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Long-term effects of hydropower installations and associated river regulation on River Shannon eel populations: mitigation and management

T. K. McCarthy · P. Frankiewicz · P. Cullen · M. Blaszkowski · W. O'Connor · D. Doherty

Abstract The Shannon, Ireland's largest river, is used for hydroelectricity generation since 1929. Subsequently, the Electricity Supply Board assumed responsibility for management of its eel stocks, due to the impact of the hydro-dam on recruitment to the commercial fishery. In order to negate a decline in juvenile recruitment resulting from the installation of hydroelectric facilities, management was focused on stocking lakes with elvers and fingerling eels. These were trapped at the hydropower facilities and in estuarine tributaries during their up-stream migrations. Due to the decline of natural recruitment in more recent times, attempts have also been made to develop an estuarine glass eel fishery. Stock levels are then monitored through annual surveys of the population trends of juvenile (glass eel, elver), growing phase (yellow eel) and downstream migrating pre-spawners (silver eels). Survey results and fishery management programmes are reviewed in this article. In addition to the long-term effects the hydroelectric facilities have had on the stock levels, there is also an annual effect on the migratory patterns of downstream migratory silver eels. In the lower reaches of the river system flow rates are regulated by the hydroelectric stations. We review previous work that had highlighted the importance of flow in determining the timing of the silver eels migrations, and assess the relationship between flow and migration in more detail through the use of hydroacoustic and telemetric studies. Current research on seaward migrating silver eel populations, suggests that spawner escapement rates can most effectively be increased by trapping migrating eels at fishing weirs located up-stream of the power station and transporting them towards the estuary.

Keywords *Anguilla anguilla* · Migration barriers · Hydroelectric dam · Flow regulation · Migration patterns

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Hydropower, Flood Control and Water Abstraction: Implications for Fish and Fisheries

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Introduction

The widespread collapse of European eel *Anguilla anguilla* (L.) stocks is a matter of great concern and current fisheries are considered outside sustainable limits (Moriarty & Dekker, 1997; ICES, 2005). The well-documented decline in glass eel recruitment, that has occurred since the 1980s reflects similar trends observed in previous decades in continental stocks and in fishery yields and it would appear that the spawning stock has declined in parallel (Dekker, 2003, 2004). The unusual population biology of this remarkable trans-Atlantic migratory species and lack of information on the oceanic phase of its life cycle have made it difficult to directly investigate many aspects of its natural reproductive biology. However, recent analyses of its population genetic structures suggest that an even longer-term decline that may linked to climate changes in oceanic circulation patterns (Wirth & Bernatchez, 2003). The need for drastic conservation measures, which seek to reduce natural and anthropogenic mortality factors in continental waters and that seek to significantly increase escapement of larger numbers of good quality spawners, has been recommended. The development of an EU eel conservation plan, that will require member states to take immediate measures and to develop eel management plans at river basin district and national levels, reflects the urgent need to protect the species from even more drastic decline. The possibility that the European eel might enter an inevitable extinction vortex, involving potential depensatory mechanisms, unless spawner runs from continental waters are restored to a level above which a terminal decline becomes inevitable has already been alluded to (Dekker, 2004).

The decline in European eel populations has been attributed to a variety of anthropogenic environmental impacts, such as: over-fishing of all life-history stages; obstacles in continental waters limiting juvenile recruitment; contaminant levels; introduced pathogens; cormorant predation; silver eel mortality during passage through hydropower turbines, pumping stations, etc; and changes in ocean circulation patterns associated with climate change (Dekker, 2004). There is no clear consensus on the relative importance of these various factors. However, the EU Commission has issued a Community Action Plan for the Management of European Eel (COM 2003) and is proposing to implement immediate and longer-term measures to achieve its objectives. Full or partial closure of fisheries, introduction of mitigation measures to reduce other anthropogenic mortalities; restoration of habitats; removal of barriers to natural migrations of eels or construction of effective eel passes, will be among the sorts of eel conservation actions specified in future national and river basin district eel management plans. The importance of improved monitoring of eel stocks and the need to ensure coordinated, internationally harmonised, data collection and analysis are recognised (Dekker, 2005)

The River Shannon, Ireland's largest river system, has a network of lakes in which European eel is an important natural component of the fish assemblages. Like many other European rivers, the hydrological features of the River Shannon have been altered during development of navigation routes, by weirs constructed for flood control, and when it was harnessed for hydroelectricity generation (Cullen, 2002). These and other environmental changes are reflected in the history of its eel fisheries and have stimulated a series of research activities over the past six decades (McCarthy et al., 1999; McCarthy & Cullen, 2000a, b, 2002; Cullen & McCarthy, 2000, 2002, 2003; Arai et al., 2006).

There is currently an upsurge in the number of works dealing with the direct impacts of hydroelectric facilities on eels through, for example, turbine damage (e.g. Haro, 2003), or on the behaviour of eels in the vicinity of hydroelectric facilities (e.g. Durif et al., 2003; Gosset et al., 2005). However, in this article, we aim to take a broader view of the impacts, with reference to the eels of the River Shannon system. We will discuss the impact the construction of the hydroelectric station may have had on natural recruitment of eels into the system; what management measures were adopted to combat the drop of recruitment; and we will analyse the impact of these mitigation measures through to the modern day through summation of the information gathered by ongoing stock monitoring programmes. A second impact of hydroelectric generation can be seen in relation to silver eel migration patterns in the lower reaches of the system. At this point flow, which is regulated by the hydroelectric facilities, is the major determinant of the timing of the silver eel migrations. We will therefore assess the link between flow and eel movement, through analysis of catch and flow statistics in addition and through use of telemetric studies. We will propose how to best utilise this relationship to maximise escapement of spawners from the system.

Eel life stages

Throughout this article, we will be making reference to all eel life stages to be found in the River Shannon system. These stages can be defined as follows:

- glass eel—the unpigmented eel that has just begun its migration into the river system. These are netted in the estuarine waters,
- elver—the pigmenting and fully pigmented, feeding stage that follows directly after the glass eel stage. These eels are captured in elver traps on the lower reaches of the river system,
- fingerling—these are small young eels, which are usually on average 5 years old. These eels are still migrating upstream out of the lower reaches of the river system and are captured in elver traps;
- yellow eels, also known as brown eels – these are the resident, feeding life stage found thought the rivers and lakes of the system, named after their colouration;
- silver eels—these are the maturing, downstream migrating life stage, named after the silvery colour their underside takes on at this stage in their life history.

In the Shannon system otolith analysis has shown that male silver eels are on average 11 years old and females 15 years, although there is a considerable range in ages, with eels of up to 25+ years having been recorded. All ages refer to years in freshwater.

