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TESTS OF TWO TYPES OF BYPASS FOR DOWNSTREAM MIGRATION OF EELS AT A SMALL HYDROELECTRIC POWER PLANT

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ABSTRACT

Efficiencies of two types of bypass, a surface and a bottom sluice, were tested for the natural downstream migration of silver eels *Anguilla anguilla* at a small hydroelectric power plant at Halsou, on the River Nive in France. Naturally migrating eels were caught after their passage through either bypass. A total of 637 eels were trapped during the three-year study. Total efficiency for both bypasses, evaluated on the basis of downstream movement of radiotagged eels, ranged from 56% to 64%. Given a bias due to hydrological conditions at the time of the runs, the precise efficiency of each separate bypass was not calculated. However, preferred passage through the bottom bypass for both tagged and untagged eels was confirmed by telemetry, as three to four times as many eels transited through the bottom bypass compared to the surface one. The behaviour of 74 individuals released in the forebay was observed by radiotelemetry. Close to half of the radiotagged eels returned up the headrace after their release, and most eventually migrated downstream over the dam with appropriate environmental conditions. Upon arrival at the power plant, eels displayed foraging behaviour in the forebay with frequent displacement interrupted by long resting periods in zones with low current. The repulsive effect of the trashrack located in front of the turbine intake increased with increasing turbined discharge. The study indicated that a trashrack with a smaller bar-spacing (around 20 mm), associated with an appropriate bypass, could deflect a large proportion of the female eels from the turbines. However, this solution needs to be tested on site to quantify the risk of mortality due to impingement on the trashrack. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: downstream migration; hydroelectric power plant; eel; *Anguilla anguilla*; bypass; radiotracking; behaviour

INTRODUCTION

Eel mortality during downstream migration, due to entrainment in hydroelectric plant turbines, is generally high because of their length (Larinier and Travade, 2002). Mortality varies considerably depending on the turbine characteristics and the mode of operation of the plant (EPRI, 2001; Desrochers, 1984; Monten, 1985; Larinier and Dartiguelongue, 1989; Hadderingh and Baker, 1998).

Many solutions have been tested to prevent eels from passing through the turbines and to direct them to bypasses which will enable their safe return to the river (EPRI, 2001): physical barriers (screens and louvres) and behavioural barriers of light (Hadderingh, 1982; Hadderingh *et al.*, 1992, 1999), sound (Sand *et al.*, 2000) and electricity (Gleeson, 1997).

Whatever the technique adopted, the efficiency of the solution as a whole depends greatly on the efficiency of the bypass. It must be located close to the place where fish have been directed and grouped, and the hydraulic conditions at its entrance must elicit behaviour favourable to passage (Travade and Larinier, 1992; ASCE, 1995; Larinier and Travade, 1999). Bypass efficiency has frequently been measured for juvenile salmonids (Larinier and Travade, 1996, 1997; Chanseau *et al.*, 1999; Croze *et al.*, 1999). Until 1999, no design criteria for devices adapted to eels were available, nor were there any reliable calculations of the efficiency of existing devices, generally designed for salmon. In 1999, taking the example of devices designed and tested for salmonids at the Halsou

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plant in France (Gosset *et al.*, 1998; Gosset and Travade, 1999), a study was undertaken of downstream bypasses for eels, drawing on the repulsive effect of trashracks to momentarily prevent fish from entrainment in the turbines and guide them to a nearby bypass in which the flow represents a small percentage of the turbined discharge. Bypasses for salmonids are located near the surface as smolts tend to swim in surface waters during their migration. For the eel, a bottom bypass might appear more appropriate given its benthic behaviour. Two types of bypass were therefore tested at the Halsou plant (River Nive): a surface discharge sluice used for the migration of salmonids, and a bottom sluice, both located adjacent to the trashrack. These experiments were conducted during three migration seasons (from the beginning of October to the end of January) from 1999 to 2001 (Gosset *et al.*, 2002). They required the installation of a trapping device downstream of the two bypasses.

Efficiencies of the bypasses were compared: (i) quantitatively by comparing the number of downstream migrants (tagged and untagged) caught in the trap; and (ii) by studying the behaviour of the eels in the forebay by means of radiotracking.

MATERIAL AND METHODS

Study area

This study was conducted at the Électricité de France (EDF) hydroelectric power plant at Halsou, located on the River Nive in southwestern France. The Nive is 80 km long and flows into the Adour estuary at Bayonne (Figure 1). Flow (mean daily flow 36 $m^3 s^{-1}$) varies widely depending on meteorological conditions, from 6 $m^3 s^{-1}$ in low-flow periods to 300 $m^3 s^{-1}$ during spates.

