Fisheries Management
and Ecology

Fisheries Management and Ecology, 2013

Mortality of European eel after downstream migration through two types of pumping stations

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Abstract Although numerous pumping stations (PS) have been used by water managers for numerous applications on rivers, canals and other water bodies, their impact on fish populations is poorly understood. This study investigates European eel, *Anguilla anguilla* (L.), mortality after natural downstream passage through a propeller pump and two Archimedes screw pumps at two PSs on two lowland canals in Belgium. Fyke nets were mounted permanently on the outflow of the pumps during the silver eel migration periods. Based on the condition and injuries, maximum eel mortality rates were assessed. Mortality rates ranged from 97 ± 5% for the propeller pump to 17 ± 7% for the large Archimedes screw pump and 19 ± 11% for the small Archimedes screw pump. Most injuries were caused by striking or grinding. The results demonstrate that PSs may significantly threaten escapement targets set in eel management plans.

KEYWORDS: *Anguilla anguilla*, barrier, delayed mortality, fish passage, injury.

Introduction

Pumping stations (PSs) have been constructed worldwide for centuries. These PSs play an important role in wetland drainage, irrigation, water diversion, agriculture, drinking water provision, flood protection, water level control, the conservation of polder areas and may even belong to a country's cultural–historical heritage (McNabb *et al.* 2003; Baumgartner *et al.* 2009; Grimaldo *et al.* 2009; Rentian *et al.* 2010; Thompson *et al.* 2011). Although the worldwide distribution of PSs is poorly quantified, in Belgium and the Netherlands alone, more than 150 and 3000 PSs, respectively, are needed to evacuate water towards the sea (Moria 2008; Stevens *et al.* 2011). Further, the development of irrigation works worldwide has increased exponentially over the past 50 years (Fernando & Halwart 2000). The South-to-North Water Diversion Project in China for instance, the largest undertaken to date, entirely relies on propeller PSs. Planned for completion in 2050, it will eventually divert 44.8×10^6 m^3 of water annually (Rentian *et al.* 2010). The increasing pressure on water resources and flood protection, for example, due to climate change, will also boost the need for controlled water provision and evacuation in future decades. McGranahan *et al.* (2007) showed that although only 2% of the world's land area is <10 m above sea level, about 10% of the world's population is located in this area and thus at risk of climate change-related flooding. Consequently, the importance of PSs is growing, which underlines that their environmental impacts should be revealed to avoid future ecological damage.

Indeed, despite their obvious benefits, PSs may severely impact the aquatic ecosystem and fish in particular. Specifically, PSs create a barrier for upstream migration of both diadromous and potamodromous fish species. Moreover, another threat may be the damage to fish migrating downstream through the PS.

Numerous experiments have been conducted in various countries (Canada, France, Denmark, United States of America, New Zealand, Sweden, the Netherlands), to determine the mortality rate after downstream passage through several hydropower turbine types, mainly on salmonids (Stier & Kynard 1986; Larinier & Dartiguelongue 1989; Koed *et al.* 2002; Ferguson *et al.* 2006; Dedual 2007; Östergren & Rivinoja 2008) but more recently on eels (Jansen *et al.* 2007; Winter *et al.* 2007; Carr & Whoriskey 2008; Calles *et al.* 2010; Lagarrigue & Frey 2010; Pedersen *et al.* 2012). Despite these efforts, there is still much to be learned on the causes

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doi: 10.1111/fme.12046

and extent of injuries in pump systems and on the significance of indirect mortality. Studies on fish injury and mortality after pump passage are scarce and focussed on passage through centrifugal irrigation pump systems (Baumgartner *et al.* 2009), Archimedes lifts with revolving barrels and internal flights (McNabb *et al.* 2003) and Hidrostal pumps (Patrick & Sim 1985; Rodgers & Patrick 1985; Patrick & McKinley 1987; McNabb *et al.* 2003; Helfrich *et al.* 2004; Thompson *et al.* 2011).

