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Success of a low-sloping rack for improving downstream passage of silver eels at a hydroelectric plant

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SUMMARY

1. The European eel (*Anguilla anguilla*) is a critically endangered species, and one major threat is the survival of silver eels migrating downstream towards the sea from lake and river rearing areas. During this migration, many eels are impinged and die on intake racks, or are injured or killed when passing through turbines.
2. Intake racks at a hydroelectric plant were modified to avoid impingement and to collect eels without injury; high mortality on both racks and in turbines was previously documented. Modifications consisted of reducing the rack gap width from 20 to 18 mm, decreasing the rack slope from 63 to 35 degrees, increasing the rack surface area by 58% and installing six openings in the rack leading to traps.
3. Downstream passage conditions for silver eels at the hydroelectric plant were significantly improved, reducing mortality from >70% at the old steep 20 mm racks to <10% at the modified 18 mm rack collection facility. No tagged eels were impinged and killed on the racks, and 80% entered the collection facility.
4. Survival can probably be improved even more, as the individuals that passed the facility most likely escaped through holes in the traps. Moreover, injured untagged eels were still encountered at the modified racks, illustrating the need for rehabilitative measures to be implemented at all obstacles between the main eel rearing areas and the sea.

Keywords: *Anguilla anguilla*, collection facility, downstream passage, passage success, telemetry

Introduction

Hydroelectric facilities constitute obstacles to upstream and downstream fish migration (Calles & Greenberg, 2009). Downstream migrating fish are often injured or killed on intake racks and in turbines when trying to pass hydroelectric facilities (Carr & Whoriskey, 2008; Calles *et al*., 2010). Eels are especially vulnerable when passing through racks, because their behaviour results in close contact with these structures (Richkus & Dixon, 2002; DWA, 2005), and because their elongated bodies increase the risk of being hit by the turbine's runner blades (Montén, 1985). Moreover, eels in many areas need to pass several hydroelectric facilities on their way to the sea, since stocking practices are frequently carried out in lakes in the upper parts of catchments; thus, cumulative losses are often severe (Larinier, 2008; McCarthy *et al*., 2008).

Fishways for upstream passage at hydroelectric facilities are rarely accompanied by corresponding measures to facilitate downstream passage for the same individuals and/or their offspring when returning downstream (Calles & Greenberg, 2009). The few measures that do exist have, as for upstream passage, almost exclusively targeted salmonid species (Ferguson, Poe & Carlson, 1998; Scruton *et al*., 2003; Ferguson *et al*., 2007; Larinier, 2008). Examples of physical measures to increase the passage success of silver eels at hydroelectric facilities can be grouped into siphons/pipes and gates/sluices, often in combination with racks. The few studies on

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siphons and pipes show that these structures allow passage of eels, but at variable (Legault *et al.*, 2003; Calles *et al.*, 2012) or unknown efficiencies (Boubée & Williams, 2006; Pedersen *et al.*, 2011). Gates and sluices constructed for other purposes are often used to allow passage of downstream moving fish, although often requiring structural modification (Gosset *et al.*, 2005; Travade *et al.*, 2010a; Greenberg *et al.*, 2012). In some cases, these bypasses and spill gates have been shown to rehabilitate downstream eel migration (Gosset *et al.*, 2005; Travade *et al.*, 2010a), and in other cases, a low proportion of the eels used the gate (Calles *et al.*, 2012). In most cases, poor passage efficiency can be attributed to features of the racks and gates, because these structures were not initially designed to bypass fish. Another common problem is that the swimming capacity of eels is not taken into account when designing bypass solutions.

Laboratory studies show a potential for fine-spaced intake racks to guide downstream moving eels towards bypasses (Amaral *et al.*, 2002; DWA, 2005; Russon, Kemp & Calles, 2010). Eels need to be allowed passage via bypasses without increased risks of impingement, which is feasible when water velocities are low in front of the racks. If velocities are high (>0.7 m s^{-1}) and the dimensions of the intake remain the same, the risk of impingement can be reduced by increasing the surface area of the rack, thereby reducing the discharge of water per rack unit area (DWA, 2005). To fit such an enlarged rack in an intake channel, it can be arranged with a low slope from the bottom to the surface (α-rack) or with a low slope from one side of the intake channel to the other (β-rack; DWA, 2005). In North America, β-racks are typically used in pairs (double β-racks or V-screens) and are angled from both sides towards the centre of the channel to create a funnel (E. Meyer, National Marine Fisheries Service, U.S.A., pers. comm.). To our knowledge, there are no published examples on the implementation and evaluation of a low-sloping, that is, angled at <45° relative to the bottom, intake rack designed to rehabilitate the downstream passage conditions for silver eels.

Most eels in the River Ätran have to pass several hydroelectric facilities between the rearing grounds and the sea, resulting in high mortalities on intake racks and in turbines (Calles *et al.*, 2010). The first attempt to rehabilitate downstream passage conditions in this river consisted of simple technical improvements of an turbine intake, but this modification functioned poorly for silver eels (Calles *et al.*, 2012). In this article, we report on a subsequent attempt to reduce mortality of downstream migrating silver eels in this river, by modifying the turbine intake racks at a hydroelectric facility. The modified racks differed from the old in several aspects: the angle in relation to the bottom (α) was reduced from 63 to 35°, the surface area was increased by 58%, the gap width was reduced from 20 to 18 mm, and six orifices in the racks leading to traps were provided. We expected silver eel survival to be higher with the modified racks compared with the old racks. This assumption was studied using radio-tagged (n = 40) and externally marked (n = 45) silver eels released upstream of the improved turbine intake and tracked as they were migrating downstream. Feasibility was studied and quantified by analysing the behaviour of tagged eels: route choice, behaviour, recapture rate in the collection facility and overall passage survival, and how these variables related to discharge conditions and hydraulic conditions.

