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Predicting downstream migration of silver eels in a large river catchment based on commercial fishery data

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Abstract Worldwide, populations of catadromous eels are in decline. Knowledge on downstream migration patterns is needed to mitigate damage caused by hydroelectric stations. Silver eel migration and its relation with environmental factors were investigated using data from a fishery located in the lower reaches of a large catchment (110 000 m^2). Migration days, indicative of different proportions (50%, 75% and 95%) of the annual run of eels (i.e. represented by the annual catch), were predicted using discriminant analyses. Efficiency of prediction was 58–95% depending on the proportion of the run targeted. The onset of migration was correlated with sunshine hours, August temperature and discharge. Julian days (i.e. photoperiod) was significantly correlated with migration days, indicating between-year similarity in the dynamics of the runs. The size of migrants varied within the migration season, reflecting differences in their initial spatial distribution.

KEYWORDS: *Anguilla anguilla*, downstream migration, environmental factors, fishery data.

Introduction

The eel, *Anguilla anguilla* L., is a semelparous species that spawns in the Sargasso Sea (Schmidt 1922). Recruitment of young eels to the continental stocks of Europe has declined to about 1% of its level in the late 1970s. Oceanic and continental factors, among which barriers to migration, have been implicated in this decline (Dekker 2003; Starkie 2003). Turbine entrainment and impingement of silver eels on the screens also cause massive mortality of adult eels (Travade & Larinier 1992; Hadderingh & Baker 1998). Up to 100% of eels entering intakes may be injured (Larinier & Travade 1998). The situation has become critical for eels and management solutions are urgently needed.

There are several ways to mitigate mortality of catadromous fish at power stations. Most involve a bypass coupled with a turbine deflection system, which are generally activated at specific periods. Other types of solutions rely on trapping the migrants before they reach the obstacle and transporting them downstream of the power station. Regardless of the solution, being able to predict timing of eel migration would be essential to optimize and carry out mitigation measures.

Silver eel downstream migration occurs primarily in autumn; in France it generally starts in October (Bertin 1951). Migratory movements occur during dark stormy nights. Eel runs have been correlated with factors related to precipitation and flood events, e.g. discharge, rainfall, wind, atmospheric depressions and turbidity. Microseismic activity and lunar phase have also been shown to affect the runs (for review EPRI 2001; Haro 2003). Although significant relationships exist between environmental factors and eel movements, predicting the timing of eel runs has proven to be challenging (EPRI 2001). The role of environmental factors appears to be site-specific and eels respond to different cues in lake/marsh areas than large rivers. Attempts have been made to model such migration patterns (Hvidsten 1985; Vøllestad, Jonsson, Hvidsten, Næsje, Haralstad & Ruud-Hansen 1986; Haro, Castro-Santos, Whalen, Wippelhauser & McLaughlin 2003)

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but results in terms of prediction of number of migrating eels are low because models have to take into account not only environmental factors, but also the number of eels physiologically ready to migrate (i.e. silver-phase eels) in a given year as well as the type of hydrosystem (river, lake, marsh) and the presence of obstacles (dams and power stations). In the case of a large river catchment such as the River Loire, France (109 930 km^2), with many tributaries, such a model would be extremely complicated and may take years to build. However, the decline of eel necessitates immediate action (Anonymous 2003).

Another approach would be to predict only the major silver eel runs. A threshold corresponding to a certain proportion of the migrants could be set and a model developed to predict the passage of this proportion of migrants. This study aimed at testing such a method as well as obtaining more knowledge on the dynamics of eel downstream migration in relation to environmental factors. Analyses were carried out on 12 years of data from a commercial silver eel fishery. The thresholds set corresponded to different percentages of each year's total catch: 50% (C_{50}), 75% (C_{75}) and 95% (C_{95}). The models developed predict the total number of days (migration days) that correspond to C_{50}, C_{75}, or C_{95}. Migration days were selected according to two different methods. With the first method, called the peak analysis, migration days corresponded to the major migratory peaks that summed up to C_{50}, C_{75} or C_{95}. With the second method (time analysis), migration days were counted cumulatively from the beginning of the fishing season until C_{50}, C_{75} or C_{95} was reached. Prediction efficiencies were compared between analyses and between years.

Material and methods

Fishery data

River Loire is the largest river in France (1012 km). The silver eel fishery is located in the lower reaches, near Montjean, approximately 40 km upstream of the estuary (Fig. 1). The authorised period for silver eel fishing in France is between 1 October and 15 February, but the fishery generally operates only until the end of December because, according to the fisherman (Y. Perraud), most of the year's silver eels have migrated by that time.

