

Silver eel mortality during downstream migration in the River Meuse, from a population perspective

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The European eel (*Anguilla anguilla*) population has decreased sharply over the past few decades owing to a combination of many factors. To determine the impact of hydropower and fisheries during the downstream migration of silver eel in the River Meuse, telemetry experiments were performed during the years 2002–2006, using 18 detection stations (NedapTrail-System®) in the river and two at the entrance to the hydropower turbines. Recaptures in fisheries were used to assess fisheries mortality. In all, 300 silver eels were surgically implanted with Nedap-transponders. For each stretch between subsequent stations, mortality rates were assessed and related to the different factors. However, to determine the overall effect on the escapement of silver eels from the River Meuse, insight into the distribution of silver eels in the entire catchment of the River Meuse is required. At two locations, mark-recapture experiments in 2002 revealed that the estimated number of migrating silver eels increased strongly in a downstream direction, suggesting that a large proportion of silver eels start their migration from the downstream stretches and tributaries of the River Meuse. Approaches and monitoring requirements that can be used to determine the impact on silver eel populations in a river basin are discussed.

Keywords: fisheries, hydropower, migration, mortality, silver eel, telemetry.

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Introduction

The population of the European eel *Anguilla anguilla* is in decline (Dekker, 2004). Many causes for the decline have been suggested, e.g. changes in the Gulf Stream, migration barriers, fisheries, habitat loss, parasite infestation, and pollution, but the relative impact of each cause remains largely unknown (Feunteun, 2002; Dekker, 2004). These factors act in combination during different life stages of the eel and may culminate in a fatal synergy if measures are not implemented (Wirth and Bernatchez, 2003). Here, we focus on the hazards faced by eels during their silver stage when moving downstream in rivers. Human impact during the descent of silver eels involves extra mortality attributable to fisheries and hydropower (Feunteun, 2002). The effect of each factor varies between river systems, depending on the intensity of fisheries and the number and allocation of hydropower plants within a catchment area. Spawner escapement from river systems has been selected as an important parameter in European eel management, requiring insight into the number of silver eels leaving a river system. Moreover, to enhance spawner escapement with effective measures, insight into the relative rates of mortality of different human impact factors is needed.

In the River Meuse, telemetry was used to identify the different sources of mortality during the downstream migration of silver eels in 2002 (Winter *et al.*, 2006). During the experiment, 150 silver eels were implanted with a transponder, released in an upstream location

of the river, then followed during their downstream migration through an array of detection stations of the NedapTrail System® (Breukelaar *et al.*, 1998). For silver eels that migrated through the Dutch section of the River Meuse, mortality attributable to hydropower was assessed to be 16–26%, and for fisheries 22–26%. The fraction that reached the North Sea was 37% (Winter *et al.*, 2006). Silver eel mortality rates, however, might differ from year to year. To estimate differences between years, an identical telemetry experiment on silver eels was carried out in the same river in 2004. In addition, we used recapture rates of transpondered eels within a monitoring programme on silver eel catches by commercial fishers (De Leeuw *et al.*, 2005) and fykenet catches within experiments at hydropower station 1 (Bruijs *et al.*, 2003) to estimate the total number of migrating silver eels in 2002 at three locations along the course of the River Meuse.

On the basis of our results, we discuss how to integrate telemetry and mark-recapture data with other information and measurements on eel population density and distribution to provide an assessment of the relative impact of the different sources of mortality at a catchment scale, a challenging task given the highly fractal dimension of most water systems (Dekker, 2000a). This is very important because knowledge of the abundance of silver eels able to reach the sea can be crucial when devising conservation strategies aimed at maximizing silver eel escapement (and therefore the spawning stock) per river basin.

Material and methods

Study area

The downstream section of the River Meuse in the Netherlands (315 km long) has seven weirs and two hydropower stations: one 254 km from the North Sea, and one 116 km from the sea (HPS1 and HPS2 in Figure 1; Winter *et al.*, 2006). Eels in the downstream sections of the Rivers Meuse and Rhine are usually fished with large fykenets with mesh size of 20 mm. In the upstream Dutch section of the River Meuse, there is electrofishing, fykenetting, and anchored stownetting at two locations, just downstream from HPS1 and HPS2.