Methods

Study site

The River Ätran (56°52′55″N, 12°28′46″E) is located in south-western Sweden and enters the North Sea (Kattegatt subbasin) at the city of Falkenberg. The catchment has an area of 3342 km^2, and discharge ranges from 20 to 319 m^3 s^{-1}, with a mean annual discharge of 48.0 m^3 s^{-1} (1961–1993), and in more recent times 59.6 m^3 s^{-1} (1990–2011; Olofsson, 2013). More details about the river and river regulation can be found in Calles *et al.* (2010). The study site, Ätrafors, is the second hydroelectric plant (HEP) in the River Ätran (HEP 2), situated about 27 km upstream from the sea. The intake channel is 290 m long and 5 m deep. At the turbine intake, the water is diverted into three intake gates, with tubes that lead to three twin-Francis turbines. The maximum load of the HEP is 72 m^3 s^{-1}, and the maximum efficiency is achieved at 65 m^3 s^{-1} (25, 25 and 15 m^3 s^{-1} per unit). Above the HEP intake capacity, water is spilled into the former channel via bottom fed spill gates (Fig. 1).

Prior to 2008, the three racks at the intake channel, angled 63.4° relative to the bottom, had 20 mm gaps between the bars (Fig. 2a). The only route past the HEP was through these racks and the turbines, except for during spill conditions when passage via the spill gates into the old river bed was also an option. The old racks caused substantial mortality of silver eels encountering the Ätrafors HEP (Calles *et al.*, 2010). The old 20 mm racks were 5.3 m long and about 5.4 m wide, resulting in a total surface area of 85 m^2. In 2008, these racks were replaced with 8.4 m long by 5.4 m-wide racks, angled

35° relative to the bottom, with 18 mm bar spacings (BSs) and a total surface area of 136 m^2 (the surface area increased by 58%, Fig. 2b). As for pre-2008, there was one rack per opening under the bridge, that is, three identical racks separated by concrete piers.

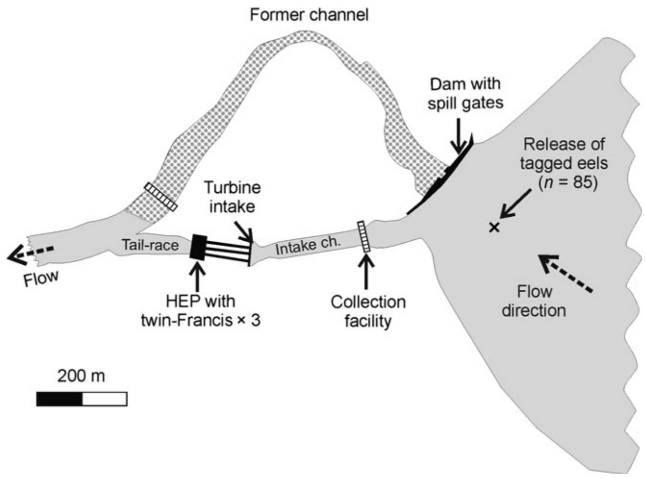

Fig. 1 Map of the Ätrafors hydroelectric plant showing the modified downstream migrant collection facility, in the River Ätran, Sweden.

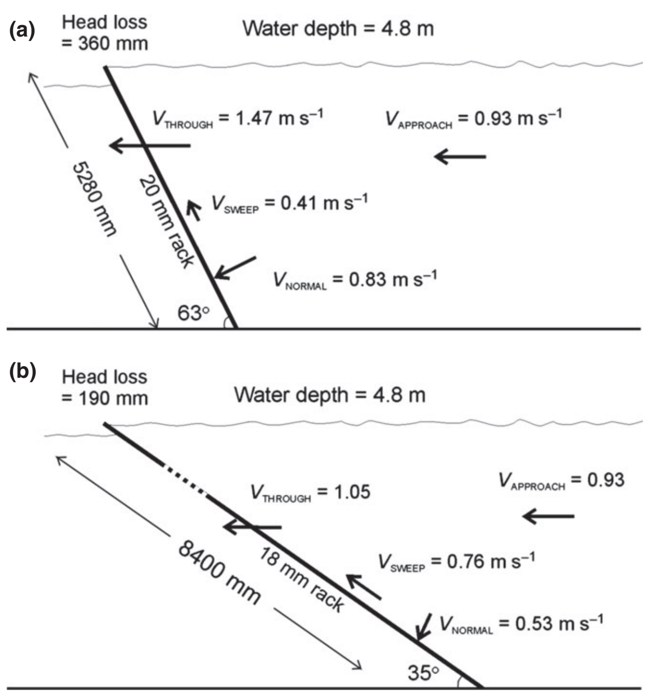

Fig. 2 Side view of the racks, with head loss, rack length, rack angle and the velocity vectors of the (a) old 20 mm racks and the (b) modified 18 mm racks at the Ätrafors hydroelectric plant, Ätran. The dotted part of the modified rack represents the position and size of the six entrances to the collection facility (traps).

The intake capacity of the HEP (72 $m^3 s^{-1}$) and the dimensions of the intake channel and the openings under the bridge were unaltered; therefore, maximum approach velocity ($V_{APPROACH}$) in front of the racks was unchanged. As a result of the increased surface area of the modified racks and the lower angle, the calculated features of the racks showed that the velocity vectors were changed. The velocity vector perpendicular to the racks (V_{NORMAL}) and the velocity through the rack ($V_{THROUGH}$) decreased, whereas the velocity vector parallel to the racks increased (V_{SWEEP}), and so the pressure on the racks was expected to be lower. In conjunction, head loss at the racks should also be reduced (Fig. 2).

