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Behavioral Study of Downstream Migrating Eels by Radio-telemetry at a Small Hydroelectric Power Plant

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Abstract.—Eels, because of their size and life cycle, are among the most vulnerable species regarding the presence of obstacles on waterways. During a study of the efficiency of two types of fish passes, the behavior of migrating European eels *Anguilla anguilla* was investigated using telemetry and trapping at a small hydroelectric power plant (southwest of France). Radio-tracking was conducted manually and by stationary receivers in the turbine area and downstream and upstream from the power plant. Sixteen eels were tagged by surgical implantation of transmitters and released upstream of the power station. Results provide insight on eel behavior during the downstream run (swimming rates and delayed migration) as well as behavior in front of both exits to the trap. Almost all tagged individuals moved upstream after the release. Most of these eels migrated downstream after a heavy rainfall, avoiding the power station by crossing the overflowing dam. They were tracked down to the estuary (16 km) over several days during which time several periods of nonmovement occurred. Descending nontagged eels transiting through either of the two tested forebay bypasses were trapped. Daily catches corresponded to movements of radio-tagged individuals. Environmental parameters were recorded and compared to the downstream run. Results clearly showed that silver eel migration was closely linked to certain environmental parameters (flow rate, turbidity, and luminosity) and that downstream migration is inhibited if favorable environmental conditions are not met, such as during daytime when turbidity is low. Direct comparison of daily catches through the bottom and surface bypasses as well as observations of radio-tagged eels in the forebay both suggest that a bottom bypass may be appropriate for safely transiting downstream migrating eels.

Introduction

Numerous fish-passes for upstream migration have recently been installed in France. Protection of downstream migrating juvenile and adult diadromous fish of different species worldwide has also become a major concern in the last decade. Recent studies mainly concern salmonids. Eels, because of their body form and life cycle, are among the most vulnerable species regarding the presence of obstacles on waterways (Berg 1986; Larinier and Dartiguelongue 1989; Richkus and Whalen 1999). Mortality of eels passing through turbines of hydroelectric facilities can be quite significant (Travade and Larinier 1992; Hadderingh and Baker 1998). Very few studies have dealt with behaviors of eels around hydroelectric facilities. It is not known whether eels are simply entrained through the turbines or if they actively search alternate passages. It is generally assumed that eels are bottom dwellers; therefore, their behavior during catadromous migration may differ from more pelagic fishes (Haro and Castro-Santos 1997) and consequently specific bypasses for eels must be developed.

The objective of our study was to examine the behavior of European eels *Anguilla anguilla* during downstream migration in order to find solutions for eels to avoid passage through turbines. Moreover, the efficiency of two types of bypasses (bottom and surface) was tested. The study was conducted at the hydroelectric power plant of Halsou in the southwest of France, from October to December 1999. A trap was installed at the outlet of the bypasses in order to capture eels during their downstream migration. A telemetry survey was conducted on transmitter equipped individuals to test the attractiveness of the bypasses as well as to obtain information on behavior of eels during their downstream run.

Being able to precisely predict downstream runs of eels in response to environmental changes at different time scales may be another way of reducing the impact of hydroelectric facilities by lowering or ceasing turbine generation during migration peaks. Information on the duration of runs and environmental cues is necessary to consider this type of solution. Thus, behavior of radio-tagged eels was analyzed in the vicinity of the power plant downstream to the estuary zone.

Methods

Project description

The EDF (Electricité de France) hydroelectric power station of Halsou is located 23 km from the sea on the Nive river in the Southwest of France. Its watershed is about 1000 km^2. The Nive results from inputs of small rivers that originate in the Pyrenean Mountains and flows approximately 80 km to the Adour estuary. The mean daily flow of the river is very unsteady depending on environmental conditions and varies between 6 and 300 m^3 s^{-1}. A dam, 172 m long and 2.5 m high, located 2 km upstream of the power station diverts the water into a power canal 925 m long and 11 m wide (Figure 1). Both the power canal and forebay area (Figure 2) are 3–4 m deep. The projectors which usually lighten the forebay area were turned off during the study period. There were no other sources of light in the vicinity. The power plant is equipped with 3 double, horizontal Francis turbines which pass a maximum flow of 30 m^3 s^{-1} over a vertical drop of 4.25 m. The maximum power generated by the plant is 900 kW. A trashrack is located in front of the intakes, with openings between bars measuring 3 cm. Two bypasses are located at the end of the canal in the forebay area. The surface bypass measures 1.38 m in width and its opening (maximum depth of 17 cm) can be adjusted by a motorized lever. The bottom bypass (4 m deep) is 1.30 m wide and 1.20 m high and is located 2.70 m from the surface bypass (Figures 3 and 4).

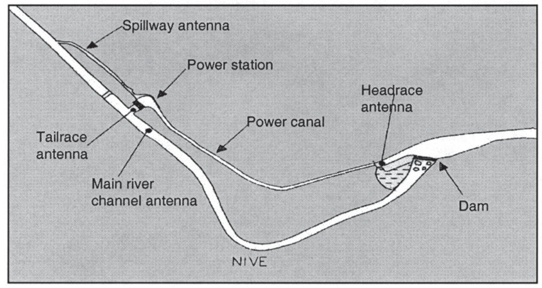


Figure 1. Study site showing the Halsou power station and the locations of radio-telemetry antennas.

Trapping conditions

Migrating eels were trapped between 7 October and 6 December 1999. A reception pool fitted with railings (0.5 cm mesh size) was built at the outlet of the spillway in order to collect fish entrained by both bypasses (Figure 3). A discharge tower (Figure 4) was built in the reception pool against the weir (3 m high), in order to maintain an opening wide enough for eels to transit through the bottom bypass without inducing unfavorable hydrodynamic conditions for eels (i.e., small opening and high velocity gradient).