The Halsou plant (Figure 2) is on the lower Nive, some 23 km from the sea. A gravity dam 172 m long and 2.50 m high diverts the water into a headrace 925 m long, 3 m deep and 11 m wide. The dam has a bypass with bottom baffles. The plant, equipped with three double horizontal Francis turbines (180 r.p.m.), generates a maximum of 30 $m^3 s^{-1}$ over a 4.25 m vertical drop. Turbines T1 (near the left bank) and T2 (at the centre of the intakes) generate a maximum flow of 8 $m^3 s^{-1}$ each. Turbine T3, on the right bank and the closest to the surface bypass, generates a maximum flow of 14 $m^3 s^{-1}$. The maximum power generated by the plant is 900 kW. The trashrack (length 20 m; height 3 m) in front of the intakes is angled at 25° in relation to the vertical and has an automated mechanical debris removal system. Spacing between the bars is 3 cm and bar thickness is 8 mm. Maximum water velocity is 1.6 $m s^{-1}$ in the headrace and approximately 0.5 $m s^{-1}$ in front of the trashrack, angled at 15° in relation to the headrace axis. The floodlights which usually illuminate the forebay area at night were turned off during the study period.

Downstream migration bypasses and trapping device

A surface bypass (flap gate with length 1.38 m, width 0.90 m), used for several years for migration of salmonid smolts, was located on the right bank of the forebay at the end of the trashrack protecting the turbines. Each time the bypass was opened, flow was set at 0.6 $m^3 s^{-1}$, but, given variations in water level due to spates and suspension of turbine operation, it varied between 0.4 $m^3 s^{-1}$ and 1.0 $m^3 s^{-1}$. Opening of the bypass caused a surface velocity parallel to the trashrack, particularly high at the turbine entrance closest to the bypass (T3).

A motorized bottom gate (width 1.30 m, height 1.20 m) on the right bank of the forebay, 5 m from the end of the trashrack and used to drain the headrace, was used as a bottom bypass. Given the water depth (around 4 m) and the resulting pressure at the bottom of the forebay, a small opening in the gate (13 cm) generated flow similar to that in the surface bypass. However, the resulting hydrodynamic conditions (a small opening for passage and a high velocity gradient) cannot be considered favourable to eel passage. A discharge tower was therefore built at the outlet of the bottom sluice, of the same height as the headrace wall. It was equipped with a vertical flap gate at the top which enabled the flow through the bottom gate to be set at the same rate as through the surface bypass (0.6 $m^3 s^{-1}$), which, for a 0.50 m vertical opening of the gate, gave a section for passage of 0.65 m^2 and water velocity of around 1 $m s^{-1}$ through this bottom bypass.

Fish passing through the bottom gate and the discharge tower fell into a reception pool 1.20 m deep which connects with the discharge canal and was initially designed to make the fall (4 m) easier on the fish. The reception pool drained partially by way of an indentation onto an inclined dewatering screen. Fish were entrained by the

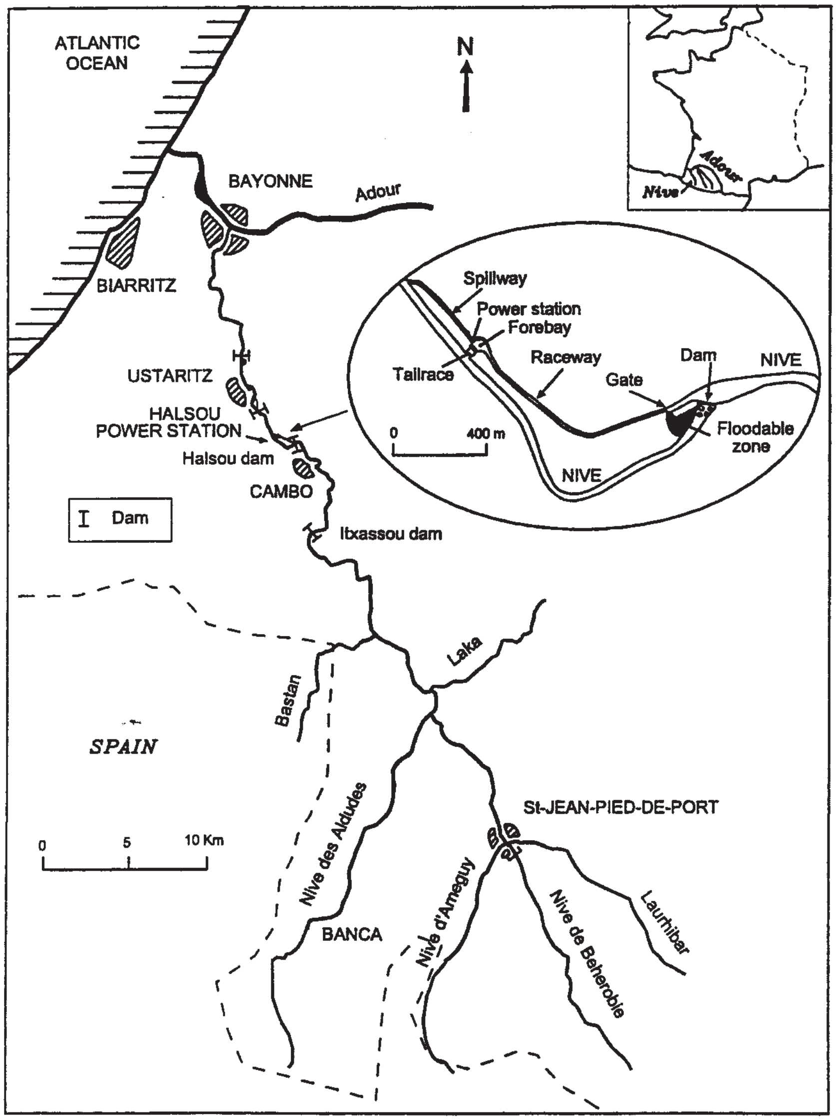

Figure 1. Geographical location and general view of the Halsou hydroelectric plant