Downstream migrating eels were caught with a stow net (length: 25 m, width: 10 m, height: 5 m), attached to the back of a boat, itself attached to the riverbank. The stow net was usually lowered at nightfall (around 18:00 hours local time) and raised approximately every 2–3 h until dawn (07:00 hours local time) to collect the eels and clear debris. Where this was not the case, notes were made by the fisherman on the starting and closing times. The fisherman counted and separated eels into small and large individuals. Although this was done arbitrarily, the 12-year data set was considered consistent because it was carried out by the same fisherman who consistently separated the eels around a threshold of 50–60 cm. Data on the fisherman's logbooks corresponded to the number of small and large eels caught in one night. Days when no eels were caught were differentiated from days when the fisherman did not operate. Thus, the number of fishing days per year (N_d) was defined as the number of operational days during one fishing season.

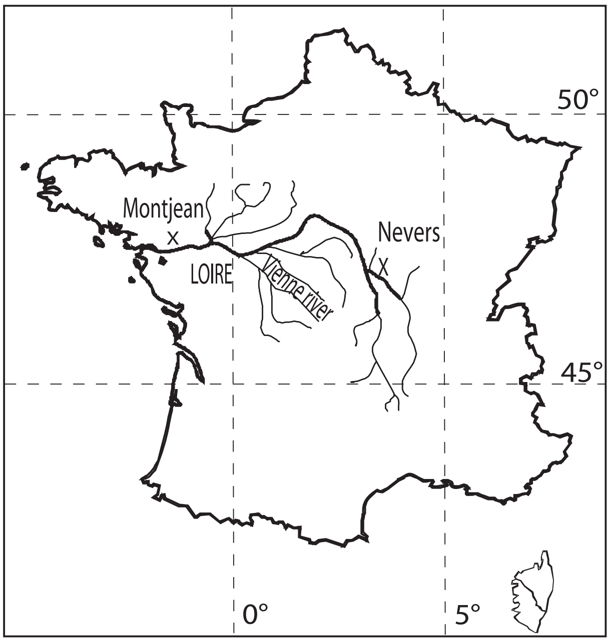

Figure 1. Map of the Loire catchment (France) and location of the silver eel fishery.

Catch-per-unit-effort (CPUE) was calculated based on the times and notes made by the fisherman as: CPUE = number of eels per night/time spent fishing. Total CPUE (CPUE_T) was defined as the sum of CPUE during one fishing season (during 1 year). The number of days (starting on 1 October) to reach 50% of CPUE_T was denoted D_{50}.

Environmental data

Discharge data for the Loire River watershed were obtained from the Diren (Direction Régionale de l'Environnement) database. Data were obtained from stations located in Montjean (at the fishery), Nevers (approximately 600 km upstream of the fishery), and on the Vienne River (Fig. 1). Daily air temperature (°C), sunshine hours (h day^{-1}), and rainfall (mm day^{-1}) data were obtained from the French national weather service, Météo France. Mean values of environmental factors during each fishing season were calculated from 1 October until the last operating day of the fishery.

Data analysis

Inferential statistics

Data were transformed [$\log(X + 1)$] to satisfy the assumption of normality. Statistical analyses were performed on a reduced data set leaving out days when the fisherman did not operate. Pearson's correlation coefficients were calculated to analyse relationships between environmental variables and the characteristics of the runs. Linear regression was used to examine trends in the size of eels during each fishing season and Julian days. A Bonferroni adjustment was made for the significance of correlation coefficients. To examine the link between the lunar cycle and eel migration, a one-way chi-squared test was used on the proportion of CPUE for 7-day periods around the full moon (3 days either side of the full moon, for example), the first and third quarter, and the new moon. A threshold of $\alpha = 5\%$ was set prior to all statistical testing.

Multivariate analysis

Stepwise discriminant analysis (SDA) and a cross-validation procedure were used for both peak and time analyses. The years with the highest number of fishing days were used to develop the model (1991–1992, 1995–1998, 2000–2001), and the remaining for the test sample (1990, 1993–1994, 1999). In the peak analysis, peak days were selected (Fig. 2a) as days with the maximum number of eels caught per night that amounted to 50% (C_{50}), 75% (C_{75}) or 95% (C_{95}) of the total number of eels caught that year. Discriminant analysis was performed on two groups: migration days and no migration days (although in reality there was some migration on those days). In time analysis, the number of days (D_{50}, D_{75} or D_{95}) to reach C_{50} (C_{75} or C_{95}) was predicted (Fig. 2b). Thus, in this analysis, the two groups corresponded to migration days including days before D_{50} (D_{75} or D_{95}) and no migration days including days after D_{50} (D_{75} or D_{95}). Environmental variables included in the analyses were: Julian days, discharge in Montjean, in Nevers and on the Vienne, temperature, rainfall, and sunshine hours. Systat 11 was used for all analyses.