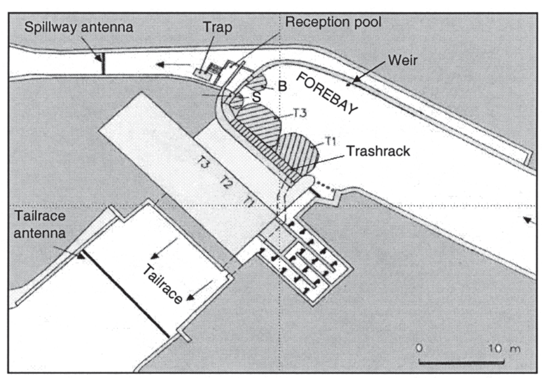


Figure 2. Top view of the power plant. Monitored areas by fixed antennas are represented by gray crossed zones: T1: turbine 1; T3: turbines 2 and 3; S: surface bypass; B: Bottom bypass. Receiver antennas in the spillway and at the tailrace are indicated.

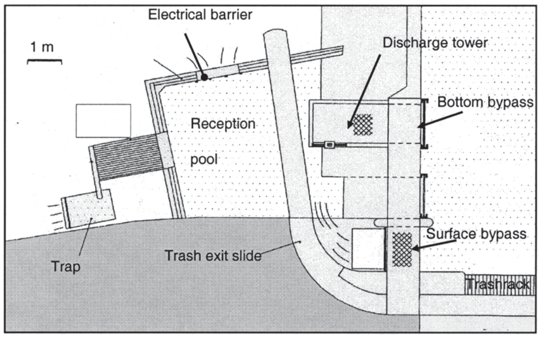


Figure 3. Top view of the trap area.

Bottom and surface bypasses were opened alternatively for 24-hour periods. Thus, fish entered either bypass, transited through the reception pool (via the discharge tower for the bottom bypass), then were entrained into the trap at the outlet. Both bypasses were adjusted so that the flow rate was set at 0.6 $m^3 s^{-1}$, although due to changes in water discharge, it sometimes varied between 0.4 and 1 $m^3 s^{-1}$. Leaves often clogged the trap entrance and the railings of the reception pool causing water to overflow, thus a possible escape of fish; therefore, an opening fitted with an electrical barrier was made in the pool so that leaves were evacuated without losing the eels. The trap was visited twice a day, morning and evening, to collect eels.

Environmental parameters

Five environmental parameters were recorded continuously (every four minutes). Probes were placed near the water intake and temperature, conductivity, turbidity, water level and flow rate were measured in the canal. Flow rate in the Nive was obtained from the DDE (Direction Departementale de l'Equipement). Rainfall and light level (radiance) were recorded. Barometric air pressure was obtained from Meteo-France. All data are expressed in universal time (GMT).

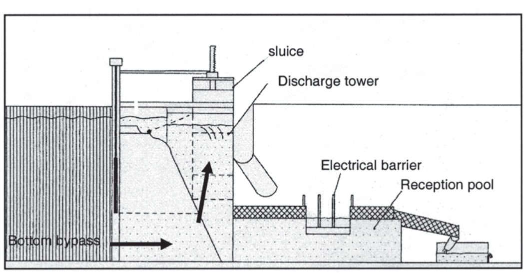


Figure 4. Side view of the trap area and discharge tower. Fish going through the bottom bypass swim up in the discharge tower and fall into the reception pool when the sluice is open.

Eel measurements

Measurements were taken on all eels caught in the trap: total length (Lt), weight (W), horizontal and vertical diameters of the eye (Dh, Dv), and head width. Eye index (EI) was calculated according to Pankhurst (1982):

$$EI = \left(\frac{Dv + Dh}{4}\right)^2 \times \frac{\pi}{Lt} \times 100$$

Eels were also identified as yellow or silver eels according to their skin color and eye index (Durif et al. 2000). Clove oil was used as an anesthetic for all measurements and tagging (Peake 1998).

Telemetry, tagging, and release of eels

Radio-telemetry was used on fifteen of the eels caught in the trap. Two different types of datalogging radio receivers were used: ATS 2000B and Lotek SRX-400. Two models of transmitters (ATS) were used depending on the size of eels: "10/28" (i.e., length = 45 mm, diameter = 11 mm, and weight = 8 g) and "10/35" (i.e., length = 56 mm, diameter = 12 mm, and weight = 11 g). Both were equipped with motion sensors, which emitted a different signal when eels had not moved for more than eight hours transmitters were implanted by surgery in the abdominal cavity (Baras and Jeandrain 1998). An incision was made in the posterior part of the abdomen and stitched with nylon thread. A hole was made through the body wall 2 cm behind the incision in order to leave an exit for the antenna. The eels were released within 12 hours after the surgery. One eel recaptured eight days after surgery exhibited no infection due to the transmitter. Nine eels were released in the power canal, six other eels were released in the forebay area. Certain eels were also marked with PIT-tags on their dorsal surface. These individuals were used to test the efficiency of the electrical barrier.

Radio-tracking

Fixed stations were established at eight locations (Figures 1 and 2) around the power plant. Stations T1 and T3 were fixed along the water intake in front of the trashrack and corresponded to turbines 1, 2, and 3. Stations S and B were located respectively in front of the surface and bottom bypasses. The four other receivers covered a distance between 20 and 40 m long; one was placed at the head of the canal. A second antenna was stretched across the main channel of the river Nive. A third receiver detected eels in the tailrace, thus eels that had transited through the turbines and the fourth antenna was set downstream from the trap in the spillway. Tracking was also conducted by foot with a portable receiver on a towpath, 2 km upstream of the dam down to the estuary (23 km). The telemetry monitoring was continued after trapping had ceased, until 15 December.

