie door de gemalen Miedema, Ropta and Schalsum viel samen met hoge afvoer van water door de gemalen (Figuur 4.4.2), welke werden veroorzaakt door regenperiodes (Figuur 4.4.1).
Van de groep alen uitgezet op 5 oktober gingen alen over een langere periode door het gemaal, terwijl de meeste alen uit de groep uitgezet op 19 oktober dezelfde avond door het gemaal migreerden.
De alen werden meer gedetecteerd gedurende de nachtelijke uren en migratie vond meestal ’s nachts plaats (Figuur 4.4.3).

5. Discussie

5.1 Aantal gedetecteerde alen

De gemalen blijken de meeste alen niet te blokkeren tijdens hun migratie richting zee, aangezien 87% van de alen die zich aandienen bij een gemaal binnen de onderzoeksperiode door de gemalen zijn gegaan. Van de resterende 13 % is het lot onbekend, maar het is mogelijk dat een deel hiervan na de studieperiode langs het gemaal is getrokken. Andere redenen voor het niet passeren van het gemaal kunnen tussentijdse sterfte, zowel natuurlijk (predatie, ziekte) als door menselijk toedoen (visserij). Er kan sprake zijn van enige blokkerende werking, maar deze bedraagt dan maximaal 13 % en meest waarschijnlijk minder door bovengenoemde redenen. Alen kunnen worden afgeschrikt door geluid en vibraties van de draaiende schroeven op afstand, maar gezien de meeste alen snel na uitzet voor het gemaal gedetecteerd werden, heeft dit voor de meeste aal niet tot onoverkomelijke problemen in de migratie geresulteerd. Alen kunnen ook afschrikken van het kroosrek voor de gemalen en meerdere migratiepogingen vlak voor het gemaal doen. In hoeverre dit heeft plaatsgevonden kan niet uit de gegevens gehaald worden, maar het kroosrek heeft uiteindelijk geen barrière gevormd voor tenminste 87% van de migrerende alen.

Van de alen gedetecteerd bij gemaal Schalsum is 58% (n=18) gedetecteerd bij een uittrekpunt, terwijl maar 3% (n=1) van de alen bij gemaal Offerhaus bij een uittrekpunt gedetecteerd zijn. De twee belangrijkste uittrekpunten waren afgedekt, maar de uittrekpunten bij de gemalen bij Stavoren en Lemmer waren niet voorzien van ontvangers. Deze gemalen hebben wel gedurende enkele perioden gedraaid. Het gemaal bij Stavoren heeft vijf perioden gedraaid, terwijl het Woudagemaal bij Lemmer drie perioden gedraaid heeft, waarvan twee periodes beperkt waren tot drie aaneengesloten dagen (Figuur 5.1.1). Het is mogelijk dat alen uit Schalsum of Offerhaus via deze twee punten uit Friesland getrokken zijn.

Bij Schalsum zijn vier alen wel gedetecteerd bij Harlingen, maar niet door de receiver direct achter het gemaal bij Schalsum. Dit is waarschijnlijk veroorzaakt door luchtbelletjes in het gepompte turbulente water achter het gemaal, die het signaal van de zenders verstoord heeft. De uitgezonden signalen zijn niet goed opgevangen door de ontvanger, die relatief dicht achter het gemaal stond. Een andere mogelijkheid is dat twee zenders tegelijk een signaal hebben uitgezonden en hierdoor niet geregistreerd zijn bij de ontvanger. De alen die niet gedetecteerd zijn, zijn waarschijnlijk niet gelijktijdig met andere alen door het gemaal gegaan. Indien dit toch het geval is, dan zou maar één detectie verstoord moeten zijn en zouden andere detecties wel weer opgevangen moeten worden. Daarnaast is het niet waarschijnlijk dat dit bij vier alen voorgekomen is, terwijl dit bij andere gemalen niet is voorgekomen.

5.2 Verblijftijden

De vertraging direct voor het gemaal was beperkt. De meeste alen (60%-86% per uitgezette groep) zijn de dag van aankomst bij het gemaal ook gelijk door het gemaal heen gegaan. Er zijn ook alen langer voor het gemaal, tot zelfs enkele maanden, gebleven. Uit andere studies is ook gebleken dat alen verschil vertonen in de snelheid waarmee een bepaald object, zoals een WKC, gepasseerd wordt.

De alen gezenderd op 5 oktober zijn gedetecteerd vlak voor het gemaal bij receiver B en achter het gemaal bij receiver C over meerdere periodes, terwijl de alen gezenderd op 19 oktober bijna allemaal de eerste avond gezien zijn bij receiver B. Dit verschil kan worden veroorzaakt door triggers om te migreren, maar ook de operatie kan effect hebben gehad. De alen die gezenderd zijn, zijn pas uitgezet toen deze zelf weer rondzwommen in de bijkomtank, dus de alen hebben niet passief verdoofd door het gemaal kunnen gaan. Daarnaast zijn bijvoorbeeld op 18 december bij gemaal Ropta het grootste deel van de populatie uitgezet op 5 oktober door het gemaal gegaan en uit ander onderzoek komt ook naar voren dat alen vaak maar gedurende enkele korte periodes massaal trekken.

Bij Offerhaus is de meerderheid van alen voor langere tijd vlak achter het gemaal (receiver C) gedetecteerd en ook vlak voor het gemaal (receiver B) zijn twee alen over langere tijd gedetecteerd. Wanneer alen lange tijd stationair zijn is het niet mogelijk om zekerheid te krijgen of de paling levend dan wel dood is. Gezien het feit dat sommige alen gedurende enkele maanden bijna continu gedetecteerd zijn, lijkt het waarschijnlijk dat dit dode alen betrof. Het beperkte aantal alen dat bij Offerhaus door het gemaal zijn gegaan en vervolgens gedetecteerd zijn bij de uittrekpunten is in lijn met wat verwacht kan worden als Offerhaus een hoog sterftepercentage bij passage zou veroorzaken.

Naast de alen die vanuit Schalsum bij Harlingen gedetecteerd zijn, is er ook een aal gedetecteerd bij Dokkumer Nieuwe Zijlen. Een studie door Witteveen en Bos in Friesland heeft ook laten zien dat alen verschillende migratieroutes gebruikten naar de uittrekpunten.

5.3 Migratiefactoren

De timing van de migratie door de gemalen Miedema, Ropta en Schalsum viel samen met een situatie waarin een waterstroom in het poldersysteem aanwezig was richting gemaal, die werd veroorzaakt doordat de pompen overtollig regenwater wegpompten. De timing van migratie bij Offerhaus had een minder goed verband met afvoer via het gemaal. In meer studies naar gedrag van aal komt naar voren dat migratie met name plaatsvindt tijdens hoge waterafvoer. Ook de activiteit van alen gedurende de nachtelijke uren wordt in veel meer studies gevonden.

6. Conclusies

- Voor het merendeel van de alen wordt de migratie niet door het gemaal geblokkeerd, aangezien 87% van de gedetecteerde alen door de gemalen zijn gegaan tijdens de testperiode. Het werkelijke percentage ligt waarschijnlijk hoger, aangezien een deel na de studieperiode kan zijn gepasseerd of middels tussentijdse sterfte aan de binnenzijde van het gemaal (visserij, predatie etc.) niet meer aan een nieuwe poging om het gemaal te passeren toe is gekomen.
- De vertraging voor de gemalen lijkt beperkt. De meerderheid van de alen (60%-86% per uitzetdag) gingen dezelfde dag na eerste detectie bij de ontvanger vlak voor het gemaal (receiver B) door het gemaal heen. Enkele alen zijn echter langer in de polder voor het gemaal gebleven.
- Bij gemalen Miedema, Ropta and Schalsum zijn de meeste alen minder dan een dag gedetecteerd achter het gemaal, terwijl bij Offerhaus 66% van de alen meerdere dagen achter het gemaal zijn gedetecteerd, waarvan sommige over lange tijd. Dit lijkt gerelateerd aan de mate waarin het gemaal schade aanbrengt aan passerende alen.
- De timing van de migratie van de alen bij gemalen Miedema, Ropta and Schalsum viel samen met een situatie waarin waterbeweging aanwezig was, doordat de gemalen water wegpompten. Voor Offerhaus was het verband tussen timing van de migratie en waterafvoer minder uitgesproken.
- Het tijdstip van de dag was van invloed, met de meerderheid van de bewegingen gedurende nachtelijk uren.

Summary

In the Netherlands, thousands of smaller and larger pumping stations are pumping water for safe water control. On locations where eels have to pass a pumping station to reach the sea, the percentage of the eel population that safely reaches the sea depends both on the percentage of the population of eel approaching the pumping station that decides to go through the pumping station (potential losses due to a 'blockage effect') and the percentage of the population that passes the pumping station unharmed (potential losses due to 'direct and delayed mortality' caused by the pumping station). Eel can hesitate or can be blocked to go through a pumping station. This report focusses on the blockage effect of pumping stations for migrating silver eels and three research questions have been investigated:

- What percentage of silver eels approaching a polder pumping station decides to pass?
- What are the delay times in migration for eels passing a pumping station?
- Which factors affect timing of migration through a pumping station?

At four pumping stations in the province of Friesland VEMCO VR2W receivers were installed at 200m and 10m before ('polder side') and 10 - 70m behind a pumping stations ('seaward side'): H.G. Miedema, Ropta, Schalsum and Offerhaus. In addition, receivers were also placed at three exit routes out of Friesland were eels cross into coastal waters: Harlingen, Dokkumer Nieuwe Zijlen en Zoutkamp. A total of 125 eels tagged with VEMCO V9 transmitters were released in the polder during several days in September and October 2011 and their behaviour in the vicinity of the pumping stations was followed until April 2012.

In total 119 out of 125 eels were detected at any receiver and 87% (corrected estimate) of the eels detected at a receiver passed the pumping stations, indicating that the blockage effect appears limited. Especially when considering that of the 13% that did not pass, some might have migrated in the following year after the study period or may have suffered mortality on the polder side, e.g. due to fisheries, predation or disease. Because of this, the blockage effect will presumably be lower than 13 %.

The majority of the eels (60%-86% per batch) passed the pumping stations within a day after arriving at a pumping station, some even within minutes after being detected at the receiver in front of the pumping station. A few eels remained present in the vicinity of the pumping station on the polder side for a long period before passage.

At pumping stations Miedema, Ropta and Schalsum, most eels were detected for less than a day at the receiver directly behind the pumping station, while for Offerhaus 66% of the eels behind the pumping station were detected for several days.

Like other telemetric studies, episodes of active downstream migration of eels were intermittent, and these 'migratory events' appeared to be linked to 'discharge periods' when the pumping station were discharging access water from the polder. Also on a diurnal scale, timing of migration activities showed a higher number of detections at night, especially during the first half of the night, as has been shown in other studies.

1. Introduction

Thousands of smaller and larger pumping stations in the Netherlands are pumping water for safe water control. For the migration of silver eel it is important that they can pass pumping stations safely on their way downstream to coastal waters. The importance of a safe passage was indicated by a study estimating that about 91 tonnes of fish gets damaged or killed by pumping stations in the Netherlands, of which about one-third is eel and two-third is other fish (Kunst et al., 2008). Bierman et al. (2012) gave a best guess of an average mortality of eels going from polders to boezem waters of 41% (minimum of 25% and maximum of 66% average mortality). Differences in damage and mortality when passing through a pumping station are dependent on fish species, length, type of pump blade and type of pump. Damage is caused by contact with blades or other objects in the pumping station, abrupt changes in pressure, turbulence and fast water flows (STOWA, 2012).

On locations where eels have to pass a pumping station to reach the sea, the percentage of the eel population migrating towards the sea depends both on the percentage of the population of eel approaching the pumping station that decides to go through the pumping station (potential losses due to a 'blockage effect') and the percentage of the population that passes the pumping station unharmed (potential losses due to 'direct and delayed mortality' caused by the pumping station). Fish passage of man-made structures such as hydropower stations can be delayed due to hesitation or completely blocked e.g. due to disturbance by sounds or vibrations from the pumping stations (Behermann-Godel & Eckmann, 2003; Winter et al., 2006). Quantitative information on the damage of a pumping station (blockage and mortality during passing) are important for statistical models estimating the population size of eel and the escapement of silver eels (Bierman et al., 2012). When silver eels are hindered or blocked by pumping stations on a large scale during their migration, the numbers of silver eels migrating to sea is a large underestimate of the total number of silver eels in the Netherlands as in current assessment models all silver eels are assumed to migrate through a pumping station (no blockage effect).

This report focusses on the blockage effect of pumping stations for migrating silver eels. Estimates on damage of fish going through a pumping station have already been assessed in several studies (e.g. Kunst et al., 2008, STOWA 2012), but estimates on the percentage of migrating eel in a water body that eventually go through a pumping station and if fish is blocked or delayed in their migration is not yet investigated in the Netherlands. This research is performed within Ministry of EZ-programs.

2. Assignment

The following research questions were asked:
Do pumping stations block or delay the migration of silver eel?