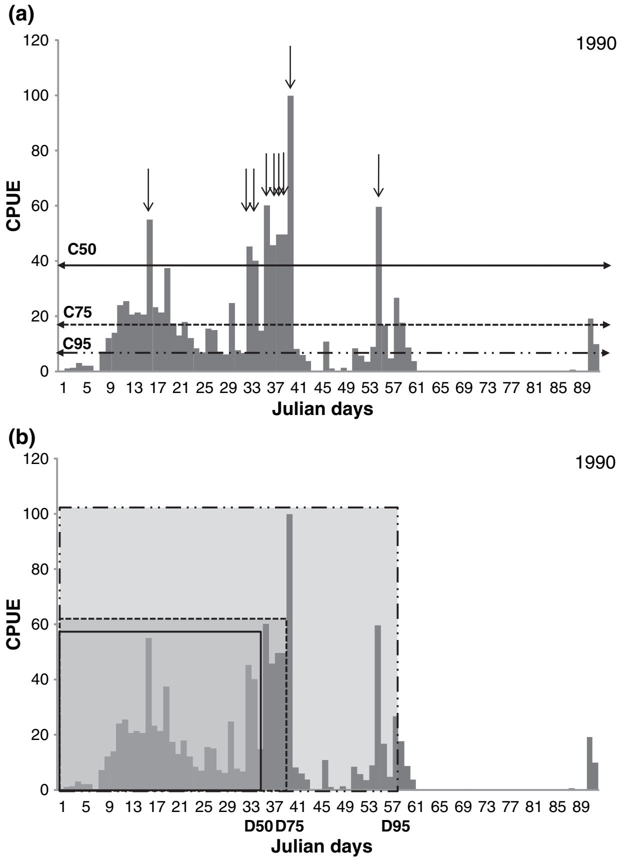

Figure 2. Eel CPUE data in 1990 illustrating how migration days were defined in the peak (a) and time (b) analyses. C50, C75 and C95 represent 50%, 75% and 95% of the year's (here 1990) total CPUE. (a) Migration days in each analysis were selected when CPUE was over the threshold (C50, C75 or C95 depending on the analysis). As an example, arrows show the days that were selected for the C50 peak analysis. (b) D50, D75 and D95 represent the number of days needed to cumulatively reach C50, C75 and C95.

Classification functions were derived from each model (peak and time analyses) and were used to determine to which category days were assigned: migration or no migration. Classification scores for each day were computed for each category according to:

$$D_i = c_i + w_{i1} \times x_1 + w_{i2} \times x_2 + \cdots + w_{in} \times x_n$$

where i denotes the category (migration/no migration), n denotes the n variables (environmental variable) which significantly contributed to the model, c is a constant, w_{in} is the weight for the nth variable in the computation of the classification score for the ith group, and x_n is the observed value for the respective case for the nth variable. D_i is the resultant classification score. An individual day was assigned to the category for which it had the highest D_i. The efficiency of the analysis was evaluated through a classification matrix, which indicated the number of days that were correctly classified.

Results

Fishing activity and CPUE

The number of fishing days per year (N_d) ranged between 30 and 66 (Table 1). Depending on the year, this represented 38–87% of the period between the start of the fishing season (1 October) and the closing day of the fishery. Elevated mean temperature reduced fishing activity (N_d and annual mean temperature: $r = -0.66$, $P < 0.05$). High mean annual discharge at the fishery also resulted in a reduced N_d ($r = -0.56$, $P < 0.05$). Very few of these fishing days corresponded with no captures: between 0 and 4 every year, except in 1999 when there were 15 days without a capture.

Total CPUE increased with N_d ($r = 0.59$, $P < 0.05$). Total CPUE was also negatively correlated with discharge at the fishery ($r = -0.72$, $P < 0.05$) and on the Vienne ($r = -0.62$, $P < 0.05$), indicating that flood conditions resulted in low $CPUE_T$. CPUE was highest during the third quarter and new moon (36% and 29% of the sum of $CPUE_T$ respectively). These values were significantly different (chi-squared test, $P < 0.05$) from the proportion of eels caught during the full moon (17%) and the first quarter (18%). Eels were caught at a wide range of temperatures: between −3 and 21 °C, but the majority (83%) were captured between 6 and 15 °C.

Size of eels

The percentage of large eels ($L_{\%}$) increased linearly throughout the fishing season (Fig. 3). Correlations between $L_{\%}$ and Julian days were significant every year ($r = 0.31$–0.84; $P < 0.05$).

Onset and duration of migration

Pooled (all years) and cumulated CPUE showed that on average, 50% of the captures were made by 8 November (day 39), 75% by 25 November (day 56), and 90% by 15 December (day 76). The day at which 50% of CPUE was recorded (D_{50}) ranged from 19 to 51 days (Fig. 4). D_{50} was significantly correlated with mean annual sunshine hours ($r = 0.75$, $P < 0.05$), indicating that low light level resulted in an early start in migration. D_{50} was negatively correlated with mean annual discharge at the fishery ($r = -0.74$) and Vienne ($r = -0.72$, $P < 0.05$). Therefore, eels migrated earlier when average discharge was high. There were no significant correlations between D_{50} and either mean temperature (calculated over the fishing period) or rainfall (mean or total amount over the fishing period); but significant correlations were found with mean August temperature ($r = 0.62$, $P < 0.05$), indicating that a warm August resulted in a high D_{50} (i.e. late migration).