Results

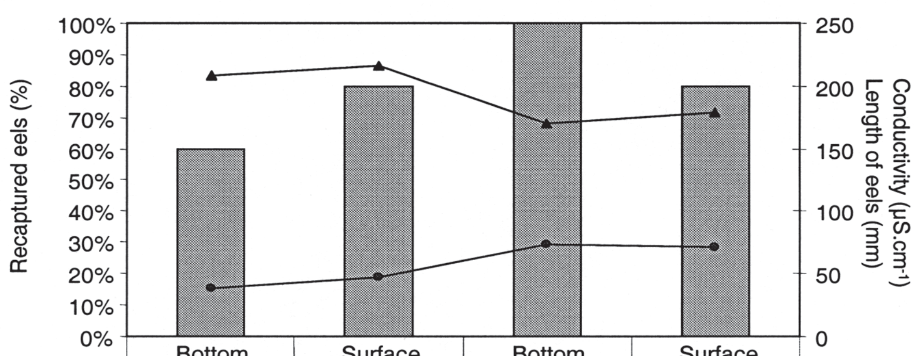
Timing of downstream runs and characteristics of silver eels.

A total of 66 eels was collected in the trap between 6 October and 6 December. Downstream runs were irregular and 77% of the eels arrived between 14 and 21 November. 90% of the eels migrated at night. Trapping was inefficient on the night of 18 November as floods caused damage to the trap installation.

Lengths of eels ranged from 30 to 93 cm. Silver phase eels were all over 42 cm so we assumed all were females (Bertin 1951; Rossi and Villani 1980; Vøllestad and Jonsson 1988; Lecomte-Finiger 1990). Eels either had a typical silver eel appearance: white belly, dark back, well separated by the lateral line; in other cases the color was more bronze-like on the side and on the ventral surface rendering it difficult to identify these individuals as silver by color alone. Eye index is related to the degree of maturation of eels (Pankhurst 1982). Durif et al. (2000) showed for *A. anguilla,* that this is also true at an early stage of silvering, before changes of color actually occur. Four eels were obviously yellow as their eye indices were lower than four. Eye indices of silver eels ranged between 6 and 13.5 (mean of 9.5). Accordingly, eels migrated at different phases of the metamorphosis process.

Electrical barrier efficiency

Small samples of eels marked with PIT-tags were released in the reception pool in order to test the efficiency of the electrical barrier. Four tests were conducted with both bypasses as hydraulic circulation in the reception pool changed according to the bypass in use, the flow from the surface bypass being directed towards the electrical barrier. Number of recaptured eels (efficiency) varied between 60 and 100% (Figure 5). Changes in conductivity were not important enough to affect the efficiency of the barrier. This is supported by the fact that, unexpectedly, the number of recaptured eels was higher when conductivity was lower. Efficiency (with the bottom bypass) was lower when small eels were tested.



	Bottom	Surface	Bottom	Surface
Recaptured eels	60%	80%	100%	80%
Mean length of eels	38	47	73	72
Conductivity	208	217	170	180
Number of eels	5	5	10	10

Figure 5. Efficiency (percentage of recaptured eels) of the electrical barrier according to the bypass in use, conductivity and length of eels.

Behavioral study of downstream migration

Migration routes—Radio-tagged eels were released either in the power canal or the forebay. Ten eels out of 15 swam upstream out of the canal. Once upstream of the study site, eels had two possibilities to migrate: they either entered the canal towards the power station or passed over the dam to reach the main channel of the river; the latter was only possible when the dam was overflowing. The majority swam over the dam as only 5 eels out of 15 passed through either the turbines or the bypass.

Downstream runs in relation to environmental parameters—Radio-tagged eels did not migrate during the new moon nor did the number of trapped eels increase. In contrast, strong relationships between downstream runs and changes in other environmental conditions were observed through captures in the trap and through individual behaviors of radio-tagged eels. Downstream runs increased when water temperature dropped from 15 to 10°C over a period of four days (Figure 6). Major run periods corresponded to heavy rainfall, an increase in flow rate, turbidity and conductivity, espe-