When pumping stations block the migration:

- What percentage of silver eels in a polder migrate through a pumping station?

When pumping stations delay the migration:

- What is the duration between release after tagging and passage through the pumping station?
- What is the duration that eels stay in front of the pumping stations before passage?
- What is the duration that eels stay behind the pumping station after passage?
- What is the duration between passage and detection at exit points?

Is there a relation between the timing of migration of eel through a pumping station and the pumped water volume and are there diurnal patterns?

3. Materials and Methods

3.1 Study areas

Four study sites were chosen to estimate the percentage of blockage of migrating eel due to pumping stations using acoustic receivers; pumping stations H.G. Miedema, Ropta, Schalsum and Offerhaus in the province of Friesland, the Netherlands (Figure 3.1.1). The selection of sites was based on location, pump type, pumping volume and the possibility of exit of fish from the polder system only through the pumping station. H.G. Miedema and Ropta pump straight into the Wadden Sea, Schalsum and Offerhaus into the Frysian Boezem. Receivers were also placed at exit points of Friesland: Harlingen and Dokkumer Nieuwe Zijlen, as well as Zoutkamp to detect eels that passed Offerhaus and Schalsum successfully in their migration to the sea (Figure 3.1.1).

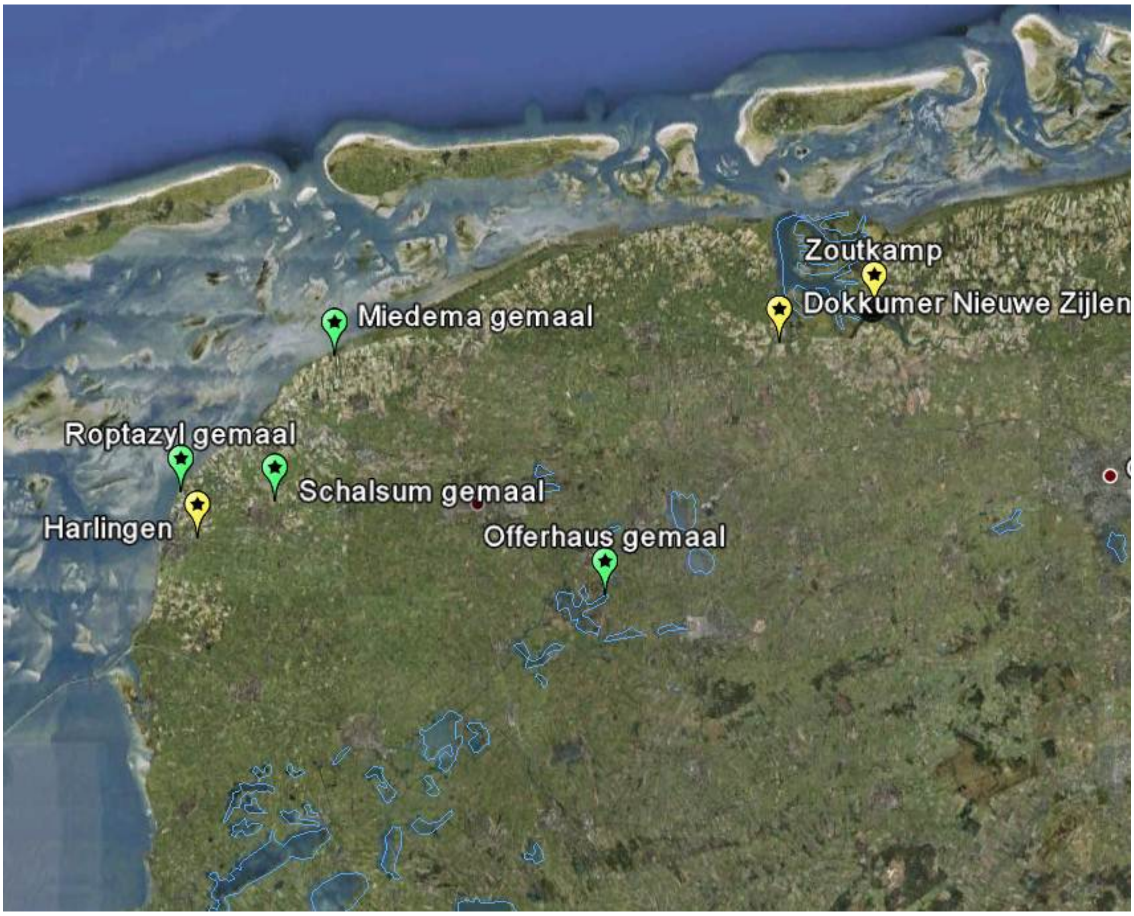

Figure 3.1.1. *Four study sites with three receivers (green mark) and receivers placed at Harlingen, Dokkumer Nieuwe Zijlen and Zoutkamp (yellow mark).*

H.G. Miedema

Pumping station H.G. Miedema (Figure 3.1.2) is located along the dike between Friesland and the Wadden Sea, close to the town of Zwarte Haan. The pumping station pumps water from an area of 8110 ha through a canal (Koude Vaart) into the Wadden Sea. The area is not connected to the canal and lake system of Friesland. The pumping station has two pumps (closed propeller pump) with a capacity of 315 m^3/min each (De Vries, 2012). A third pump takes water from a canal along the dike and has a capacity of 70 m^3/min. The average yearly pumping volume between 2006-2010 was around 40 million m^3. At the Wadden Sea site, water runs through a 300 m long canal that leads into the Wadden Sea.

Figure 3.1.2. *H.G. Miedema; the canal in front of the pumping station (left), pumping station (middle) and the canal behind the pumping station leading to the Wadden Sea (right).*

Ropta

Pumping station Ropta (Figure 3.1.3) is located along the dike between Friesland and the Wadden Sea, close to the town of Roptazijl. The pumping station pumps water from an area of 5010 ha. The pumping station pumps water from a canal into the Wadden Sea, using two larger pumps (closed propeller pump) with a capacity of 180 m^3/min each, and a small third pump with a capacity of 100 m^3/min. A fish passage was built in 2000 to facilitate fish (glass eel, stickleback) migrating from the Wadden Sea to the polder site near this pumping station (Brenninkmeijer *et al.*, 2005). The average yearly pumping volume is estimated at about 27 million m^3 (Paap, Wetterskip Fryslan, pers. Comm.).

Figure 3.1.3. *Ropta; the canal leading to pumping station Ropta (left), pumping station (middle) and the canal behind the pumping station leading to the Wadden Sea (right).*

Schalsum

Pumping station Schalsum (Figure 3.1.4) is located between the towns of Franeker, Dongjum and Schalsum. The pumping station pumps water from an area of 3165 ha. The pumping station pumps water into a canal that leads to the Van Hanrinxma Canal between Leeuwarden and Harlingen, and consists of two pumps (archimedes screw) with a capacity of 150 m^3/min each. The average yearly pumping volume is about 14 million m^3.

Figure 3.1.4. *Schalsum; the canal in front of the pumping station (left), pumping station (middle) and the pump blades (right).*

Offerhaus

Pumping station Offerhaus (Figure 3.1.5) is located close to the town of Earnewald. The pumping station pumps water from an 2.250 ha area into an area with shallow peat lakes and the water will eventually stream towards Lauwersmeer through Dokkumer Nieuwe Zijlen. The pumping station has three pumps with a total capacity of 228 m^3/min. One pump is an open pump (open propeller pump), with a fish exclusion device (FIS: nine flashing lights) in front of the entrance to the pump, while two pumps are Fishtrack pumps. The average yearly pumping volume is unknown, but estimated at about 9 million m^3 (Paap, Wetterskip Fryslan, pers. Comm.).

During the end of September and 2nd November, an experiment was also conducted by TAUW at pumping station Offerhaus for testing the FIS exclusion device. For this experiment some fykes were set in front and behind the pumping station and emptied twice per week. Fykes were also placed behind the pumps on several evenings. For the batch released at 25th October, this experiment only took place during the evening of 27th of October and 2nd of November.

Figure 3.1.5. *Offerhaus; the canal adjacent to the pumping station (left), pumping station (middle) and the rear of the pumping station (right).*

3.2 Receivers placement at study sites

In total, 15 VEMCO receivers were placed for this study during September 27 and 29 in 2011; 12 receivers around the pumping stations and three receivers in total at exit points of Friesland near the Wadden Sea: one in Harlingen, Dokkumer Nieuwe Zijlen and Zoutkamp (Figure 3.1.1).

At each of the four pumping station sites, three VEMCO VR2W receivers were placed. One receiver was placed at 220-280 meters in front of the pumping station (Offerhaus 115 meters, receiver did not face the pumping station in a straight line) for detection of eels in the polder at distance from the pumping stations, one receiver just in front of the pumping station at 7-35 m, and one receiver behind the pumping station at 45-105 m (Table 3.2.1, Figure 3.2.1 and Figure 3.2.2). All receivers were retrieved at April 2 and 4 2012 to collect the data.

Table 3.2.1. *Distance of receivers to pumping station in meters.*

Pumping station	***Distance of VR2W in polder further away from station***	***Distance of VR2W in polder close to pumping station to station***	***Distance of VR2W behind pumping station to station***
Miedema	255	25	85
Ropta	280	35	105
Schalsum	220	7	45
Offerhaus	115*	15	105

** distance measured over water, since the receiver is around a corner from the pumping station.*

Figure 3.2.1. *Schematic overview of receiver placement near a pumping station.*

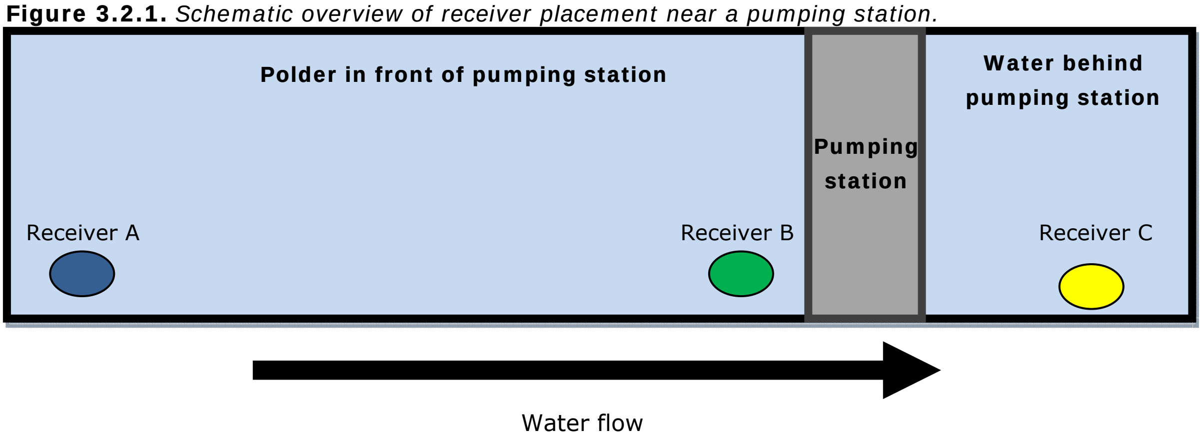

Figure 3.2.2. *Receiver placement at each study site; H.C. Miedema (top left), Ropta (top right), Schalsum (bottom left) and Offerhaus (bottom right).*
Blue mark (receiver A) indicates receiver at distance from the pumping station at polder side.
Green mark (receiver B) indicates receiver close to pumping station at polder side.
Yellow mark (receiver C) indicates receiver behind pumping station.
Blue fish ("Uitzet") indicates release sites of the eels (Chapter 3.5)

3.3 VEMCO receivers and transmitters

For this study, VEMCO coded V9-2L transmitters and VR2W receivers were used to detect eel behaviour around pumping stations. VEMCO coded transmitters and VR2W receivers operate with sound at 69 kHz (www.vemco.com).

A VR2W receiver (Figure 3.3.1, left) records the identification number and time stamp from acoustic transmitters as a tagged animal travels within receiver range. The VR2W consists of a hydrophone, receiver, ID detector, data logging memory and battery, all housed in a submersible case. The VR2W has a battery life of approximately 15 months and can store 1-million detections. To deploy a VR2W, the receiver was moored with tie-wraps along a line, which was connected to two weights at the bottom and a pop-up float (Figure 3.3.1, middle). Data from the receivers can be exported to a computer through a Blue Tooth connection using the VEMCO VUE software package.

VEMCO coded transmitters are available in different sizes (Figure 3.3.1, right). Each tag sends an acoustic pulse train (8 pulses in approximately 3.2 seconds) at pre-set time intervals. These acoustic pulse trains are random about an average delay time to minimise collisions between different tag pulses. Each pulse train includes a specific ID number for each tag to track the individual fish. The V9-2L transmitters used for this study were programmed to send a pulse train random between 40 to 70 seconds, with an estimated tag life of 261 days. Shorter random pulse trains would increase chance of tag collisions and misdetections. The V9-2L tags have a length of 29 mm and a width of 9 mm, weight of 4.7 gram in air and a power output of 146 dB re 1uPa @1m.