Migration dynamics and environmental factors

Every year, CPUE distributions over time displayed more or less similar patterns, consisting of several discontinuous waves of migration (Fig. 5a,b,c). In

Table 1. Annual mean values of environmental factors during the fishing season between 1990 and 2001

Year	N_d/N_p	Temperature (°C)	Rainfall (mm)	Sunshine hours (min day^{-1})	Discharge (m^3 s^{-1})		
					Fishery	Vienne	Nevers
1990	61/95	9	161	183	389	101	142
1991	54/64	9	160	165	324	99	103
1992	45/54	10	151	159	905	278	301
1993	53/79	8	122	137	1046	279	281
1994	30/79	12	199	153	1376	268	291
1995	61/88	10	129	193	413	134	84
1996	42/62	10	140	181	430	122	181
1997	66/85	10	207	211	418	167	67
1998	58/83	8	158	152	621	160	114
1999	47/88	9	278	154	1006	243	169
2000	53/61	11	227	175	1164	325	221
2001	43/63	11	105	232	513	105	117

Rainfall corresponds to the sum over the fishing period.
N_d is the number of fishing days per year.
N_p is the number of days between the opening day (1 October) and the closing day of the fishery.

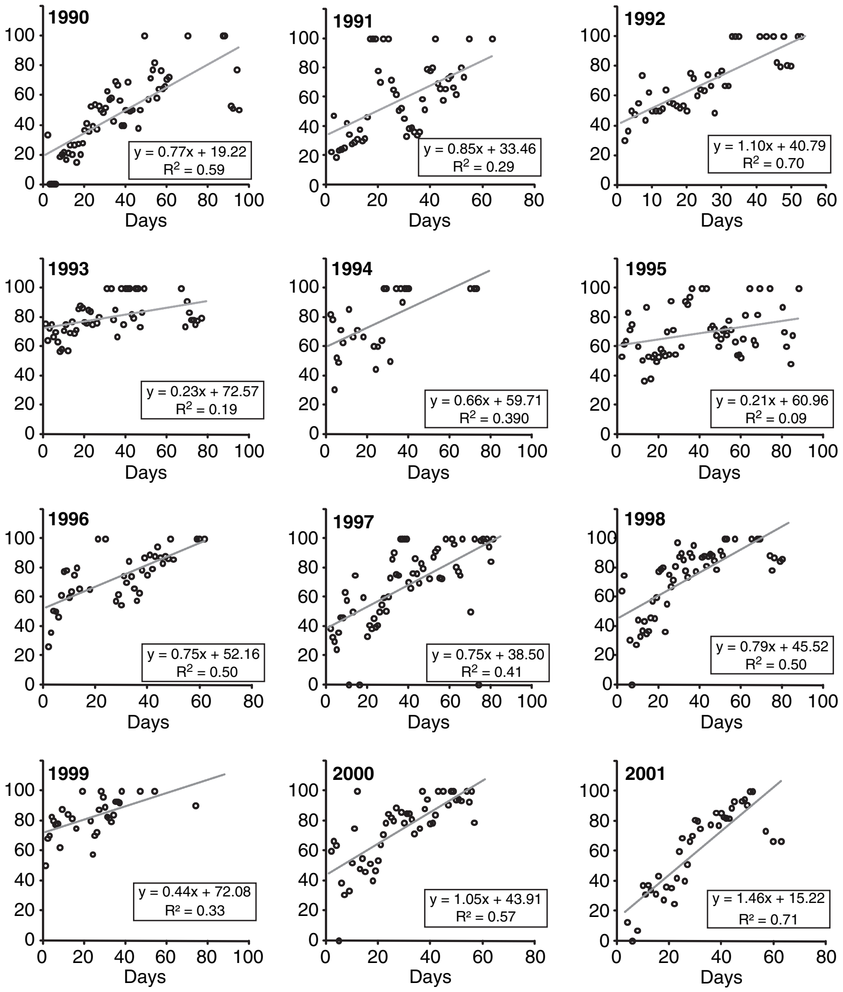

Figure 3. Percentage of large eels caught in one fishing night ($L_{\%}$) according to the number of days after 1 October between 1990 and 2001. Linear regression equations and correlation coefficients are indicated for each year.

certain years the majority of eels were caught during one or two narrow peaks (1994, 1996, 2000 and 2001), while in other years, catches were spread over time (1990 and 1993). Relationships between CPUE and discharge were not clear, but certain discharge peaks (especially on the Vienne and in Nevers) could be associated with peaks in CPUE (e.g. in 1993, 1994, 1997 and 2001), while others remained totally unexplained (1991, 1995 and 1996). Significant, but contradictory, correlations with environmental factors were found in 4 years. In 1992, CPUE was negatively, while in 1999 it was positively correlated with temperature ($r = -0.51$ and 0.46, respectively, $P < 0.05$). In 1999, negative correlations were found with discharge on the Vienne ($r = -0.52$, $P < 0.05$). However, for other years, correlations with discharge at the fishery were positive (in 1998, $r = 0.41$ and in 2001, $r = 0.47$, $P < 0.05$). Overall, correlations were statistically significant but the explanatory power poor.