current onto the screen and caught in a trap, where they were captured in nets. A screen 30 cm high was installed on the pool wall to prevent the escape of fish, while maintaining a constant water level.

For the trap to be effective, despite flooding and clogging by debris carried by the Nive, it was decided, after some problems in 1999, to open a passage to evacuate debris from the rack and screen at the top of the pool wall. To keep fish from escaping, an electrical barrier was installed in this new opening. The efficiency of the barrier, composed of four vertical electrodes supplied by an impulse generator, was tested with eels tagged with PIT (passive integrated transponder) tags. Five batches of from five to ten eels were released in the reception pool in 2000 and 2002, when the bottom bypass was operating or the surface bypass was open. Mean efficiency calculated from catches in the trap (clogging less than 50%) was on the order of 80% (Gosset *et al.*, 2002) and was not dependent on which bypass was in operation.

Surface and bottom bypasses were opened alternately every other day for one 24-hour test. The trap was sampled twice a day for the first two years, at around 8:30 am and 6:00 pm, and at least once a day (8:30 am) in the third year. Fish captured were identified and their main morphological characteristics were recorded (weight

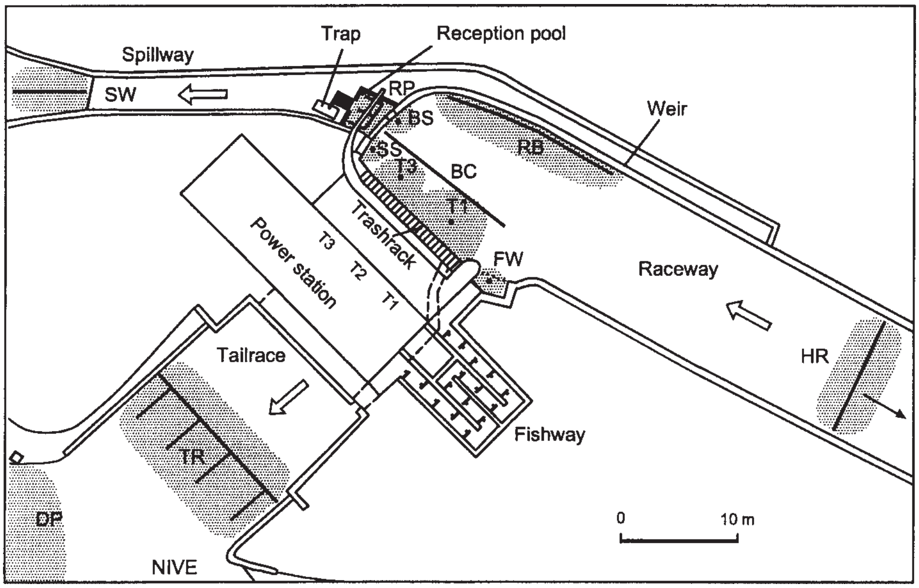

Figure 2. General view of the Halsou hydroelectric power plant and radiotelemetry surveillance zones (see text for explanations)

and head thickness measured horizontally, but also total length and vertical and horizontal eye diameters). These data were used in a complementary study (Gosset *et al.*, 2002; Durif, 2003). Captures were compared on a daily basis.

Radiotracking

Most of the radiotagged eels had been trapped at the power station. In 2000 and 2001, however, eels were caught upstream of the dam by electrofishing, enabling tagging of silver eels prior to the first catches. Potential migrants were identified on the basis of their external measurements (Durif *et al.*, 2000).

Transmitters were surgically implanted in the abdominal cavity of eels anaesthetized with clove oil (Baras and Jeandrin, 1998). The trailing antenna transmitters used were uncoded ATS 10/28 model (frequency 48 to 49 MHz, length 45 mm, diameter 11 mm, weight 8 g) with mortality switches. The ratio of transmitter weight to eel weight was equal or inferior to 2% (except for three cases). An exit hole was made for the antenna with a hollow needle through the body wall 2 cm behind the incision stitched with nylon thread. No apparent infection was found on one eel recovered 3 weeks after its release; the incision had healed properly though the exit hole was slightly inflamed.