Study area

The Shannon river basin district (Fig. 1), defined with respect to the objectives of Water Framework Directive, includes an area of about 18,000 km^2, mostly in the lowland central area of the Republic of Ireland but with a small part (6 km^2) of the upper River Shannon basin extending across the border to Northern Ireland. It has been estimated that there are more than 1,600 lakes, totalling about 440 km^2 surface areas, though the majority are less than 0.5 km^2, and about 16,000 km of river channel in

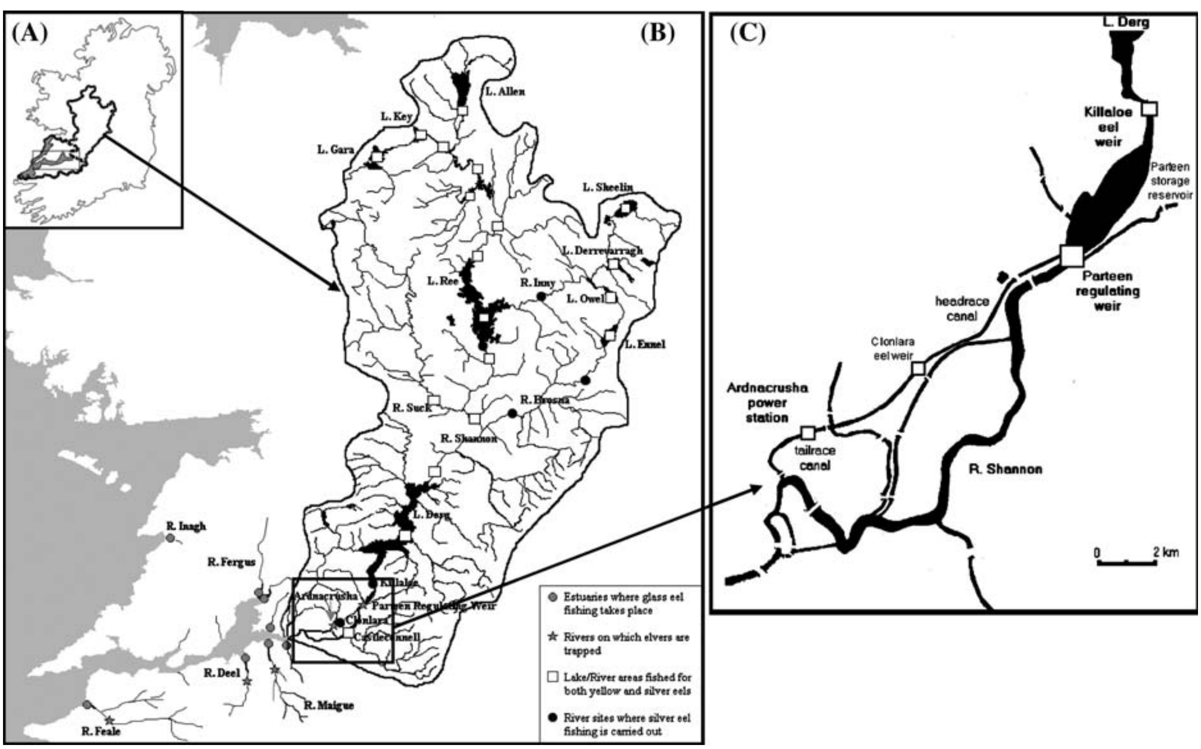

Fig. 1 Maps showing: (**A**) Ireland, with Shannon WFD river basin district (coastal/transitional waters shaded) and River Shannon basin; (**B**) Lakes and tributaries of the Shannon River basin and (**C**) Lower Shannon River, with the locations of the Ardnacrusha hydroelectricity facilities indicated. All eel sampling sites are highlighted in (**B**)

the river basin district. The area includes about 73% agricultural land and 12% wetland, mostly peatland habitat.

The River Shannon (Fig. 1), which discharges to a 97-km long, 5,002 km^2 estuary, drains an area of approximately 11,700 km^2, upstream of Limerick. The total water surface area is about 4100 km^2 but the ten larger lakes represent 90% of the total lake area. Most of the lakes are shallow and mesotrophic to eutrophic. The three largest, Loughs Allen (35 km^2), Ree (105 km^2) and Derg (117 km^2), are in a series of lakes though which the main river channel flows. The gradient is remarkably low, with the river rising at about 152 m above sea level and then flowing southwards with only a 12-m drop in altitude over 185 km, before finally descending more rapidly to sea level. The principal rivers flowing to the Shannon estuary are the River Feale (1153 km^2, 34.6 $m^3\ s^{-1}$) River Maigue (1075 km^2, 15.6 $m^3\ s^{-1}$) and River Fergus (881 km^2, 25.7 $m^3\ s^{-1}$).

The Ardnacrusha generating station (86 MW), constructed between 1925 and 1929, is located 3 km upstream of the tidal limit of the river at Limerick city (Fig. 1) and it harnesses 10,400 km^2 of the catchment area upstream. In 1931, it supplied 96% of Ireland's electricity needs. Nowadays, although it accounts for less than 2% of national electricity requirements, it remains of great importance as a rapidly available source of power at peak demand and for cover in cases of emergency or sudden breakdown elsewhere in the national grid (Cullen, 2002). The Ardnacrusha station is equipped with three vertical shaft Francis turbo-generators (installed in 1929) and one vertical shaft Kaplan turbo-generator (installed in 1934) operating under an average head of 28.5 m and supplied via 6 m diameter penstocks. A major refurbishment, with new turbines being installed, occurred in the 1990s. A 12.6-km headrace canal supplies the power station with the up to 400 $m^3\ s^{-1}$ water supply needed for maximum generation levels. A 2.4-km long tailrace canal returns the station discharge back to the River Shannon. The Parteen regulating weir, located at the head of the headrace canal, servers to divert the main flow of the River Shannon to the power station. A storage reservoir immediately upstream of the regulating weir provides supplementary impounded water. A statutory 10 $m^3\ s^{-1}$ compensatory flow must be discharged to the main river channel. Since the 1980s the bulk of this water passes through a 600 kW turbine located at the Parteen Regulating Weir, the remainder feeds a fish pass. In times of high water, when Ardnacrusha is drawing it's maximum load, and the level of Lough Derg rises above 33.56 m, excess water is allowed down the river channel through any or all of the set of three 18 m gates undershot gates located at the Parteen Regulating Weir. This process is referred to as "spillage". The mean annual flow of the River Shannon at Killaoe, located 3 km upstream of the regulating weir, is 186 $m^3\ s^{-1}$. The mean summer discharge is 99 $m^3\ s^{-1}$ and the mean winter discharge is 274 $m^3\ s^{-1}$. However, flows may be as low as 10–15 $m^3\ s^{-1}$ in dry summers or over 700 $m^3\ s^{-1}$ in major floods. In former years, regulation of lake levels in Lough Allen (Fig. 1) also was important in the water storage strategy. River flow patterns are also locally controlled, at other weirs located in the middle and upper catchment, for navigation and alleviation of flooding. The principal ones are located at the outlets of Loughs Allen and Ree and in the river channel at Rooskey, Termonbarry and Meelick. Some small privately operated hydropower turbines have been installed in the upper catchment and some tributaries.

Upstream fish migration at Ardnacrusha, other than by trap and truck intervention for elvers, is mostly via a Borland-type fish lift constructed in 1959, though some upstream movements can also take place via a double lock (70 m) navigation canal route that is incorporated into the dam structure. At the Parteen regulating weir, natural fish ascent is facilitated by a "pool and traverse" type fish pass. Elver traps, which also capture small ascending yellow eels, have been operated at Ardnacrusha since 1959 and a trap at the Parteen fish pass is also used since 1985 to trap ascending small yellow eels. The juvenile eels are used for lake stocking.

For downstream migrants there are a number of options available depending on flow conditions. During times of headrace discharge the 10 m navigation gate at the entrance to the headrace canal is typically lifted and fish may migrate via the 9 m deep headrace canal to the powerstation. At this point they must pass through large trash screens (with 60 mm bar intervals) which are present from water surface to forebay bottom, before passing via the turbines to the tailrace area, from which they then have unimpeded passage to the nearby tidal estuarine area. The alternative route is via the main river channel which in low flow conditions can be accessed via the small turbine, which receives the bulk of the compensatory flow, or via the fish pass. Alternatively, in times of exceptionally high discharge when spillage occurs, they may pass downstream via a set of three 18 m wide undershot gates.