From the different diadromous fish species impacted by PSs, European eel, *Anguilla anguilla* (L.), may be one of the most vulnerable. These eels, now referred to as silver eel, migrate downstream and must pass PSs to reach their spawning grounds in the Sargasso Sea. At no point during the silvering process, eels become sexually mature. The final phase of the eel's transformation takes place during its oceanic journey (Righton *et al.* 2012). During the last decade, the evidence of a drastic decline in North Atlantic and global eel populations has been the scope of research (Limburg & Waldman 2009). Like the Japanese eel, *Anguilla japonica* Temminck and Schlegel (Tseng *et al.* 2003) and American eel, *Anguilla rostrata* (L.) (Haro *et al.* 2000), the European eel stock has declined dramatically (Moriarty & Dekker 1997) and its stock is now judged to be outside safe biological limits (ICES 1999). This decline has been attributed to a number of factors, including habitat fragmentation by migration barriers that prevent the movement of eels between fresh water and the sea (Feunteun 2002). To aid the conservation and recovery of European eel stocks, the European Union recently adopted Council Regulation EC no. 1100/2007. The Regulation requires a management system that ensures 40% escapement of the spawning stock biomass, defined as the best estimate of the theoretical escapement if the stock had been completely free of anthropogenic influence. To achieve this objective efficiently, insight is needed into the different factors affecting eel loss during downstream spawning migration. Although research has predominantly focussed on the impact of turbines, the mortality of eel after passage through PSs has received little attention. Except for studies on forced live transfer of American eels under laboratory (Patrick & Sim 1985) and field conditions (Patrick & McKinley 1987) through a Hidrostal pump, to date, no studies have quantified the impact of other types of PSs on downstream migrating catadromous eel species under natural conditions.

Therefore, the number, size and mortality rates of eel migrating through two different PS types, a propeller pump station (PPS) and an Archimedes screw pump station (APS), were assessed according to eel condition and the different injuries they sustained after PS passage. Further, the timing and magnitude of downstream migrating European eel were analysed. The results may support river managers and stakeholders to prioritise PS mitigation efficiently and to conserve eel stocks.

Materials and methods

Study sites and data collection

The two most common types of PSs in Flanders (Belgium) were investigated: a propeller PS (PPS) and an Archimedes screw PS (APS). The PPS on the Avrijevaart Canal in Ertvelde, Belgium, was built in 1969 (Fig. 1). The Avrijevaart Canal is the outflow of a man-made network of ditches and drainage canals that were dug around the 13th Century. The PPS drains a drainage area of 8000 ha and wetted area of 51 ha. It evacuates water from the Averijevaart Canal (4.30 m above sea level, asl) to the Ghent–Terneuzen Canal (4.50 m asl). The PPS has seven pumps and a total discharge capacity of 8 $m^3 s^{-1}$. Four small and three large four-blade propeller pumps (L-PP) can each discharge 0.8 and 1.6 $m^3 s^{-1}$, respectively. The L-PPs have a cast-iron casing and an outside diameter of 0.8 m, a core diameter of 0.41 m and they operate at 420 rpm. The spacing between the casing and the blades is 2 mm.

The APS Isabella on the Leopold Canal was built in 1987 and drains a drainage area and wetted area of, respectively, 17 156 and 193 ha. The Canal was dug between 1843 and 1854 to drain water in this agricultural lowland area. The APS evacuates water from the Leopold Canal (1.40 m asl) to the Braakman estuary (1.97 m asl in summer, 1.42 m asl in winter). Under rare conditions during winter, when the water level in the Leopold Canal is higher than the water level in the Braakman estuary, sluice gates in a bypass channel parallel to the APS are opened, which then allows gravity discharge and free up- and downstream fish migration. It has five Archimedes screw pumps resulting in a total discharge capacity of 14 $m^3 s^{-1}$. The two small (S-ASP) and three large (L-ASP) Archimedes screw pumps each can discharge 1.6 and 3.6 $m^3 s^{-1}$, respectively. The L-ASPs operate at 21 rpm and the S-ASPs at 25 rpm. The operational length of the L-ASPs is 5.34 and 4.67 m for the S-ASPs. All screws have three fixed flights, while the leading flight edges are not fitted with any protective rubber strips. The gap between the flights and the concrete trough was designed to be 30 mm. The L-ASPs have an outside diameter of 3 m, a core diameter of 1.52 m and flight heights of 0.74 m. The S-ASPs have an outside diameter of 2 m, a core diameter of 1.016 m and flight heights of 0.492 m. As the screws rotate, water and fish that are trapped between the flights, centre tube and trough, are carried up the trough and are discharged over the sill at the head of the upper channel.