Displacement was monitored by manual (loop antenna) and automated radiotracking throughout the study site. From 9 (in 1999) to 16 (in 2001) fixed ATS (2000B) and LOTEK (SRX_400) dataloggers operating in the 48–50 MHz band were used for automated monitoring. In 1999 and 2000, five zones were defined (Figure 3): SS (surface sluice), BS (bottom sluice), T1 (in front of turbines T1 and T2), T3 (in front of turbine T3) and RB (along the spillway on the right bank). Four additional locations were also monitored but with less precision, in order to determine whether individuals were still in the study zone, i.e. inside the forebay or the headrace: SW (in the spillway), TR (tailrace), HR (entrance to the headrace), and DP (downstream of the power plant). In 2001, three additional stations were installed: FW (entrance to the fishway), BC (in front of the trashrack at the bottom of the forebay), RP (in the reception pool). Zone T2 represented the intersection of zones T1 and T3 and was approximately in front of turbine T2. The NR zone corresponded to places where there was no automatic reception. Two dataloggers were sometimes used for a single zone as, despite a minimum scan time of 5 s, it becomes impossible to scan with precision when more than four or five frequencies are programmed simultaneously. Different types of antennae were used depending on the shape and size of the monitoring zone: an immersed short wire antenna for spherical reception, an immersed long ‘twin-lead’ antenna for a cylindrical zone, and an aerial antenna (loop) for broad directional

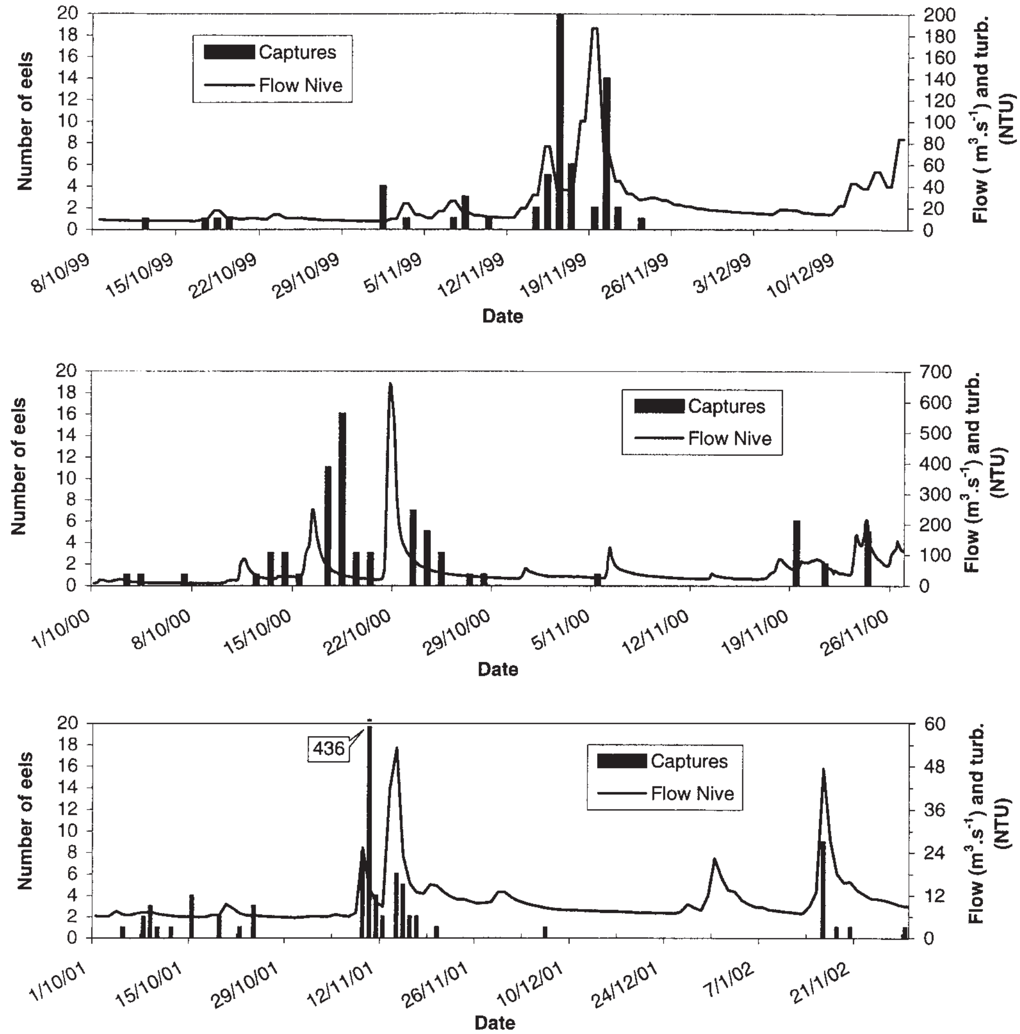

Figure 3. Daily captures of downstream migrating eels during the 1999, 2000 and 2001 studies in relation to flow and turbidity of the River Nive

reception. Each monitoring zone was precisely calibrated (signal-gathering distance determined by adjusting the gain) by manually moving a transmitter in the water.