Peak analysis

Significant models were obtained in all three analyses D_{50}, D_{75} and D_{95} (Wilk's lambda test: $P = 0.048$, 0.003 and 0.018 respectively). Environmental factors that contributed significantly to the analyses are listed in Table 2. Discharge at the fishery had the highest contribution in the D_{50} and D_{75} analyses, indicating a link between peaks of migrating eels and local discharge. Rainfall was the only contributing factor in the D_{95} analysis. Classification functions derived from the model are listed in Table 3. The prediction efficiencies (or percentage of correct classification) were relatively low, around 50% for all the peak analyses (Table 4). In the D_{50} analysis, prediction efficiency was

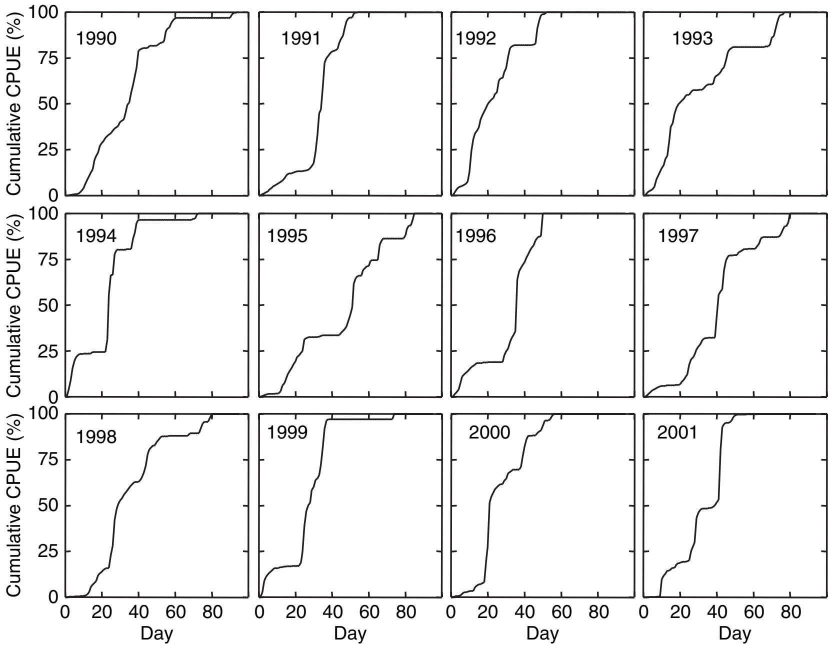

Figure 4. Cumulative sum of CPUE (%) over the fishing season between 1990 and 1991.

extremely variable depending on the year: between 17% and 83% (Table 4). Hence the number of misclassified days ranged from 7 to 44 in the D_{50} analysis, from 16 to 32 in the D_{75} analysis and from 15 to 30 in the D_{95} analysis. Prediction efficiencies over the year were a little more consistent in the D_{75} and D_{95} analyses. Thus a slightly better prediction was obtained when trying to predict all the peaks rather than some of the peaks. Prediction efficiency per year in the D_{50} analysis was negatively correlated with discharge at the fishery, and thus was lowest, when discharge was highest ($r = -0.92$; $P < 0.05$).

Time analysis

Significant models were obtained in all three analyses D_{50}, D_{75} and D_{95} (Wilk's lambda test $P < 0.0001$ in all three analyses). Four or five of the seven variables significantly contributed to the analyses (Table 2). Julian days was the major contributor in all analyses followed by discharge at the fishery. Temperature showed a negative contribution, indicating an effect of decrease in temperature. The next significant contributors were either rainfall (D_{50} analysis) or sunshine hours (D_{75} and D_{95} analyses). The latter also showed negative contributions in both analyses, indicating a stimulating effect of decrease in light level. Overall prediction efficiencies ranged from 79% to 95% depending on the analysis (Table 1). This corresponded to a number of misclassified days from 0 to 8 days in the D_{50} analysis, from 1 to 16 days in the D_{75} analysis and from 2 to 23 days in the D_{95} analysis, depending on the year. Prediction efficiencies were not significantly correlated with any environmental factor.

Discussion

Ecological significance of the peak and time analyses

The peak analyses showed that it is easier to predict all the downstream runs of eel rather than only the major ones. Rainfall was the only contributing factor when predicting 95% of the CPUE (D_{95} peak analysis). Every rain event coincided with a migratory event, but not all migratory events were accompanied by rainfall. Thus, the necessary migratory environmental conditions are met with precipitations, but they can also be achieved otherwise.