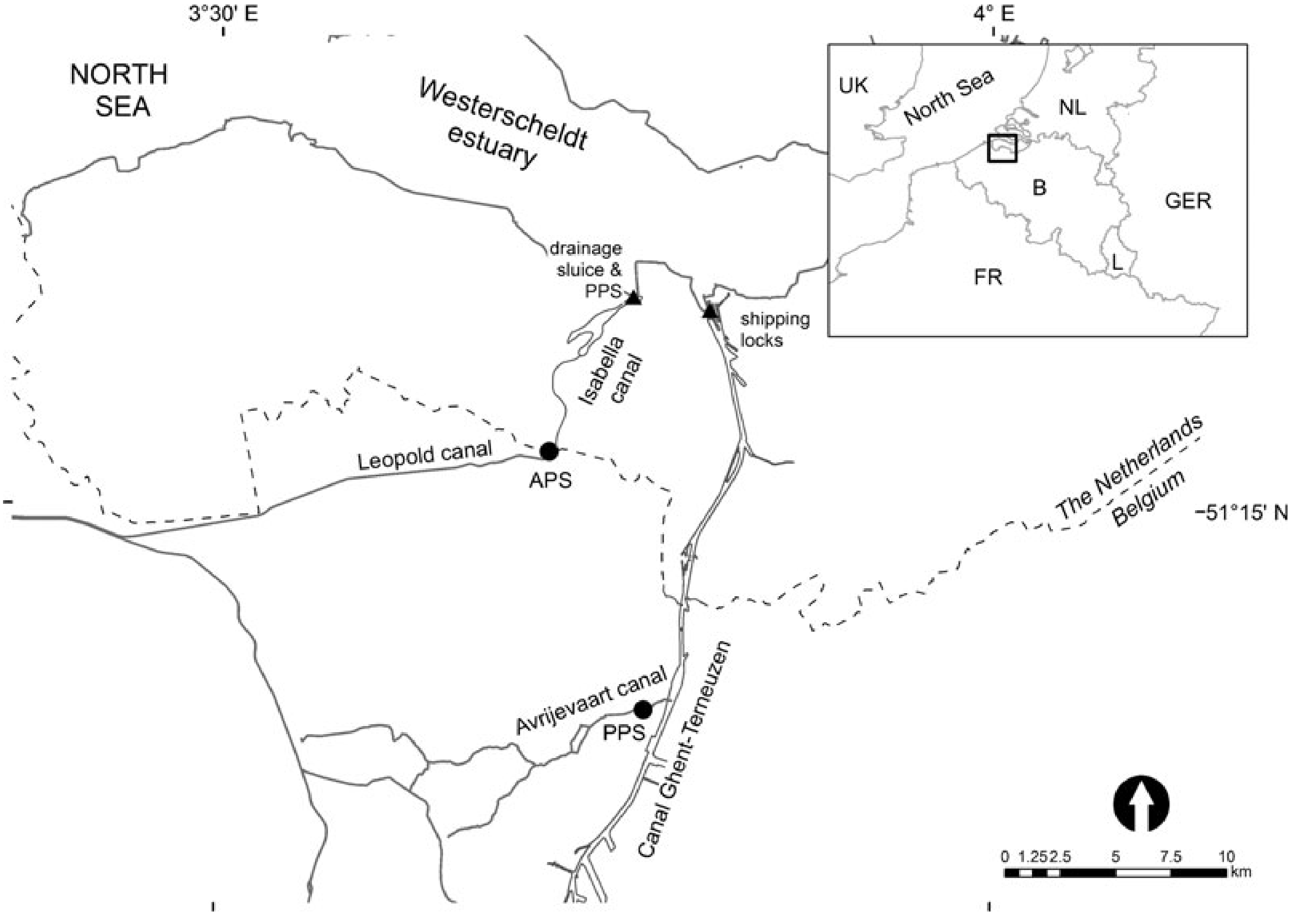

Figure 1. Map of study area showing the Leopold canal and Avrijevaart canal and the respective location of the Archimedes screw pump station and propeller pump station on both canals.