To allow eels to pass the Ätrafors HEP, the modified racks were equipped with two entrances on each side of the three racks, that is, six in total. Each entrance is 0.25 m wide and 1.0 m long, and taking the 35° angle of the rack into account, the water depth in each entrance is 0.57 m (Fig. 3). To allow for operation of the collection facility at varying water levels, the entrances are submerged corresponding to a water depth of 0.8 m to the upper part of the entrances. The entrances cover the depth interval 42.15–42.72 m.a.s.l., and so they will be situated above water when the reservoir levels is 42.00–42.15 m.a.s.l.

Tagging programme

Evaluation of the modified racks at the Ätrafors HEP followed the same procedure as in Calles *et al.* (2010). Tagging and handling followed standard procedures (Jepsen *et al.*, 2002). The eels were either surgically radio-tagged (*n* = 40, model F1540, 2.0 g; Advanced Telemetry Systems (ATS), Isanti, MN, U.S.A.) or externally tagged using streamer tags (*n* = 45, model PST transparent polyethylene streamer tag 13s, Hallprint, Australia).

Prior to tagging, the eels were anaesthetised using benzocaine (2 g in 10 L water, median time until anaesthetised was 18 min, range 10–39 min). Morphological parameters recorded during tagging were as follows: length (mm), weight (±10 g), degree of silvering (0–3), the length of the left pectoral fin (±0.1 mm) and the vertical and horizontal eye diameter (±0.1 mm). The median time for the entire procedure was 2 min (range c. 1–5 min) when streamer-tagging and 3.9 min (range c. 3–8 min) when radio-tagging. After tagging, recovery of all eels was monitored prior to release c. 1–5 h later. No eels showed any signs of injury or died during this period of recovery. The releases were performed after dusk (20:55–00:00) since eels mainly migrate nocturnally.

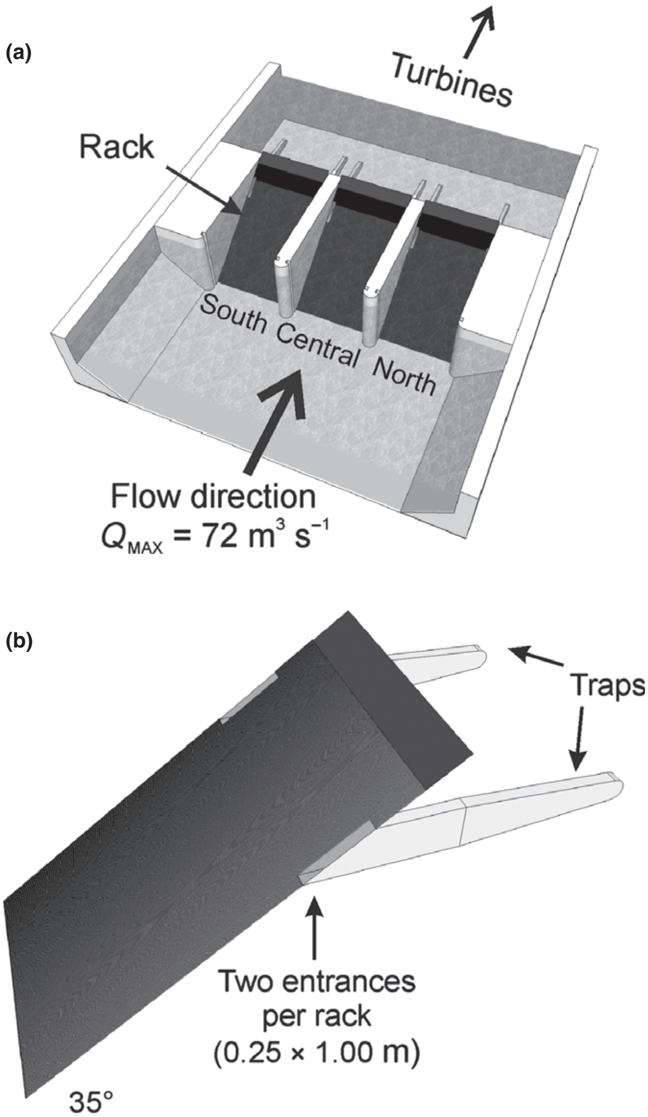

Fig. 3 The downstream migrant collection facility at Ätrafors hydroelectric plant, Ätran. (a) View from above the facility showing the three low-sloping 18 mm racks and (b) detailed view of one rack with the associated entrances and traps.

In addition to the degree of silvering, the sexual maturation of each individual was estimated by calculating the Eye Index (left eye) according to Pankhurst (1982) and the Fin Index (left pectoral fin) according to Durif, Guibert & Elie (2009). Individuals had an average size (±SE) of 776 ± 13 mm (range 510–1060 mm) and an average weight of 834 ± 46 g (range 200–2080 g). The median Eye Index was 9.1 (range 7.0–14.5), the median Fin Index was 5.0 (range 4.0–6.5) and the degree of silvering was 33% for silver degree 1, 61% for degree 2 and 6% for degree 3.

Tagged individuals were released on five occasions in the Ätrafors HEP reservoir about 300 m upstream of the modified racks (Fig. 1, Table 1), which was identical to the reservoir release site in the evaluation of the old racks at the Ätrafors HEP (Calles *et al.*, 2010). After release movements of the radio-tagged eels were documented until they were recaptured in the collection facility or until the end of the study (8 November). All the eels caught in the collection facility were visually checked for signs of injury and altered behaviour, as compared to the general condition of eels before tagging. The radio-tagged individuals were manually tracked in the vicinity of the Ätrafors HEP on a daily basis, and at least twice a week when located further downstream (model R2100; ATS, Isanti, MN, U.S.A.). Seven automatic stations (model R4500; ATS) continuously monitored the river for radio-tagged eels in the area near the intake channel: one automatic station covered the area between the reservoir and the intake channel and the remaining six automatic stations were placed at the racks (one at the base and one near the top of each of the three racks). The automatic stations stored tag information relating to date, time, frequency and relative distance from the antenna (signal strength).