Time analyses yielded high prediction efficiencies. Migration days could be predicted with high efficiency (up to 95%), mainly using Julian days and discharge. Julian days can be considered as a proxy for photoperiod. D_{50} was also correlated with summer water temperature, sunshine hours and discharge. This is in agreement with Vøllestad, Jonsson, Hvidsten & Næsje (1994) who found that day length was the main factor explaining variation in the duration of the migration of silver eel. They also found that summer temperature

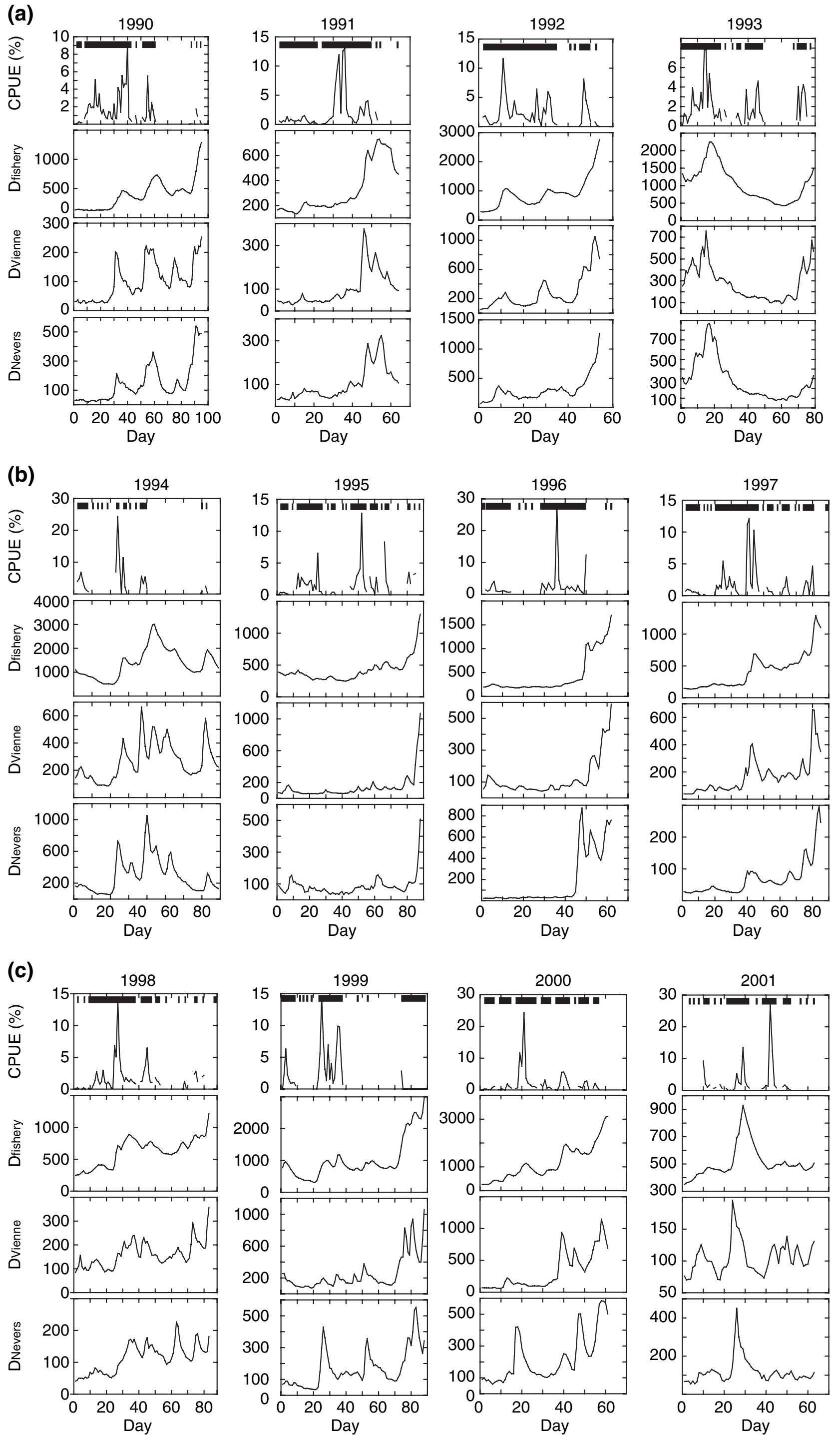

Figure 5. Eel CPUE data and discharge at the fishery, on the Vienne and in Nevers (m^3 s^{-1}) according to days (day 1 corresponds to the opening of the fishing season on October 1). Axis titles are only indicated on the far left (*y*-axis) and at the bottom of the figure (*x*-axis). Black horizontal bars represent fishing days (N_d). (a) Period from 1990 to 2003, (b) from 1994 to 1997 and (c) from 1998 to 2001.

and discharge explained almost all of the variation in the start of the eel run. High discharge resulted in faster transport for eels and therefore increased the rate of migration (early D_{50}). Thus, two factors affect the onset of migration: light level (in terms of photoperiod and sunshine hours) and August temper-

Table 2. Significant variables in each peak and time analyses

	D_{50}	D_{75}	D_{95}
Peak analysis	D_{fishery} (0.73) Sunshine hours (0.63) Rainfall (0.62)	D_{fishery} (0.64) Julian days (0.52)	Rainfall (1)
Time analysis	Julian days (0.77) D_{fishery} (0.5) Temperature (−0.12) Rainfall (0.11)	Julian days (0.74) D_{Nevers} (0.26) Temperature (−0.23) D_{Vienne} (0.21) Sunshine hours (−0.16)	Julian days (0.57) D_{Nevers} (0.44) D_{Vienne} (0.23) Sunshine hours (−0.17)

Numbers in parentheses are the coefficients of the canonical discriminant function and they indicate the contributions of the variables to the discriminant mode.