A series of three hydraulically operated silver fishing weirs equipped with 8 (9.15 m × 3 m) nets, described by O'Leary (1982), are located (Fig. 1) 140 m apart in the headrace canal at Clonlara 4.7 km upstream of Ardnacrusha. However, these have not been operated in recent years due to technical problems. These structures were previously used for commercial eel fishing in conjunction with the commercial fishing weir operated at Killaloe 19.7 km upstream (Fig. 1) of Ardnacrusha. The Killaloe weir, described in more detail by McGrath et al. (1976) and Cullen & McCarthy (2000), covers about 90% of the river width, and can be fished using up to 34 coghill nets (8 m long, 10 m opening diametre). The nets are either of the older manually operated type (22 nets), attached to metal wattles, or are hydraulically operated (12 nets). Low flow conditions, which are typical of the early part of the Killaloe fishing season often render this impressive structure relatively inefficient as a means of silver eel capture. In recent years the purpose of the Killaloe silver eel weir has shifted from commercial to conservational. Silver eel captures are now transported overland and re-released downstream of the generating station to help boost spawner escapement levels from the system.

River Shannon eel fishery management: historical perspectives

Following construction of the hydroelectricity dam at Ardnacrusha, significant negative impacts on both the commercially important diadromous migratory species, Atlantic salmon *Salmo salar* and European eel, became apparent as stock levels declined. For example, reports from 1908 and 1928 indicate that the silver eel catches were at least 69 tonnes and 65 tonnes respectively in those years. However, by the 1940s they had declined to mean annual values of 17.8 tonnes and 9.6 tonnes in the 1950s (Quigley & O'Brien, 1996). This decline was attributed to a major decline in natural recruitment into the river system as a direct consequence of the installation of the hydroelectric facilities. As a consequence, the state controlled Electricity Supply Board (ESB) that operated the hydroelectricity power station at Ardnacrusha became increasingly involved in management of River Shannon fisheries. ESB initiated a major eel stocking programme, with the installation of an elver trap at Ardnacrusha and a similar one at Parteen. The stocking programme involved facilitating natural Shannon recruitment and supplementing the stocked material with elvers trapped at other rivers, such as the River Feale, River Maigue and River Inagh (Fig. 1). This elver collection on other rivers lead to development of new elver traps, suited to low head capture locations (O'Leary, 1970). ESB began commercial silver eel fishing in 1937 at three locations, Killaloe, Athlone and Castleconnell, but in 1940 the several small weirs at Castleconnell were soon abandoned. A new eel weir, built in 1940, at Killaloe was intended to capture a large portion of the descending silver eels and thus replace the former fishing effort at Castleconnell. Three new eel weirs, operated since 1966, 1981 and 1982, at Clonlara in the Ardnacrusha headrace canal (O'Leary, 1982), and some small upper catchment stations fished intermittently over the years, contributed to a relatively small but variable extent to the annual silver yield from the Shannon. Indications of improving catches in the 1980s suggested that the stocking programmes were having a significant effect on the eel populations. This led to the initiation of comprehensive surveys of the Shannon eel resources in the early 1990s, and which is still continued as annual eel monitoring programmes, in addition to an attempt to increase the input of the stocking programmes to the system. The annual monitoring programmes have involved groups of authorised, two person, fishing crews which are required to fish specific locations or zones in accordance with survey research team directions and that must provide log book details of daily catches on a weekly basis. They are allowed to sell catches to an authorised eel dealer, under ESB staff supervision and their catches are analysed regularly at lakeshore and sales point locations. Extensive fishery independent surveys, using similar fishing techniques, are also undertaken through out designated fishing seasons. Data on size frequencies, ages, sex ratios parasite burdens, etc. are compiled and analysed on an annual basis. Results of these surveys and related research projects are presented below.

Juvenile eel recruitment and stocking

The stocking programmes adopted as mitigation measures to address the adverse effects of the Shannon hydropower structures on eel recruitment were most effective in late 1970s and the early 1980s when catches of elvers were at their highest in both the Shannon at Ardnacrusha and at estuarine tributaries such as the River Feale. Over 10 tonnes of elvers were captured in 1979 (Fig. 3). However, since then declining natural recruitment has made it progressively more difficult to achieve the targets set for either fishery development or stock conservation that had been suggested by several studies (Moriarty, 1982; Quigley & O'Brien, 1996; McCarthy et al., 1996). An intensive (1995–1999) study (O'Connor & McCarthy, unpublished) of the problem focused on the potential harvesting of glass eels in the Shannon estuary for the lake stocking programme. A pilot scale glass eel fishery captured 480 kg, 396 kg and 468 kg, in the years 1997, 1998 and 1999, respectively, which significantly increased numbers of juvenile eels available stocking in those years. Other than experimental studies, this fishery mostly involved, use of conical (1.5 m diameter, 2.5 m long) nets, with 1–3 mm mesh and detachable cod ends for removal of catches. These were typically attached to bridges over estuarine tributaries (Fig. 1) and fished in the 3–4 h period preceding high tide and nets were examined hourly. However, in subsequent years, due to declining catches and poor economic returns to the fishermen, this activity has declined and in 2005 the glass eel catch of the single crew still fishing was only 41 kg. Catches of elvers in the Rivers Feale, Maigue and Inagh (Fig. 1), which formerly contributed significantly to the stocking programme, have also undergone major declines. Though improvements undertaken in 1996/7 to the Ardnacrusha elver trap proved initially beneficial (2120 kg in 1997), catches have continued to decline. Further improvements for trapping facilities at Ardnacrusha and Parteen are proposed.

Other stocking measures adopted in the past decade, included electrical fishing of juvenile eels from lower Shannon River and tributaries for transport to the fishery area. Electrofishing surveys and some limited silver eels fishing at Castleconnell on the lower reaches of the River Shannon indicated that high eel densities occurred in these locations (average 0.45 eels m^{-2}), producing predominantly male dominated silver eel populations. Limited stocking with farm reared fingerlings was also considered; however, neither of these methods are now considered to be appropriate on either biological or economic grounds. Natural migration to the River Shannon, which must have prevented total collapse of the declining eel fishery in the 1930–1960 period, is difficult to assess. The three potential up-stream routes identified (Parteen fish pass, Ardnacrusha boat canal lock gates and the Ardnacrusha fish lift) do not appear to provide significant opportunities for elver recruitment to the extensive area of eel habitat in the Shannon lakes. Observations made in 1994–1997, by analysis of video records of 4493 lift cycles, indicated that yellow eels (10–30 cm) constituted about 25.4% by number of fish passing through the Borland lift at Ardnacrusha. The majority of eels observed were moving upstream and, with the exception of small numbers of silver eels, many of the downstream eel movements seemed to involve fish moving upstream that had failed to leave the fish lift. The yellow eels were observed ascending via the lift from April to September (n = 14961, for 1994–1997) but they mostly moved upstream in the months of June (25.6%), July (35.1%) and August (36.15). Microchemical and ultrastructural analyses otoliths of yellow eels, from the lower part of the Shannon River, a midland lake, and silver eels captured at Killaloe showed that all the specimens examined had spent their entire continental life-history in freshwater (Arai et al., 2006) and that none had spent time in the estuarine transitional waters other than as incoming glass eels.

Eel population trends and fishery yield

The steady declines in both yellow and silver eel populations in the Shannon system (Fig. 2), as indicated by fishery dependent and fishery independent survey results, is a matter of concern. In the past 4 decades the management of the fishery was mainly focused on the potential economic benefits that might

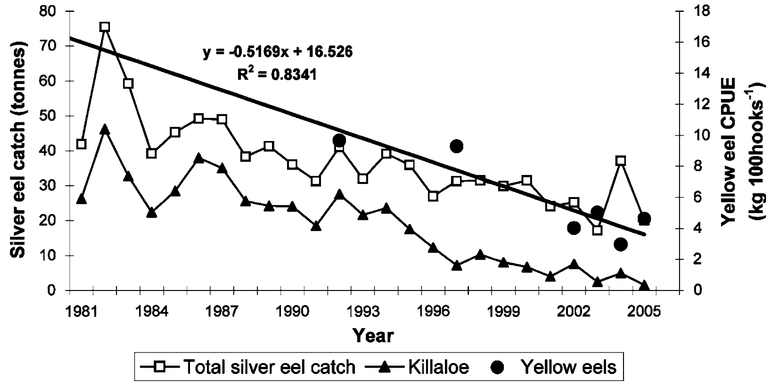

Fig. 2 The decline in yellow eel catches on the River Shannon as indicated by a regression analysis of the CPUE data recorded from annual fishery-independent longline surveys. Similar declines in silver eel populations, as indicated by the annual catches for the entire fishery and for the main downstream fishing site, the Killaloe eel fishing weir

arise from stock enhancement measures. However, as natural recruitment was observed to steadily decline, McCarthy & Cullen (2000a) recommended a more realistic and conservation approach to the management of the fishery. A target of 1.5 tonnes, comprising combined catches from a pilot glass eel fishery and enhanced trapping of elvers and fingerlings, was suggested. The progressive decline in natural recruitment (Fig. 3) now makes even the latter stocking model seem unachievable as it becomes more and more difficult to reach the indicated target level.