One-way valves on the outlets of all pumps prevent water flowing back and block upstream fish migration. At both PSs, trash racks in front of the upstream inlets of the pumps have a 10-cm bar spacing and are automatically cleaned with rotating grabs to prevent accumulation of debris. Trash racks are therefore probably no physical barriers to most downstream migrating eel as their body width rarely exceeds 10 cm. Discharge data from all pumps at both stations were automatically logged by the Flemish Environment Agency (www.hydronet.be). The eel populations upstream of the PSs are the result of limited upstream dispersion/migration possibilities of juvenile eel through a gravity discharge channel and a vertical slot fish pass (unpublished data) at the APS and of former glass eel stockings at both PSs.

One L-PP of the PPS and one L-ASP and one S-ASP of the APS were sampled. On the outflow of the large and the small pumps, 40- and 20-m long fyke nets with reducing funnels were mounted, respectively. The net mesh size decreased from front to back, from 2 cm, over 1.5 cm to 0.5 cm. The final compartment of the net (length: 5 m) was made of knotless material to minimise damage to fish epidermis. A funnel in the final net compartment prevented fish swimming back to the pump. Nets were mounted permanently on the outlets during the study periods.

During pumping activity, the flow conditions in the canals change from stagnant to slow flowing. Following the automated PS operation, the pumps only evacuated water when the water level upstream exceeded a fixed threshold (1.50 m asl). If the water level kept rising once one pump was operating, other pumps were started. Pumps stopped when the level upstream reached a fixed base level (1.30 m asl). In this study, the monitored pumps automatically started first. When this was not sufficient, additional pumps were automatically activated and thus downstream migrating fish could be missed during sampling. Fish were routinely sampled every Monday, Wednesday and Friday, with additional sampling if the pumps were operating during periods of high rainfall. Downstream eel migration through the LPP was studied from 25 July to 20 August 2008 and from 15

September to 3 November 2008. Due to fyke net repairs, monitoring was interrupted between 21 August and 14 September. The L-ASP and S-ASP were studied from 30 September to 25 November 2009 and from 16 October to 25 November 2009, respectively.

After emptying the nets, all eel were immediately transferred into large aerated reservoirs. The condition (dead or alive) of each individual eel and their physical status based on visible external or internal injuries were examined. Fish injuries were divided into four categories: (1) injury free; (2) minor superficial scratches; (3) (internal) bruising, swelling or bleeding and (4) presence of cuts/slashes, decapitation or divided into parts. In case of decapitated or incomplete eel, the number of eels was determined only by counting the number of heads. If the eel was intact, eel characteristics were measured: body mass (nearest g), total length (nearest mm), pectoral fin length and horizontal and vertical eye diameters (to the nearest 10^{-1} mm) (Durif *et al.* 2005). The six stage classification according to Durif *et al.* (2009) was used to divide eel in growing eel (stages I to FII), pre-migrant females (stage FIII) or migrant females and males (stages IV, FV and MII). Silver eel sex ratios were also based on size, with all eels >450 mm assumed to be female. Pumped eel were split in two size classes: 351–450 mm (male pre-spawners and immature females); >450 mm (female pre-spawners) (Bark *et al.* 2007).

Data analysis

Based on the condition and injuries, eel mortality rates can be assessed according to different scenarios: for example, a minimum or direct mortality scenario and a maximum or delayed mortality scenario. The minimum mortality rate is then the ratio between the number of dead eel and the total number of eels pumped, irrespective of living eels with visible external or internal injuries. However, it was considered more appropriate to use the maximum mortality rate, calculated as the ratio between the number of dead eels plus the number of living eels with lethal visible external or internal injuries (injury category 3 and 4) and the total number pumped, as this best quantifies eel loss during downstream migration through PSs.

Results

Numbers, sex ratio, migratory status and timing of migration

In total, 211 eels were caught: the L-PP passed 39 eels (length range: 400–810 mm), the L-ASP passed 125 eels (length range: 370–936 mm) and the S-ASP passed 47 eels (length range: 392–831 mm). There was an underrepresentation of male eels. Catches in all pumps were dominated by females and ranged from 85 ± 6% to 100 ± 0% according to Durif *et al.* (2005) (Fig. 2).