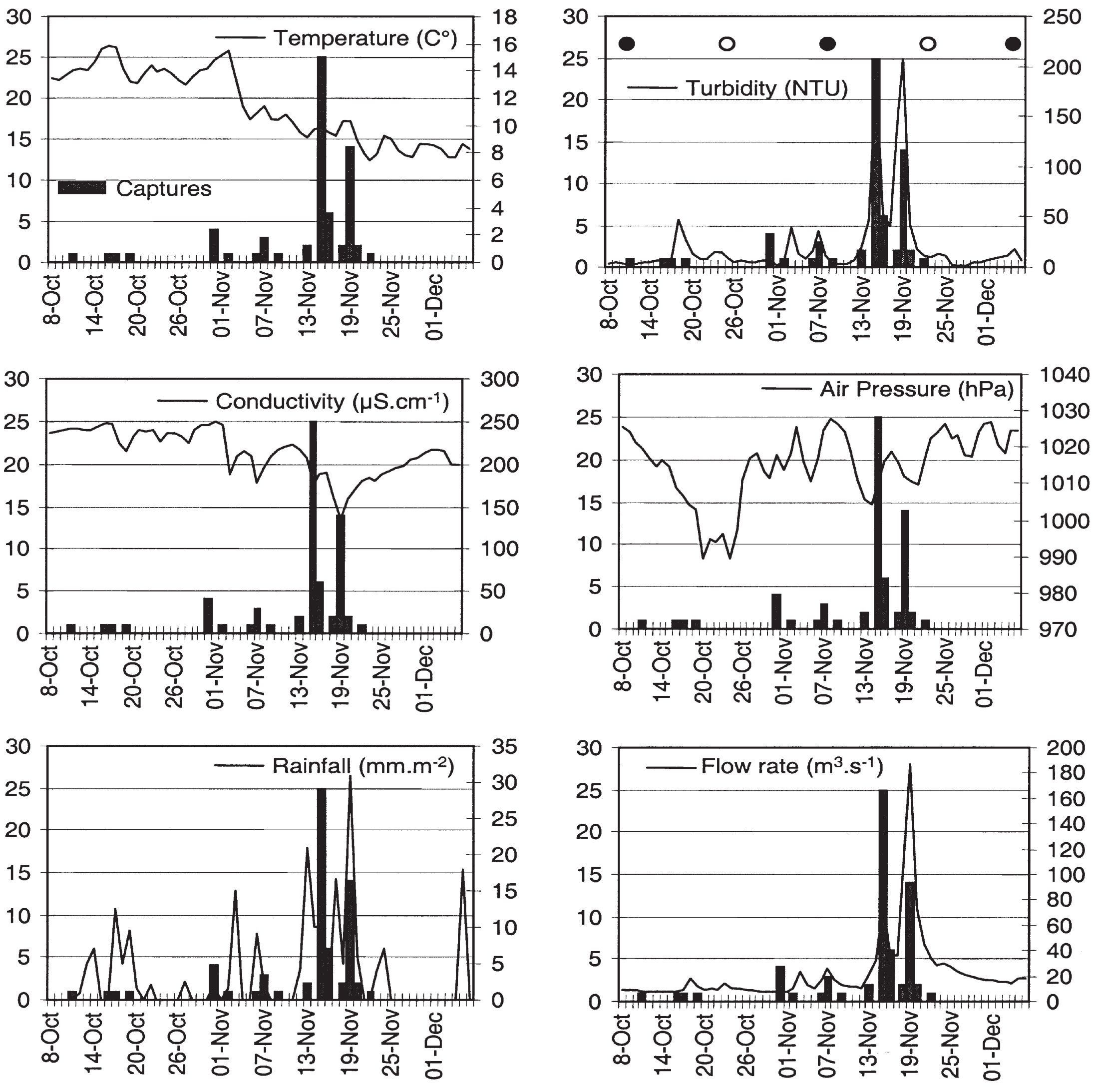


Figure 6. Daily captures of migrating eels in the trap in relation to moon phases and environmental parameters (*x*-axis: sample date; *y*-axis (left): daily number of captures; *y*-axis (right): value of measured parameter).

cially between 14 and 21 November. Captures of eels were significantly correlated ($P < 0.05$) with rainfall, turbidity, flow rate, and conductivity (Table 1). On 1 November, four eels were captured two days before the actual changes in rainfall, flow rate, turbidity, and conductivity. The only noticeable change coinciding with these captures was a slight rainfall and a drop in air pressure. No migration occurred between 20–30 October even though air pressure had notably decreased (Figure 6).

Observations of radio-tagged eels characterized individual behaviors before and during their migration down to the estuary. After release, eels all swam to two specific locations either in the forebay area or 2–3 km upstream of the facility where they remained for various periods of time. They moved very little and as transmitters were equipped with a motion sensor, it was noted that they often remained still for four to five days at a time. Timing between release of eels and directed downstream movements ranged from 1 to 28 days. Thus, departure did not seem to be related to the day of release but corresponded to specific environmental conditions (Figure 7). Downstream runs of tagged fish took place on three occasions. Not all eels made a continuous run to the estuary. Seven eels (out of 15) stopped less than 24 hours after they had left. Their second run took place 1–26 days later (Figure 7; Table 2) when environmental conditions were favorable. One eel was recaptured in the trap. Migration episodes occurred when air pressure dropped (1005 hPa minimum) but not all decreases in air pressure resulted in downstream movements. Conductivity also decreased to at least 175 mS cm^{-1} during these episodes. High turbidity and flow rate peaks appear to be the parameters most related to peaks in eel runs, but on 16 and 17 November, eels stopped moving when turbidity and flow rate decreased suddenly. They resumed their migration when again these two parameters increased. Two individuals (tags 410 and 871) did not follow the same pattern in their behavior as their migration occurred outside of the environmental window, no eels were caught in the trap on those days, and environmental parameters were not favorable. Tag signals of eel 871 were lost on the 24th, but because this eel was not looked for on the following days we cannot be sure it had really left on that day. Eel 410 was the only recaptured tagged eel, and we cannot make conclusions regarding its migrating behavior.

Because time of passage had been recorded at fixed receivers, we analyzed onsets of migration on a 24 hour scale. Before their run tagged eels were less than 3 km away from the receivers; thus the recorded time corresponded approximately to their time of migration. Departures of eels to environmental parameters showed significant variations over a 24 hour period on days when migrations occurred (Figure 8). Since continuous data on flow rate in the Nive was not available, we used turbidity as a surrogate. Almost all eels departed when radiance was lower than 100 µmol s^{-1} m^{-2}. One eel left at midday when radiance was around 300 µmol s^{-1} m^{-2}; however, turbidity was maximum at that moment. Migration occurred when turbidity was at least 60 NTU except for eel 410 on 30 November (Figure 8).

Behaviors of migrants in the forebay

Radio-tagged eels—The first nine radio-tagged eels were released in the power canal. Six of them swam upstream and did not enter the forebay area at all. It was further decided to release the six other eels closer to the power station. In

Table 1. Pearson correlation matrix of daily catches of eels in the trap and values of environmental parameter. Correlation coefficients in bold are statistically significant ($P < 0.05$).

	Eels	Temperature	Turbidity	Conductivity	Air Pressure	Rainfall	Flow rate
Eels	**1**						
Temperature	–0.091	**1**					
Turbidity	**0.824**	–0.147	**1**				
Conductivity	**–0.395**	**0.734**	**–0.602**	**1**			
Air Pressure	–0.078	**–0.405**	–0.121	–0.276	**1**		
Rainfall	**0.412**	–0.092	**0.587**	**–0.403**	–0.084	**1**	
Flow rate	**0.637**	–0.325	**0.890**	**–0.757**	0.004	**0.591**	**1**