Figure 3.3.1. *VEMCO VR2W receiver (left), receiver mooring with a float and a weight (middle), and VEMCO transmitters V9 and V7 (right).*

3.4 Detection range

To assess the detection range of the transmitters, three single detection tests were done, one during the beginning of the test period and two at the end. Turbulence, higher temperature, back ground noise at 69 kHz, high level of suspended matter, shallow waters or a receiver being blocked from the transmitter through e.g. obstacles in the water can decrease the detection range of the transmitters (Payne et al., 2010; How & de Lestang, 2012, Welsh et al., 2012). VEMCO V9 transmitters were found to have a detection range of around 450 meters by a study of Simpfendorfer et al. (2008), while V9-2L transmitters in a study by Payne et al. (2010) had a detection distance of 200 meters. How & de Lestang (2012) did a test with the V9-2L transmitter and found that on average at about 133 meters distance the number of detected pulses was 50%, at about 350 meters this was 30% and at 420 meters only 5% of the pulses were detected. In reef environments, detection range can be even shorter, with only 62% of the pulses detected at 50 meters and 4% at 150 meters (Welsh et al., 2012).

For the detections range tests, a single V9-2L transmitter was used, which was sending a pulse every 10 seconds. This transmitter was held in the water for several minutes at fixed positions with 35-40 meter distance between each position.

3.5 Implanting eels with V9 tags

The silver eels used in this study were obtained from two commercial fishermen who have fishing rights in the studied areas. Only eels with a completely silver white ventral side were used, rejecting individuals with yellow or partly yellow ventral sides, which were presumed not to be in the silver eel stage yet. 125 eels between 61cm and 104cm total length were used (Table 3.4.1). Males do not grow that large before migrating (Dekker, 2000), thus all used fish were females.

Table 3.4.1. *Numbers of eels and lengths of the eels.*

Pumping station	Number of eels	Minimum Length	Mean length	Maximum length
Miedema	31	62.4	72.2	85.2
Ropta	31	61.5	72.8	86.1
Schalsum	31	61.2	72.3	94.0
Offerhaus	32	71.0	80.7	104.5

Because it was difficult to obtain sufficient eels from each study area, most eels were obtained from outside the study areas. For pumping stations Miedema, Ropta and Schalsum all eels were caught in the Van Harinxma Canal in Harlingen and transported to the study locations, while for Offerhaus only eight eels were caught in the polder behind the pumping station. The other eels released near Offerhaus were caught elsewhere in the Oude Veen lake area.

All individuals were anaesthetized with 2-phenoxy-ethanol (0.9 $ml.l^{-1}$) and measured (mm total length). The eels were surgically implanted with a V9-2L transmitter in the body cavity by making a mid-ventral incision of 2-3 cm in the posterior quarter of the body cavity. The used surgical procedure was the best among five different procedures tested for European eel by Baras and Jeandrain (1998), and used by IMARES (Winter et al., 2006). Eels were also tagged with a Floy-tag, so fishermen could report a recapture. Surgery lasted 3-5 minutes. Eels were observed in a recovery tank until 'normal' swimming behaviour reappeared and then released at the study site.

For Miedema, Ropta and Schalsum all eels were released in two batches at the same distance from each pumping station during 5 and 19 October 2011, at 1150-3000 meter from the pumping station. At

Offerhaus the eels were released during 28 September at a distance of 850 m from the pumping station and 25 October 2011 at a distance of 850 and 1800 m from the pumping station (Table 3.4.2).

Table 3.4.2. *Distance of release point in the polder to each pumping station and the number of eels released at each site per batch. For Offerhaus eels were released at two distances from the pumping station.*

Pumping station	Distance release site from pumping station (m)	28/9/2011	5/10/2011	19/10/2011	25/10/2011
Miedema	1750		15	16	
Ropta	1150		15	16	
Schalsum	3000		15	16	
Offerhaus	850	8			12
Offerhaus	1800				12

3.6 Data analysis

For each eel, the moment of first and last detection was taken. The time duration between first detection at receiver A and last detection at receiver B, first detection at receiver B and first detection at receiver C and first and last detection at receiver C was determined. Also the number of detections were calculated. These data were compared to data on water volume pumped at each station (data not available for Offerhaus) and time of day (hour, and sunset and sunrise).

The data from the receivers were corrected from time drift using a linear relationship, which was done with the VEMCO VUE software. The receivers rely on crystal oscillators to keep track of time. Due to manufacturing variations, the frequency of the crystal oscillators vary slightly between receivers. Over time the clock drifts and loses or gains time. A receiver may drift up to 4 seconds per day.

The VEMCO receiver partly overlapped in detection range and as a result eels were sometimes detected at the same time by both receivers placed within the polder. These detections were relabelled as observations seen by both receivers and were removed from the data with detections by only the receivers further away from the pumping station and close by the pumping station.

4. Results

4.1 Range test

The range tests gave a maximum detection range of approximately 200 meters during a test in the polders in front of Schalsum (27-09-2011) and Offerhaus (02-04-2012), while in Miedema (04-04-2012) the detection range was over 300 meters (Figure 4.1.1, left). In Offerhaus, where the pumping station is situated at a side arm of the polder, the detection range of receiver B, close to the pumping station, was around 80 meters (Figure 4.1.1, right). Detection ranges can possibly be shorter with e.g. high turbulence during water pumping. The detection data from the receivers at Schalsum, Ropta and Miedema showed that during the autumn of 2011, there was an area where receivers A and B overlapped. Also there were areas where receivers A and B did not overlap in detection range, suggesting the detection range was less than 300 meter as found at Miedema in April 2012.

Figure 4.1.1. *Detection range at Miedema (left) and Offerhaus (right) the beginning of April 2012. Red marks indicate range test point. At Miedema the range test transmitter was detected by both receivers in the study area, and the border of the detection area was not yet detected. Detections of transmitters on the receiver close to the pumping station during the study period indicated that the detection range was often less than during this range test. At Offerhaus the green area marks detection area for the receiver close to the pumping station (receiver B) and blue area (receiver A) the detection area for the transmitter in de polder.*

4.2 Location: number of eels detected at receivers

4.2.1 Number of eels detected at pumping stations

Of the 125 eels tagged, 119 eels were detected at least at one receiver (Table 4.2.1) and the percentage of eels detected at a receiver and passing the pumping stations was between 81% (minimum) and 87% (when corrected for a batch from Offerhaus and four eels from Schalsum) combined over all pumping stations. In total, 96 eels were detected behind the pumping station at any time during the test, so at least 81% of the tagged eels went through a pumping station during this study. Four eels were detected at the receiver at Harlingen, but were not detected at the receiver behind Schalsum. Eight of the 119 eels were detected at only receiver A, but not at receiver B, close to the pumping station. From these eight eels, five came from the batch of eight eels that were tagged in Offerhaus and one eel from this batch was also not detected at all. Correcting the percentage of 81% for the batch from Offerhaus and the four eels from Schalsum, results in a corrected percentage of eels passing the pumping stations of 87%.

For each of the study areas the percentage of eels detected at a receiver and passing the pumping station was 73% for Miedema, 94% for Ropta, 100% for Schalsum (including the four eels detected at Harlingen) and 53% for Offerhaus. When excluding the eight eels from the first batch for Offerhaus, the percentage of eels passing the pumping station at Offerhaus was 71%.

Table 4.2.1. *Numbers of eels detected at the receiver A, both A and B, B, C, C or exit points and the percentage of eels detected at any receiver and passing a pumping station.*

Pumping station	Eels tagged	Detected at any receiver	Only at A, not at B & C	A	Overlapping area between A and B	B	C	At C or exit points	% eel behind pumping station
Miedema	31	30	2	30	16	24	22	22	73
Ropta	31	31	0	20	22	31	29	29	94
Schalsum	31	30	0	30	27	30	26	30	100
Offerhaus	32	28	6	28	18	21*[1]	15	15	53/71*[2]
Total	**125**	**119**	**8**	**108**	**83**	**106**	**92**	**96**	**81/87*[3]**
%		100	7	91	70	89	77	81	

**[1] 1 eel of probably died in front of the pumping station, concluded from a high number of detections over a long period*

**[2] Percentage for Offerhaus excluding batch 1 was 71%*

**[3] 81% is the estimate including the first batch from Offerhaus. When excluding this batch 1 (8 eels), this results in a corrected percentage of 87%.*

4.2.2 Number of eels detected at exit points or caught by fishermen

A total of 19 eels were detected at Harlingen (n=17) and Dokkumer Nieuwe Zijlen (n=2), which is 58% of the eels tagged in Schalsum and 3% for the eels tagged in Offerhaus (Table 4.2.2). Two eels from Schalsum were caught near Welsrijp and Dongjum, which are close to pumping station Schalsum. The eels at Miedema en Ropta migrated directly from the polder through the only available pumping station directly into the Wadden Sea.

Table 4.2.2. *Numbers of eels detected at Harlingen, Dokkumer Nieuwe Zijlen, Zoutkamp or caught by a fishermen either inside or outside the study areas.*

Pumping station	**Harlingen**	**Dokkumer Nieuwe Zijlen**	**Zoutkamp**	**Caught and released outside the study area**	**Caught and released inside the study area**	**Caught and not released inside the study area**
Miedema	0	0	0	0	1	0
Ropta	0	0	0	0	1	0
Schalsum	17	1	0	6*[1]	0	0
Offerhaus	0	1	0	1	2*[2]	2*[3]
Total	**17**	**2**	**0**	**7**	**4**	**2**
(%)	14	2	0	6	3	2

*[1] *four of these eels were also detected by the receiver at Harlingen*

*[2] *one eel was caught in net within detection distance of receiver B for several days*

*[3] *two eels were found dead within the polder in a bisamrat trap (not within reach of a VR2W receiver)*

4.3 Duration: Time between detections at different receivers

4.3.1 Duration between release and detection at pumping stations

Eels tagged at Miedema, Ropta and Schalsum at 5 October (Figure 4.3.1, left top) were detected first at receiver B over a long period of time, with nine eels first detected after more than 10 days, and the latest detected 172 days after release. Eels tagged at 19 October (Figure 4.3.1, left middle) were almost all detected at the same day as the release. Only four eels were detected at receiver B later than the tagging day, with the latest eel detected 17 days after release. For Offerhaus (Figure 4.3.1, bottom left) eels were also detected over a longer period of time, but 12 eels released at 25 October were detected one day after release.

Eels tagged at 5 October were detected behind the pumping stations by receivers C over a longer period of time compared to the batch released at 19 October (Figure 4.3.1, top right). At 9 October a peak in first detections behind the pumping station was found at Schalsum with three eels, at 12 October at Miedema with four eels and at 18 October at Ropta with nine eels. Most eels from the batch of 19 October were however detected at receivers C at the same day as the release (Figure 4.3.1, middle right). At Offerhaus, no eels were detected at the same day of release behind the pumping station, seven eels were detected behind the pumping station one day after release (Figure 4.3.1, bottom right).

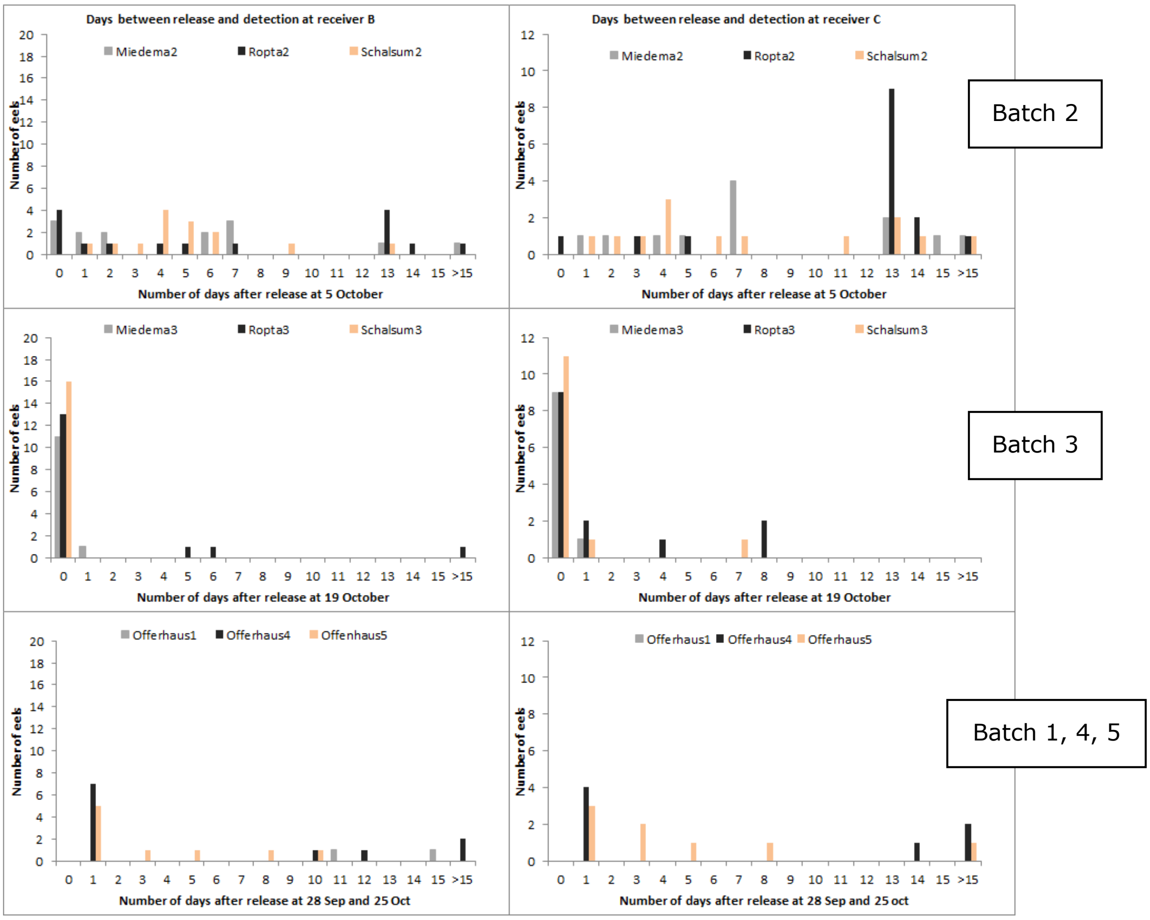

Figure 4.3.1. *Days between release and first detection at the receiver B (left) and days between release and first detection at receiver C (right).*
1=release at 28 September, 2=release at 5 October, 3=release at 19 October, 4 & 5 =release at 25 October.