Abiotic factors

Hourly data on total discharge, turbine discharge and spill discharge were provided by the HEP owner E.ON Vattenkraft AB. Temperature was recorded every 15 min by loggers (HOBO® water temp pro, V2; Onset®, Bourne, MA, U.S.A.). Flow velocities at the three Ätrafors intake racks and into the inlet channel were measured with an Acoustic Doppler Current Profiler (ADCP, Sontek M9 River Surveyor®; San Diego, CA, U.S.A.). In particular, the measured flow conditions were related to turbine discharges equal to 8.5, 20.5 and 43.5 m^3 s^{-1} and the velocity pattern at the Ätrafors intake was generated through linear interpolation for all the discharge conditions that occurred during the study period.

Results

Hydraulics

Discharge typically observed during eel migration in autumn is about 60 m^3 s^{-1}, which corresponds to the turbines HEP operating at near 100% efficiency. At these conditions, the approach velocity upstream of the bridge and racks ranged from 0.11 to 0.90 m s^{-1}, with the highest velocities recorded in mid channel and the lowest along the sides of the channel (Fig. 4). When the water reached the bridge, where the total area is reduced

Table 1 Groups of tagged eels released upstream of the Ätrafors silver eel collection facility in 2008. The number of released (OUT) and recaptured (RECAP) individuals is presented for each group, where the recapture refers to eels found in the traps of the collection facility. The minimum passage success includes all eels that successfully passed the HEP, either by being caught in the collection facility, passing with spill water or surviving passing through the turbines

	Radio-tagged			Streamer-tagged			Total tagged			
Release date	OUT (*n*)	RECAP (*n*)	RECAP (%)	OUT (*n*)	RECAP (*n*)	RECAP	OUT (*n*)	RECAP (*n*)	RECAP	Passage success (%)
2008-10-15 22:15	5	5	100	8	8	100	13	13	100	≥100
2008-10-16 22:54	5	4	80	5	5	100	10	9	90	≥90
2008-10-17 23:12	5	5	100	5	4	80	10	9	90	≥90
2008-10-20 21:55	10	7	90	10	9	90	20	16	80	≥90*
2008-10-23 20:55	15	10	86	17	11	65	32	21	66	≥74†
	40	31	90	45	37	82	84 (85)	68	82	≥86

*18 of 20, including two radio-tagged individuals that were not recaptured, but that passed successfully via the spill gates and the old river bed.

†23 of 31, including two radio-tagged individuals that were not recaptured, but that passed successfully via the collection facility and the turbines, and excluding one individual that never approached the rack or the spill gates, and remained in the reservoir until the end of the study.

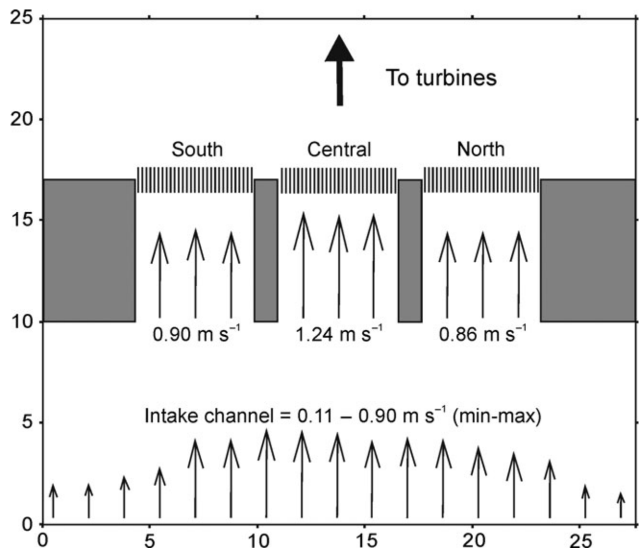

Fig. 4 Flow velocities at the Ätrafors intake (upstream the bridge and between the piers) related to discharge of 60 $m^3 s^{-1}$. Data are from linear interpolation of the measurements at total discharges of to 8.5, 20.5 and 43.5 $m^3 s^{-1}$. The maximum velocity was observed approaching the central rack (1.24 m s^{-1}) followed by the south rack (0.90 m s^{-1}) and the north rack (0.86 m s^{-1}).

because of the bridge and its piers, average velocities increased. The highest water velocity was observed for the central rack (1.24 m s^{-1}), followed by the south rack (0.90 m s^{-1}), and the lowest water velocity was observed at the north rack (0.86 m s^{-1}). The overall pattern remained the same when the discharge into the turbines varied during the study period (i.e. ranging from 38 to 67 $m^3 s^{-1}$, Fig. 5). At 40 $m^3 s^{-1}$, which can be used to represent the minimum observed discharge condition during eels migration, the velocity ranged between 0.05 m s^{-1} and 0.78 m s^{-1} upstream the bridge and between 0.65 m s^{-1} and 0.87 m s^{-1} approaching the racks between the piers.

Catches and fish guidance efficiency

A total of 196 eels were caught in the rack traps from 12 October until 3 November, of which 68 were tagged and 128 were untagged. The total recapture rate for tagged eels was 80%, or 68 of 85 tagged individuals. The recapture rate did not differ between tag types, 78% for the radio-tagged (31 of 40) and 82% for the externally tagged (37 of 45) (chi-squared test to compare observed and expected recapture rates for radio- and externally tagged eels, df = 1, $\chi^2 = 0.006$, $P = 0.58$). The likelihood of recapture decreased with time, from 100% for the first group released to 66% for the last group released (Table 1; linear regression, $y = -0.039x + 1549.9$, $R^2 = 0.954$; $P = 0.003$). Only a small proportion (4%) of the recaptured tagged eels showed signs of injury and altered behaviour, whereas the corresponding proportion of the untagged eels was 27%, including severely injured and dead eels.