Telemetry experiments

In the River Meuse, 18 fixed stations based on the telemetric method NedapTrail System[®] were used (Breukelaar *et al.*, 1998). Silver eels were caught with fykenets with 20 mm mesh by a professional fisher during September 2002 and September 2004 in the River Meuse at Ohé en Laak, The Netherlands (Figure 1). In total, 150 silver eels in September 2002 and 150 in 2004 were surgically implanted with transponders and released at Ohé en Laak according to the protocol described by Winter *et al.* (2006). Determination of the silversing stage was based on colouration. Even though this method is not as reliable as one based on eye diameter and pectoral fin length (Durif *et al.*, 2005), taking into account only those eels that migrated downstream after release beyond station 3 probably excluded those eels that eventually may have been misclassified as silver eels (Winter *et al.*, 2006). The eels ranged from 64 to 93 cm total length. Because of the marked sexual dimorphism (Tesch, 1977; Dekker, 2000b), it was possible to identify all eels as female. Each transponder had an instruction label and could be discovered easily while preparing eels for consumption. A clearly readable reward of €30 was offered for every tag recovered, to estimate fisheries mortality.

The effects of implanting the transponders on the mortality and behaviour of silver eels were tested in a tank experiment before the study (Winter *et al.*, 2005). There was no effect on mortality and

timing of activity, no tag loss, nor any signs of expulsion or encapsulation by tissue. The eels with implanted transponders, however, showed a significantly lower activity level than the controls.

Mark-recapture experiments

The abundance of silver eels migrating through the Dutch section of the River Meuse was estimated by mark-recapture experimentation in autumn 2002. Eels implanted with transponders in the 2002 telemetry experiment were recaptured at three sites, namely (i) the turbine fykenet catches at the exit of HPS1 downstream detection station 3, as described by Bruijs *et al.* (2003), (ii) the anchored stownet fishery in the main stream directly downstream of HPS1 detection station 3 and the weir, and (iii) the anchored stownet fishery in the tailrace of HPS2 directly downstream of detection station 10 (Figure 1). The anchored stownets at both locations are part of an annual fykenet-monitoring programme (Bruijs *et al.*, 2003; De Leeuw *et al.*, 2005).

The unbiased modified Lincoln–Petersen method, which assumes that the ratio of the marked individuals (M) to the population (N) is equal to the ratio of recaptured fish (R) to the catch taken for census (C) (Ricker, 1975; Pollock *et al.*, 1990), was used to estimate the total population of eels passing through each of the three sections during the period when transpondered individuals were caught, i.e. after the date of first detection of a transpondered eel at the detection station directly upstream of each location. The number of eels with transponders passing the detection station directly upstream of each location was used as M . From the measured R and C at each location, N was estimated as follows:

$$N = \frac{(M + 1)(C + 1)}{R + 1} \quad (1)$$

To calculate the standard deviation (s.d.), R was treated as a binomial variable when low numbers of eels (<25) were