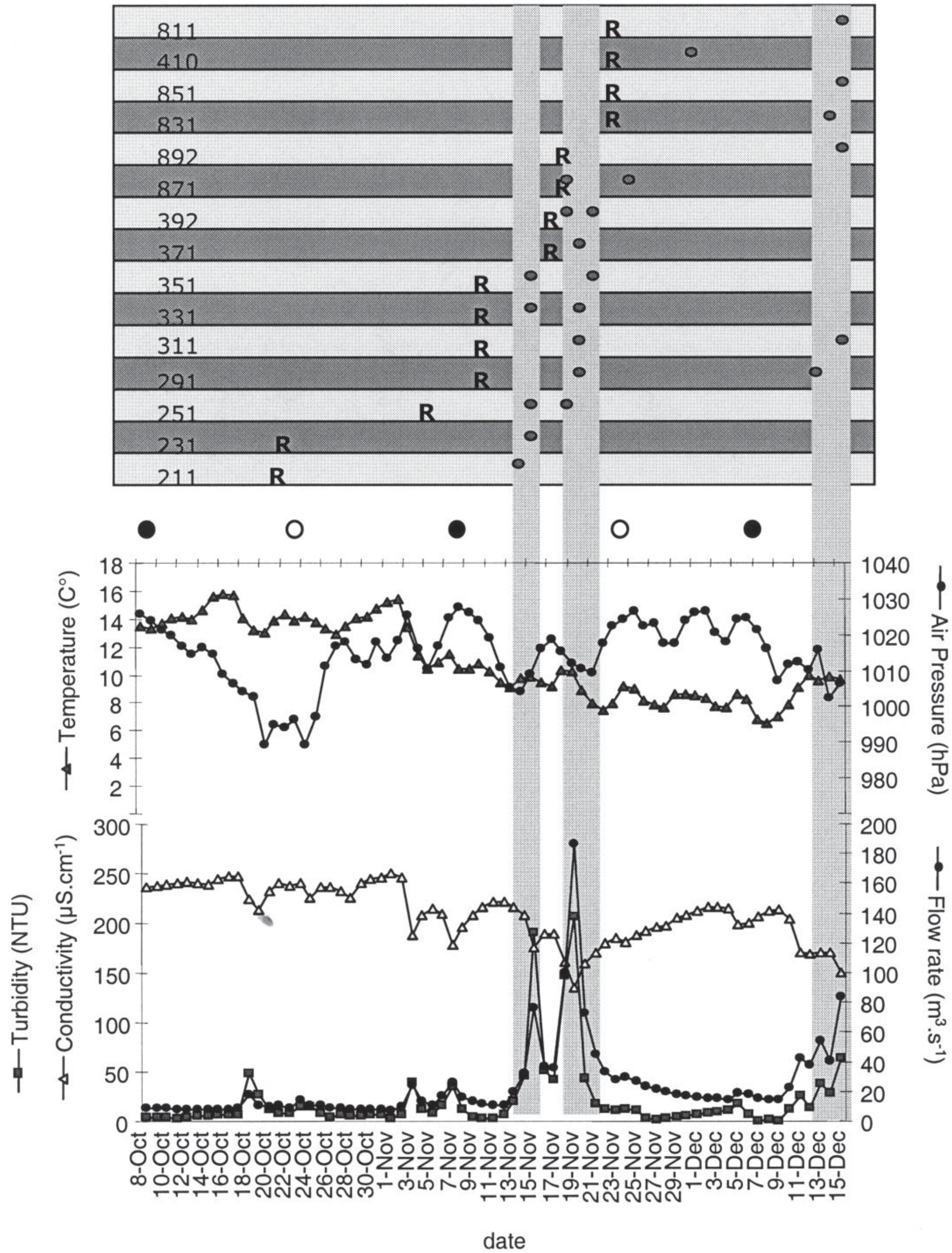


Figure 7. The graphic on the top shows for each tagged individual their date of release (R) and the day(s) on which they made a downstream run. All migration episodes lasted less than 24 hours and were thus represented by a dot. Tag numbers are listed on the left. Departures of eels are related to moon phases and environmental parameters (bottom graphics). Time intervals represented by shaded rectangles indicate the time periods (favorable meteorological windows) when almost all eels migrated.

Table 2. Movements of the 15 radio-tagged eels. Nine eels were released in the power canal and 6 in the forebay. For the first downstream run, date and time (hours) were obtained from receivers. Their second run usually occurred further downstream, out of the surveillance zone and date was obtained from manual tracking.

Release location	Tag number	Length of eels (cm)	Date of release	Upstream move-ment	Dow-stream passage	Rest period before 1st run	First run		Rest period before 2nd run	Second run
Power Canal	211	57	20 Oct.	Yes	Dam	23 d	14 Nov.	23:28		
	231	63	21 Oct.	Yes	Dam	23 d	15 Nov.	11:57		
	251	59	4 Nov.	Yes	Dam	11 d	15 Nov.	18:27	3 d	18 Nov.
	291	68	9 Nov.	Yes	Dam	10 d	19 Nov.	1:28	24 d	13 Dec.
	311	65	9 Nov.	Yes	Dam	10 d	19 Nov.	3:20	26 d	15 Dec.
	331	68	9 Nov.	Yes	Dam	6 d	15 Nov.	4:32	3 d	18 Nov.
	351	73	9 Nov.	Yes	Dam	6 d	15 Nov.	5:32	6 d	21 Nov.
	371	65	16 Nov.	Yes	Dam	3 d	19 Nov.	18:16		
	392	61	16 Nov.	No	Turbines	2 d	18 Nov.	19:34	3 d	21 Nov.
Forebay	871	81	17 Nov.	No	Bottom bypass	1 d	18 Nov.	14:30	5 d	24 Nov.
	892	91	17 Nov.	Yes	Dam	28 d	15 Dec.	18:34	28 d	
	831	93	22 Nov.	No	Bottom bypass	22 d	14 Dec.	16:42		
	851	82	22 Nov.	No	Bottom bypass	23 d	15 Dec.	18:38		
	410	71	22 Nov.	No	Bottom bypass	8 d	30 Nov.	18:02		
	811	90	22 Nov.	Yes	Dam	23 d	15 Dec.	15:32		

