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Research paper

Downstream migration of European eel (*Anguilla anguilla* L.) in an anthropogenically regulated freshwater system: Implications for management

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ABSTRACT

Connectivity between freshwater habitats and marine areas is heavily obstructed by anthropogenic structures (e.g. weirs, pumping stations, sluices…), leading to a high pressure on diadromous fish populations. A better understanding of fish migration behaviour in relation to these barriers is needed to take proper mitigation actions. We investigated the impact of migration barriers on downstream migrating European eel (*Anguilla anguilla* L.) by tracking 50 acoustically tagged eels between July 2012 and March 2015 in a Belgian polder area. The study area was selected due to the presence of a wide range of migration barriers, such as two pumping stations, a weir and tidal sluices. These structures regulate the water level, resulting in discontinuous flow conditions. The results showed that migration was primarily nocturnal and discharge appeared to be the main trigger for migration in the polder. We also observed substantial delays and exploratory behaviour near barriers. Delays can have a serious impact on eels since their energy resources are limited for a successful *trans*-Atlantic migration. In addition, delays and exploratory behaviour can also increase predation and disease risk. The obtained knowledge can contribute to efficient management such as improved fish passage and guidance solutions.

1. Introduction

Worldwide, water levels of freshwater systems are controlled by structures such as pumping stations, weirs, dams and sluices. These structures hamper the movement of aquatic organisms, especially diadromous fish (Baumgartner et al., 2009; Lassalle et al., 2009; Thompson et al., 2011). Polders are one particular ecosystem type where the role of barriers is crucial. A polder is an anthropogenic system where water is maintained at a lower level than outside the polder by pumping stations and weirs, which are two types of barriers that can negatively influence migration of both diadromous and potamodromous fish species (Buysse et al., 2014; Falke and Gido 2006). Due to climate change, the associated rising sea level and a growing human population, pressure on dewatering systems is likely to intensify in the future, resulting in the development of more polders with their accompanying migration barriers (Beatty et al., 2014; Hannah et al., 2007; Hermoso and Clavero 2011; Maceda-Veiga 2013). In recent years, the importance of aquatic habitat connectivity has been recognized and is being addressed in management practices, resulting in developments to improve fish migration. As such, fish-friendly pump adaptations and fishways have been developed to reduce mortality (Buysse et al., 2015; Clay 1994). However, the efficacy of many presumably fish-friendly adaptations remains to be established (Boggs et al., 2004; Gowans et al., 1999; Keefer et al., 2004; Marmulla 2001; Roscoe and Hinch 2010). Next to mortality effects, pumping stations may also affect migration behaviour, resulting in delays or even migration stops. Consequently, delays or migration stops may result in a higher predation risk or reduced fitness and therefore contribute to the decline of a species (Marmulla 2001).

In this study, we selected the European eel (*Anguilla anguilla* L.) as a model species for downstream migrating fish encountering migration barriers. The European eel is a facultatively catadromous fish species, which grows in coastal and freshwater habitats (i.e. the yellow eel stage) of Europe and North-Africa. After two to 20 or more years, they

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migrate over ca 6000 km as silver eels to the spawning grounds in the Sargasso Sea, depending entirely on the fat reserves they have accumulated during the yellow eel stage (Chow et al., 2010; Tesch 2003). During the last decades, recruitment of the European eel has declined between 90% and 99% (Dekker and Casselman 2014), making it a critically endangered species according to the IUCN Red List (Jacoby and Gollock, 2014). Various causes likely contribute to this decline, such as migration barriers, habitat deterioration, pollution, human-introduced parasites, fisheries and changes in ocean climate (Buysse et al., 2014; Feunteun 2002; Køie 1991; Miller and Tsukamoto 2016; Moriarty and Dekker 1997). To aid conservation and recovery of European eel stocks, the European Union adopted a Council Regulation (European Eel Regulation; EC no. 1100/2007) which imposes a management system that ensures 40% escapement of the spawning stock biomass, defined as the best estimate of the theoretical escapement rate if the stock were completely free of anthropogenic influences. Adequate mitigation measures to improve the escapement rate therefore require proper insight in eel migration behaviour and how this is affected by current management practices.

We used acoustic telemetry to reveal migration routes and link the detection data with biotic and abiotic data, thus providing knowledge about what variables trigger migration and whether eels encounter delays near barriers. This information can be implemented in management measures to improve silver eel escapement rates.

Downstream migrating European eels were tracked from a polder area in Flanders (Belgium) into the Schelde Estuary (SE, The Netherlands). We selected the study area due to the presence of a wide range of migration barriers, such as two pumping stations (an Archimedes screw pumping station (APS) and a propeller pumping station), a weir and tidal sluices. Previous research showed silver eel mortality rates up to 19% at that particular APS (Buysse et al., 2015). We assessed five research questions related to downstream eel migration behaviour: (1) do eels take different migration routes; (2) does eel behaviour change significantly in the vicinity of barriers; (3) does migration follow a circadian pattern; (4) does migration start at a specific point in time; and (5) do environmental variables influence migration? The results of this study will support river and/or polder managers to facilitate downstream eel migration and hence contribute to the conservation of the eel stock.