A multiple linear regression analytical model was constructed, to make predictions about the future of the Shannon fishery. This was based on time series data on recruitment, (expressed as elver equivalents) annual catch data (yellow and silver eels) and the estimated escapement downstream of the Killaloe eel weir (as determined by weir efficiency studies). Parteen fingerlings were all considered to be 5-year-old individuals but no account was taken of possible age related variation in survival rates. For the purposes of the model, a weir efficiency of 30% was used and mean sizes of eels captured in recent yellow

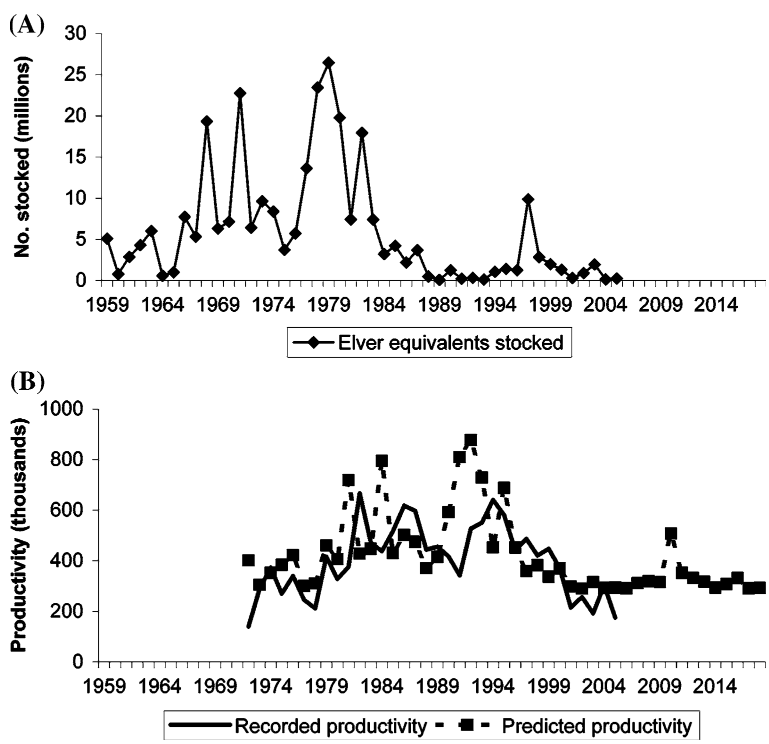

Fig. 3 (**A**) Long term data series for eels stocked into the River Shannon expressed in terms of numbers of elver equivalents stocked per annum. (**B**) Related data series for recorded productivity (combined yellow and silver eel catches, plus estimates of escapement) and predicted River Shannon eel productivity (derived from the available stocking and productivity data using a linear regression model and a 13 year time lag)

and silver eel surveys were applied. Correlation analyses, using various time-lag intervals, suggested that a 13-year time lag was statistically most appropriate. This was deemed biologically realistic, as mean ages of 12 years for fyke net captured yellow eels and mean ages of 11 years and 15 years for male and female silver eels respectively had been determined by otolith analyses. The model predicts productivity (yield plus escapement) as numbers of eels but these can also be converted to biomass estimates (approx 300,000 eels = 76 tonnes).

The estimates of potential escapement take no account of the hazards associated with passage through the turbines and other obstacles to migration downstream of Killaloe. In effect, only a small percentage of the silver eels that the Shannon stocks produces pass via Killaloe at present, this is due to the fact that in recent years the fishing effort has increased and this has mostly been in the upper part of the river basin. The progressive decline in the Killaloe eel weir catches (Fig. 4) since the mid-1990s is inversely correlated with the catch levels in the upper basin sites. Prior to 1994, most upper system catches were made at the now abandoned Athlone eel weir but since then more effective fishing with anchored long-winged river nets has been increasingly employed and the numbers of fishermen and sites fished has also increased.

Since 1959, a total of 126.9 tonnes of juvenile eels (glass eels, elvers and fingerlings combined) have been stocked to the Shannon lakes and this equates to more than 278 million elvers. The fishery capture data and estimates of escapement downstream of Killaloe (Fig. 3) suggest that survivorship of the juvenile eels stocked from 1959–1980 was much lower than in the subsequent years, allowing for a 13-year time lag for growth to mean capture size or maturity to the silver eel phase than in subsequent years. Expressed in terms of biomass, the ratios of yield to stocked juveniles were estimated as 13.63 for 1959–1980 stockings and 25.98 for 1980–1993 stockings. The most likely explanation for the differences between the two periods is that extensive undocumented and illegal exploitation of the Shannon eel stocks occurred during the 1970s and 1980s. No evidence of environmental changes, natural or anthropogenic, likely to have reduced eel survival rates during that period has been obtained.

Silver eel migration patterns

The inter-annual, seasonal, and within river basin variations in silver eel catches obtained during commercial and experimental survey fishing activities in the Shannon have been analysed previously (McCarthy & Cullen, 2000b; Cullen & McCarthy, 2003). Silver eel migrations of the upper catchment generally reflect the typical lunar periodicity, well known to traditional fishermen, and large catches may be obtained over a few days during the last quarter of the lunar cycle. Effects of weather and rapidly rising lake water levels and stormy conditions, are also seen and influence the seasonality of the major eel movements. The effects of hydrometric and meteorological factors were analysed in detail by Cullen & McCarthy (2003) using daily catch data from the Killaloe eel weir, in the lower Shannon. At

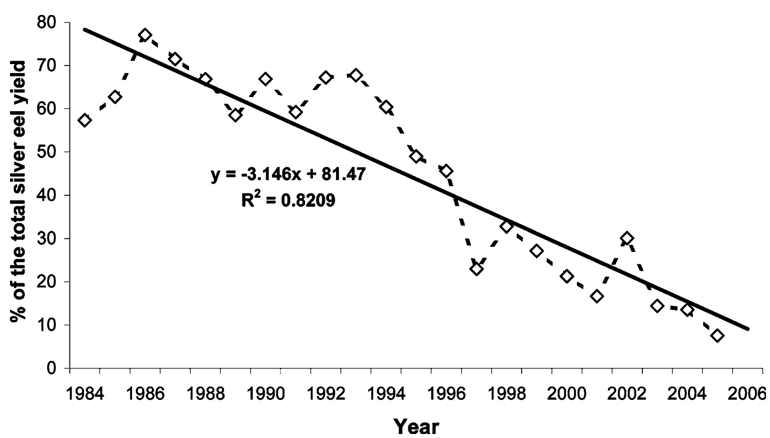

Fig. 4 Long term variation in the percentage of the total annual Shannon silver eel yield captured at the Killaloe weir, along with the results of a linear regression analysis of the data

this location, the underlying lunar periodicity of silver migration is normally obscured. The main migrations, as reflected in the catch levels at the Killaloe eel weir, are generally later in the season (November/December), although migration peaks have often occurred in January–March. This reflects the effects of river and lake regulation and increased hydropower generation in colder months.