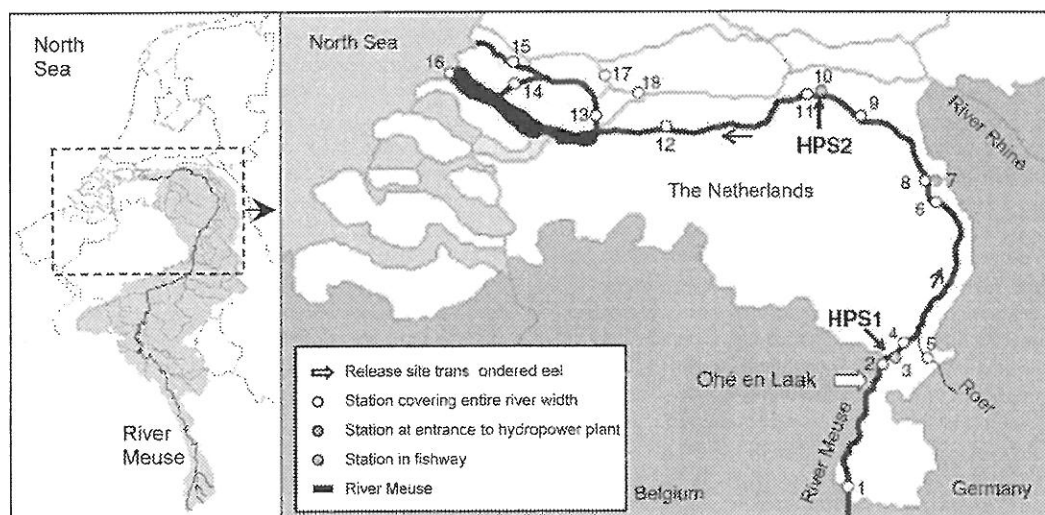


Figure 1. Map of the study area with the River Meuse catchment area (shaded) in the left panel; and (right panel) showing the 18 detection stations and the hydropower plants (HPS1 and HPS2), and the release site of the silver eels at Ohé en Laak in 2002 and 2004. Small arrows along the river indicate the direction of flow.

recaptured, and the variance was estimated according to Seber (1970) as

$$\text{var}(N) = \frac{(M+1)(C+1)(M-R)(C-R)}{(R+2)(R+1)^2} \quad (2)$$

For the turbine fykenet catches, covering one turbine during one of every three days during the monitoring period following the date of first detection (Bruijs *et al.*, 2003), the size of the population was estimated by assuming that these catches were representative of the non-sampled days in between and taking into account that, during this period, an average of 2.2 turbines were activated (Bruijs *et al.*, 2003). For the anchored stownet-monitoring programme at the two locations, the number of silver eels caught in the period after the first detection date for transpondered silver eels were used to estimate population size. To extrapolate the population size of silver eels passing during the entire autumn migration period, we used the fraction of silver eels caught before and after the first detection of transpondered eels from the anchored stownet fisheries, which also covered the migration period before the first silver eel with a transponder was detected. In addition, the reporting rate of recaptured transponders is estimated to be 60–70% (Winter *et al.*, 2006). Therefore, the population size was also estimated by correcting for the rate of underreporting within the anchored stownet estimates.

Data analysis

Passage data were stored in a data-logger at each station, and automatically retrieved daily by a telephone line connection. To derive the estimated mortality per factor for the 2004 experiment, we used the assessment methods described by Winter *et al.* (2006) for the 2002 experiment, which included a minimum estimate for fisheries mortality based on the number of reported recaptures of transpondered eels, a correction for the reporting rate of recaptured eels, indicated to be 60–70%, an estimate for minimum hydropower mortality from the number of eels detected at the entrance to the hydropower stations but not detected directly downstream of these (further referred to as “direct” HPS mortality), and, because not all eels that are injured by turbine blades suffer instantaneous mortality (Hadderingh and Bakker, 1998; Bruijs *et al.*, 2003), an assessment of additional “delayed” HPS mortality based on the number of eels with transponders entering the turbines and the length–mortality relationships determined for HPS1 (Bruijs *et al.*, 2003). For further methodological details, see Winter *et al.* (2006).

Further, proportional hazard models (Genstat; Xu, 2000) were used to estimate survival rates per stretch over the entire period 2002–2006 in which all detections took place. In this analysis, disappearance rates per stretch could only be attributed to a mortality cause when the fate of an individual eel was known, i.e. a reported recapture by commercial or recreational fisheries, or a measured disappearance after entering a hydropower station. Therefore, the disappearance rates of individual eels with an unknown fate include non-reported recaptures by fisheries and delayed hydropower station mortality.

Results

Telemetric experiments in 2002 and 2004

In both 2002 and 2004, commercial fisheries and hydropower caused substantial mortality during the downstream migration

of silver eels in the River Meuse (Figure 2, Table 1). The fraction that reached the sea and the fishing mortality were estimated to be somewhat lower in 2004 than in 2002, although hydropower mortality was greater in 2004 than in 2002.

For the stretches between detection stations in the downstream Dutch section of the River Meuse (260 km), using all data that the 300 silver eels with transponders yielded during the years 2002–2006, the mortality rate per factor (i.e. direct hydropower mortality, reported fisheries mortality, and disappearances for unknown causes) was assessed with proportional hazard models (Figure 3). Greatest mortality was in the river stretch downstream of HPS2 (between stations 9 and 11) and in the downstream stretch between stations 12 and 15/16. Hydropower station mortality was considerable. Fisheries mortality was highest in the stretches between detection stations 9–11 and 12–15/16. As would be expected for silver eels, recreational fisheries recaptured very few.