All the radiotracked eels were released within hours of being tagged: 15 ($355\,g < W < 1694\,g$; mean = 850 g, SD = 112) in 1999, from 20 October to 22 November; 30 ($397\,g < W < 873\,g$; mean = 608 g, SD = 24) in 2000, from 10 October to 26 November; 25 ($390\,g < W < 1370\,g$; mean = 623 g, SD = 40) in 2001, from 9 November 2000 to 23 January 2002. The first nine eels (1999) were released in the headrace 350 m upstream of the plant; all others were released in the forebay, on the right bank near the spillway. After the first tests, it was observed that most fish returned up the headrace immediately after being released and could therefore not be observed in the forebay.

Environmental factors

Hydro-Invest/Logicap physicochemical multiprobe dataloggers continuously recorded temperature, conductivity, turbidity, water level in the headrace, atmospheric pressure, daylight, and moonlight. Rainfall was noted manually; mean daily flow in the Nive was obtained from the DIREN (Direction Régionale de l'Environnement) of Aquitaine; turbined discharge and water level in the tailrace were obtained from EDF (Electricité de France).

RESULTS

Comparison of passage between bottom and surface bypasses

A total of 637 silver eels were captured in the trap after passing through the two bypasses in three years (66 in 1999, 75 in 2000 and 496 in 2001). The vast majority of captures were at night and during twilight, i.e. between 6:00 pm and 8:30 am (90% in 1999 and 98% in 2000). Downstream migration takes place in successive runs (for periods of four days maximum) between which there is very little passage: 74% of captures were during two runs in 1999, 87% in four runs in 2000 and 95% in three runs in 2001 (Figure 3). In 2001, with hydrological conditions particularly favourable to downstream migration through the headrace (an increase in flow in the Nive with no spillage over the dam), 436 individuals were caught in a single night, accounting for 88% of the captures that season.

Each year, more eels were caught passing through the bottom bypass: 95% in 1999, 72% in 2000 and 63% in 2001 (excluding the exceptional capture of 436 individuals in one night). It is probable that the rise in the number of eels trapped when the surface bypass was open in 2000 and 2001 was essentially due to installation of the electric barrier, which increased the efficiency of trapping. The same trends were found with radiotagged eels over the three years (8 to 14% for the surface bypass and 42 to 53% for the bottom bypass; Table I). Efficiencies of the two bypasses could not be accurately compared as their fishing efforts were not constant over the period. Clogging of the entrance to the trap, which varied from one day to the next and occurred primarily when the surface bypass was open, may have facilitated the escape of some eels. The number of reliable tests (when the entrance to the trap was more than 80% clogged, tests were not considered reliable) was therefore lower for the surface bypass than for the bottom bypass (Figure 4). This disparity in the tests leads to an underestimation of passages through the surface bypass, given that downstream migration of eels varies greatly (Figure 3) and occurs when flow increases and thus when floating debris is more abundant, increasing the risk of clogging.

General migrating behaviour and effects of the hydroelectric facility

In 1999, eight of the nine eels released upstream of the power station swam back up the headrace (six directly, two after going back and forth in the headrace one or more times), then took up waiting positions (displacement of very small amplitude) in the Nive, 2 to 3 km upstream of the dam for periods of between *c*. 2.5 days and 24 days. They then migrated over the dam during a spate period between 15 and 19 November. The last eel remained in the headrace for *c*. 2 days then migrated via the plant. Of the six eels released in the forebay, four migrated through the plant and two swam up the headrace, one in 2 h and the other in *c*. 2.5 days. They remained in the Nive upstream of the dam (for 28 days and *c*. 20.5 days), then migrated through the plant during a spate on 15 December.

Table I. Distribution of radio-tagged eels at the power plant

		1999	2000	2001	Total
Released		15	25	34	74
Passed at the station*		5 (33%)	11 (44%)	20 (59%)	36 (49%)
Swam through the power station, directly or after a stay in the raceway†	Bottom sluice	4	5 to 9	6	15 to 19 (42 to 53%)
	Surface sluice	0	1 to 3	2	3 to 5 (8 to 14%)
	Turbines	1	1 to 3	8 to 9	10 to 13 (28 to 36%)
	Station weir	0	0 to 1	3	3 to 4 (8 to 11%)
	Fishway	0	0	0 to 1	0 to 1 (0 to 3%)
Total efficiency of the 2 sluices†		80%	72 to 80%	40%	56 to 64%
Swam upstream of the raceway and come back into the Nive*	Dam	10 (66%)	13 (52%)	5 (15%)	28 (38%)
	Abandoned or lost	0	1 (4%)	8 (40%)	9 (12%)
	Dead	0	0	1	1 (1,4%)

*Percentage calculated according to the number of tagged fish.
†Percentage calculated according to the number of fish that passed through the power plant.