4.3.2 Duration between first and last detection in front of pumping stations

69% of the eels that passed through the pumping stations were detected first at receiver A and last at receiver B within one day, while 9% where detected last at receiver B or first at receiver C for 11 days or longer after first detection at receiver A (Figure 4.3.2). For eels that did not pass, 17% of the eels stayed within the vicinity of the receivers A and B, while 33% of the eels where detected at receiver A for 11 days or longer after first detection at receiver A.

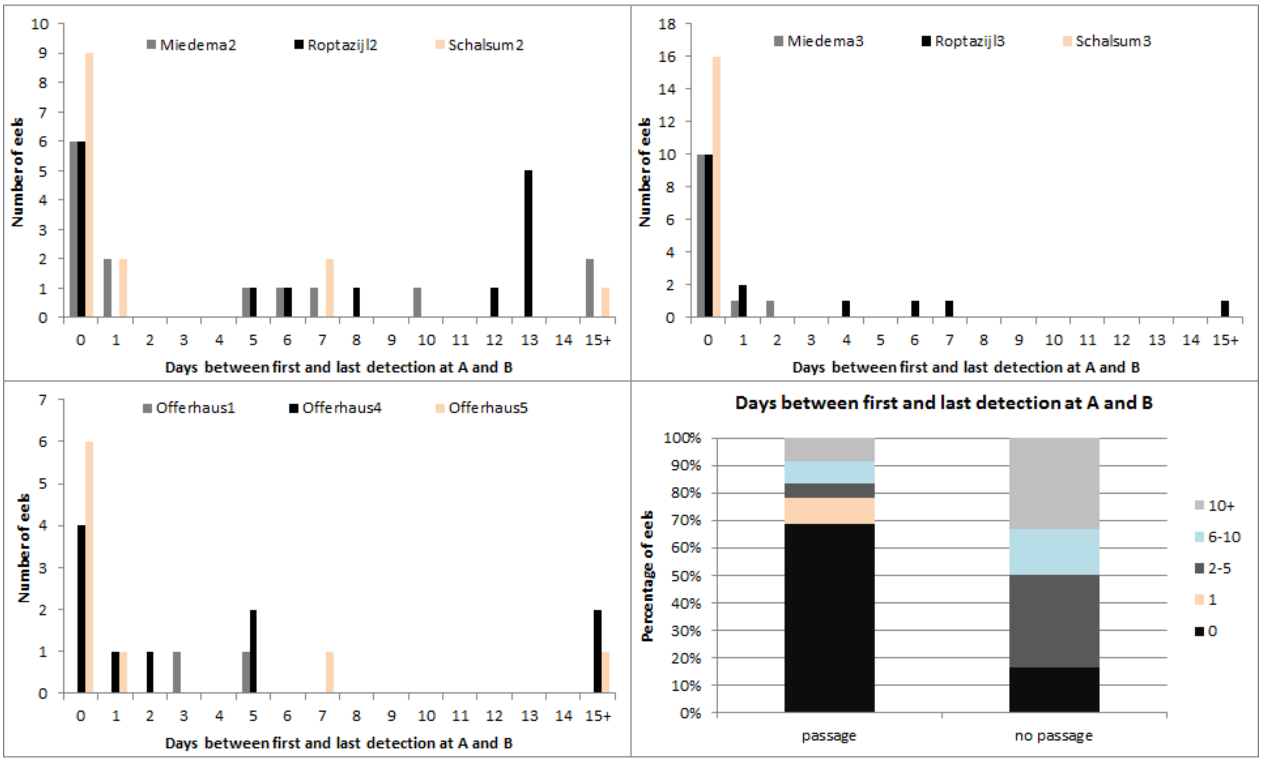

Figure 4.3.2. *Days between first detection at receiver A and last detection at receiver A or B (before swimming back into the polder of passage through the pumping station for period 2 (upper left), 3 (upper right), 1,4 and 5 (lower left) and difference between eels that passed through the pumping stations and eels that did not have passed through the pumping stations (lower right).*
1=release at 28 September, 2=release at 5 October, 3=release at 19 October, 4 & 5=release at 25 October.

4.3.3 Duration between detection in front and behind pumping stations

The majority of eels passed the pumping station the same day of first detection at receiver B. 60% of the eels released at 5 October at Miedema, Ropta and Schalsum (24 out of 40 eels detected both in front and behind pumping station) passed the pumping station at the same day (Figure 4.3.3, top left), while 86% (30 out of 35 eels) of the eels released at 19 October passed the pumping station the same day (Figure 4.3.3, middle left). For Offerhaus 71% (10 out of 14 eels) of the eels released at 25 October passed the pumping station the same day (Figure 4.3.3, bottom left) with no noticeable differences between batches four and five.

10 eels from the batch released at 5 October went through the pumping station within an hour after first detection in front of the pumping stations (Figure 4.3.3, top right), while for the batch from 19 October, 19 eels went through the pumping station within an hour after first detection at receiver B (Figure 4.3.3, middle right). Five eels released at Offerhaus at 25 October went through the pumping station within the hour after first detection (Figure 4.3.3, bottom right).

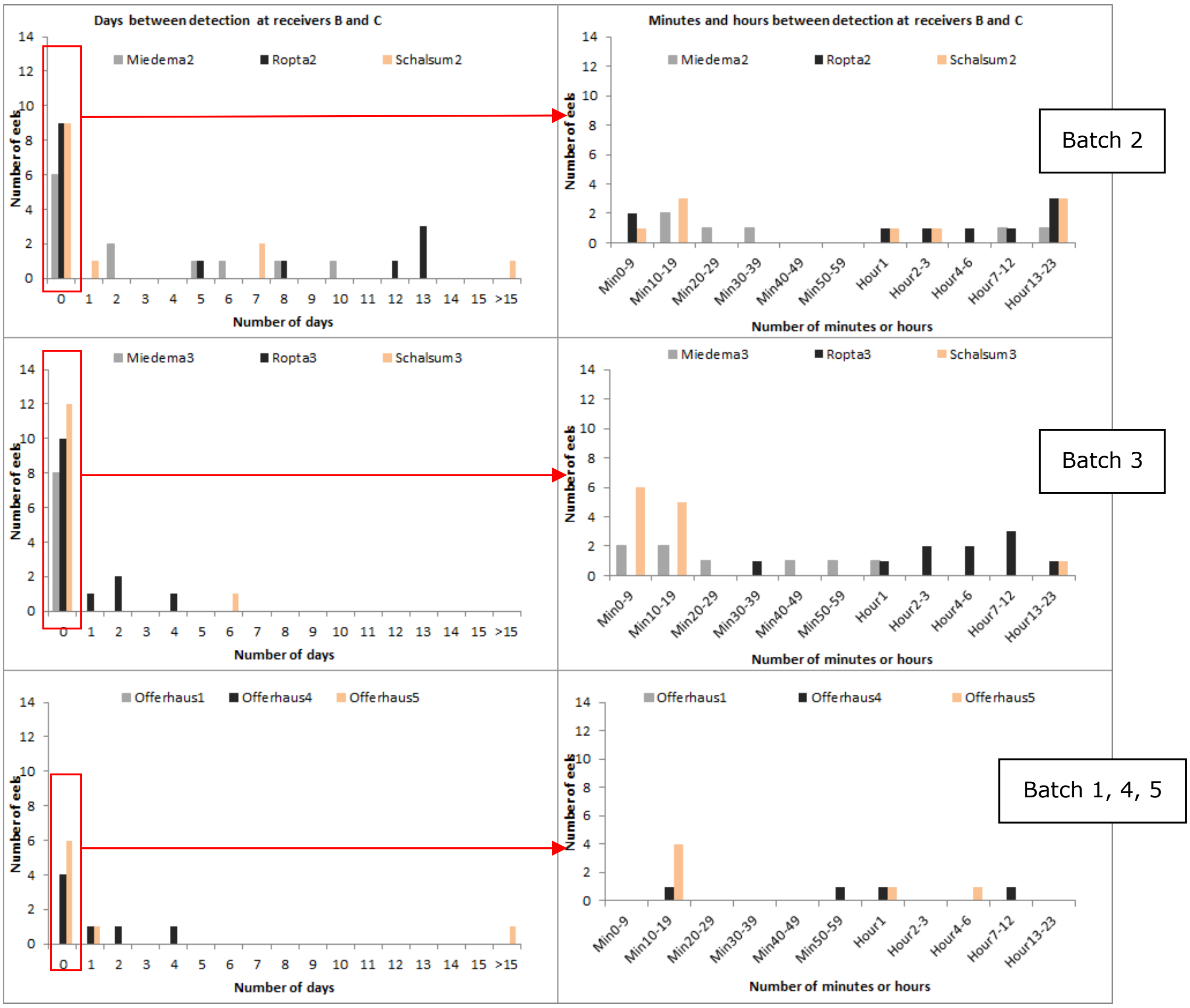

Figure 4.3.3. *Days between first detection at receiver B and C in days (left) and in minutes or hours for eels that went through the pumping station within a day (0 values in left figures) (right). 1=release at 28 September, 2=release at 5 October, 3=release at 19 October, 4 & 5=release at 25 October.*

4.3.4 Duration of first and last detections behind pumping stations

At Miedema, Ropta and Schalsum most eels were detected for less than a day at receivers C, while for Offerhaus more eels stayed during a longer period of time (Figure 4.3.4). For Miedema, 19 out of the detected 22 eels were detected only within a day, with 13 eels only detected once. For Ropta and Schalsum, eels also had more detections, while for Ropta, also four eels were detected at the receiver one day after first detection behind the pumping station. For Offerhaus, all eels had more than 24 detections at receiver C and there were no noticeable differences between both batches.