Mark-recapture experiments in 2002

The total number of silver eels passing through the full width of the River Meuse directly downstream of detection station 10, i.e. through the weir, fishway and HPS2 combined, was more than a factor of 2 higher than at the upstream section of the River Meuse directly downstream of detection station 3, i.e. the weir, fishway and HPS1 combined, as derived from the mark-recapture experiments (Table 2).

Discussion and conclusions

Annual variation in mortality rates for downstream-migrating silver eels in the River Meuse

Variation between years was greatest for hydropower mortality, and lowest for fisheries mortality and for the fraction of eels disappearing because of other causes (Table 1). Differences in river discharge patterns between years appear to play an important role in the year-on-year variation in fisheries and hydropower mortality that silver eels suffer during their downstream migration (Jansen *et al.*, 2007).

From the telemetric experiments, only reported fisheries mortality and direct hydropower mortality could be determined. A relatively large proportion of the eels that disappeared in subsequent river stretches had an unknown fate (38% in 2002, 35% in 2004; Table 1). It was estimated that after correcting for underreporting of recaptured eels and delayed mortality at the hydropower stations, some 11–25% of the 2002 batch and 10–22% of the 2004 batch of eels that disappeared had an unknown fate. Candidate causes for these are natural mortality by disease or predation, a higher underreporting rate than 60–70%, tag loss or failure, and extra mortality related to the experimental treatment of eels. See Winter *et al.* (2006) for an extensive discussion of these factors. As a marginal experimental effect cannot be ruled out, overall escapement might be somewhat greater than observed.

Population size estimates from mark-recapture experiments

For the population size of silver eels passing the River Meuse near detection station 3, two independent estimates are available: (i) from the turbine fykenet experiment, and (ii) for the anchored stownet fishery. After correcting for a 60% reporting rate of the commercial fishery with the anchored stownet, the extrapolated population size over the entire period at this section is close to

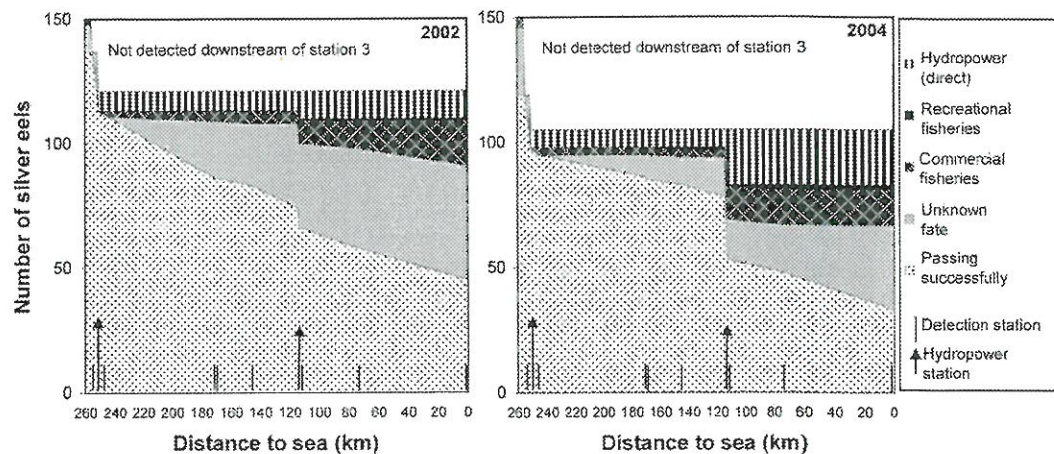


Figure 2. The progressive fate of the 150 silver eels with transponders released in 2002 (left panel) and 2004 (right panel) along the course of the River Meuse. Eels passing detection station 3 and the adjacent weir were considered to have restarted their downstream migration after release (Winter *et al.*, 2006). The decrease in numbers between stations is evenly divided within each stretch.

the population size extrapolated from the turbine fykenet experiments, where all eels were checked for presence of transponders by researchers (58 000 vs. 54 000; Table 2). This gives confidence in the estimates, but these estimated population sizes should be regarded as an indication of population size only, given the assumptions that underlie the Lincoln–Petersen method (Ricker, 1975; Pollock *et al.*, 1990). Ideal mixing might not necessarily be true, even though the timing of the transpondered eels (Winter *et al.*, 2006) was distributed over the entire migration period deduced from other monitoring programmes (Brujns *et al.*, 2003), nor might the catches be entirely representative of all the silver eels passing. The Lincoln–Petersen method performs best

in closed systems, whereas the uncertainties in open river systems are greater.