Catches at all pumps were dominated by pre-migrant females (FIII), 67 ± 31% in the L-PP, 51 ± 9% in the L-ASP and 64 ± 14% in the S-ASP (Fig. 2). The percentage of female residents in the L-PP, L-ASP and S-ASP were 22 ± 27%, 11 ± 6% and 13 ± 10%, while migrant females (FIV and FV) accounted for 11 ± 20%, 22 ± 7% and 15 ± 10% at the respective pumps. Only

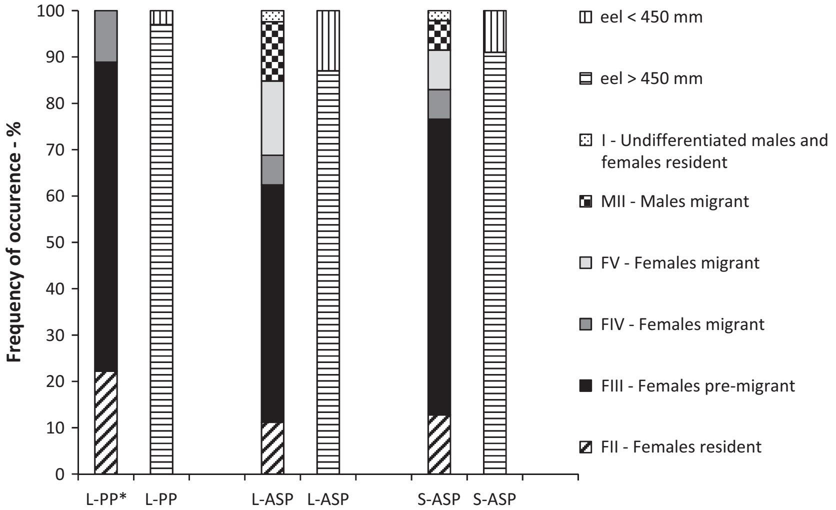

Figure 2. Proportions of the various stages associated with silvering by pump type according to Durif *et al.* (2005) (I, FII, FIII, FIV, FV and MII) and male/female eel ratio by pump type according to Bark *et al.* (2007) (<450 mm: male pre-spawners or immature females; >450 mm female pre-spawners) (L-PP*: Durif classification based on only 9 measured or intact eels) (L-PP: N = 39, L-ASP: N = 125 and S-ASP: N = 47).

one small eel (total length: 400 mm), of which no silver eel characteristics were measured, was caught in the L-PP and was therefore classified as a male migrant or immature female. Male presence was low in the L-ASP and S-ASP; 13 ± 6% and 6 ± 7%, respectively, were male migrants and 2 ± 3% and 2 ± 4% were undifferentiated males or resident females.

Peak operation in 24 h at the PPS was recorded on 7th August with almost 120 000 m³ of water pumped resulting in the first eel catches on 8th and 11th August, with 6 and 7 eels, respectively. Between 4th and 9th October, more than 427 000 m³ water was pumped with 13 and 10 eels caught on 6th and 8th October. In between these peak flow events, three eels were caught on 15th and 17th September (Fig. 3).

The APS operation was very low between 30th September and 22nd November. Heavy pumping started on 23rd November with peak operation on 24th November and more than 854 000 m³ water pumped. On this day, 110 eels were caught in the L-ASP and 39 in the S-ASP. Eel catches before this date were very low (23 eels in total; Fig. 4).

Injuries and mortality

Only two females passed the L-PP alive, one without visible injuries (alive – cat. 1: 3 ± 5%; total length: 560 mm), whereas the other one (total length: 650 mm) passed with severe and lethal injuries and was therefore classified as alive – cat. 3: 3 ± 5%. All 36 dead females were bruised (dead – cat. 3: 29 ± 14%), cut or decapitated (dead – cat. 4: 66 ± 15%). The smallest eel was killed but showed no visible injuries (dead – cat. 1: 3 ± 31%; total length: 400 mm).

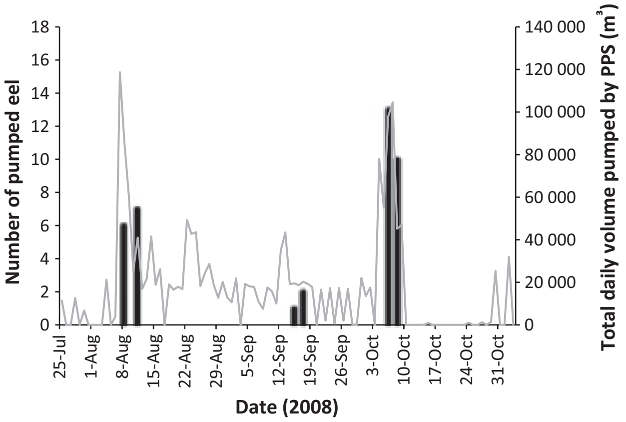

Figure 3. Number of eel (▮) that passed through a large propeller pump (LPP) between July and November 2008 (no monitoring between August 21st and September 14th) and the total daily water volume pumped (—) by all pumps of the propeller pump station.