The influence of flow variations on silver eel catches in the lower River Shannon is clearly visible in the pattern of capture of eels at the Killaloe eel weir, as was also the case for the Clonlara eel weir when it was still operated. An example of this is shown in Fig. 5 where a marked increase in flow coupled with spillage at the Parteen regulating weir triggered an increase in silver eel catches, despite it being during the brighter phase of the lunar cycle (i.e. first lunar quarter and full moon).

In order to assess the effects of high flows and associated spillage on these migratory patterns data on the silver eel catches was analysed in relation to flow and spillage for the fishing seasons of 1981–1982 to 2005–2006 inclusive. During this time spillage occurred in all but 5 of the years, over varying periods of time ranging from 2 days (1.2% of the fishing season) to 94 days (86.2% of the fishing season) at an average rate of 27 days per fishing season. Although in earlier years there was extended fishing, with the silver season often starting in September and lasting for 6 months, fishing in more recent years is carried out on a more limited basis, with the fishing season lasting usually up to three months maximum.

The relationship of flow to capture rates was clearly illustrated by significant relationships between catch levels and flow data for the years in which spillage occurred. A correlation analysis between catch and spillage information indicated that both the total catch of silver eels was significantly correlated to the number of days of spillage that occur (Spearman Rank Correlation coefficient (rS) 0.637, $P = 0.003$), and also to the total percentage of the catch that was recorded during the spillage period (rS 0.516, $P = 0.021$). The importance of spillage was also indicated by the relationship between the proportion of the catch that is captured during spillage periods and the percentage of the total flow through Killaloe that is accounted for by spillage (rS 0.475, $P = 0.035$).

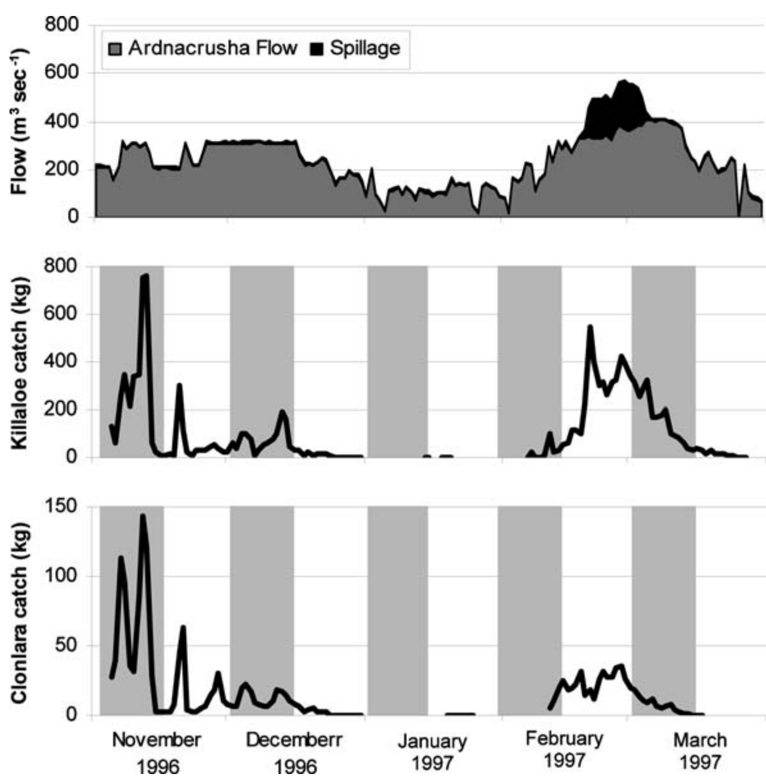

Fig. 5 Patterns of flow rates at Ardnacrusha (headrace) and at Parteen Regulating Weir (spillage) in relation to the capture rates of eels at the Killaloe and Clonlara eel weirs during the 1996–1997 silver eel fishing season. The flow through Killaloe is the combined Ardnacrusha and spillage flow rates. The lunar dark period (i.e. from the start of the last lunar quarter to the start of the first lunar quarter is highlighted on the catch graphs in grey

Spillage is an important indicator of high water levels and high flow in the lower River Shannon system, and although spillage rates up to 385 $m^3 s^{-1}$ have been recorded in past years, this is the exception rather than the norm. Spillage rates generally less than 200 $m^3 s^{-1}$ (77.6% frequency). Spillage, especially when it occurs at high levels should contribute to the escapement of silver eels from the Shannon system as they then have the chance to travel down the original river channel, bypassing the Ardnacrusha generating station.

In order to investigate the number and speed of eels travelling through the headrace canal a hydroacoustic study of fish migration patterns was undertaken at Clonlara, in the Ardnacrusha headrace canal, from 17:45 h on 8/12/2004 to 8:00 h on 10/12/2004. Measurements were performed using a stationary transducer which was directed horizontally across the canal. In order to facilitate statistical analysis the full monitoring period was divided into separate surveys, of approximately 26 min duration. A SIMRAD EY500, split beam echo sounder with frequency 120 kHz was used. The opening angles of the elliptic transducer were 4° and 10°. The smaller angle of the transducer beam was oriented downward. The pulse duration was set to 0.3 ms, repetition rate to the maximum limit and the TS threshold to −50 dB. The insonified zone was from the right to the left bank of the canal (38 m). In order to obtain data undisturbed by transducer and bank proximity, the data for the 4 m nearest to the transducer and the 2 m closest to the left bank were excluded from the analysis. Thus, the volume of the analysed part of the beam cone was about 300 m^3. The area of the insonified fish passing window (from right to left canal's bank) was about 47 m^2 As the total area of the canal's cross section was about 297 m^2, the total number of passing fish could be calculated (assuming that the insonified part of the water column was representative for the whole cross section from the point of view of spatial distribution of migrating fish). For data analysis, Simrad EP 500 post-processing software was used. This allows for tracking fish in three dimensions and thus determination of the absolute direction of travel. Only fish migrating down the canal were considered for further analysis. For estimating fish abundance the trace tracking counting method was used.

Results of the hydroacoustic surveys are summarised in Fig. 6, together with a calibration curve relating eel size to target strength. The latter was derived, by releasing eels of known size, though a 10-cm pipe to an insonified zone in 6 m diameter fish storage tanks across which the hydroacoustic system was deployed. Due to the overlap in TS values for male and small female silver eels it was not possible to distinguish the sexes accurately in field surveys.

However, clear patterns of fish movement could be discerned and these were correlated with the variations in discharge that resulted from changes in generation levels at Ardnacrusha over the study period (Fig. 6). As it was not possible to sample fish at the survey location, precise data on the fish assemblage involved are not available. Some small trout were observed and bycatch data for the Killaloe eel weir suggests that some perch fry might also have been among the fish carried don stream by the headrace canal current speed that varied from 0.19 to 1.18 m s^{-1} during the survey period (Fig. 6). The TS for perch fry, determined in previous studies (e.g. Frouzowa & Kubecka, 2004) allowed them to be excluded from fish counts but overlap in trout and eel TS ranges did not allow them to be distinguished in daytime surveys. However, it can be reasonably assumed that the fish moving at night, and generally in speeds exceeding current speed, were all eels. The high numbers of nocturnally migrating eels, and the manner in which their migratory activities were affected by the differences in discharge patterns, is of particular interest.