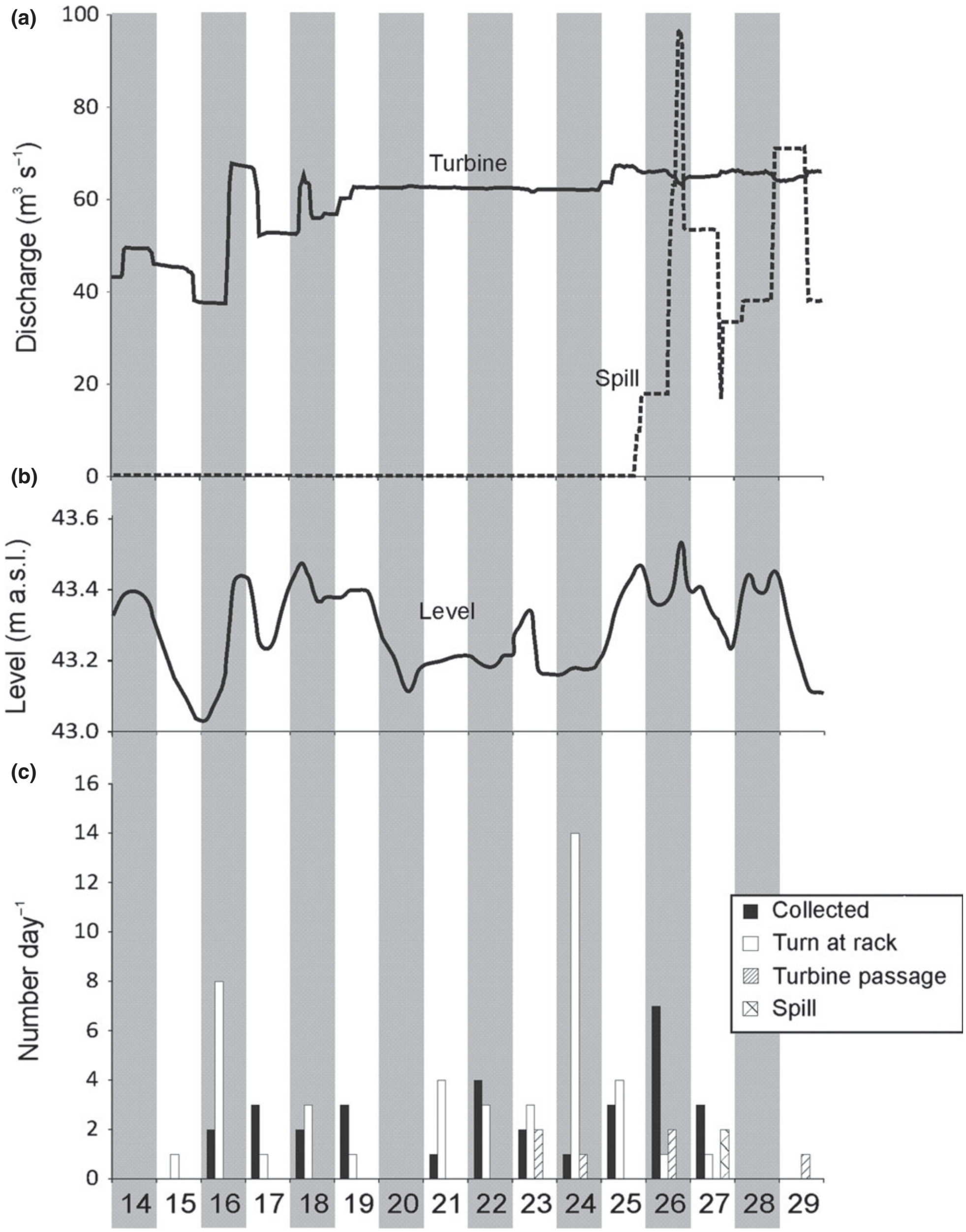

Fig. 5 (a) Daily average turbine and spill discharge, (b) daily average reservoir level and (c) the daily number of eels collected/trapped (collected), observed turning at racks and escaping upstream (turn at racks), passing through the turbines (turbine passage) and passing the dam with spill water released through the spill gates into the former channel. Ätrafors hydroelectric plant, the River Ätran, 2008.

The fish guidance efficiency (FGE) for radio-tagged eels was 82% (31 of 38), with the FGE defined as percentage of individuals that approached the racks at least once and eventually entered the rack entrances, that is, two individuals that never visited the racks were excluded. The overall passage success for the radio-tagged eels was 90% (35 of 39), as some of the eels choosing other routes than into the collection facility also succeeded in passing the HEP. Of the radio-tagged individuals that were considered to have successfully passed the plant, the majority (89%) were visually examined, and the remaining individuals (11%) were tracked when migrating downstream, that is, no visual examination after passage.

Route choices and depth preference

The radio-tagged eels that were not caught in the collection facility either swam out with the spill water (n = 2) or swam through the racks/rack traps (n = 6). The two eels that swam via the spill gates did so during the spill discharge peak 26–27 October (Fig. 5), and successfully continued downstream from the Ätrafors HEP. The individuals that passed the Ätrafors HEP without being found in the collection facility or observed moving out through the spill gates (n = 6, 15%) could only have passed by swimming through the rack or escaping from the rack traps through holes that were discovered at the end of the study. One of the individuals that passed the racks remained in the intake channel, and its final fate was unknown. Of the five eels that entered the turbines, three were killed and two continued swimming downstream (60% turbine-induced mortality).