Distribution of silver eels along the River Meuse

The percentages and rates presented in Table 1 are only applicable to silver eels that start their migration at Ohé en Laak (the release location). Along the course of the River Meuse and its tributaries, silver eels start their downstream migration from different locations, depending on the distribution of eels in the entire Meuse catchment. The overall mortality rates depend on the different mortality rates per stretch that a group of silver eels subsequently suffers while moving downstream from a specific location. In a downstream direction, more and more eels that spent their pre-reproductive stage in the tributaries and downstream section of the River Meuse start their migration to the sea once sexual maturity is reached and therefore join the silver eels that had already started their migration farther upstream. Eels starting their migration downstream are obviously subject only to the mortality factors encountered downstream from the starting point of their migration. Whether the abundance of

Table 1. The fate (%) of the 121 eels in 2002 and 105 eels in 2004 that resumed their downstream migration separated into different categories (successful to sea; suffering mortality by fisheries or hydropower; unknown fate, e.g. natural mortality, experimentally induced disappearances or still present alive after battery depletion, as observed with telemetry, and as estimated from this work and according to Winter *et al.*, 2006).

Category	Batch 2002 (<i>n</i> = 121)		Batch 2004 (<i>n</i> = 105)	
	Observed (%)	Estimated (%)	Observed (%)	Estimated (%)
Successful passage to sea	37	>37	31	>31
Commercially fished	15	21–25	13	19–22
Recreationally fished	1	1	2	3
Hydropower mortality (total)	9	16–26	21	25–34
Hydropower (direct)	9	9	21	21
Hydropower (indirect)	–	7–17	–	4–13
Unknown fate	38	11–25	35	10–22

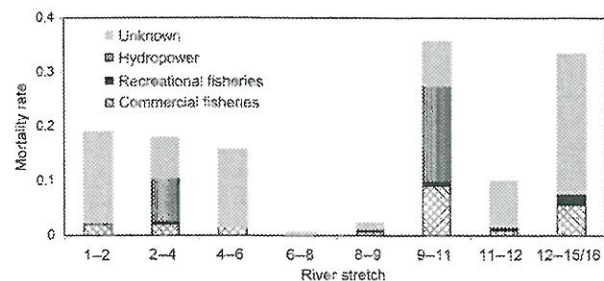


Figure 3. Mortality rates between upstream river stretches 1–2 (between detection stations 1 and 2) and the downstream stretch covered by the detection station 12 and the seaward detection stations 15 and 16 (see Figure 1 for the position of the detection stations). Disappearances attributable to unknown causes also include unreported fisheries recaptures and delayed hydropower mortality (see text).

Table 2. The estimated population size of silver eels in the River Meuse based on mark-recapture data at three catch locations: two near HPS1 (the entire river section directly downstream of detection station 3), and one near HPS2 (the entire river section directly downstream of detection station 10).

Full river width directly downstream of detection station	M	C	R	Period (after first detection)	Estimated population size \pm s.d. during period since first detection	Extrapolated population size (during entire period)	Extrapolated population size (entire period, 60% report rate)
3 ^a	104	1 104	3	8 September–16 February	29 006 \pm 12 699	54 000	–
3 ^b	97	1 922	3	8 September–16 February	47 114 \pm 20 614	88 000	58 000
10 ^b	60	6 708	3	21 October–16 February	102 312 \pm 44 217	218 000	145 000

For all locations, the numbers of eels passing during the period after the first detection of transpondered silver eel in 2002 are estimated \pm s.d. In addition, extrapolations over the entire migration period for silver eels were made based on a fykenet monitoring programme and by assuming a reporting rate of 60% for recaptures.

^aWithin the fykenet catches covering one turbine at HPS1 in 2002 (Bruijs *et al.*, 2003).