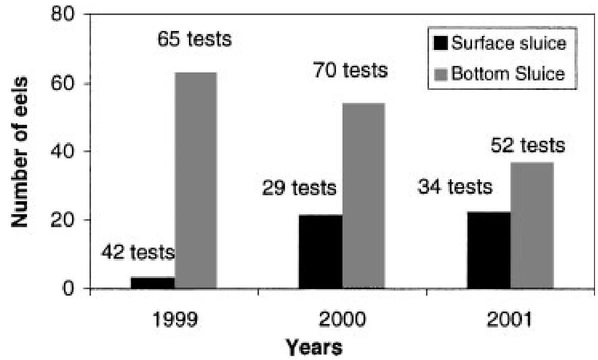

Figure 4. Number of unmarked eels caught in the trap according to the bypass in use

In 2000, of 25 eels released, 14 swam back up the headrace (taking between 6 h and *c*. 10 days), seven immediately after the release and seven after a period in the forebay. They then swam up the Nive, to the same zone as in 1999, where their displacement was quite variable over periods ranging from *c*. 2 to 65 days. With a single exception (rapid downstream migration over the dam), these eels passed over the dam when flow increased in the Nive: four between 22 and 25 October, and five between 21 and 23 November. Ten eels migrated directly by way of the plant.

In 2001, 34 eels were monitored in the forebay (four of the 30 tagged eels having been recaptured and put back in the water). Sixteen swam up the headrace (taking between 30 min and 16.5 days). One eel died at the headrace exit and the other 15 returned to the same area in the Nive as in previous years. Two again swam down the headrace 3 and 45 days later, then passed over the spillway. Five passed over the dam during the spates of 13 November 2000 and 16–17 January 2001. The last eight had not yet migrated by the end of January, when trapping and automated monitoring were suspended. Six eels were still in the Nive upstream of the dam on 5 February but all had migrated downstream of the plant by 14 February, probably at the time of the 7 February spate. Eighteen eels migrated directly through the power plant after a variable stay in the forebay or the headrace (one month, in the case of one eel).

Each year, a large proportion of tagged eels (between 38% and 50% over the three years; Table I) swam up the headrace and remained in the Nive upstream of the dam. They then migrated downstream over the dam during environmental windows corresponding to increased flow and turbidity, and reduced conductivity (Durif *et al.*, 2003). The time between release and migration activity depended only on these specific environmental conditions. The total time before reaching the plant (from 1 to 49 days) varied widely depending on the individuals and the date of release. Only four eels initially swam back up the headrace and then migrated back downstream through the same channel, before transiting through the power plant. Furthermore, it was observed, by comparing tracked eels and trapping results, that downstream migration of ratiotagged eels occurred at the same time as for the untagged eels.

Behaviour in the forebay area

In 1999, of the nine eels observed in the forebay, four migrated through the bottom bypass and one transited through the turbines (Table I). Much displacement between zones was observed, as were long waiting periods in areas with little current (RB). Only two eels passed through the small area in front of the surface bypass (SS). Eight out of nine eels approached the bottom sluice (BS) but only four actually swam through it. The number of approaches and the time spent in each zone varied widely. For instance, one eel spent 25 periods of between 30 s and 23 min in zone BS while another passed through the zone only once; both, however, migrated through the bottom bypass. No patterns in mean frequency and duration of approaches (Figure 5) were found that characterized overall behaviour (time spent in the forebay varied from 30 s to more than 22 days). The eels swam frequently in front of turbines T1 and T2 (zone T1) and in front of the bottom sluice (BS) but remained longer in T1 and especially along the spillway (RB), where total residency could exceed 22 days.

In 2000, 18 eels were tracked in the forebay but the particularly unfavourable hydrological conditions (numerous spates) limited monitoring precision, and uncertainties remain with respect to the path taken by some individuals (Table I). As in 1999, there was great heterogeneity in exploratory behaviours. Zone BS and above all zone SS were rarely visited, both in terms of number of approaches and residence time (Figure 5). The zone in front