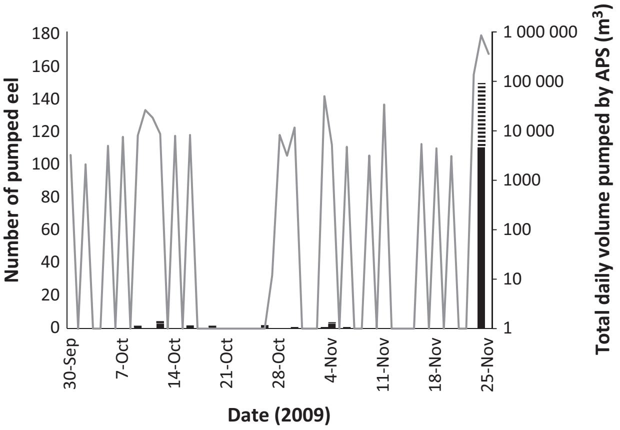

Figure 4. Number of eel that passed through a large (▮ L-ASP) and small (═ S-ASP) Archimedes screw pump between October and November 2009 and the total daily water volume pumped (—) by all screws of of the Archimedes screw pump station.

Twenty eels smaller than 450 mm passed the L-ASP and S-ASP without injuries (alive – cat. 1: 100 ± 0% and 100 ± 0%, respectively), as did 111 females (alive – cat. 1: 75 ± 8% and 67 ± 14%, respectively). However, nine females got bruised (alive – cat. 3: 4 ± 4% and 12 ± 10%, respectively), while 11 had minor superficial scratches (cat. 2: 6 ± 4% and 12 ± 10%, respectively). Moreover, 21 females were bruised and killed (dead – cat. 3: 16 ± 7% and 9 ± 9%, respectively) (Fig. 5).

Following the maximum scenario, the mortality rate for the PPS was 97 ± 5%. The mortality rate in the APS was lower. The large Archimedes screw had a mortality rate of 17 ± 7%, whereas the small Archimedes screw had a 19 ± 11% mortality rate.

Discussion

Numbers, sex ratio, migratory status and timing of migration

Based on data from the Flanders freshwater fish monitoring network(vis.inbo.be), eel densities in both canals were in the range 0–1 eel 100 m² (Stevens *et al.* 2011). Therefore, it was not surprising that the total number of downstream migrating eel was low for both PSs. Catches were dominated by female eels. This was confirmed by the eel classification according to Bark *et al.* (2007), which generated similar results. Relationships between migration dynamics, barriers and the scarcity of upriver stocks of eels and distorted population structures in rivers have been discussed by White and Knights (1997). They found that the number of immigrants decreased rapidly upstream of tidal limits, whilst the average size

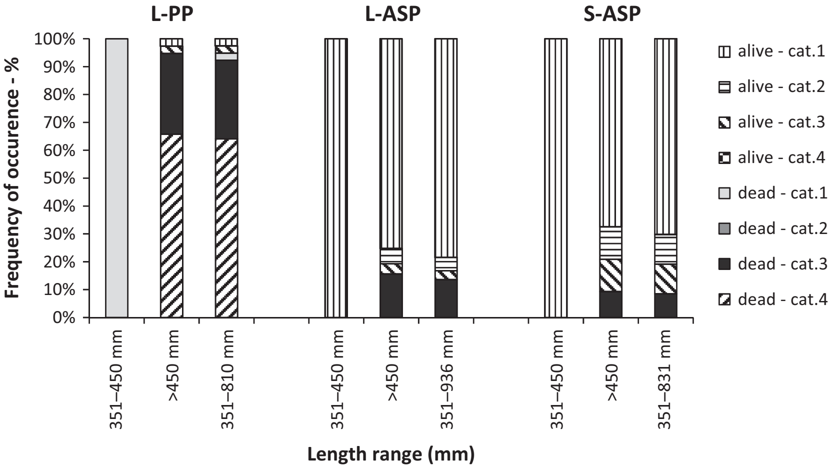

Figure 5. Proportions of the various injuries categories (Dead: categories 1–4 and Alive: categories 1–4) by eel length (according to Bark *et al.* (2007), 351–450 mm: male pre-spawners or immature females; >450 mm: female pre-spawners) and pump type.