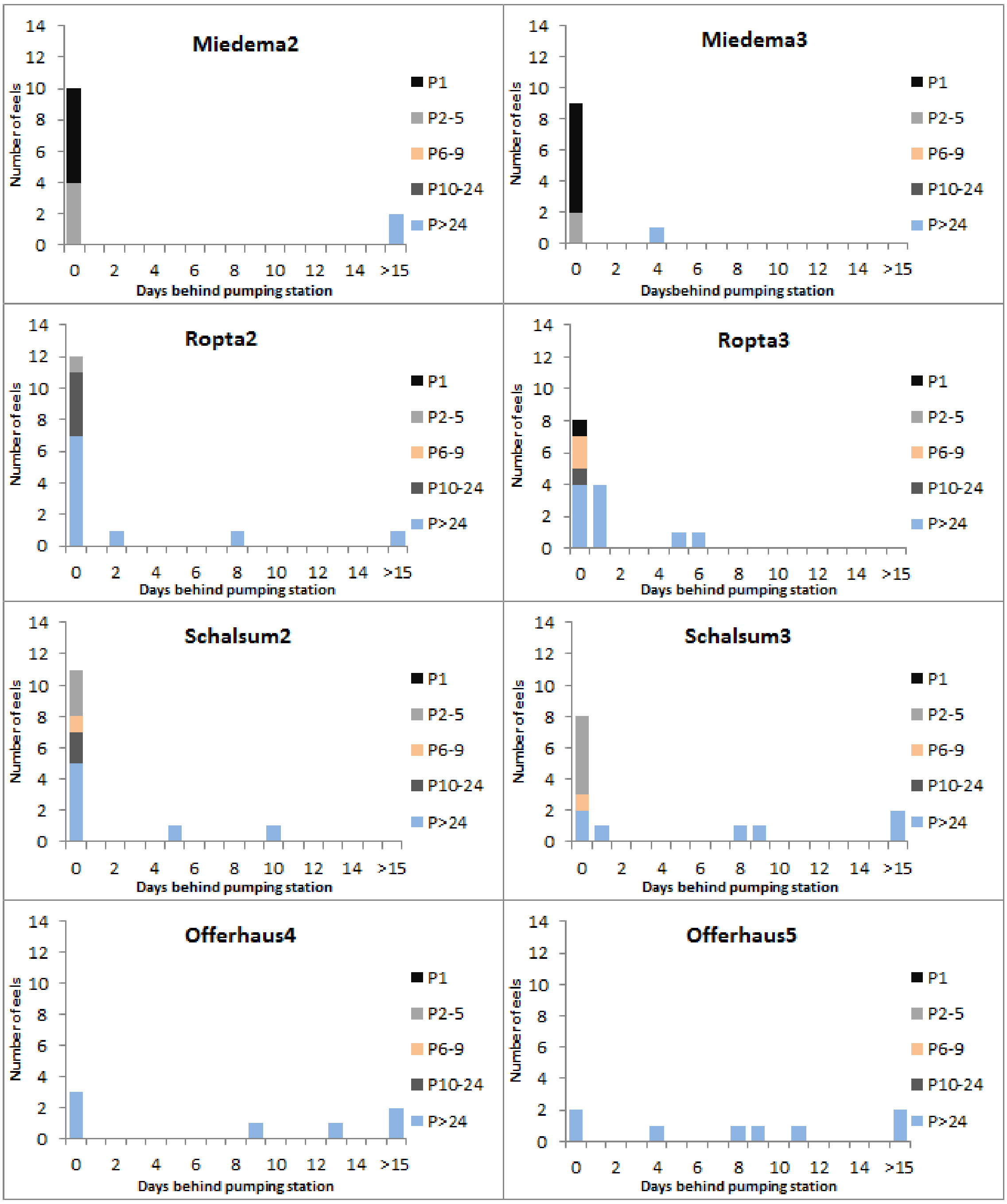

Figure 4.3.4. *Days between first and last detection at the receiver C and the number of detections, grouped in 1, 2-5, 6-9, 10-24 and more than 24 detections during the entire sampling period. 2=release at 5 October, 3=release at 19 October, 4 & 5=release at 25 October.*

4.3.5 Duration between last detection behind pumping stations and exit points

From the 19 eels detected at either Harlingen and Dokkumer Nieuwe Zijlen, for 11 eels it took 1-3 days to get from the pumping stations to the exit points, while for three eels it took over 10 days (Figure 4.3.5).

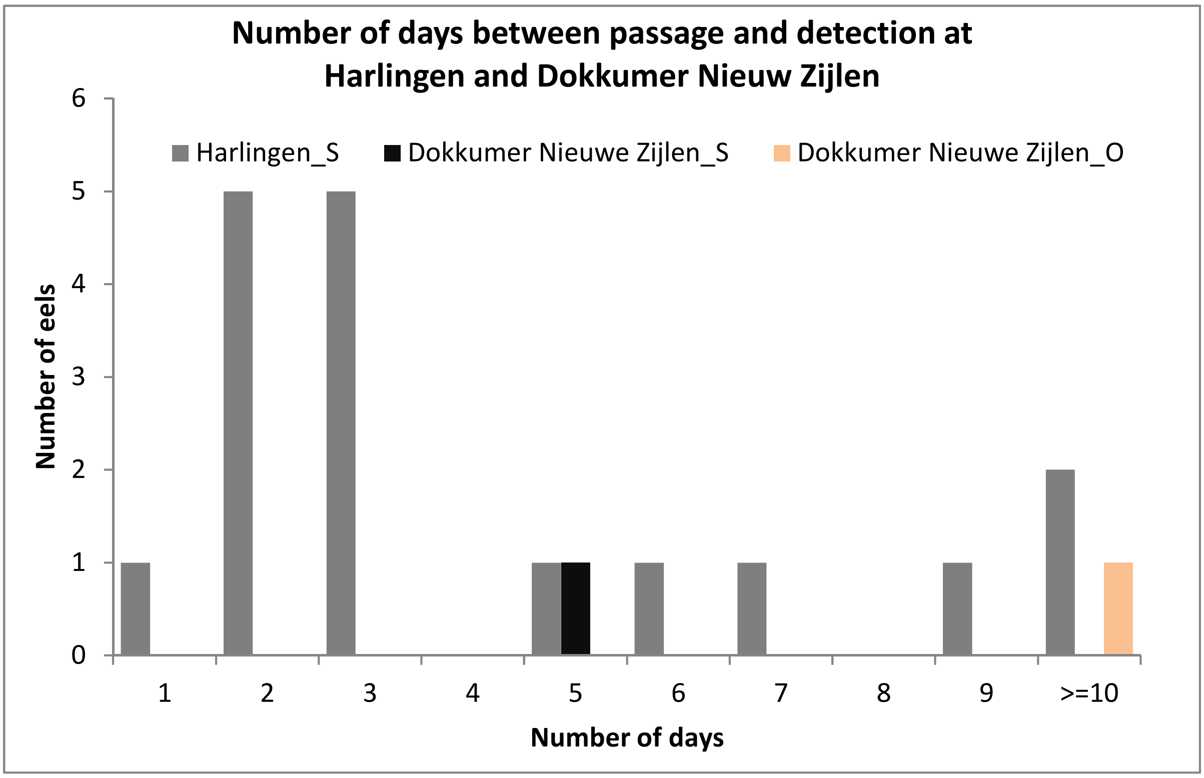

Figure 4.3.5. *Number of days between first detection at receiver C (for four eels not detected at receiver C, the last detection at receiver B was taken) and detection at Harlingen or Dokkumer Nieuwe Zijlen for Schalsum (_S) and Offerhaus (_O).*

4.4 Factors associated with the timing of migration through pumping stations

4.4.1 Volume of water pumped through pumping station

At Miedema there were two peaks in migration through the pumping station: at 12 October with four eels and at 19 October with 9 eels (Figure 4.4.2a and Figure 4.3.1), at Ropta there were two peaks in migration at 18 and 19 October with nine eels per day (Figure 4.4.2b and Figure 4.3.1), while at Schalsum there were two peaks at 9 October with three eels and 19 October with 11 eels (Figure 4.4.2c and Figure 4.3.1). All peaks in eel migration through the pumping stations happened during periods of peaks in water volume pumped through the pumping stations, following periods of rainfall (Figure 4.4.1). For Offerhaus, seven eels released at 25 October went through the pumping station at 26 October. No data on the volume of water was available (Figure 4.4.2d), but data on the percentage of time that the pumping station was working did not show a period of extensive pumping of water.

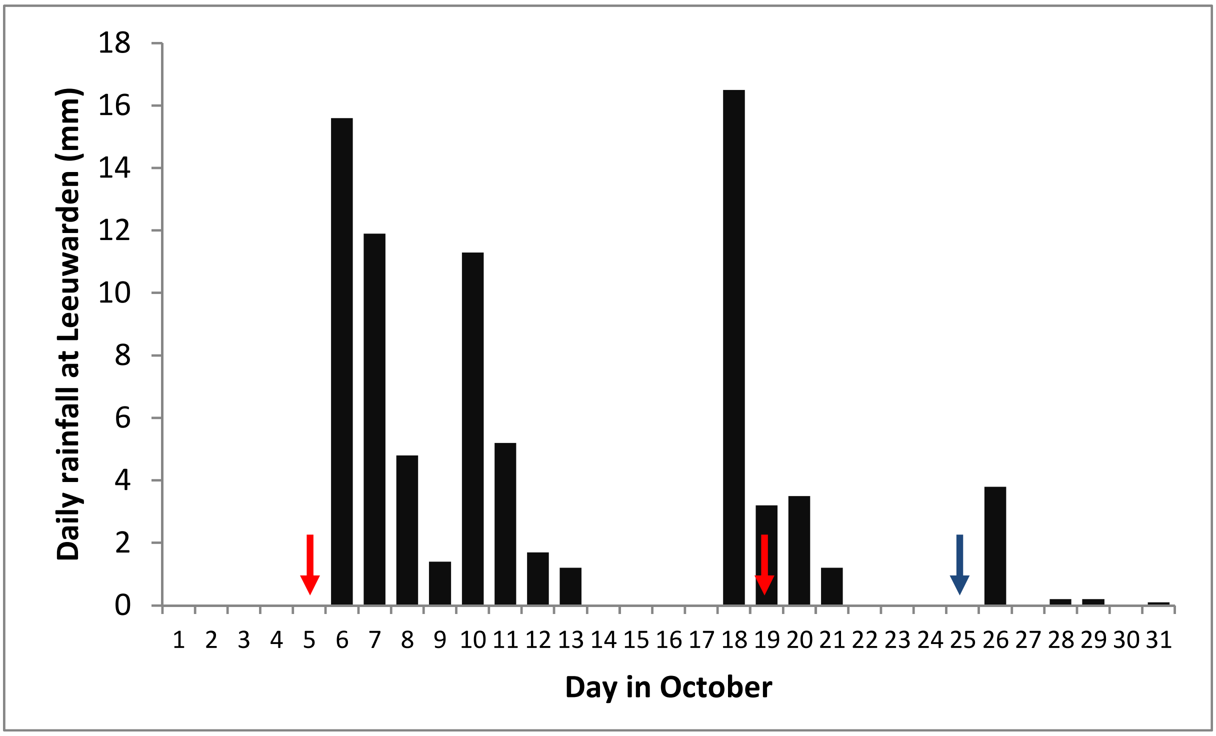

Figure 4.4.1. *Daily rainfall (mm) at station Leeuwarden during October 2011. Data from Royal Netherlands Meteorological Institute. Red arrows indicate date of release at Miedema, Ropta and Schalsum, blue arrow date of release at Offerhaus.*

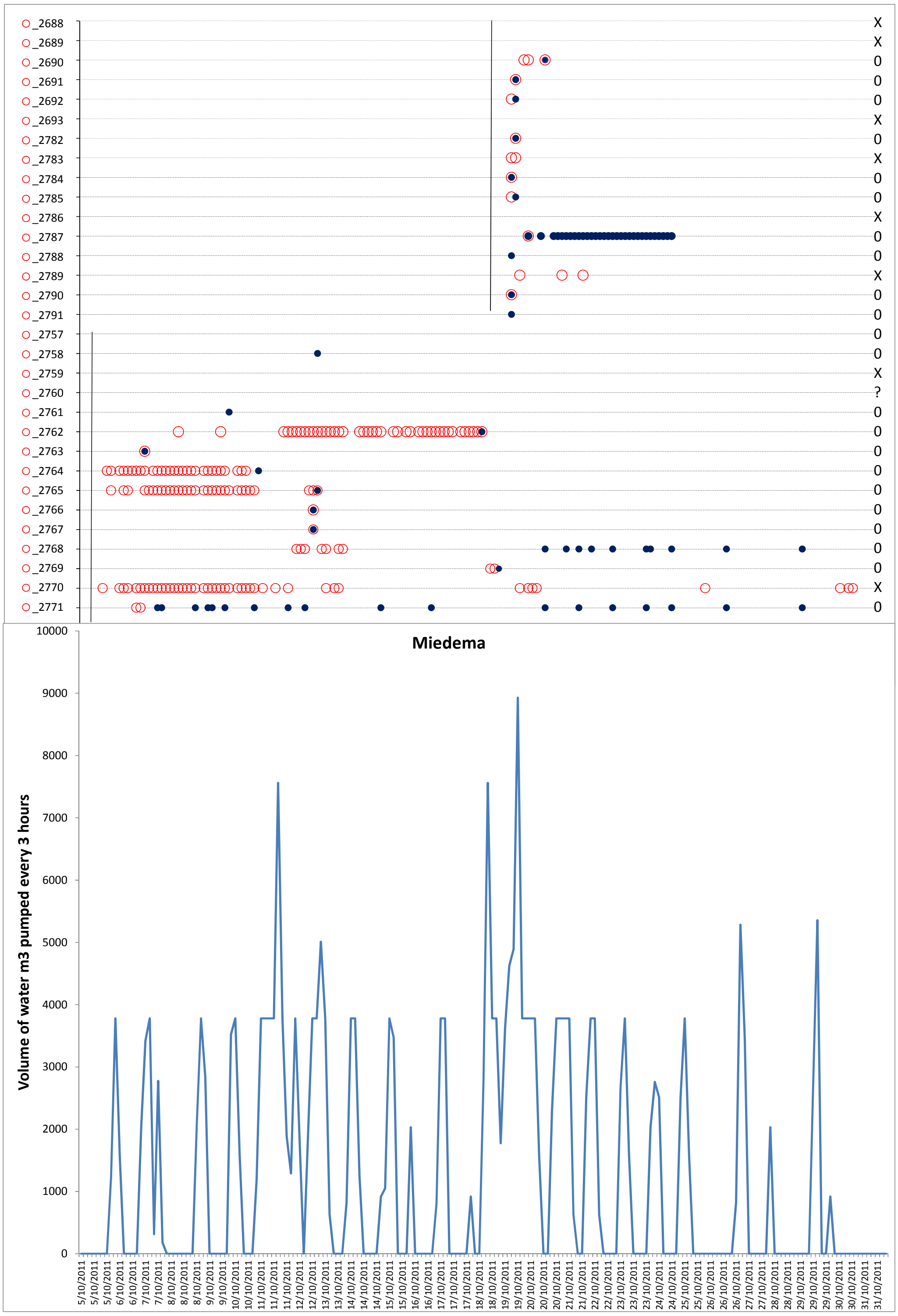

Figure 4.4.2a. *Miedema. Detection of transmitter at receiver B in front of pumping station (red open circle) and receiver C (blue closed circle) behind pumping station (top), and volume of water pumped by the pumping station per 3 hours (bottom) between 5 and 31 October. Vertical lines in top graph show the release date.*

X=eel did not go through pumping station,

?=eel not detected at any receiver,

0=eel went through pumping station during study.