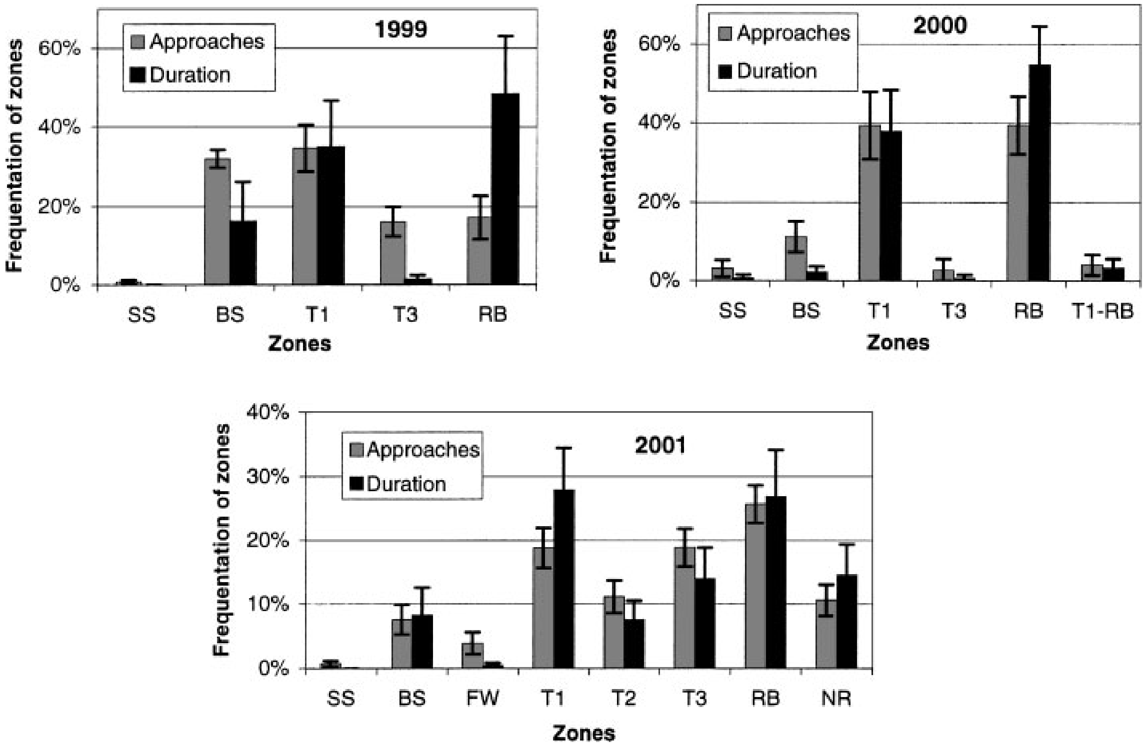

Figure 5. Mean percentage of the residence time in each area during 1999, 2000 and 2001 studies. Error bars correspond to standard deviation

of the turbine which often generated the highest discharge (T3) was passed through only once. The proportion of time spent in zones T1 and RB was the highest. Approaches in these two zones were comparable in number (35 and 45) but total residency (for all eels) along the spillway (RB) was even higher than in T1 (close to 8 days, compared with 2 h 45 min). Generally speaking, residency in each zone was lower than in 1999. For the entire forebay, durations varied between 34 s and 3.25 days.

In 2001, 27 eels were tracked in the forebay and patterns of passage were quite different from those of 2000 (Table I). The proportion of eels passing through the turbines was higher than in the other years (Figure 5); this is probably due to the fact that low flow velocities through the trashrack (slower turbined discharge) reduced the repulsive effect. In 2000, the mean turbined discharge (mean discharge in the hour preceding the passage of each eel) was 16.4 $m^3 s^{-1}$ and the global efficiency of the two bypasses ranged from 72 to 80% (Table I); in 2001, however, mean flow (11.7 $m^3 s^{-1}$) was significantly lower (Student's *t*-test: $t = 2.70$; $P = 0.012$) as was global bypass efficiency (40%). Foraging behaviour was much the same as in 1999 and 2000, with some variations which may have been due to the lower turbined discharge and frequent shutdowns of the turbines. Zone SS was rarely visited but at least 12 eels entered zone BS. Zone RB was still a 'rest area' for at least five individuals (residency longer than 1 day). The zones in front of the turbines (T1, T2, T3) were more frequently visited and may even have served as rest areas (more than 10 days in T1 for one eel, for example). The number of approaches and time spent in the other zones (Figure 5) were comparable. Time spent in the forebay varied from 5 min to *c.* 14.25 days.

Several conclusions can be inferred from analysis of eel behaviour in the forebay of the Halsou plant.

- The number of approaches and time spent in the different monitoring zones were highly variable and reveal no preferential movements. Behaviour was generally characterized by alternating phases of exploration of the forebay area and rest in areas where velocity gradients were very low (counter-current in RB, or T1 when turbines were not operating).
- The zone in front of the surface bypass was used infrequently, regardless of the hydrological conditions. On the other hand, while time spent in front of the bottom bypass was low, approaches were four to six times more

frequent (2000 and 2001) than those observed near the surface bypass. It would therefore appear that the eels seek passage at the bottom rather than on the surface.

- Areas in front of a turbine in operation were rarely visited, particularly if the discharge was high. The trashrack in front of the turbines seems to have a repulsive effect which increases with higher velocities.
- While eels spend more time at the bottom of the river, they are also capable of rapidly swimming up a 3 m water column (no significant delay was observed in the case of transit through the discharge tower, for example).

DISCUSSION

Evaluation and comparison of bypass efficiencies

As noted by numerous authors (Voellestad *et al.*, 1994; Hadderingh *et al.*, 1999; Watene *et al.*, 2003; Durif *et al.*, 2003), there is a clear relationship between peak downstream runs and increases in water level and flow rate. This irregularity in migrating behaviour and the difficulty in maintaining reliable trapping conditions (clogging) represent two major obstacles for any rigorous quantitative assessment of bypass efficiency for natural downstream migration. Strict comparison of the efficiency of the two bypasses based on trapped radio-tagged eels suffers from the same bias, but a preference for the bottom bypass was clearly confirmed by the rates of passage through each bypass. With the exception of 1999 (no electric barrier), passage through the bottom bypass appeared to be three to four times higher than at the surface bypass. However, alternate opening of the two bypasses gave eels the possibility of choosing a preferred bypass after a maximum wait of 24 hours. It can therefore not be definitively stated that the efficiency of the surface bypass would have been as low if it had been the only one available throughout the study period. The overall efficiency of the two bypasses cannot be denied: over the three-year period, it ranged between 56% and 64%, and was significantly high (72% to 80%) in 2000, a year of high turbined discharge, compared to 2001 (40%) when turbining was lower. It should be remembered that during eel passage, discharge in the bypasses, which varied throughout the study, represented 2 to 5% of the turbined flow.