and age increased. The number and severity of barriers to be surmounted exerted a greater effect than distance alone. Their results implied that the effect of barriers on upstream migration correlates with the absence of eels or low adult stocks deeper in the catchments. Although males and small females are sometimes reported to migrate earlier in the season (Haraldstad *et al.* 1985), the chance that male migrants were missed is small. Monitoring at the PPS started early and the first eels caught were large females. Moreover, no heavy pumping operation at the APS was recorded from June/July until the beginning of the study (www.hydronet.be). Glass eel stockings in the Avrijevaart Canal date from 1995, 2003 and 2006 and elver stockings in the Leopold Canal date from 1997, 1998 and 1999 (Source: Agency for Nature and Forest). It is possible that most males, silvering from the age of >4 years (van Ginneken *et al.* 2007), migrated seaward in preceding years.

The results show that increased pumping activity and thus discharge during periods of heavy rainfall is one of the main triggers for downstream eel migration in these otherwise stagnant canals. During the highest discharge events in the Avrijevaart Canal, at the beginning of August and October, 85% of the total eel catch migrated seaward. In the Leopold Canal, only one high discharge event occurred at the end of November with 87% of the total eel number migrating seaward. A high number of eels descending were recorded in late November coinciding with an increase in water discharge (Haraldstad *et al.* 1985), while others also reported reactions to flows in natural river systems (Behrmann-Godel & Eckmann 2003; Durif *et al.* 2003). Surprisingly, stage III females (pre-migrant) were dominant in the catches between October and November at the APS. It was assumed that the majority would have been at stage IV (beginning of first downstream movements) or V (the migrating stage) because transition from stage III to IV probably occurs at the end of the summer season (Durif *et al.* 2005). This dominance may be explained by the exceptional long dry period from September until the end of November 2009. Lack of precipitation and no pumping activity created long stagnant water conditions, and these conditions may have delayed the silvering process. The window during which eels were able to pass the APS in 2009 was relatively late and sudden in the migration season and therefore also short. However, PSs may also impact eels during their growth phase, and stage III females as well as female residents (FII) can be migratory.

Surprisingly, silver eel catches varied substantially over the sampling period. This emphasises the importance of evaluating a PS over a longer period to cover all silver eel migration peaks. Indeed sampling PSs on isolated periods may underestimate densities of migrating eel and thus total eel mortality, in contrast to continuous sampling. This was demonstrated by a large-scale evaluation of PSs in the Netherlands, where PSs were evaluated over a short period and on fixed points in time (STOWA 2012).

Injuries and mortality

The maximum mortality rate at the propeller pump was very high (97 ± 5%) while both Archimedes screw pumps had significantly lower mortality rates. Mortality did not differ substantially between the L-ASP and S-ASP, 17 ± 7% and 19 ± 11%, respectively. Due to the underrepresentation of male eels, no sex-dependent mortality could be calculated. Water managers often consider classic Archimedes screws as fish friendly and may be misled by pump manufacturers or the known application of Archimedes lifts to convey cultured fish. The results, however, showed that adult eel pass APSs with biologically significant damage. As for turbines, pump mortality is variable and depends on pump type. Although not tested, size, runner speed, number of blades and the space between the flights and the trough are likely to affect eel survival.

Their relatively long body length makes eel particularly susceptible to the impacts of PSs. Furthermore, not only silver eel but also other life stages may be affected after coincidental passage through PSs. McNabb *et al.* (2003) and Durif *et al.* (2003) reported that large fish and eel are more likely to be impacted by physical strike with mechanical components. Most eels passing the PPS were decapitated or cut, while bruised individuals sometimes had visible skin decoloration of the posterior part, which could be an indication of broken vertebrates. These severe injuries resulted from collisions with the propeller blades and the housing of the pump. Cada (2001) classified this type of injury as strike injury. Some decapitated eel had clearly been stuck in the pump for a longer time and came out skinned and showing evidence of decay. As described by Cada (2001), non-visible injuries may arise from PP passage, caused by rapid and extreme pressure changes, cavitation, shear stress and turbulence. Although the majority of eels passed the APS injury free, a considerable percentage displayed signs of bruising, sometimes combined with skin decoloration and possibly broken vertebrates, while some eels had only superficial scratches. These types of injuries can be caused by strike of the leading edge of the flight at the intake of the screw or by squeezing through narrow gaps between the flights and the concrete trough, a mechanism called grinding (Cada 2001).