The majority of the visits were recorded by the antennae placed at the base of the racks (77%), as compared to the antennae at the top of the racks (23%). The activity of radio-tagged eels also differed between racks, with most visits made to the central rack followed by the south lateral rack and the north lateral rack (Fig. 6; chi-squared test to compare observed and expected number of visits at the three racks, df = 2, $\chi^2 = 6.07$, $P = 0.048$). Lateral racks were preferred, with 76% of the passages, whereas the central rack only collected 24% of the passing eels, but this difference was not statistically significant (chi-squared test to compare observed and expected number of passages at the three racks, df = 2, $\chi^2 = 1.61$, $P = 0.448$). Consequently, the proportion of visits resulting in a successful passage was lowest for the central rack (15%), followed by the north rack (29%) and the south rack (41%) (chi-squared test to compare observed and expected number of visits resulting in a successful passage at the three racks, df = 2, $\chi^2 = 15.74$, $P < 0.001$). Hence, the highest number of visits occurred

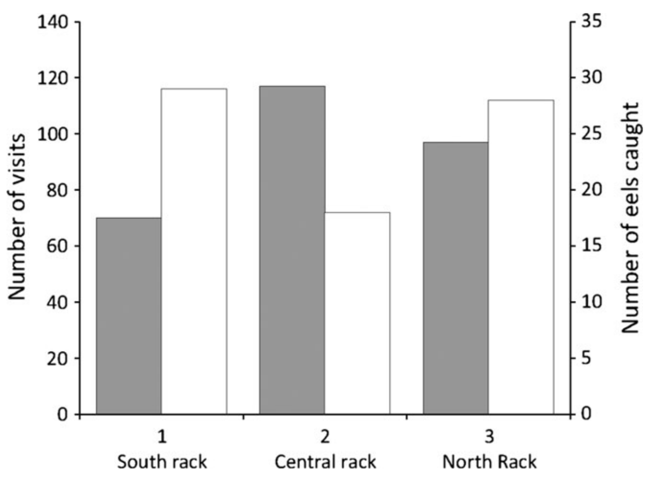

Fig. 6 Total number of visits made by eels at three different racks (first y-axis, grey bars), and the corresponding total number of eels caught in the collection facility (second y-axis, white bars) at Ätrafors hydroelectric facility in 2008.

at the rack with the highest approach velocity (i.e. the central rack), whereas the highest proportion of successful passages was associated with low approach velocities (i.e. the lateral racks; Figs 5 & 6).

Within 1 day after release, 41% of the radio-tagged eels made their first visit to the racks; this increased to 56% after 48 h, 69% after 72 h and 84% after 96 h. All eels that made at least one visit to the racks did so within 11 days. A large proportion of the radio-tagged individuals entering collection facility did so on their first visit (n = 20 of 31; 65%), which was observed for two of the eels that passed through the racks/collection facility (n = 2 of 6; 33%). The individuals that swam to the rack and turned and swam back upstream into the reservoir at least once (n = 16, hereafter called 'turns') eventually visited the rack between two and seven times. The median value for turns was three visits to the rack, that is, the median eel visited the rack three times, turned back upstream two times before passing on the third visit. Most of the events (80% turn, 86% passage) were recorded at turbine discharges >60 m^3 s^{-1} corresponding to V_{NORMAL} of 0.45–0.53 m s^{-1} and V_{SWEEP} of 0.65–0.76 m s^{-1} (Table 2).

Timing and duration of visits

The duration of each individual visit at the racks ranged from 1 min to more than 10 h (Table 2), but 21% of the events lasted 1 min or less. Successful passages into the traps typically occurred after a short stay at the racks (median 3 min), with about half of the eels (48%) finding the entrances to the traps within 1 min after arrival. The vast majority of the visits preceding a successful passage (78%) lasted <30 min, with the longest visit recorded lasting for 6 h 42 min. By contrast, visits eventually resulting in a turn lasted longer (median 28 min) than the aforementioned visits before successful passage (Mann–Whitney, $U_{76} = 1160.0$, $P < 0.001$). Eels that turned at the racks and swam back upstream into the reservoir returned within a median of 14 h 8 min, and 43% of returns occurred within 12 h from the previous upstream escape. The time range between repeated visits was 1 min up to 6 days (142 h 15 min). The time from release to passage ranged from 20 min to 10.9 days, with a median value of 2.9 days.

Passage events were not related to changes in water levels or discharges, as 52% (17 of 33) of the events occurred when levels were decreasing (chi-squared test, df = 1, $\chi^2 = 0.02$, $P = 0.55$), and 61% (20 of 33) occurred when discharges were increasing (chi-squared test, df = 1, $\chi^2 = 0.74$, $P = 0.27$).

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Table 2 Duration of visits to the racks and corresponding water velocity vectors for radio-tagged eels caught in the collection facility (collected eels) or passing and proceeding into the turbine intake (not collected eels). Each visit resulted either in the eels turning and swimming back upstream into the reservoir (turn), successfully entering the entrances to the collection facility (entry) or passing the facility and proceeding towards the turbines (pass)

	Collected eels		Not collected eels		
Parameter	Turn	Pass (entry)	Turn	Pass	All
Visits					
No. of events	26	31	19	6	57
No. of eels	11	31	4	6	37
Time spent at rack					
Median (min)	24	3	31	3	18
Min. (min)	8	1	7	1	1
Max.	7 h 30 min	6 h 42 min	10 h 14 min	1 h 32 min	10 h 14 min

Most turn events (73%, 33 of 45) occurred when total discharge was decreasing (chi-squared test, df = 1, $\chi^2 = 5.13$, $P = 0.020$). Turn events were also associated with increasing water levels (69%, 31 of 45), but the difference between increasing and decreasing levels was not significant (chi-squared test, df = 1, $\chi^2 = 3.30$, $P = 0.055$). Most visits occurred during night-time, with 92% of the passages and 87% of the turn events. No peak in activity was observed during night, but instead visits were evenly dispersed during the dark period. All visits occurred between full and new moon, with 56 of 82 visits being recorded from waning to new moon.