It has been shown that for salmonid smolts, bypass efficiency depends on shape, location in relation to trashracks, and hydrological conditions near the entrance (Larinier and Travade, 1999). Bypass shape and discharge values must now be optimized for eels. While a bottom bypass appears preferable, it presents the significant drawback of requiring construction of a tower to regulate discharge and to prevent high velocities at the entrance of the bypass. At Halsou, the channel is not very deep (3 m), but this is not the case for most power stations, where the drop is far greater. In these cases, the construction required may be costly or complicated and not always possible at existing plants. The solution might be to use existing surface bypasses (flap gates), already used for salmon juveniles, to ensure eel passage at optimum cost and in the shortest possible time. No estimations were found in the literature of the efficiency of such devices for migrating eels. In light of the results obtained at Halsou, it therefore would be wise to conduct field tests of the efficiency for eels of a surface bypass open continuously, already shown to be efficient for smolts.

Exploratory behaviour in the forebay

Eels demonstrated foraging behaviour in the forebay. Total time spent in this area ranged between 30 s and *c.* 14.25 days, and the number of approaches and time spent in the different zones monitored were extremely variable. It is very difficult to estimate the exact time spent searching for a bypass, as some areas (in front of the trashrack and near the river bottom) can occasionally be used for resting, when hydrological conditions are favourable (low or no turbined discharge). Resting periods near the spillway can be explained by the virtual absence of current in this area, as well as by the presence of a large sand and mud tumulus created by counter-currents. Acoustic tracking of 10 eels (Bégout-Anras, 2001; Bégout-Anras *et al.,* 2001) confirmed these results and showed that most displacement was near the bottom. It is probable that, particularly at night, there is movement also between the bottom and the surface. This behaviour has already been observed even in deeper (10 m) water (Haro *et al.*, 2000). The migratory behaviour of silver eels is therefore very different from that of salmonid smolts, which generally remain only briefly (a few minutes to a few hours) in the forebay before rapidly passing through the power plant (turbines or bypasses). It is also probable that trajectories and time spent in the forebay are strongly linked to the configuration of the facility.

Effect of the trashrack

Eels passed several times in front of the trashrack without going through the bars, even though the spacing was large enough (3 cm) for their passage (80% of the eels at Halsou, of which 98% are female, have a head width of less than 3 cm) (Gosset *et al.*, 2002). This tends to confirm that the trashrack had a repulsive effect, which appeared to increase with turbined flow, and therefore with higher velocity. This was apparent not only from a comparison of bypass efficiency but also from time spent in areas near the turbines in 2000 and 2001. The efficiency of both bypasses was lowest (40%) and the number of passages through the trashrack highest (40 to 45%) in 2001, when turbined flow was lowest. In the range of velocities found at Halsou (between $0.25\,m\,s^{-1}$ at 50% power and $0.5\,m\,s^{-1}$ at full power), therefore, the trashrack effect appears to cancel out the positive rheotropism of silver eels, which tend to prefer passage through water sections with the strongest current (Nilo and Fortin, 2001). It is therefore highly probable that a rack with 2 cm bar spacing (close to 90% of the eels in the Nive have heads more than 2 cm wide) would prevent entrainment of almost all silver eels in the Nive.

CONCLUSIONS

This experimental study, carried out on a small power plant, has shown that a downstream migration device composed of a bypass with a discharge of 2 to 5% of the turbined discharge located near a trashrack with 3 cm bar spacing could be partially efficient for adult eels. The results indicated that a bottom bypass was preferable to a surface bypass but their respective efficiency has not been precisely quantified. The efficiency of such a device is only partial (56 to 65%), and not sufficient for most power plants given the high mortality induced by the passage into the turbines. Efficiency could be improved by reducing the bar spacing of the trashrack (close to 2 cm) which would block the major part of the eel population (90% of the eel population of the River Nive). This solution requires a low water velocity in front of the trashrack (about $0.3\,m\,s^{-1}$) to prevent eel impingement on the trashrack and resulting mortalities. This solution needs to be tested by on-site experiments at hydroelectric power plants of various sizes and configurations.

Another possible solution would be to suspend turbine operation during downstream runs of eels but, given the resulting production losses, this would only be possible if one could reliably predict runs, at least a few hours in advance. The difficulty of making such predictions (Euston *et al.*, 1997; Haro *et al.*, 2002) would appear to limit this possibility at the present time.

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