As the maximum scenarios consider potentially lethal injuries, they involve some uncertainty on eel mortality. Indeed, eel may survive passage through PS types, but their injuries can limit successful migration to their spawning grounds or they may be disorientated and thus more susceptible to predation, for instance, by great cormorants, *Phalacrocorax carbo sinensis,* (Keller 1995), which were often seen foraging downstream of both PSs. Predation and delayed fish mortality after turbine passage have been reported numerously (Cada 2001; Odeh *et al.* 2002; Ferguson *et al.* 2006). Next to physical injuries, other factors such as lipid reserves (Belpaire *et al.* 2009), environmental pollutants (Maes *et al.* 2013) and a swim-bladder parasite (Palstra *et al.* 2007) have been reported limiting contribution to the spawning stock. This indicates that the calculated maximum mortality rates come closest to the actual mortality rates. Consequently, although some silver eel manage to pass PSs without any visible injuries, both PPSs and APSs may severely limit sustainability of eel populations.

Future research and challenges

This study emphasises that PSs may significantly threaten the achievement of the Eel Directive goals in European lowland areas. Restocking has been carried out at the two study sites and has also been proposed by many countries in their national management plan. This study shows that restocking is irrelevant or not optimal in sites where 97 ± 5% (L-PP), 17 ± 7% (L-ASP) or 19 ± 11% (S-ASP) of the eels are killed during their downstream migration. Likewise, restoration actions such as improving upstream passage (e.g. installing an elver ladder) cannot be successful before reducing downstream mortality. The impact of PSs on upstream migrating elvers was not tested, but reduction in upstream colonisation deserves attention in future research. As these effects are less direct and obvious than eel mortality by PSs, long-term monitoring of migrating elvers may provide insight into this indirect impact of PSs. Future research could focus on the cumulative impacts of PSs on eel populations. This study only identified the effect of two pump types at two different sites but often a cumulative effect has to be taken into account when eels have to pass more than one PS on their seaward migration. Eels passing the studied APS can encounter a second PPS on the Isabella Canal in the Netherlands (Fig. 1) just before entering the Westerscheldt estuary, which illustrates that cross-border measurements are a necessity. Lowland regions with dense waterways networks and PSs, like Flanders (Belgium) and the Netherlands, can have high cumulative eel mortality caused by pumps resulting in a relative high impact on the European eel population. When passing PSs, they often end up in large river systems where new migration obstacles await, such as hydropower plants, dams, weirs and sluices. Future research may also focus on coupling mortality estimates by obstacles, such as PSs, to eel density distribution at large spatial scale to provide mortality estimates at the catchment or eel management unit levels.

Technology may exist to create fish safe PSs but first insight into the scale and extent of the problem is needed. European water managers should be motivated to take up- and downstream mitigation measures. Protecting silver eels and females in particular is crucial in attempts to recover the European eel (Dekker 2004; Winter *et al.* 2007).

Delay at PSs due to underwater sound and turbulence and the implications of the consequential increased energetic costs needs to be the subject of future research. Besides the obvious impact on silver eel, PSs may also substantially affect yellow eel populations outside the autumn eel migration period. The yellow eel mortality rates demonstrate that PSs also affect individuals that are classified as non-migratory. Although the significance of this impact remains unknown, future research should also focus on the impact of PSs outside the silver eel migration period and could quantify this effect by relating densities of pumped yellow eel to eel densities in the watercourses upstream the PS.

Acknowledgments

This research was funded by the Flemish Environment Agency. Emilie Gelaude, Raf Baeyens, Seth Martens and Yves Jacobs assisted with the data collection. Pieter Vandenbroucke gave database support. We thank Koen Martens, Maarten Lauwers and Ronny De Keer from the Flemish Environment Agency, Peter Jolie, Nico Gaelens, Jurgen Duym and Michel De Smet from the Zwarte Sluispolder and Sven Van Daele from the Watering De Burggravenstroom for their cooperation.

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