A significant number (41.5%) of visits occurred when approach velocity was equal to 0.86 m/s (normal velocity 0.49 m/s, sweeping velocity 0.70 m/s), with a prevalence of turn events. Furthermore, 78.6% of visits occurred when approach velocities were in the range 0.80–0.90 m/s, and all events were recorded within the range 0.51–0.92 m/s (normal velocity 0.29–0.53 m/s, sweeping velocity 0.42–0.76 m/s). Considering the 31 individuals that were caught in the collection facility, turn events were recorded at an average approach velocity of 0.76 m/s (normal velocity 0.44 m/s, sweeping velocity 0.63 m/s), the full range being 0.51–0.89 m/s (normal velocity 0.29–0.51 m/s, sweeping velocity 0.42–0.73 m/s); the passage events were recorded at an average approach velocity of 0.82 m/s (normal velocity 0.47 m/s, sweeping velocity 0.67 m/s), the full range being 0.54–0.90 m/s (normal velocity 0.31–0.52 m/s, sweeping velocity 0.44–0.74 m/s).

Discussion

The downstream passage conditions for silver eels at the Ätrafors HEP were significantly improved by replacing the steep 20 mm racks with the modified 18 mm rack collection facility. Mortality was reduced from >70% (96% for eels >750 mm) to <10% (Calles *et al.*, 2010), and similar examples cannot be found in the literature. Not only did most of the radio-tagged eels find their way into the entrances of the collection facility, but none of them were impinged on the racks. Eel survival with the modified system can probably be improved even more, as the individuals that passed the facility most likely escaped through holes in the traps. The solution appears to be most promising, but for a full assessment of the technique it needs to be tested at more sites and evaluated for more species. Injured eels were still encountered at the modified racks, illustrating the need for additional rehabilitative measures between the River Ätran eel rearing areas and the sea since eels today have to pass several HEPs before arriving at the Ätrafors collection facility. Our study covered only 1 year, and needs to be repeated and extended to cover the entire migration period.

Other measures

Most attempts to rehabilitate downstream passage conditions for eels at HEPs have comprised modifying the existing structures and have been limited in scope. In such cases, racks typically fail to prevent downstream moving fish from passing, and entrances of bypasses and collection facilities have not been ideally positioned for passage. In River Ätran, no eels used a surface bypass at the Herting HEP (HEP 1), most likely due to the failure of the adjacent 90 mm intake rack preventing eels from proceeding into the turbines (Calles *et al.*, 2012). There are few, if any, rehabilitative measures for silver eels at HEPs that match the efficiencies found in our study. The only other published study of passage efficiency of silver eels at an α-rack is from the Danish Tange HEP (36 $m^3 s^{-1}$ intake capacity), where the turbine intake was equipped with a steep 10 mm α-rack

(60°) and three 300 mm bypass pipes at 0.5 m depth (Pedersen *et al.*, 2011). Although the exact passage routes at the Tange HEP were not studied, in total 23% of the silver eels successfully passed the HEP and continued downstream, presumably using the bypass system. At the Baigts HEP in France (30 $m^3 s^{-1}$ intake capacity), a surface bypass positioned at the end of a 30 mm β-rack, originally designed for salmon, was found to aid eel downstream migration (Travade *et al.*, 2010a). Since several other passage routes were available at this site; however, a low proportion of the eels used the bypass facility resulting in a bypass FGE of only 3–22%. The overall escapement for the Baigts HEP, that is, all eels passing the HEP via spillways and bypasses, was highly variable ranging from rather poor (40%) to high (92%). A 30 mm β-rack in combination with a surface and a bottom sluice at the Halsou HEP (30 $m^3 s^{-1}$ intake capacity) on the River Nive in France had a combined passage efficiency of 56–64%, but the exact efficiency of each bypass could not be determined (Gosset *et al.*, 2005). Silver eels passage studies from large HEPs are scarce, but in a study from the United States, the movement patterns and bypass efficiency was studied at the Cabot station HEP (>300 $m^3 s^{-1}$ intake capacity) (Brown, Haro & Castro-Santos, 2009). The forebay of Cabot station is 10 m deep, and the rack is spaced 35 mm at the uppermost 3.5 m, below which the BS increases to 102 mm. The rack was steep, 73° relative to the bottom, but since the incoming water has to make a sharp turn when passing through the rack and entering the turbines, the rack could be considered as a β-rack. The guidance efficiency of the rack and the associated surface bypass was only 11%, and so the majority of the tagged eels passed the racks and entered the turbines presumably in the lower part of the water column (Brown *et al.*, 2009).

Comparison of modified and old facilities

Several factors differed between the old and modified racks at the Ätrafors HEP. Important modifications were the reduced gap width, the increased rack area, the reduced rack angle and the openings in the racks. The old 20 mm rack only allowed passage of eels <680 mm total length, and the 18 mm rack prevented even smaller eels from passing. Travade *et al.* (2010b) studied the maximum length of eels that could pass a certain BSs, with BS = 0.028 × TL. Applying this relationship to the racks at Ätrafors, the maximum length of eels capable of passing through the gaps of the old 20 mm racks would be 714 mm, which was close to the observed maximum length of 680 mm (Calles *et al.*, 2010). The corresponding predicted maximum eel length for the modified 18 mm rack is 643 mm, but since the largest individual of the six eels passing the modified racks was 940 mm (1100 g) passage could not have occurred through the racks. Furthermore, the racks probably also acted as a behavioural barrier, as 12 radio-tagged eels <643 mm chose to enter the traps instead of passing through the rack, which has previously been argued for eels not passing physically passable racks (Travade *et al.*, 2010a). Hence, the modified racks prevented eels from passing and were also successful in reducing risk of impingement. The importance of a low angle when diverting eels has been previously shown in laboratory experiments (Amaral *et al.*, 2002).