Table 3. Classification functions for the peak and time analyses

Peak analysis

	D_{50}		D_{75}		D_{95}	
	Peak	No peak	Peak	No peak	Peak	No peak
Constant	−49.822	−45.988	−49.527	−47.062	−0.953	−1.152
Log ($SH+1$)	3.713	3.415	0	0	0	0
Log (D + 1)	32.818[a]	31.689[a]	38.348[a]	37.544[a]	0	0
Log (R + 1)	3.481	2.743	0	0	2.524	1.901
JD	0	0	−0.174	−0.183	0	0
Log (T + 1)	0	0	0	0	0	0

Time analysis

	D_{50}		D_{75}		D_{95}	
	Migration	No migration	Migration	No migration	Migration	No migration
Constant	−66.561	−86.152	−44.998	−56.731	−32.307	−45.161
Log ($SH+1$)	0	0	3.357	2.882	2.339	1.941
Log (D + 1)	43.906[a]	49.756[a]	7.068[b]	9.261[b]	6.623[b]	9.543[b]
			21.759[c]	23.927[c]	23.691[c]	25.472[c]
Log (R + 1)	−2.635	−1.819	0	0	0	0
JD	0.157	0.305	0.134	0.277	−0.080	−0.014
Log (T + 1)	18.593	17.311	21.064	18.526	0	0

Values correspond to the weights to be assigned to each environmental variable in predicting either D_{50}, D_{75}, or D_{95}. SH: sunshine hours in mn.day^{-1}. D: discharge in m^3.s^{-1} ([a]: at the fishery, [b]: in Nevers, [c]: on the Vienne). R: rainfall in mn. JD: Julian days. T: air temperature in °C.

ature. It is probable that these factors activate migration via the silvering process. The advantage of depending on seasonal cues is to synchronize puberty, so that the future spawners will be physiologically ready for migration at the same time. In salmonids, temperature and photoperiod trigger smoltification (Hoar 1988). Smoltification and silvering can be compared because they both include physiological and morphological changes that prepare the fish for life in the marine environment. The hypothalamus probably receives information about light and temperature, then triggers, through the pituitary gland, the release of hormones that affect morphological and behavioural changes. The silvering process mainly takes place in August (Durif, Dufour & Elie 2005; van Ginneken, Durif, Balm, Boot, Verstegen, Antonissen & van den Thillart 2007) with low August temperatures resulting in early onset of migration. One should also observe that eels migrate earlier at northern latitudes, where summer temperatures are lower, such as in the River Imsa in Norway (Vøllestad *et al.* 1986). By leaving earlier, these eels, which have more distance to cover, will probably reach the spawning grounds at the same time as other subpopulations.

Table 4. Prediction efficiencies (%) of the classification functions in the peak and time analyses for the prediction of 50%, 75% and 95% of yearly CPUE

	Prediction efficiencies					
Year	Peak 50%	Peak 75%	Peak 95%	Time 50%	Time 75%	Time 95%
1990	74	59	56	98	90	90
1991	78	69	50	87	89	94
1992	33	58	51	89	93	84
1993	38	40	55	87	70	57
1994	17	47	47	100	87	67
1995	77	68	51	87	77	82
1996	83	55	60	88	93	90
1997	74	56	72	99	94	80
1998	50	60	59	97	90	88
1999	30	49	51	96	94	96
2000	17	49	55	94	96	79
2001	42	53	65	84	98	91
Total prediction efficiency	44 (58)	49 (59)	53 (58)	95 (91)	85 (90)	79 (85)

Total prediction efficiencies of the test sample are indicated in the last row. Efficiencies calculated with the learning sample are indicated in parentheses.

A model for eel downstream migration: triggering and releasing factors

The following model was proposed to explain the onset and dynamics of eel downstream migration. Light level (photoperiod and sunshine hours) and summer temperature can be considered as migratory triggers, although they do not directly affect migratory movements but activate silvering. At the silver stage the behaviour of eels changes and they display a kind of restlessness, which has been linked to an increase in thyroid activity (Fontaine 1975). The urge to migrate is therefore already present in silver eels but is most of the time inhibited by light. During daytime, silver eels stop swimming. Consequently, silver eel fishermen only fish after the sun sets. However, pauses may go beyond 12 h. Migrants sometimes pause for several weeks if there is an obstacle or when the light level is too high (Vøllestad *et al.* 1994; Durif, Gosset, Rives, Travade & Elie 2003; Watene, Boubée & Haro 2003). They remain motionless until the next environmental window when they resume migration, as shown by motion detector radio-tags (Durif *et al.* 2003). Eels are strongly photophobic and the inhibition caused by light surpasses the stimulatory effect of flow according to Hadderingh, Van Aerssen, De Beijer & Van der velde (1999). Cullen & McCarthy (2000) managed to deflect migrating eels using artificial lights placed 4 m over the surface of the water. A full moon and clear skies will also inhibit migration. This has always been reported by fishermen and eel scientists, as was found in this study.