As can be seen (Fig. 6), on the first night of the study the generation of electricity declined though the hours of darkness and the numbers of eels migrating was lower than on the subsequent night, when they continued to migrate throughout the hours of darkness and even into the early morning period. The latter phenomenon, sometimes observed at the Killaloe eel weir when, in former times, silver eel catches were higher, appears to have been a direct result of the extended nocturnal power generation activity. Swimming speeds of eel, determined for fish migrating at night and orientated directly with the flow, ranged from 0.29 to 1.4 m s^{-1}in excess of actual current speed. Thus the actual rates of downstream displacement ranged from 0.61 to 2.28 m s^{-1}. Variations in eel swimming speeds occurred on the 1st night (Fig. 6), with eels in the earlier part of the night (20:00 h to 01:00 h) travelling faster (0.81–1.40 m s^{-1}) than those in the later period (01:00 h

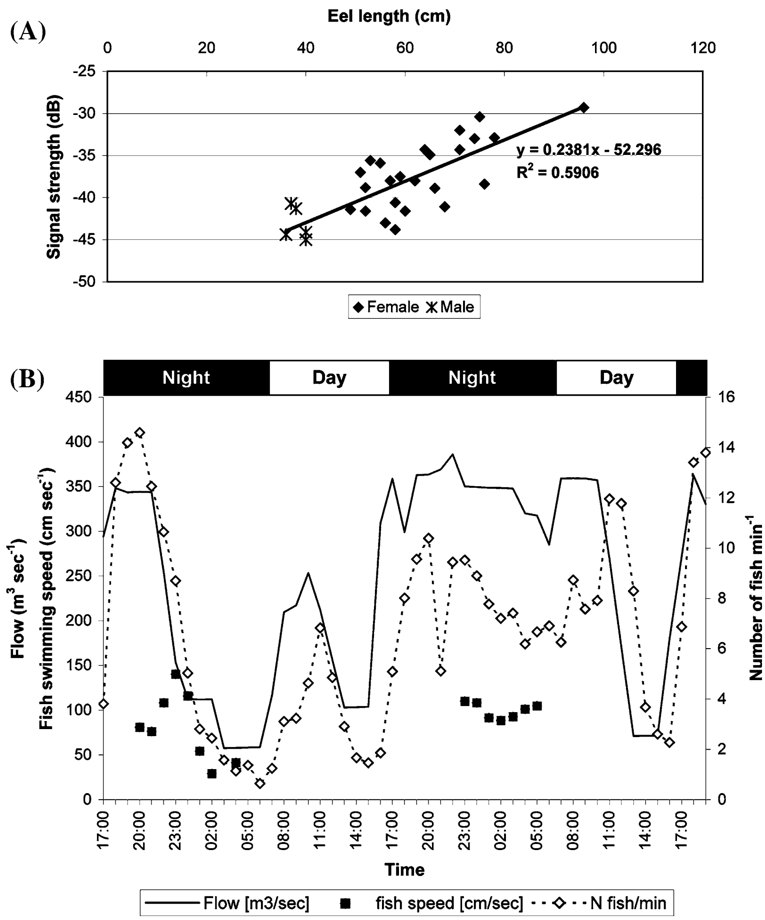

Fig. 6 (**A**) Relationship between eel size and target strength determined during calibration of hydroacoustic system, (**B**) patterns of fish migration observed (8–10/12/2004) in the Ardnacrusha headrace canal at Clonlara, together with the variation in discharge and estimated nocturnal swimming speeds of eels

to 0:500 h) which may have been slowing down (0.29–0.54 m s^{-1}) in response to reduced discharge and a natural diel cycle in migratory activity. Observations at the Killaloe eel weir suggests that, other than when peak migrations are in progress, silver eels generally migrate downstream in the earlier half of the night and no such decline in swimming speeds (0.89–1.10 m s^{-1}) was evident on the second night, when the migration activity was higher.

Telemetric tracking of three radio tagged and one acoustically tagged silver eels in the headrace canal in January 1993 indicated that eels were not generally moving faster than the current speed. The eels tracked over distances ranging from 720 m to 4770 m, travelled downstream at different mean speeds (0.43, 0.71, 0.96 and 1.16 m s^{-1}) in an approximately 1.1 m s^{-1} canal current. However, the tagging may have affected their capacity to migrate as effectively as those observed hydroacoustically in 2004.

During the 1992–1994 silver eel fishing seasons good opportunities to study silver eel downstream migrations were available. The tag recovery data, for 16.3% of 1515 eels tagged in the 1992/3 season and for 16.0% of the 2813 eels tagged in the 1993/4 season, provided data on eel weir capture efficiencies and on rates of eel movement though the river system (McCarthy et al., unpublished). A combination of anchor, FLOY, and transponder, PIT, tags were used. Some indications of rates of movements, expressed as travel speeds that alternatively assume 24 h movements or more realistically based on nocturnal (15 h darkness) movements only (Table 1). The estimated rates of migration showed considerable variation among eels and also the effects of delays due to the lunar periodicity of silver eel migrations. Recapture intervals thus varied following release at short distances upstream of capture points. Some eels were recaptured less than 24 h from the time of release, others took up to 10 weeks (till the end of the fishing

Table 1 Estimated travel speeds, km 24 h^{-1} (mean, median and range) based on the assumption that eels (a) travel continuously (b) travel only in hours of darkness for tagged silver eels released at Athlone and Meelick and recaptured at Killaloe

Release point and date	No. Released/ % recaptured	Sunrise–sunset minutes	Continuous migration km 24 h^{-1}			Nocturnal migration km 24 h^{-1}		
			Mean	Median	Range	Mean	Median	Range
Athlone 26.11.1992	98 14%	950	4.55	9.19	1.48–24.13	6.9	13.92	2.24–36.56
Meelick 24.10.1992	83 20%	833	1.47	1.64	0.67–13.33	2.54	2.8	1.16–22.98
Meelick 28.10.1992	50 16%	842	1.39	1.72	0.6–2.13	2.38	2.97	1.03–3.67
Meelick 04.12.1992	73 10%	971	4.8	5.33	1.9–17.77	7.12	7.96	2.84–26.52

season), while in the most extreme cases some eels were recaptured the following fishing season, over 1 year later. The rates of movement recorded in the more recent hydroacoustic surveys at Clonlara are consistent with the higher rates of riverine movement recorded among the tagged eels in the earlier study (Table 1).

Eel weir efficiency estimates, based on recapture rates for eels released upstream of Killaloe, allowed for estimation of the proportions escaping downstream. These efficiencies recorded at Killaloe, which indicate what portion of the downstream migrating eels are captured, varied from 4% to 40%, with the higher values being more typical of high flow/high catch dates. Estimates of spawner escapement downstream of the Killaloe and Clonlara fishing weirs in 1992–1994 ranged from 45.9 tonnes to 111.7 tonnes per season. Information on the routes taken downstream of Killaloe was limited to interpretation of catch data and tag recoveries for Clonlara. It was presumed that relative volumes of water passing downstream via the original river channel (statutory minimum flow, plus spillage) or via the headrace canal (up to 400 $m^3 s^{-1}$) strongly influenced the choice made by the downstream migrating eels. The limited data from Clonlara indicated that the vast majority of the eels migrated via the headrace canal in both fishing seasons, despite the greater volume of spillage in the 1993/4 season. The large numbers of eels observed passing downstream via the headrace canal during the more recent hydroacoustic surveys (Fig. 5) illustrates the importance of hydropower generation linked flow patterns in this regard.

Although there is no direct information available on the proportion of silver eels that successfully pass through the power station at Ardnacrusha there are indications that not all of the eels pass safely through the turbines. The cormorant *Phalacrocorax carbo*, with winter roosts of several hundred birds near Ardnacrusha and over 250 pairs breeding in upper Lough Derg, is an important natural predator on fish in the lower Shannon area and the estuary. Previous studies (Doherty & McCarthy, 1997) on their diets and foraging activities showed eels were also important, in terms of both numbers (9%) and biomass (17%), in their overall diets. When feeding in the Ardnacrusha tailrace during the silver eel migration period up to 41% of the prey captured by cormorants were eels, mostly ones damaged by passage through turbines. Through use of X-ray on eels found dead below the dam, or captured in experimental nets directly downstream of the power station, it was confirmed that even specimens without gross external wounds could have internal damage to the spinal column and internal organs. The size frequency of eels taken by the opportunistically feeding cormorants was similar to that for Killaloe eel weir catches (Doherty & McCarthy, 1997).