2. Methods

2.1. Study area

The study area is comprised of three subareas, which are all part of the Schelde river basin: a polder (Flanders, Belgium), the Braakman pond (The Netherlands) and the SE (The Netherlands) (Fig. 1). The polder covers an area of about 200 km^2 and is drained via the Leopold Canal (LC). The LC is an unnavigable waterway of approximately 46 km long, 10–20 metres wide and one to four metres deep. It extends from Heist at the Belgian coast to Boekhoute. Generally, it is a stagnant water system, but during dewatering, it can have a slow flowing current (on average 1.21 $m^3 \cdot s^{-1}$ during this study period). Within the polder area, the LC connects different habitats such as ponds and small and large polder ditches with variable width and depth (Table 1). The Braakman is a brackish pond in The Netherlands, connected to the polder area in Belgium, with a mean chloride concentration of 3265 $mg \cdot L^{-1}$ (range 580–8200 $mg \cdot L^{-1}$), a surface of approximately 2.05 km^2 and a depth up to 14 m. It is located at approximately one third of the SE (starting from the estuarine mouth) and functions as a transition area between the freshwater polder and the polyhaline zone of the SE. The latter is the lowest part of the Schelde river and leads to the North Sea. The funnel shaped estuary is approximately 55 km long with a variable width between two and eight km. It is characterized by intensive tidal action and strong currents and contains many sand banks, mudflats and salt marshes, resulting in a high turbidity.

To dewater the system during high precipitation, water is pumped from the LC (1.40 m above sea level (a.s.l.)) into the Braakman pond (1.97 m a.s.l. in summer, 1.42 m a.s.l. in winter) via an APS in the Isabella Canal (Boekhoute), and flows gravitationally into the SE via a tidal sluice (Fig. 1). In case gravitational flow is insufficient to dewater the system, propeller pumps in the tidal sluice are used. In cases of exceptionally high precipitation, the polder system can also be dewatered towards Zeebrugge by lowering a weir in the LC (Sint-Laureins) (Fig. 1).

The APS has de Wit modifications to reduce fish mortality during passage, and along the APS a de Wit fishway is present (Buysse et al., 2015) (**Fig. S1**). The propeller pumps in the tidal sluice at the border between the Braakman pond and the SE do not have fish-friendly adaptations. In the western direction, connectivity from the polder area to marine areas is blocked by a low-head weir in Sint-Laureins and a tidal sluice in Heist at the freshwater − sea border.

2.2. Tagging procedure

During the summer and autumn of 2012, 566 eels were caught in the polder and at the APS. From July to August 2012, 526 eels were caught with double fyke nets, which were placed in the LC, ponds and large polder ditches. At each location, four double fyke nets were placed and emptied during four consecutive days. Between the 5th and 16th of October 2012, another 40 eels were caught with two fyke nets attached to the outlet of two pumps of the APS during a survey to study eel mortality after passage (Buysse et al., 2015). Total length (TL, to the nearest mm) and body weight (W, to the nearest g) were measured and 50 eels (26 eels in the polder and 24 at the APS) were selected as large enough to tag with a mean length of 684 mm ± 75.76 mm (range 556 mm − 874 mm) and mean weight of 683 g ± 260.23 g (range 381 g − 1615 g). In this study, only females were tagged, since males are smaller than the minimum size handled in this study (< 450 mm (Durif et al., 2005)). Also note that the eels caught at the APS were checked for deformities and lesions prior to tagging.

In 2012, 46 eels were tagged with V13-1L coded acoustic transmitters (13 × 36 mm, weight in air 11 g, random delay between 80 s and 160 s, life time 1116 days, frequency 69 Hz) and four with V7-4L coded acoustic transmitters (7 × 22.5 mm, weight in air 1.8 g, random delay between 45 s and 95 s, life time 157 days, frequency 69 Hz) from VEMCO Ltd (Canada, http://www.vemco.com). After anaesthetising the eels with 0.3 $ml \cdot L^{-1}$ clove oil, tags were implanted according to Baras and Jeandrain (Baras and Jeandrain, 1998). After recovery in a quarantine reservoir, eels were released at their catch location.

2.3. Acoustic network

An acoustic network of 56 automatic listening stations (ALSs) (VR2W, VEMCO Ltd), which register the tag numbers with date and time (i.e. the time stamp) of the detection, was deployed in the harbour of Zeebrugge (n = 1), the polder area (n = 27), the Braakman pond (n = 6) and the SE (n = 22) (Fig. 1). The two ALSs in the Isabella Canal were considered part of the Braakman pond and detection data were handled accordingly. ALSs were moored at strategic locations to maximise the probability of detection: up- and downstream of each migration barrier, an ALS was deployed. Furthermore, ALSs were placed at each entry of a pond or polder waterway into the LC, while a uniformly distributed pattern in the Braakman pond was achieved. At the mouth of the Braakman into the SE, a double semi-circular array of ALSs was deployed in the SE, combined with one array stretching from the left to the right bank of the estuary. In the polder area and the Braakman pond, the stations were moored at the bank with weights and a small buoy. In this way, the hydrophone had an upward direction in the water column. In the SE, ALSs were moored at marine buoys, attached to a three-metre long chain with a weight at the end for stability. This resulted in downward directed hydrophones.