total, the behavior of nine eels was observed in the forebay area (Table 2). Only one individual (Tag 392; head width of 3.5 cm) transited through the turbines (T1). It was not detected by any other receiver and we therefore conclude that it headed straight for the turbines and did not search for any other means of passage. At that moment the generated flow rate was at its maximum (approximately 28 $m^3 s^{-1}$). Four eels went through the bottom bypass at moments when the generated flow varied between 15 and 28 $m^3 s^{-1}$. They all first made incursions in front of the trashrack. Their head width ranged between 4.5 and 6 cm so we assumed that the narrow trashrack blocked their passage. Two eels (Tags 811 and 892; head widths of 5 and 5.5 cm) spent only five minutes in the forebay area before swimming upstream. The generated flow was approximately 10 and 20 $m^3 s^{-1}$, respectively. Both were detected by the trashrack and bottom bypass receivers. Eel 211 (head width of 3.5 cm) stayed 34 hours in the forebay area before the upstream movement. It moved on rare occasions to the bottom bypass and trashrack but did not go through either even though its size permitted passage through the bars. The generated flow during that period was approximately 5 $m^3 s^{-1}$. Eel 311 (head width of 4 cm) returned twice to the power plant (Figure 9). It made several incursions in front of the trashrack and the bottom bypass but did not transit through either structure. The generated flow at that time was approximately 3.9 $m^3 s^{-1}$. It left the canal on 1 December and migrated over the dam on 15 December. The flow generated by the plant was also low on that day: 5 $m^3 s^{-1}$. For all observed eels, incursions were most frequent around the trashrack then at the bottom bypass. Very few movements were detected around the surface bypass.

Bottom versus surface bypass—Monitoring of radio-tagged individuals showed that eels were more attracted to the bottom bypass than the surface bypass. Attractiveness of both bypasses was also evaluated by daily captures according to the bypass in use. During the first part of the study, we were able to maintain a 24 hour cycle until 15 November for each bypass. The number of eels trapped with the bottom bypass was considerably and significantly greater (94%) than with the surface bypass (6%) (chi-square test, $P < 0.1$). However, as trapping conditions were considerably ameliorated with the bottom bypass because fewer leaves and debris reached the reception pool, the direct comparison of

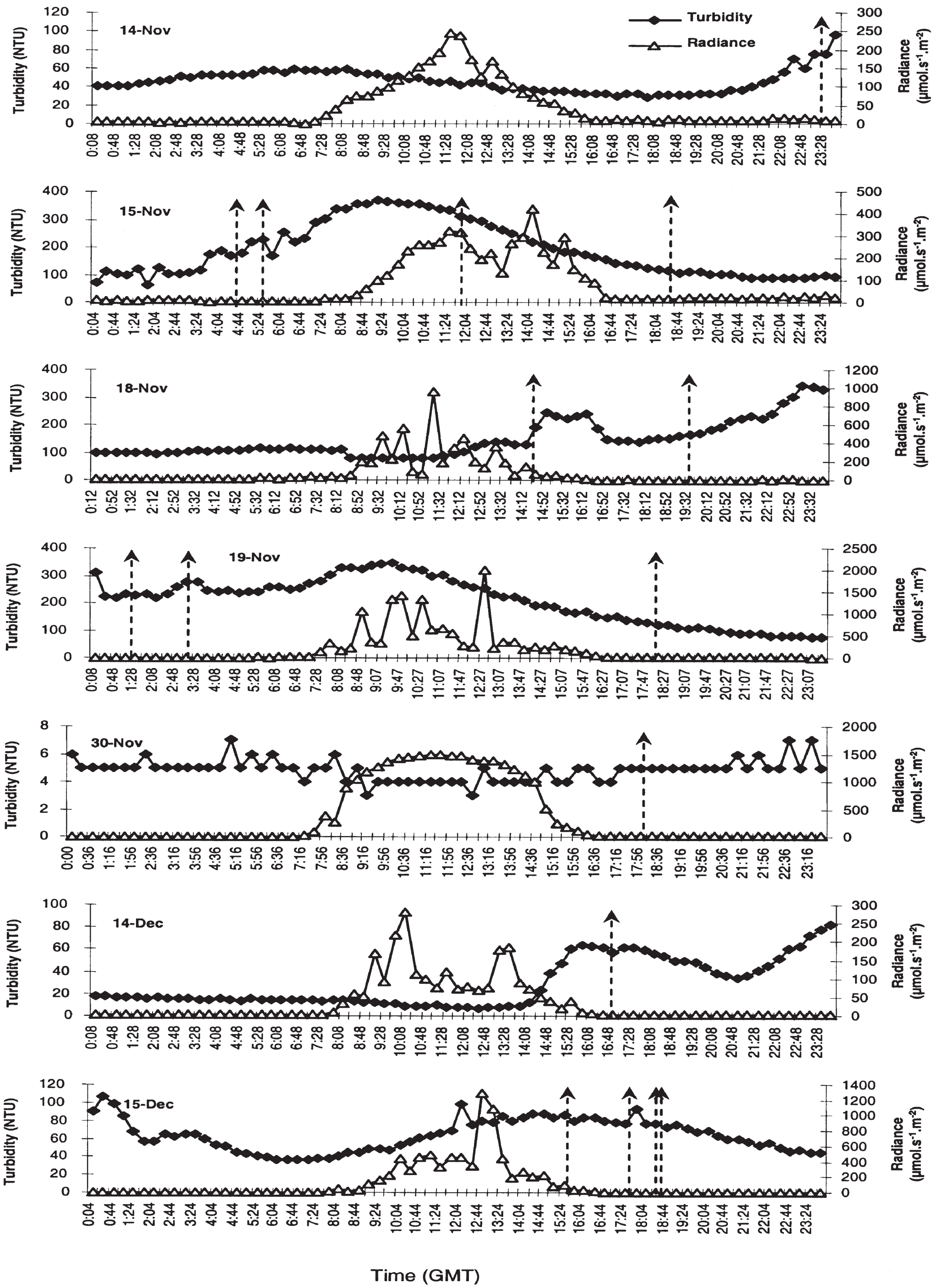


Figure 8. Migrating behavior of eels at a 24 hour scale in relation to radiance and turbidity. Each graphic represents one day. Arrows correspond to their timing of departure (time at which they were detected by receivers).