Adult silver eels can swim against velocities of >2 m s^{-1} (Russon & Kemp, 2011b), but the recommended maximum velocity at mechanical barriers has been set to 0.5 m s^{-1} to minimise the risk of impingement and injury (DWA, 2005). The maximum approach velocity at the Ätrafors racks was >1 m s^{-1}, which remained the same when the racks were changed since no modifications were made to the intake channel. At the old racks, the 63° angle relative to the bottom resulted in a normal velocity vector that was twice the sweeping velocity, indicating a high risk of impingement, which was indeed observed as 58% of all tagged eels were impinged and died (Calles *et al.*, 2010). When the angle relative to the bottom was reduced to 35°, the ratio was essentially reversed as the lower angle resulted in a sweeping velocity that was 1.4 times higher than the normal velocity vector, thus lowering the risk of impingement. As long as the silver eels can spend time at the rack without risk of impingement, they seem to be capable of escaping upstream against high water velocities (Calles *et al.*, 2010; Russon & Kemp, 2011b). Our results confirm that approach velocities higher than the typically recommended 0.5 m s^{-1} can be allowed at turbine intakes, if low-sloping racks with traceable bypasses are used to facilitate downstream passage (DWA, 2005; Travade *et al.*, 2010a).

Since the openings in the racks leading to the traps did not divert any water away from production, it was decided to have several large openings. However, this is normally not the case, since water used for attracting and passing fish into and through a bypass is typically lost from production, adding to overall project costs. No detailed velocity measurements were made in the entrances to the collection/trapping facility, so we can only speculate on discharge. Their combined surface area is 1.5 m^2, which is equivalent to about 1% of the surface area. If flow through these openings is similar to the rest of the rack, the maximum combined discharge would be 0.8 $m^3 s^{-1}$. However, considering the large surface area of the trapping nets the openings should have less hydraulic resistance; thus, the water velocity into and in front of the racks should be similar (c. 1.0 m s^{-1}), implying a total discharge of about 1.5 $m^3 s^{-1}$.

Eel behaviour at the racks

Similar to Jansen *et al.* (2007), we found that the eels followed the main current into the intake channel. The majority visited the central rack first and remained close to the base of the racks and eventually moved to one of the lateral racks for passage or upstream escape. Most rack passage occurred shortly after arriving on the racks (non-explorers). Upstream escape typically followed an extended stay at the racks (explorers). Explorers and non-explorers at HEPs have been reported earlier by Travade *et al.* (2010a) and Brown *et al.* (2009). The shift of eels between the lower and the upper parts of the racks indicate that search behaviour occurred. Brown *et al.* (2009) observed both lateral and vertical search behaviour of silver eels at a rack at the Cabot station on the Connecticut River. We do not know if the individuals that escaped upstream, after spending time near the racks (turns), hesitated to enter the collection facility or if they were unable to locate the openings of the racks.

Previous studies have shown that eels do not to respond until physical contact has been made with the obstacle (Russon & Kemp, 2011a), and that contact typically results in active search behaviour for an alternative route past the obstacle (Brown *et al.*, 2009), or an immediate flight response (Behrmann-Godel & Eckman, 2003). If water velocities are high, however, eels typically just sit on the racks trying to force their way past, which was probably the case for the old racks in Ätrafors (Calles *et al.*, 2010). Observations at the modified racks indicate that most eels arriving at the racks either passed successfully within minutes, and if they failed to pass they escaped upstream, emphasising the need for entrances that are easily found and with hydraulic conditions that favour passage.

The entrances to the Ätrafors collection facility are located near the surface. The water level in the reservoir is variable; therefore, the entrances are at times located at the surface or more than 1 m deep. Eels prefer bottom-oriented routes (Durif *et al.*, 2002; Gosset *et al.*, 2005; Calles, Rivinoja & Greenberg, 2013), and failure of some bypass systems has been attributed to entrances being at the surface (Pedersen *et al.*, 2011). Other examples exist of surface bypasses used by downstream migrating eels, even in favour of existing bottom-oriented entrances (Travade *et al.*, 2010a). The present study shows that surface oriented entrances can have a high passage efficiency and could even be the best solution if the rehabilitative measure is targeting the entire fish community and not only silver eels, as further outlined below.

Pros and cons of the Ätrafors solution

Not only did the modified low-sloping racks at Ätrafors HEP reduce silver eel mortality, but there was also a significant reduction in head loss at the racks, without removing water from electricity production (Persson & Holmberg, 2009). Hence, from all aspects, the new solution is an improvement compared with the old, even though the installation of a bypass or a collection facility will be associated with a substantial cost. Furthermore, the measure at the Ätrafors HEP is a collection facility and not a bypass facility, which means that all eels have to be repeatedly handled by man before they reach the sea. Currently, eels have to pass another HEP downstream of Ätrafors, and so all eels caught at Ätrafors are transported past this next HEP to avoid turbine-induced mortality. In the near future, however, the HEP downstream of Ätrafors will be reconstructed allowing for two-way passage. This means that the openings in the racks will have to be connected to some kind of a bypass, or a bywash, resulting in construction costs and additional costs of water diverted away from the turbines. Another potential problem with facilities intended to collect eels, instead of bypassing them, is that eels tend to migrate downstream during floods and so a certain proportion of them will move with the spill water and hence not be 'saved' from other hydroelectric facilities positioned further downstream. The Ätrafors collection facility worked well for collecting silver eels, but at most HEPs entire fish communities would benefit from rehabilitated downstream passage conditions. Hence, future solutions should target entire fish communities, including many species and several life stages (Russon & Kemp, 2011a). A low-sloping α-rack with a bypass system, with the bypass entrances located at the surface, was recently designed and implemented at a small HEP in the Swedish River Emån, with the aim to rehabilitate downstream passage conditions for as many as possible of the 33 fish species found in that river.

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