Fishery management and conservation measures

The decline in European eel, recorded throughout its range, is clearly evident in the results of the analyses of River Shannon eel populations illustrated in Fig. 2. Following the construction of the hydroelectric facilities there was an immediate drop in natural recruitment. However, although this was recognised and mitigation measures were introduced the continued decline in availability of stocking material means that poor recruitment is resulting in diminished numbers of both yellow and silver phase eels in the river system. Improvements to existing juvenile eel trapping facilities at Ardnacrusha and Parteen can be achieved as part of a set of mitigation measures in respect of the obstacles to up-stream eel migration that the hydropower facilities represent. The early success of the Shannon eel stocking programmes, initiated in 1959, prior to the collapse in natural recruitment, illustrates the contribution that such trap and truck measures can potentially make to eel fishery management and stock conservation (McCarthy et al., 1999). However, it is not known if the capture of estuarine glass eels or the transport of elvers from other rivers entering the Shannon estuary, for stocking Shannon lakes will be possible in future. Thus, though very significant conservation measures can be implemented, the future of the Shannon eel populations will ultimately be determined by the success or failure of the pan-European recovery plan for the species.

These trends in recruitment are of importance both because of local fishery conservation imperatives and because of the need to rapidly prepare national and river basin district eel management plans, in compliance with the proposed EU eel recovery plan. The European Water Framework Directive also requires measures for restoration of freshwater fish assemblages, including removal of obstacles to their migrations. Major reductions in fishing mortality are therefore being considered, as part of a River Shannon eel management plan. Future fishing will, apart from stock monitoring, mainly involve silver eels which will be captured only for conservation purposes. Reductions in other anthropogenic eel mortality factors, and removal of obstacles to natural patterns of eel migration in the system will also be required. These mitigating measures give rise to considerable technical and administrative problems.

The general biology of the eel in the Shannon river system is reasonably well known (McCarthy et al., 1999) and the influence of environmental factors on the downstream migration of silver eels has been described (McCarthy & Cullen, 2000a, b; Cullen & McCarthy, 2000, 2003). The importance of discharge patterns and river regulation, as factors affecting the seasonality and between year variation in silver eel migration, is appreciated. Use of hydroacoustic techniques (Fig. 6) can provide new insights and may, in conjunction with use of telemetry and other tagging methodologies, prove particularly helpful in determining rates and directions of eels in proximity to obstacles, screens, and by-pass channels (Haro et al., 1999). However, it is not yet known if modification of lower Shannon flow patterns, through changes in generation protocols at Ardnacrusha or by appropriately timed spillage at the Parteen, will be sufficient to mitigate for mortalities and disruptions to seaward eel migrations caused by the hydropower structures and by river regulation. No direct measurements have been made on the survival rate of silver eels passing through the power station and extrapolation from published data is not easy. Mortality rates associated with entrainment of eels in power station intakes and in passage through turbines appear to vary considerably from site to site, depending on local hydraulic conditions, power station configuration, turbine type, water head, generation levels etc. Published estimates of turbine mortality vary from 5% to 100%. A variety of methodologies have been adopted in these studies, including: calculations based on turbine-specific rating values and prevailing flow conditions; observations on eels captured downstream of power stations; telemetry, conventional tag-recapture analyses and use of balloon tags (von Raben, 1955; Larinier & Dartiguelongue, 1989; Mitchell & Boubee, 1992; Hadderingh & Bakker, 1998; Berg, 2003, Durif et al., 2003). Observations on the passage of eels through turbines at two large North American hydroelectricity dams, using balloon tag technology indicated mortality rates close to 25% in both cases (Normandeau Associates & Skalski, 2000). A recent study of passage through run of the river Kaplan turbines, using transponder tagged silver eels, in the River Meuse indicated that the combined mortality incurred by silver eels migrating through two power stations was only 15.8% (Bruijs et al., 2003).

Since the station at Ardnacrusha has unique structural and hydraulic features, and operates both Francis and Kaplan turbines, it is difficult to extrapolate from such studies and for the present a precautionary assumption of high mortality rates is being assumed. Observations on eels captured by netting immediately downstream, though of a qualitative nature confirmed the nature of the injuries as did the selective predation on damaged eels by cormorants. No silver eel mortalities are observed at the Ardnacrusha vertical 60 mm trash screens, though other species, such as bream do accumulate and die there from time to time. Alternative designs for bar racks and louvers, such as those discussed by Amaral et al. (2003), while potentially useful in other locations where construction of appropriate scale by-pass channels are possible, are unlikely to be of benefit in Ardnacrusha.

It is assumed that the strategy to be adopted for mitigation of the effects of the hydropower station on silver eel escapement will involve a combination of three separate measures: Controlled spillage of water to the original river channel during lunar dark periods and peaks in the eel migratory season, as determined at Killaloe eel weir and other up-river sites; reduction, where possible, in night time power generation during peak eel migrations; release of silver eels downstream of the dam. The extent and timing of the alterations to spillage and nocturnal power generation, will be determined by results of on-going and new studies on silver eel migrations in the lower Shannon. The feasibility of the proposed trap and truck measure has already been demonstrated. A pilot scale scheme, which aimed to release 10% of the silver eel yield for safe escapement to the estuary, involved 15%, 10.8%, and 7.5% of the total Shannon catches in the past three years. The silver eels released in 2006–2007 represented the total catch at Killaloe for the season. However, as can be seen in Fig. 2, catches at Killaloe have declined dramatically due to increased fishing at upstream sites (Fig. 4). Thus it would be possible to capture virtually the entire silver eel run, as is now done mostly for commercial sale, if required for conservation measures. This could be done more effectively by focusing fishing activities on key sampling locations, determined by local environmental conditions and trap efficiencies, but it would still be expensive and logistically complex. However, at least to a partial extent, this conservation option seems likely to be important in future management of Shannon eels. Trap and transport of silver eels round hazards such as hydropower stations, applied effectively in rivers in Germany and New Zealand, is recognised as being a practical solution when effective diversion of silver eels to by-pass channels is not possible (Richkaus & Dixon, 2003). Increased capture efficiency at fishing weirs, as initially considered by McGrath et al. 1976), though use of deflection screen technologies could improve the overall effectiveness of a truck and transport programme on the Shannon. A considerable amount of research has been undertaken responses of eels to behavioural barriers, including their responses to light, sound, water jets, air bubbles, electrical fields (Richkaus & Dixon, 2003). However, though these technologies may only have limited value in diverting eels in fast flowing waters, such as the Ardnacrusha headrace canal, they could be helpful in diverting eels to efficient trapping locations up-stream, from which they could be safely transported past the dam structures. Lights at the Killaloe eel weir have been shown to affect the distribution of eel catches among the nets fished (Cullen & McCarthy, 2000). There are historical references to use of fires by traditional fishermen to increase their silver eel catches and in Britain Lowe (1952) used light to deflect eels to alternative sides of smaller rivers being fished experimentally with paired nets.

A comprehensive approach to eel conservation should ultimately underpin the eel management plans for this and other anthropogenically impacted European rivers. The need for inter-national collaboration in eel research is increasingly evident and this can include: development of models for use in data-poor regions; development of new mitigation measures; development of new monitoring techniques and generally improving knowledge of the complex behaviour and life-cycle of the European eel.

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References

Amaral, S. A., D. A. Davis, M. Metzger, T. C. Cook & G. E. Hecker, 2003. Biological evaluation of a hydro turbine designed to minimize fish injury and mortality. American Fisheries Society Annual Meeting of the Worldwide Decline of Wild Fish Populations, August 10–14, 2003, Quebec, PQ, Canada American Fisheries Society Annual Meeting 133: 316–317.