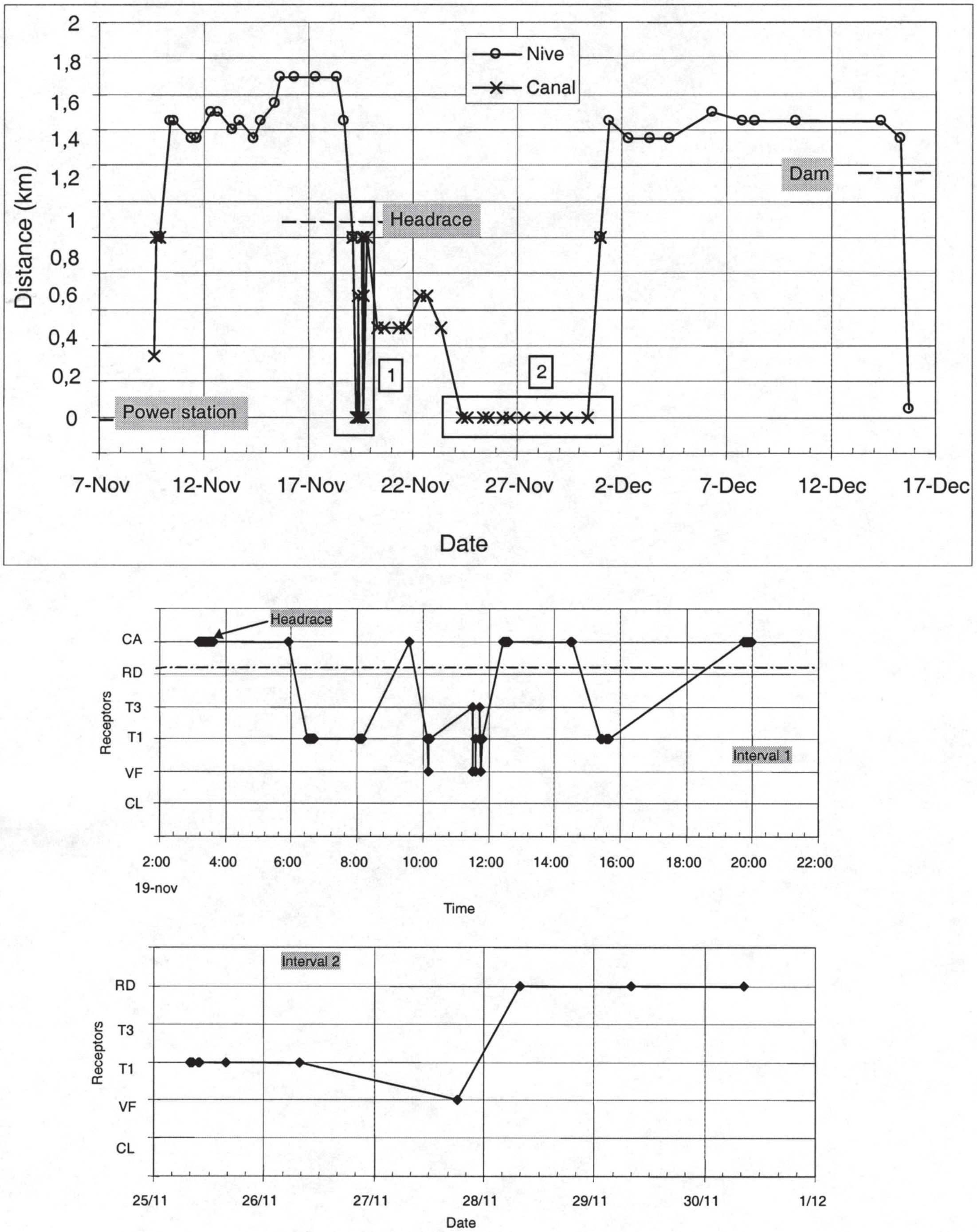


Figure 9. Behavior of eel 311 through radio-tracking data. The two lower graphics represent enlargements of the time the eel spent in the forebay area, materialized in the top graphic by rectangles 1 and 2.

captures is biased. Still, this result is supported by the behavior of telemetered eels.

Discussion

Characteristics of silver eels

No male eels were captured in the trap during the study period. Observations of males migrating earlier than females have often been made (Tesch 1979; Haraldstad et al. 1985; Jessop 1987). This would be due to a difference in geographical location of the two sexes: as size of eels increases with distance from the sea, males would be located further downstream (Deelder 1954; Tesch 1979; Helfman et al. 1984; Vøllestad et al. 1986; Moriarty 1986; Helfman et al. 1987; Krueger and Oliveira 1997). The fact that the larger eels arrived later at the study location supports this. Either, our study site was located too far upstream to catch any migrating males, or we missed a peak of migration as trapping started in early October, whereas migrating season may start sooner. Another possible explanation concerning the absence of males in our sample, is that smaller eels (i.e., males) were entrained in the turbines. However, 26% of the total catch had a head width less than 3 cm (clear distance between rails of the trashrack) so the lack of males cannot be entirely attributed to passage through turbines.

Behavior of downstream migrants in relation to environmental parameters

Downstream migration was analyzed by two means: telemetry and trapping of eels. Effect of handling and radio-tagging of eels on their behavior is difficult to assess (Richkus and Whalen 1999). We detected no observable influence of tagging on migrating behavior over the course of the study. Upstream movement of eels after their release may have been a short term response to capture, handling, and tagging. Although, this behavior could also be attributed to the sudden change of environment when eels approached the power plant and the lack of a suitable area for them to remain until they resumed their migration. Moreover, in the present study the delay between release of eels and onset of migration was extremely variable and strongly related to environmental parameters. All departures of radio-tagged eels corresponded to peaks of migrants in the trap. This supports the assumption that the potential bias induced by surgical implantation of transmitters on a certain number of individuals is limited.