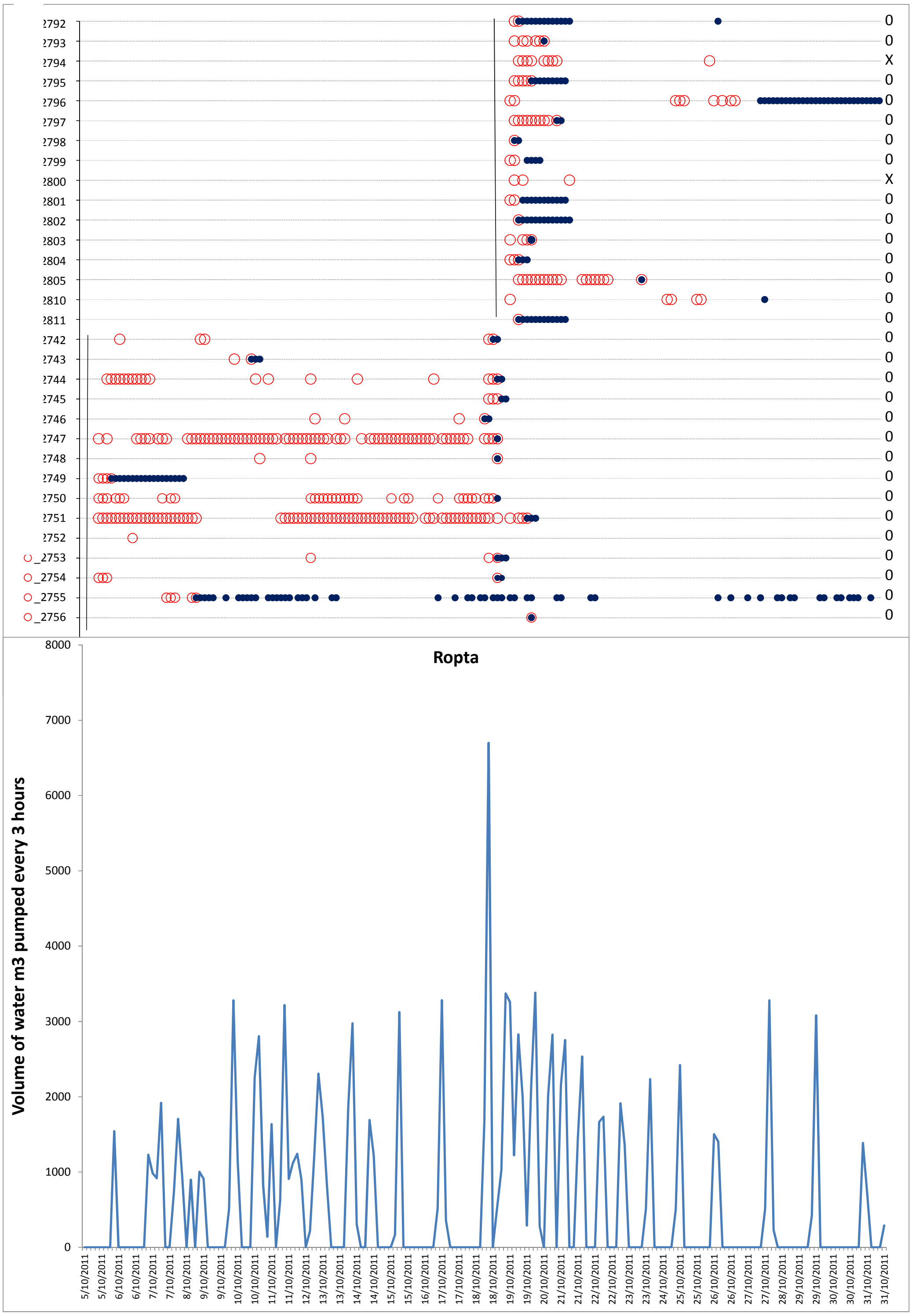

Figure 4.4.2b. *Ropta. Detection of transmitter at receiver B in front of pumping station (red open circle) and receiver C (blue closed circle) behind pumping station (top), and volume of water pumped by the pumping station per 3 hours (bottom) between 5 and 31 October. Vertical lines in top graph show the release date.*

X=eel did not went through pumping station,

?=eel not detected at any receiver,

0=eel went through pumping station during study.

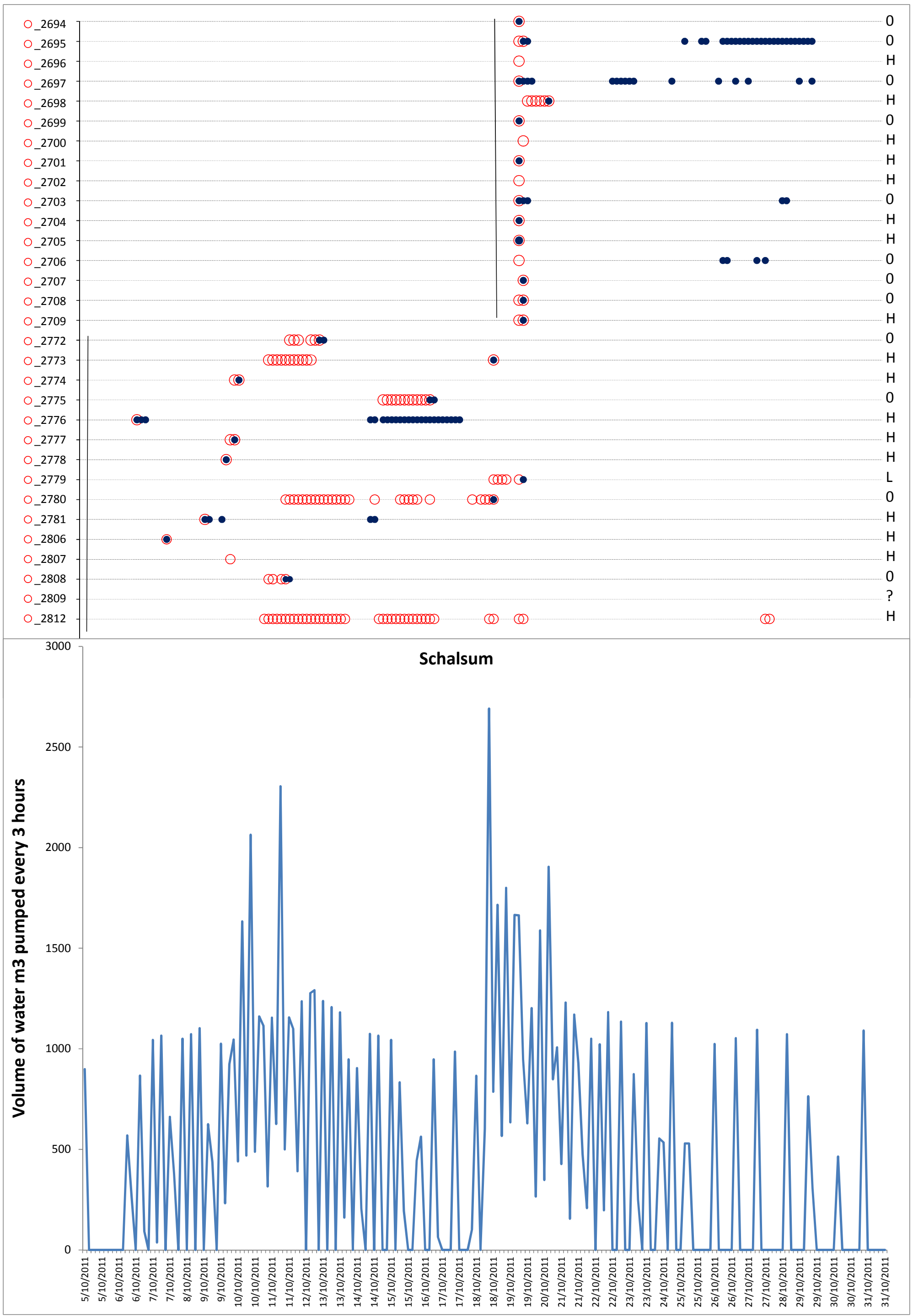

Figure 4.4.2c. *Schalsum. Detection of transmitter at receiver B in front of pumping station (red open circle) and receiver C (blue closed circle) behind pumping station (top), and volume of water pumped by the pumping station per 3 hours (bottom) between 5 and 31 October. Vertical lines in top graph show the release date.*

X=eel did not went through pumping station,

?=eel not detected at any receiver,

0=eel went through pumping station during study, but was not seen at exit points,

H=detected at Harlingen,

L=detected at Dokkumer Nieuwe Zijlen.

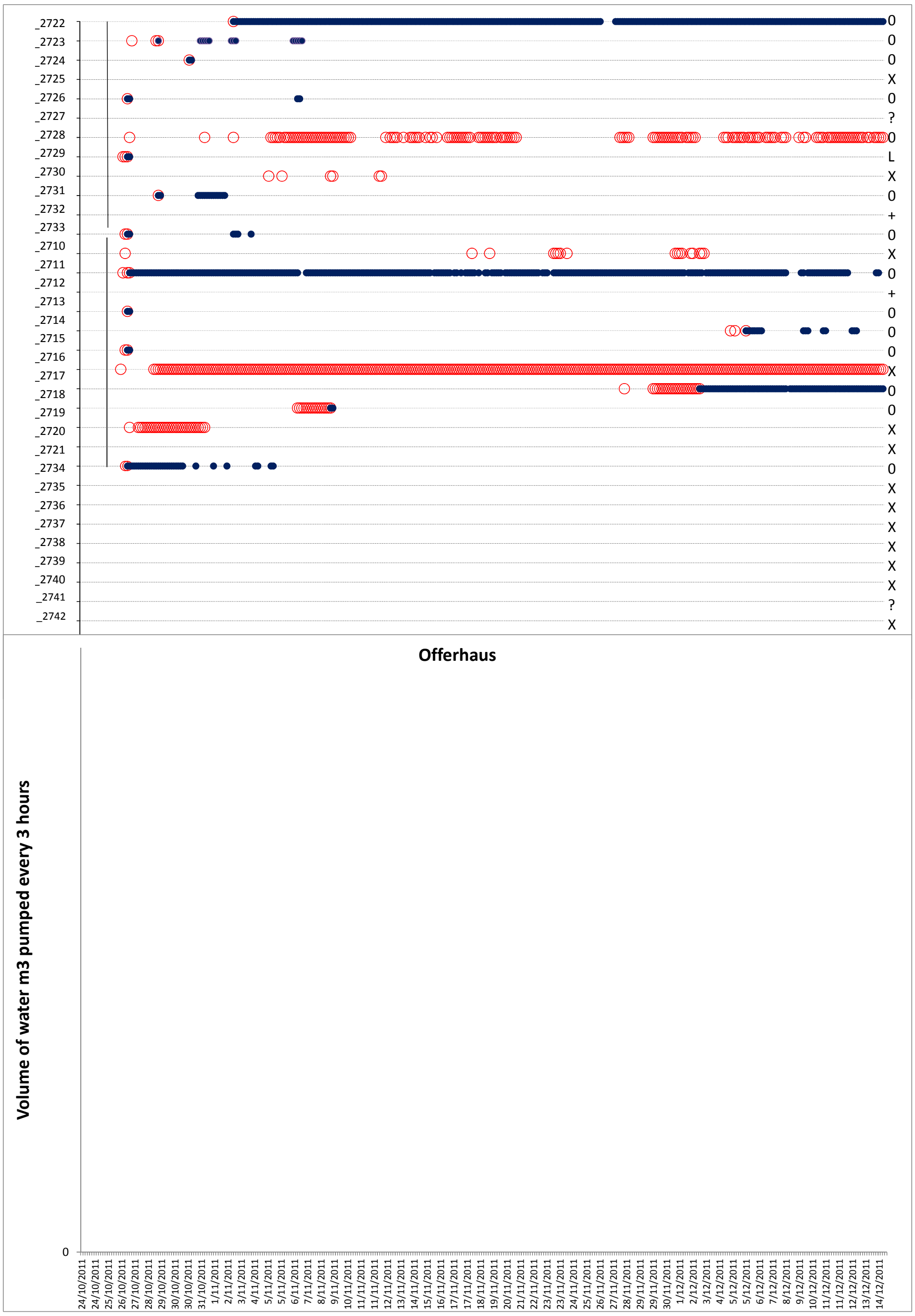

Figure 4.4.2d. *Offerhaus. Detection of transmitter at receiver B in front of pumping station (red open circle) and receiver C (blue closed circle) behind pumping station (top), and percentage of time (periods of 15 minutes) that pumps were working per 3 hours (bottom) between 24 October and 5 December (bottom right). Vertical lines in top graph show the release date.*
No data on the volume of water pumped by the pumping station was available.
X=eel did not went through pumping station,
?=eel not detected at any receiver,
+=found dead in bisamrat trap in Offerhaus polder,
0=eel went through pumping station during study, but was not seen at exit points,
H=detected at Harlingen, L=detected at Dokkumer Nieuwe Zijlen.