^bWithin the anchored stownet monitoring programme (De Leeuw *et al.*, 2005) directly downstream of HPS1 and detection station 3, and directly downstream of HPS2 and detection station 10.

overall migrating silver eels increases or decreases along the river course therefore depends on contrasting forces, i.e. mortality factors that tend to reduce the number of eels along the way, and recruitment of newly migrating eels from tributaries and downstream river sites that tend to increase the number of silver eels. The results of the mark-recapture experiments show that along the course of the river, the number of silver eels increases sharply, despite the rates of mortality they suffer on the way downstream.

Linking mortality rates per stretch to population distribution

To determine the overall mortality rates and fraction that reach the sea of all silver eels in the entire River Meuse catchment combined (i.e. the Meuse population), it is necessary to combine the mortality rates in each river stretch and tributary with the number of silver eels starting their migration in each region. For each group of silver eels starting in a specific river stretch or tributary, the consecutive mortality rates in the downstream stretches measured by telemetry can be used to assess the overall mortality rate and ultimately the total silver eel escapement from the River Meuse catchment area only when the distribution of the silver eels starting their migration is known. The difficulty in this approach lies in assessing the number of all silver eels starting per stretch, which was beyond the scope of our study and is very challenging to determine. The mark-recapture experiments suggest a large increase in the number of silver eels starting to migrate along the course of the River Meuse. On the distribution of silver eels starting to migrate, little is known for any river (Dekker, 2004). Moreover, eels display different patterns of distribution depending on sex (Laffaille *et al.*, 2006), female silver eels usually dispersing farther upstream into river systems than males. To assess the distribution of silver eels starting to migrate and needed for estimating the impact of different mortality factors for each sex in an entire river catchment, the approaches below might be used.

- (i) Estimate the number of silver eels migrating at a series of locations along the river course by mark-recapture experiments, as demonstrated earlier for two locations. Using the mortality rates per stretch as measured by telemetry and

the numbers passing both ends of each stretch (the “immigration” and “emigration” rates), the number of silver eel starting to migrate from that stretch can be estimated.

- (ii) Monitor yellow eel distribution (by sex) in each stretch. From the densities, growth, and length frequencies, the number of silver eels that will start their migration can be assessed (Feunteun *et al.*, 2000). Then link these to the mortality rates per subsequent downstream stretch, as measured by telemetry.
- (iii) Model the eel distribution (or different scenarios of distribution patterns) in the river catchment, based on habitat distribution in combination with density measurements per habitat or data from other river basins. Then link the distribution per stretch with mortality rates, as mentioned earlier.

These three approaches can also be used in combination for different parts of a river basin, depending on the data available.

Implications for management

To address the difficult task of halting the decline of the European eel, telemetry in combination with monitoring and modelling the silver eel stage appears to be a promising tool to aid management decision-making and the setting of priorities for possible control measures. To help maximize the escapement of silver eels from a river catchment, telemetry can be used to:

- (i) measure the mortality rates suffered by silver eels and detect bottlenecks in downstream migration routes, allowing the relative impact per mortality factor to be determined;
- (ii) measure the timing of downstream migrating silver eels in real time. This can be used to act as an early warning system, e.g. for temporarily shutting down hydropower to minimize mortality rates or to divert eels through discharge sluices (e.g. the downstream sluices in the Haringvliet Dam, station 16; Figure 1) or weirs by changes in water management (Jansen *et al.*, 2007).
- (iii) evaluate management measures by determining pre- and post-measure rates of mortality;
- (iv) set requirements for the design of monitoring programmes on the distribution of (silver) eels throughout a river basin,

and vice versa for existing monitoring programmes or data-series on eel distribution and densities.

- (v) compare mortality rates between different river basins in relation to estimated population sizes per river basin, to set the most effective protection measures for the European eel population as a whole.

Because the escapement of female silver eels is estimated to be less than that of male silver eels, it is believed that protecting female silver eels is particularly crucial to attempts to recover the European eel (Dekker, 2000b, 2004). A combination of telemetry, monitoring, and modelling might bridge the gap between individual behaviour and the population dynamics of silver eels in river basins, and permit comparisons between river basins to aid the prioritization of measures to be taken Europe-wide.

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