Temperature has been largely identified as a probable trigger for downstream migration. Although no definite threshold value can be given for downstream runs of eels, it is well known that migration coincides with a drop in temperature (Lowe 1952; Westin and Nyman 1977; Westin and Nyman 1979). In our study, an increase in the number of migrating individuals actually took place when temperatures dropped significantly from 14 to 10°C. A sudden decrease in temperature, rather than a threshold may be a trigger for downstream migration. This would explain the wide variability in thermal preferenda at the onset and during migration as well as the unexpected spring/summer silver eel runs observed by fishermen and other researchers (Frost 1950; Boëtius 1967; Haro 1991). Migration episodes may also correspond to drops in barometric pressure (Lowe 1952; Deelder 1954; Hvidsten 1985). Here again, it seems that there is no threshold value as migration did not increase when pressure was at its lowest, but that the effect may have been induced by the sudden change.

Four environmental parameters were significantly correlated to eel catches: turbidity, conductivity, rainfall and flow rate. These variables were all correlated. Observations of radio-tagged eels gave us clues as to which parameter had an influence on migration. The 24 hour scale observations suggest that eels wait for the darkest conditions to migrate when radiance is low and turbidity is high. This parameter is not a trigger but a requirement as luminosity will inhibit migration since eels rarely migrated during daytime. It is probably through the effect of light that moon phases influence migration events as there was no link between lunar cycle and downstream runs. Conductivity is proportional to salinity. The maximum change in conductivity during the study period was 100 mS cm^{-1}. This corresponds approximately to a salinity lower than one. Whether eels can detect such small salinity differences is unknown and needs further testing.

Both approaches of the migration phenomenon—telemetry and trapping—indicate that water discharge seems to be one of the most influential parameters such as stated by fishermen and other researchers (Frost 1950; Lowe 1952; Deelder 1954; Hain 1975; Tesch 1979; Haraldstad et al. 1985; Hvidsten 1985; Vøllestad et al. 1986; Vøllestad et al. 1994; Hadderingh et al. 1999; Boubée et al. 2001). We believe it acts as a trigger as well as a migratory vector such as for glass-eels (Elie and Rochard 1994) that will allow migration if the above environmental conditions are met.

Variations in barometric pressure and consequently water temperature appear necessary for the onset of the silver eel migration and may have a "wakening" effect on the eel. These changes may stimulate the first movements of eels after their sedentary period (yellow phase) during which metamorphosis occurs. If conditions in light (luminosity/turbidity) are favorable, then adequate water discharge will trigger eels to migrate. Thus, intensity of runs will depend on the synergy of these parameters which will determine the onset and the persistence of the phenomenon.

As we have seen in our study it may take several favorable "meteorological windows" for eels to complete their descent of the river even over a short distance as in the case of the Halsou system (23 km). Eels alternated between periods of migration and rest. Observations were made on a limited number of individuals as radio-monitoring can only involve small samples at a time. Moreover, during a mark–recapture experiment, Therrien and Verreault, (this volume) observed that migration speed was highly variable as eels took 2–44 days to travel a distance of 7800 m. In our study, all eels did manage to reach the estuary before the end of the migratory season, however, in a larger catchment with greater distances to swim, and if unfavorable migrating conditions persist, one can hypothesize that silver eels may not complete their descent in time, particularly when obstacles (dams, hydroelectric facilities) are present. The silvering process would continue as eels descend the river. This would explain the variability in stages of metamorphosis observed in silver eels.

Behavior of eels at obstacles and bypasses

Our results show that bottom types of bypasses may be more appropriate for this species according to their behavior during downstream migration. However, as we have already mentioned, the comparison between daily catches with either bypasses was biased: first of all, because trapping efficiency was considerably improved with the bottom bypass and second, because the number of eels varied from day to day depending on environmental conditions. Thus, monitoring of radio-tagged eels appears to be the most appropriate method. In this way, we did observe that eels were more attracted to the bottom bypass, but these observations were made on a limited number of individuals and this point needs further investigation. Turbine intake flow is still very attractive for downstream migrating eels compared to the low bypass flow. Moreover, it seems that only body size will prevent eels from passing through trashracks when approach velocities are high. Male and female silver stage European eels shorter than 65 cm have a head width equal to, or smaller than 3 cm, and are thus likely to pass through turbines. Under these circumstances, the only demonstrated solution to turbine entrainment of eels is to decrease the bar spacing in front of water intakes. Further studies should lead towards defining a threshold value for bar-spacing according to size of migrants. Still, high approach velocities can result in impingement and death/injury of eels, regardless of bar spacing (Haro, personal communication).

In our study, the majority of eels arriving in the forebay chose to pass over the dam upstream of the canal. During a similar study on the behavior of silver American eels at a small hydroelectric facility, (Haro et al. 2000) observed that telemetered eels moved upstream several times and seemed reluctant to pass the power plant. Watene et al. (this volume) indicate the same type of behavior on telemetered individuals, as one eel made up to 23 attempts to pass the facility. This particular behavior of eels could be an advantage as bypasses could be installed further upstream; in the case of Halsou, at the dam level. Finally, another potential solution is to cease power generation during migration episodes as the runs seem to be restricted to short intervals corresponding to specific "meteorological windows." This would be feasible in small hydroelectric plants such as Halsou. Boubée et al. (2001) indicate that rainfall can be a good predictor as it anticipates water flow. Regardless of the mitigation measure (alternate generation schedule, installation of bypasses and behavioral or physical barriers) site specific models including several practical environmental parameters (temperature, rainfall, turbidity and luminosity) must be developed to predict migrations of silver eels and optimize their safe passage of hydroelectric facilities.

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