4.4.2 Diurnal patterns in migration

The hour of first detection at the receiver behind the pumping station was mainly during 8 pm and 6 am for the batch released at 5 October at Miedema, Ropta and Schalsum with 35 out 40 eels detected between these hours (Figure 4.4.3, top left). For the batch release at 19 October most eels were detected during 4-11 pm, with 31 out of 37 eels detected during these hours (Figure 4.4.3, top right). At Offerhaus almost all eels were detected during 0-4 am, with only one eel detected at 10 pm (Figure 4.4.3, bottom left).

Pumping stations were active during night and day, suggesting that activity of the pumping station did not limit migration opportunities for eels (Figure 4.4.3, bottom right). For Miedema and Ropta, the volume of water pumped during nightly hours is more than during daily hours, but for Schalsum this pattern is not clear.

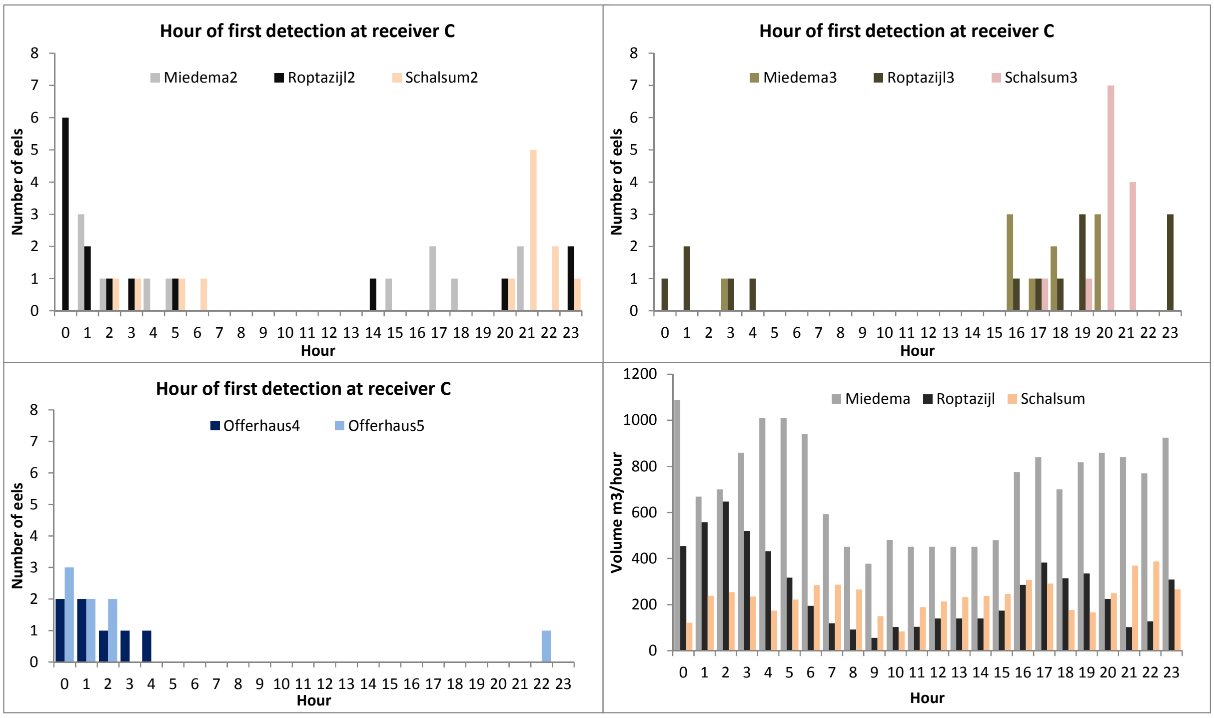

Figure 4.4.3. *Hour of first detection at receivers C.*
Top left: release at 5 October at Miedema, Ropta and Schalsum,
Top right: release at 19 October at Miedema, Ropta and Schalsum,
Bottom left: release at 25 October at 850m (4) and 1800m (5) at Offerhaus,
Bottom right: average volume of water (m^3) per hour through the pumping stations over days that eels went through the pumping station for Miedema, Ropta and Schalsum.

The average number of detections during day and night time per batch (Figure 4.4.4, left) showed that for all batches, except Offerhaus at 28 September (n=2), more fish were detected during nightly hours between sunset and sunrise than during daylight hours between sunset and sunrise. For Miedema and Ropta, eels were more active during daylight for the third batch compared to the second batch, but for Schalsum the opposite seems to be the case. Patterns in percentage of detections for individual eels during day and night time differed between eels only detected during day and eels only detected during night (Figure 4.4.5).

The swimming activity of eels in front of a pumping station during day and night time could be influenced by the duration of an eel staying in front of a pumping station, but this does not seem the case. When eels move to the pumping station and are delayed by the station, they could show more swimming activity during day or more during night time. A clear pattern in the average percentage of detections during day and night time at the receiver in front of the pumping stations could not be detected for eels that stayed less than a day in the polder after first detection and eels that stayed for a longer period (Figure 4.4.4, right).

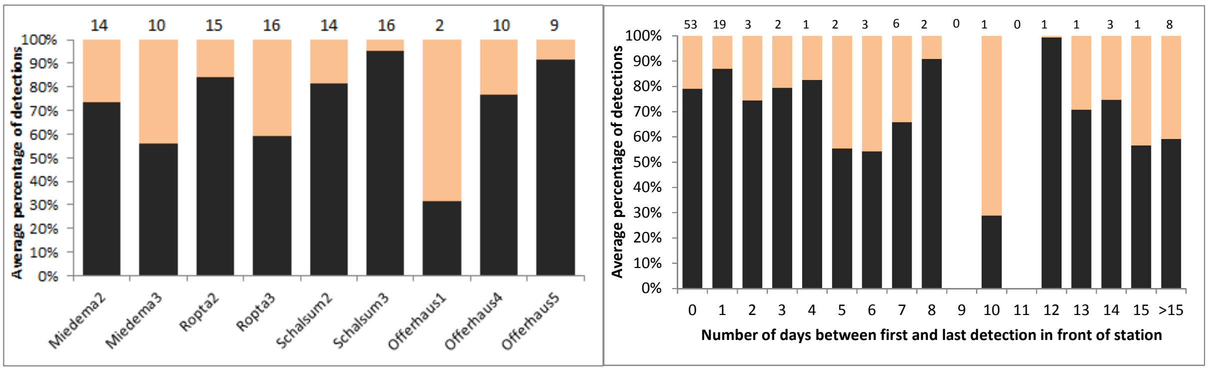

Figure 4.4.4. *Left: average percentage of number of detections at receiver B in front of pumping station during night (dark bars: between sunset and sunrise) and day (light bars: between sunrise and sunset) per batch. Right; average percentage of number of detections at receiver B against number of days between first and last detection at receiver B during day and night over all eels combined. Numbers above bars indicate number of eels.*

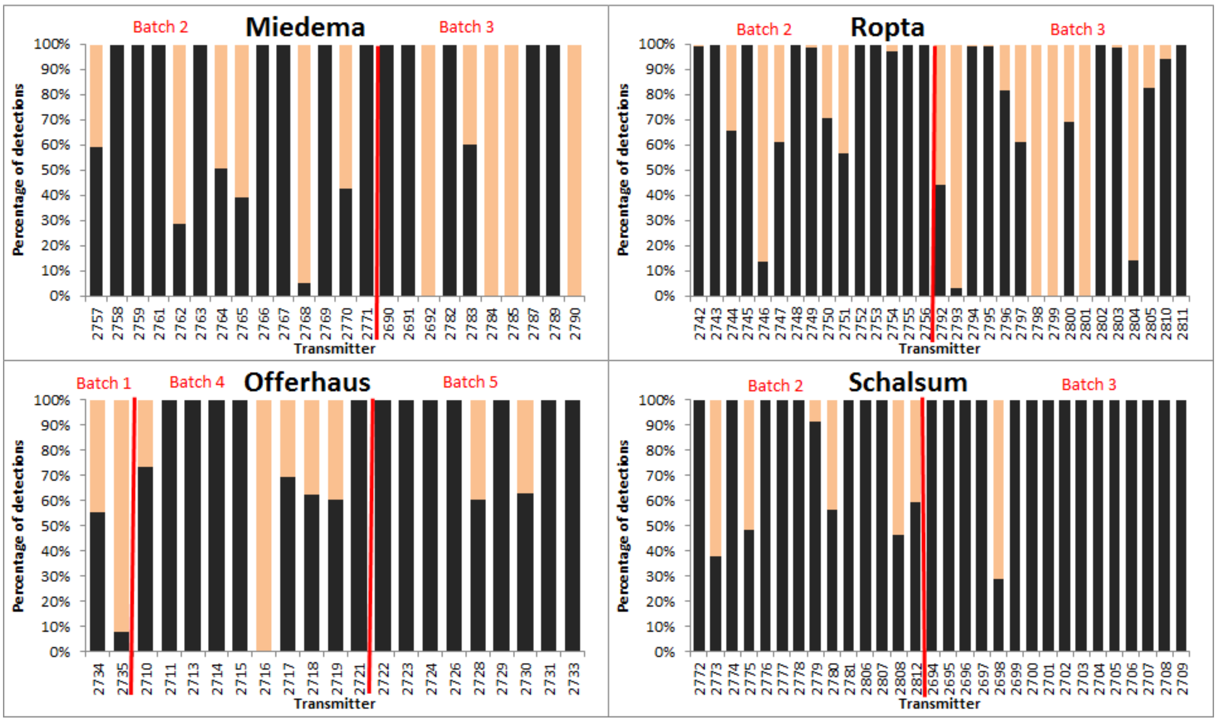

Figure 4.4.5. *Percentage of number of detections at receiver B during night (dark bars: between sunset and sunrise) and day (light bars: between sunrise and sunset) for each transmitter.*

5. Discussion

5.1 Location: number of eels detected at receivers

5.1.1 Number of eels detected at pumping stations

The pumping stations caused at maximum a limited blockage to the migration of eels, since of 87% (range between pumping stations 71%-100%) of the eels detected at the receivers in front of the four pumping stations passed the pumping stations during the test period of October 2011 to April 2012. Especially when considering that of the 13 % that did not pass, some might have migrated in the following year after the study period or may have suffered mortality on the polder side, e.g. due to fisheries, predation or disease. Because of this, the blockage effect will presumably be even lower than 13%. Pumping stations could block or delay eels during their migration, due to sounds or vibrations which may scare migrating fish or due to physical blockage. Sounds or vibrations from the pumps could scare eels away at greater distance from the pumping stations. However during this study, most eels were detected at the pumping station the same day after release when pumps were active, suggesting that eels were hardly disturbed at greater distance due to noise or vibrations of the active pumps. It is possible that eels did show some hesitation or recurrence behaviour due to noise or vibrations.

At short distance, eels may hesitate to pass a pumping station, due to visual or physical contact with e.g. the trash rack in front of the pumping station. Several studies indicated circling behaviour of eel in front of the trash rack (Behrmann-Godel & Eckmann, 2003; Gosset et al., 2005; van Keeken et al., 2010, 2011). In a study of Behrmann-Godel & Eckmann (2003), three out of six tagged eels passed through the turbines of a hydropower station (HPS) on day of arrival, while three other eels approached the turbines, turned round and swam rapidly upstream near the riverbank up to 1 km, from where they approached the structure again. This behaviour was repeated several times per day and on consecutive days until finally the eels passed through the turbines. Observations with a DIDSON acoustic camera at pumping station IJmuiden (van Keeken et al., 2010, 2011) showed that eels reacted to the trash rack in front of the pumping station by turning and swimming away from the pumping station just in front of the trash rack or after contact with the trash rack. From the detection data from the study in Friesland, the number of attempts to pass the trash rack cannot be obtained, but eels were able to pass the trash rack and pumping station eventually.