Eels start their migratory movements when inhibitors (i.e. light) are suppressed. This can happen in many ways. Rain events have been closely associated with migration in this study and at several sites in New Zealand (Boubée, Mitchell, Chisnall, West, Bowman & Haro 2001; Watene *et al.* 2003; Boubée & Williams 2006). High winds are most often followed by eel runs on the River Shannon in Ireland (Cullen & McCarthy 2003). River turbidity caused by discharge can be used to predict migratory peaks on the River Nive in France (Durif *et al.* 2003). Clouds, a dark moon or a storm can all act as releasing factors allowing the eels to swim downstream during this particular environmental window. Inhibition by light will be lessened in deeper parts of the river. On the Lough Derg in Ireland, McGrath, O' Leary, Sharkey & Murphy (1979) observed silver eels concentrate near the lake outlet at the onset of migration, because the canal is much shallower than the lake, and they wait for highly turbid conditions to emigrate in a single large group. This type of behaviour can explain exceptional peaks such as in 1996 on the Loire when a long period of calm and sunny weather preceded the peak on day 35. On that day, a small rain event, that did not have any outcome on discharge, was enough to release migration. It is possible that eels were grouped in deeper parts of the river waiting for turbid conditions to cross more exposed locations.

Close associations between eel runs and flow were found in 18 of 20 studies reviewed by Haro (2003). Discharge will probably always 'release' migratory movements, but it is not a necessary condition; eels migrate downstream even in low- or no-flow hydrosystems: lakes, estuaries, marshes, or coastal areas (e.g. Okamura, Yamada, Tanaka, Horie, Utoh, Mikawa, Akazawa & Oka 2002).

Predicting migration and mitigation measures

Reducing or ceasing turbine generation at the time of downstream migration of eels is considered as one of the most cost-effective systems that could be developed. However, this relies on the ability to predict downstream runs of eels. The analyses between CPUE and environmental factors were disappointing. Visual comparison suggested that some peaks were related to certain flow events in some tributaries, but it was not possible to show this at a large scale and over the whole data set. Lags were introduced in the series to improve pattern recognition but this did not increase significance nor remove contradicting results (results not shown).

Attempts to model migration and number of migrants were made in small river catchments, but the percentages of explained variance were either very low (20%) (Euston, Royer & Simons 1997) or highly variable (from 9% to 68%; Hvidsten 1985). Haro *et al.* (2003) used precipitation events and the characteristics of the runs, in terms of cumulative eel descent, to test different hypothetical operation scenarios at a hydroelectric station. Potential reduction on mortality was as great as 50%, but the authors concluded that simulation models would have to be site-specific. Furthermore, this type of approach would only be possible for small watersheds. Being able to predict individual runs quantitatively relies on triggering factors (temperature and photoperiod), releasing factors (as defined here), including the local topography and the number of silver eels susceptible to migration.

The onset and rate of migration (time of silvering) can be predicted more efficiently (79–95% efficiency on the test sample). Even if eel runs occur discretely (in more or less high and narrow peaks), migration dynamics are regular over the years. Every year, around the same time, the same proportion of individuals migrated and can be predicted based on photoperiod, discharge, temperature and sunshine hours. Further precision can be obtained by examining summer temperatures (i.e. cold summers will result in early migration). This indicates that over the years the different portions of the catchment yield approximately the same number of eels. Prediction efficiency was very high for 50% of the year's CPUE. Efficiencies slightly decreased for 75% and 95% of yearly CPUE (85% and79%), but were nevertheless satisfactory. Such analyses should be carried out on other watersheds where fisheries data, trap data or other monitoring data exist. The use of classification functions to define migration or no migration day can easily be implemented. This could be the basis for alerts as to when bypasses and deflector systems are to be put into operation, or for setting net traps and transportation of migrants. Hydroelectric power plants may be willing to use such a system to stop generation during those migration days.

It is tempting to advise implementation of mitigation measures only during a sufficient migratory period defined as the number of days needed for a certain proportion of the population to migrate. However, early migrants should not have advantage over late migrants. A pattern in the size distribution of eels with larger individuals arriving later in the season and therefore initially located upstream of the catchment was found. Such a distribution was observed by Gandolfi Hornyold (in Bertin 1951), Helfman, Facey & Hales (1987), Oliveira (1999) and Vøllestad (1992). Although large eels are not restricted to upstream habitats and can be found in coastal zones, they seem to be the most representative at upstream locations. If mitigation measures were only to take place during the first part of the migration, then larger eels would suffer. Moreover, these larger eels (over 700 mm) have been shown to have the best reproductive potential (Durif, Dufour & Elie 2006).

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