Arai, T., A. Kotake, & T. K. McCarthy, 2006. Habitat use by the European eel *Anguilla anguilla* in Irish waters. Estuarine, Coastal and Shelf Science 67: 569–578.

Berg, R., 2003. Damage by turbines. In Thorpe, J. E. (ed.), The Eel. By F-W. Tesch 3rd edn., Blackwell Science, Oxford: 326–327.

Bruijs, M. C. M., H. J. G. Polman, G. H. F. M. van Aerssen, R. H. Haddringh, H. V. Winter, C. Deerenberg, H. M. Jansen, U. Schwevers, B. Adam, U. Dumont & N. Kessels, 2003. Management of silver eel: human impact on downstream migrating eel in the River Meuse. Final Report Contract Q5RS-2000-31141. KEMA, The Netherlands.

COM (2003). Development of a community action plan for the management of the European Eel. Communication from the Commission to the Council and the European Parliament. 573(Final). Brussels 1.10.2003.

Cullen, B., 2002. Some notable features of the design and operational history of Ardnacrusha since 1929. In Bielenberg, A. (ed.), The Shannon Scheme and the Electrification of the Irish Free State. The Lilliput press, Dublin: 138–154.

Cullen, P. & T. K. McCarthy, 2000. The effects of artificial light on the distribution of catches of silver eel, *Anguilla anguilla* (L.), across the Killaloe eel weir in the lower river Shannon. Biology and Environment: Proceedings of the Royal Irish Academy. 100B: 165–169.

Cullen, P. & T. K. McCarthy, 2002. Wildlife bycatch in a commercial eel fishery on the River Shannon, Ireland. Irish Naturalists' Journal 27: 49–56.

Cullen, P. & T. K. McCarthy, 2003. Hydrometric and meteorological factors affecting the seaward migration of silver eels (*Anguilla anguilla*, L.) in the lower River Shannon. Environmental Biology of Fishes 67: 349–357.

Dekker, W., 2003. Did lack of spawners cause the collapse of the European eel, *Anguilla anguilla*? Fisheries Management and Ecology 10: 365–376.

Dekker, W., 2004. Slipping through our hands - Population dynamics of European eels. Doctoral Thesis, University of Amsterdam: 186 pp.

Dekker, W. (ed.), 2005. Report of the Workshop: National Data collection European Eel. Sangba Saby (Stockholm, Sweden), 6–8 September, 2005. Fiskeriverket, Swedish Board of Fisheries, Stockholm.

Doherty, D. & T. K. McCarthy, 1997. The population dynamics foraging activities and diets, of great cormorants in the vicinity of an Irish hydroelectricity generating station. In Bacetti, N. & G. Cherubini (eds), Proceedings of the 4th European Conference on Cormorants Supplemento alle Richerche di Biologia della Selvaggina, 26: 133–143.

Durrif, C., C. Gosset, J. Rives, F. Travade & P. Elie, 2003. Behavioural study of downstream migrating eels by radio telemetry at a small hydroelectric power plant. American Fisheries Society Symposium 33: 343–356.

Frouzowa, J. & J. Kubecka, 2004. Changes of acoustic target strength during juvenile perch development. Fisheries Research 66: 355–361.

Gosset, C., F. Travade, C. Durif, J. Rives, & P. Elie, 2005. Tests of two types of bypass for downstream migration of eels at a small hydroelectric power plant. River Research and Applications 21:1095–1105.

Hadderingh, R. H., & H. D. Bakker, 1998. Fish mortality due to passage through hydroelectric power stations on the Meuse and Vecht Rivers. In Jungwirth, M., S. Schmutz & S. Weiss (eds), Fish Migration and Fish Bypasses. Fishing News Books, Oxford: 315–328.

Haro, A., 2003. Downstream migration of silver-phase Anguillid eels. In Aida, K., K. Tsukamotu & K. Yamauchi (eds), Eel Biology. Springer Verlag, Tokyo: 215–222.

Haro, A., D. Degan, J. Horne, B. Kulik & J. Boobee, 1999. An investigation of the feasibility of employing hydroacoustic monitoring as a means to detect the presence and movement of large adult eels (genus *Anguilla*). CAFRC Internal Report No. 99-01, US Geological Survey.

ICES, 2005. Report of the ICES/EIFAC Working Group on Eels. 22–26 November 2004, Galway, Ireland. Copenhagen: ICES CM 2004/ACFM: 90.

Larinier, M. & J. Dartiguelongue, 1989. La circulation des poisons migrateurs: Latransit a travers les turbines des installations hydroelectique. Consuel Superior de la Peche. Bovers, France.

Lowe, R. H., 1952. The influence of light and other factors on the seaward migration of the silver eel (*A. anguillla*, L.). Journal of Animal Ecology 21(2): 275–309.

McCarthy, T. K. & P. Cullen, 2000a. Eel fishing in the River Shannon: eel population changes, fishery management options and fishery conservation issues. A Synthesis Report on the River Shannon Eel Management Programme 1992–2000. Electricity Supply Board, Dublin: 21 pp.

McCarthy, T. K. & P. Cullen, 2000b. The River Shannon silver eel fisheries: variations in commercial and experimental catch levels. Dana 12: 67–76.

McCarthy, T. K. & P. Cullen, 2002. Ireland's changing freshwater habitats: anthropogenic impacts, fishery management problems and ecohydrological perspectives. Ecohydrology and Hydrobiology 2: 143–148.

McCarthy, T. K., M. O'Farrell, P. McGovern, P. Buckley & L. Copley, 1996. Management of juvenile eel stocks for fishery enhancement. Aquaculture Explained, No. 17. Bord Iascaigh Mhara, Dublin.

McCarthy T. K., P. Cullen & W. O'Connor, 1999. The biology and management of River Shannon eel populations. Fisheries Bulletin (Dublin) 17: 9–20.

Mc Grath, C. J., D. P. O'Leary, P. J. Sharkey & D. F. Murphy, 1976. Experimental electrical guidance system for eels at Killaloe eel weir on the River Shannon. I.C.E.S./E.I.F.A.C. Symposium on Eel Research and Management, No. 66. Helsinki, Finland

Mitchell, C. T. & J. A. T. Boubee, 1992. Impacts of turbine passage on downstream migrating eels. New Zealand Freshwater Fisheries Miscellaneous Report. 112: 47.

Moriarty, C., 1982. Development of two eel *Anguilla anguilla* fisheries in Ireland. Proceedings of the North American Eel Conference, 1982. Ontario Fisheries Technical Series 4: 66–69.

Moriarty, C. & W. Dekker (eds), 1997. Management of European Eel. Fisheries Bulletin (Dublin) 15: 110.

Normandeau associates & J. Skalski, 2000. Estimation of survival of American eel after passage through a turbine at the St Lawrance-FDR Power Project. March 1998. Final Report of Normandeu Associates to the New York Power Authority, White Plains, New York.

O'Leary, D. P., 1970. A Low Head Elver Trap. E.I.F.A.C. Consultation on Eel Fishing and Technologies, Hamburg, Germany, 12th–17th October, 1970.

O'Leary, D. P., 1982. Clonlara, 2nd Fishing Station, EIFAC Report, Electricity Supply Board, Dublin.

Quigley, D. & T. O'Brien, 1996. The River Shannon eel fishery: a management review. Archives of Polish Fisheries 4: 249–266.

Richkaus, W. A. & D. A. Dixon, 2003. Review of research and technologies on passage and protection of downstream migrating catadromous eels at hydroelectricity facilities. American Fisheries Society Symposium 33: 377–288.

von Raben, K., 1955. Kaplan turbinen und fische. Wasserwirtschaft, Stuttgart 48: 60–63.

Wirth, T. & L. Bernatchez, 2003. Decline of North-Atlantic eels: a fatal synergy? Proceedings of the Royal Society London B 270: 681–688.