5.1.2 Number of eels detected at exit points or caught by fishermen

Of the eels released at Schalsum, 58% (n=18) was detected at an exit point, while only 3% (n=1) of the eels from Offerhaus were detected at an exit point. The two major exit sites were covered, the weirs at Harlingen and Dokkumer Nieuwe Zijlen, while two other exit points from Friesland where not covered; pumping stations Hoogland in Stavoren and Wouda in Lemmer. Both exit points were assumed not the main exit points for eels tagged near the pumping stations of Schalsum and Offerhaus.
Miedema and Ropta pump directly out to the Wadden Sea, so no eels were expected to end up at any of the exit points of Harlingen and Dokkumer Nieuwe Zijlen. Both exit stations at Stavoren and Lemmer only pump during periods of high water in the province of Friesland. Pumping station Hoogland was working during five periods during the test period, while pumping station Wouda only worked during three periods, of which two were only three days (Figure 5.1.1). While both pumping stations were not considered the main exit points, it is possible that some eels from Schalsum and Offerhaus migrated through these pumping stations and as a consequence remained undetected.

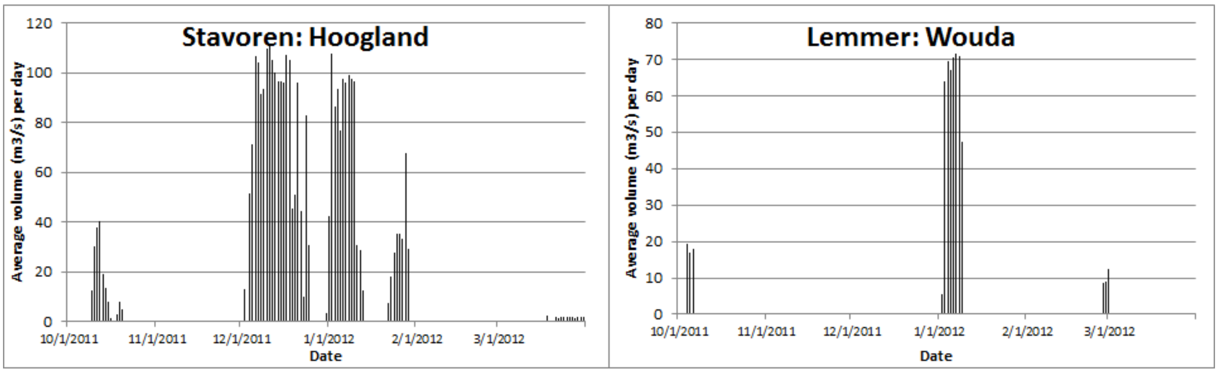

Figure 5.1.1. *Average volume of water pumped by pumping stations in Stavoren and Lemmer per day.*

5.1.3 Misdetections

The misdetections of eels behind Schalsum were probably caused by water turbulence. Four eels from Schalsum were detected at Harlingen, but were not detected at the receiver behind the pumping station. Three eels passed in the evening of 19 October and one at 10 October, all during a period that the pumping station was active for a longer period due to rainfall. The absence of detections from these eels could be caused by either a misdetection due to disturbance of the transmitter signal or to overlapping transmitter pings. The transmitter signal is acoustic and could be disturbed by small pockets of air in the turbulent water pumped behind the pumping station. The receiver behind the pumping station at Schalsum was placed within the vicinity of the pumping station and because of the activity of the pumping station during the evening that the eels migrated through the pumping station, this seems to be the cause. Another explanation could be overlapping signals from two transmitters, but since the eels did not pass at the same time, this does not seem to be the case. A transmitter sends an acoustic pulse train of eight pulses in 3.2 seconds and when all these pulses are received by the receiver, the receiver records the detection. When two transmitters send a pulse-train simultaneously, both pulse trains will overlap and a false detection is recorded at the receiver (Pincock, 2012). However, because the transmitters were programmed to give a random signal between 40-70 seconds, the chance that overlapping detections happen twice or more in a row is low. When assuming that a detection behind the pumping station follows within several minutes after the last detection in front of the pumping station, no overlap in detections with other eels at the time of passing through the pumping station occurred for these four eels, making this cause less plausible.

5.2 Duration between detections at pumping stations

5.2.1 Duration between release and detection at pumping stations

Eels tagged at 5 October were detected for the first time at the pumping stations of Miedema, Ropta and Schalsum over a longer period of time, while eels tagged at 19 October were almost all detected at the same day as the release, with only three eels detected later than the tagging day. This difference in detections could be caused by eel triggered to migrate, but one could also discuss the operation procedure as cause of the migration through the pumping stations at 19 October following the operation procedure. Some eels may have behaved unnaturally because of the experimental treatment and carrying the transponder. In a controlled tank-experiment (Winter *et al.*, 2005), no differences in timing of activity between treated and control group were found, but activity level was significantly lower in the treated group.
The eels were kept in a tank after the operation and only released when they were swimming actively, ruling out the option that eels were sedated and as a result passively floating along with the water. However, because of the operation the behaviour of at least some eels could be influenced and the

frequency of migrations could have been increased during this day, compared to not operated eels. Eels from the first batch from Ropta also showed high migration numbers at 18 October, while eels from the first batch from Miedema and Schalsum also had peaks in migration during a period, showing that migration during single periods is a common feature in eel migration. Lowe (1952) concluded that eels migrated in major peaks on very few nights during a season.

5.2.2 Duration between detection in front and behind pumping stations

The delay in front of a pumping station appeared to be small for most eels with the majority of the eels (60%-86% per batch) passing the pumping station within a day after arriving at a pumping station. Some eels passed within minutes after being detected at the receiver in front of the pumping station, while some eels stayed in front of the pumping stations for a prolonged period of time. Of the 136 eels detected at the entrance of a hydropower station in the river Meuse by Winter *et al.* (2006), differences in time between first detection and passage also differed, with 60% of the eels detected once (one detection or a continuous series of detections with 2 min intervals), while 40% showed recurrence with larger intervals above 2 minutes, varying from several minutes to several weeks.

5.2.3 Duration between first and last detections behind pumping stations

Detections over a longer period of time in front or behind the pumping station in the vicinity of the receiver could either be caused by an eel staying near the pumping station alive, or a dead eel laying within the detection distance of the receiver. No distinction could be made in detections between these two causes, however long periods of continuous detections could indicate a higher change that the eel is dead. At pumping station Offerhaus 66% of the eels behind the pumping station were detected for several days, with several eels detected for more than 15 days, while most eels were detected for less than a day at the receiver behind the pumping stations Miedema, Ropta and Schalsum. At Offerhaus several eels were detected behind the pumping station over a period of several days up to several months, while also two eels were detected in front of the pumping station for several months. The limited number of eels from Offerhaus that were detected at the exit points is most likely explained by a relatively high percentage of eels not surviving the passage of this pumping station.

5.2.4 Duration between last detection behind pumping stations and exit points

Of the eels released at Schalsum, most were detected at Harlingen, and one eel at Dokkumer Nieuwe Zijlen. A study by Witteveen and Bos (2012), where eels were tagged with small pit-tags and released at four different sites in Friesland (Dokkum, Gaastmeer, Harlingen and Suawoude), also showed that eels do not always take the shortest route to an exit point. From 231 eels tagged and released near Harlingen, nine were recaptured in Harlingen, while three went towards Dokkumer Nieuwe Zijlen and were caught in Dokkum (between Harlingen and Dokkumer Nieuwe Zijlen). Of 243 eels released in Dokkum, 18 went to Dokkumer Nieuwe Zijlen while 11 eels went to Harlingen. Also 58 eels were caught near Dokkum at a later time. These eels were assumed to still swim around at release site and were not ready to migrate. The silver colouring of the ventral and dorsal sides may not always represent the silvering stage (Durif et al. 2005). Some eels could indeed still be in the 'yellow' resident stage and therefore not motivated to move downstream directly after release. The silvering process could be reversible to some extent (Durif et al., 2005, Winter et al., 2006).

5.3 Factors associated with the timing of migration through pumping stations

5.3.1 Volume of water pumped through pumping station

The migration of eels through the pumping stations Miedema, Ropta and Schalsum was triggered by water flow of high volumes of water pumped through the pumping stations, caused by periods of rainfall. The migration through Offerhaus could not be linked directly to pump activity. In common with other telemetric studies, episodes of active downstream migration of eels were intermittent, and these 'migratory events' appeared to be linked to 'discharge periods' when the pumping station were discharging access water from the polder (Deelder, 1954; Vøllestad et al., 1994; Bruijs et al., 2003; Durif et al., 2003; Winter et al., 2006; Travade et al., 2010). Most downstream migrations of eels at the river Meuse in 2002 for a study by Winter et al. (2006) took place during a high discharge event late October to early November. Vøllestad et al. (1994) found that water temperature and day length are important factors to initiate migration, whereas water discharge may influence the migratory speed once the "decision" to migrate is made. Downstream migration during high water discharge may be advantageous for many reasons; energy requirement for the migration is lower due to the 'tailwind', consequently downstream passage is more rapid and water is more turbid both decreasing predation risks. If favourable conditions do not appear, silver eels probably postpone the downstream migration to next years (Vøllestad et al., 1994). Deelder (1954) proposed that eel migration in Dutch polders increased in relation to increased water flow rather than water level as key factor, since water levels remains in approximately the same level or are even falling.

5.3.2 Diurnal patterns in migration

Time of day was of influence on migration through the pumping stations, with more eel movements and pumping station passage during nightly hours. On a diurnal scale, timing of migration activities shows a higher number of detections at night, especially during the first half of the night (Winter et al., 2006; Breukelaar et al., 2009; Travade et al., 2010; Riley et al., 2011). Riley et al. (2011) studied eels with pit tags over two years at the River Itchen, UK and found that the movement of eels was significantly correlated with the time of sunset, with 72% or the recordings during the hours of darkness. Also Baras et al. (1998) found higher activity of eels in a Belgian tributary of the River Meuse after sunset during the first part of the night and eels ending their activity before sunrise. Some eels however left their diurnal residence before sunset, but only during low light conditions with rain and cloudy sky.

During the migration at sea, eels are also most active during dark. Westerberg et al. (2007) tagged eels with data storage tags and release them in the Baltic Sea. Swimming activity was between dusk and dawn, starting at a light level corresponding to civic twilight and ending in the morning at generally the same light level. During daylight, the eels rested on the seabed at depths of 2–36 m. Swimming depth was typically close to the surface with up to 95% of swimming time spent within 0.5 m of the surface. The eels migrated a considerable distance between recapture and release sites, indicating a mean rate of travel of ~16 km/day (Westerberg et al., 2007).

6. Conclusions

Location: number of eels detected at the receivers

- Blockage effect of the pumping stations appears to be limited, since a total of 87% (corrected estimate) of the eels detected at a receiver passed the pumping stations. Especially when considering that of the 13 % that did not pass, some might have migrated in the following year after the study period or may have suffered mortality on the polder side, e.g. due to fisheries, predation or disease, or passage occurred unnoticed due to misdetection behind the pumping station. Because of this, the blockage effect will presumably be lower than 13%.

Duration: time between detections at different receivers

- The delay in front of a pumping station was for most eels minor. The majority of the eels (60%-86% per batch) passed the pumping station within a day after arriving at a pumping station, some even within minutes after being detected at the receiver in front of the pumping station. However some eels stayed in front of the pumping stations for a prolonged period of time.

- At pumping stations Miedema, Ropta and Schalsum, most eels were detected for less than a day at the receiver behind the pumping station.

- At pumping station Offerhaus 66% of the eels behind the pumping station were detected for several days, with several eels detected for more than 15 days.

- Factors associated with the timing of migration through pumping stations. The migration of eels through the pumping stations Miedema, Ropta and Schalsum seems to be associated with a water flow caused by high volumes of water pumped through the pumping stations, caused by periods of rainfall.

- The migration through Offerhaus could not be linked directly to pump activity.

- Time of day was of influence, with more eel movements and pumping station passage during nightly hours.

Implications for management

In this study, locations were selected where eel had no other option to reach sea than to pass the pumping station. It was found that the blockage effect at the four selected pumping stations appeared to be limited. Therefore the mortality rate in the pumping stations reflects well the overall loss of silver eel at these locations, which is the dominant situation in polders and smaller pumping stations. However, on locations where besides a pumping station, also other potential passage routes are available, such as ship locks, fish passages or discharge sluices, recurrence behaviour and delays may affect the percentage of eels that eventually migrate through a pumping station. In these cases, which occur especially at larger exit points, overall mortality rate of eels passing the location may be well lower than the mortality rate of eels passing the pumping station, as demonstrated for eel approaching a complex of pumping station and different types of sluices at IJmuiden, where mortality rate of eels passing the pumping station were > 47 %, but overall mortality of the entire location assessed at only 1.5-2.9 % (Winter, 2011).

7. Quality Assurance

IMARES utilises an ISO 9001:2008 certified quality management system (certificate number: 124296-2012-AQ-NLD-RvA). This certificate is valid until 15 December 2015. The organisation has been certified since 27 February 2001. The certification was issued by DNV Certification B.V. Furthermore, the chemical laboratory of the Fish Division has NEN-EN-ISO/IEC 17025:2005 accreditation for test laboratories with number L097. This accreditation is valid until 27 March 2013 and was first issued on 27 March 1997. Accreditation was granted by the Council for Accreditation.

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Justification

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Approved: MSc. A. Paijmans
Onderzoeker

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Approved: Drs. J. Schobben
Afdelingshoofd Vis

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