CM 2006/J:20

Not to be cited without prior reference to the author

Going with the flow – Can managing flow regimes aid in promoting silver eel spawner escapement from the Irish River Shannon system ?

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Abstract

Migration patterns of silver eels are influenced by a number of environmental factors e.g lunar periodicity, flow patterns, water temperature, rainfall, wind direction and barometric pressure. Previous studies have highlighted the importance of all of these factors in relation to the patterns of catches of silver eels made on the River Shannon. The River Shannon, the largest River in the British Isles, is harnessed for hydroelectricity generation in it's lower reaches. In upper catchments regions the main influencing factor appears to be the lunar cycle, whereas in lower reaches this is often obscured by the effects of flow patterns. Analysis of 25 years of daily catch statistics from a silver eel weir, located 3km upstream of the regulating dam and 15.6km upstream of the power station, in relation to flow patterns highlighted the importance of flow regimes as determinants of the patterns of eel migrations. These results were further substantiated by a series of tagging experiments carried out using a combination of anchored and PIT tags. 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. However, the possible additional benefits of flow management will be discussed, with particular reference to the potential for spawners to bypass the power station and escape the system through a series of undershot gates in the regulating weir which allow for water to be spilt down the main river channel, away from the headrace canal.

Introduction

A variety of environmental and anthropogenic factors which influence the migratory patterns of Anguillid eels have been identified (Thorpe, 2003). Since the time of Aristotle the importance of the lunar cycle in regulating the timing of the migrations of silver-phase eel in many places has been recognized. However, in more recent times several other environmental factors have been shown to be of importance and in many cases the interplay of a number of factors has been shown to influence silver eel movements. Among the potential factors known to influence downstream migration behaviour in Anguilla species that Haro (2003) listed are: flow, water temperature, lunar phase, rainfall, wind, microseisms, barometric pressure, light intensity, photoperiod, water turbidity and water conductivity.

On the River Shannon, Ireland's largest river system, there is a long history of eel fishing and the silver eel fishery has been monitored for research purposes for several decades (Moriarty, 1990, McCarthy and Cullen, 2000, and Cullen and McCarthy, 2003). The influence of various environmental factors on silver eel migratory patterns differs throughout the network of rives and lakes that make up the River Shannon system. In the uppermost reaches of the system the migrations of silver eels seem to be clearly influenced by lunar cycle (McCarthy and Cullen, 2000). However, further down the system this lunar influence becomes less obvious and in the lower most reaches flow appears to play a dominant role in determining patterns of migration (Cullen and McCarthy, 2003). Since the late 1920s the Shannon has been dammed on it's lower reaches for hydroelectricity generation purposes. For this reason, and for flood control purposes, the flow regimes on the lower reaches of the river are regulated.

In recent years eel catches on the River Shannon system have declined, mirroring the overall decline that has been recorded and recognized throughout the range of the European eel. (Dekker, 2004). In development of a European eel recovery plan, a number of conservation measures have been proposed. In particular, there is a widely recognised need to increase the quantity and quality of eel spawner escapement from European rivers. With this is mind, we analysed a 25-year data series of the silver eel catches from the lower River Shannon and we related these catches to records of the concurrent flow regimes. We also present some previously unpublished information on tagging experiments carried out in the 1990s, which further highlight the importance of flow on the movement of eels in the lower reaches of the River Shannon. Through analysis of flow management related information, we aim to assess if flow management can potentially be used as a tool to boost spawner escapement from the River Shannon system.

Study Area

The Shannon river basin district (Fig 1) includes an area of about 18,000 km^2, and discharges to a 97 km long, 5,002km^2 estuary, draining an area of approximately 11,700 km^2, upstream of upstream of the tidal limit. The total water surface area is about 4100 km^2 but the ten larger lakes represent 90% of the total lake area. 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.

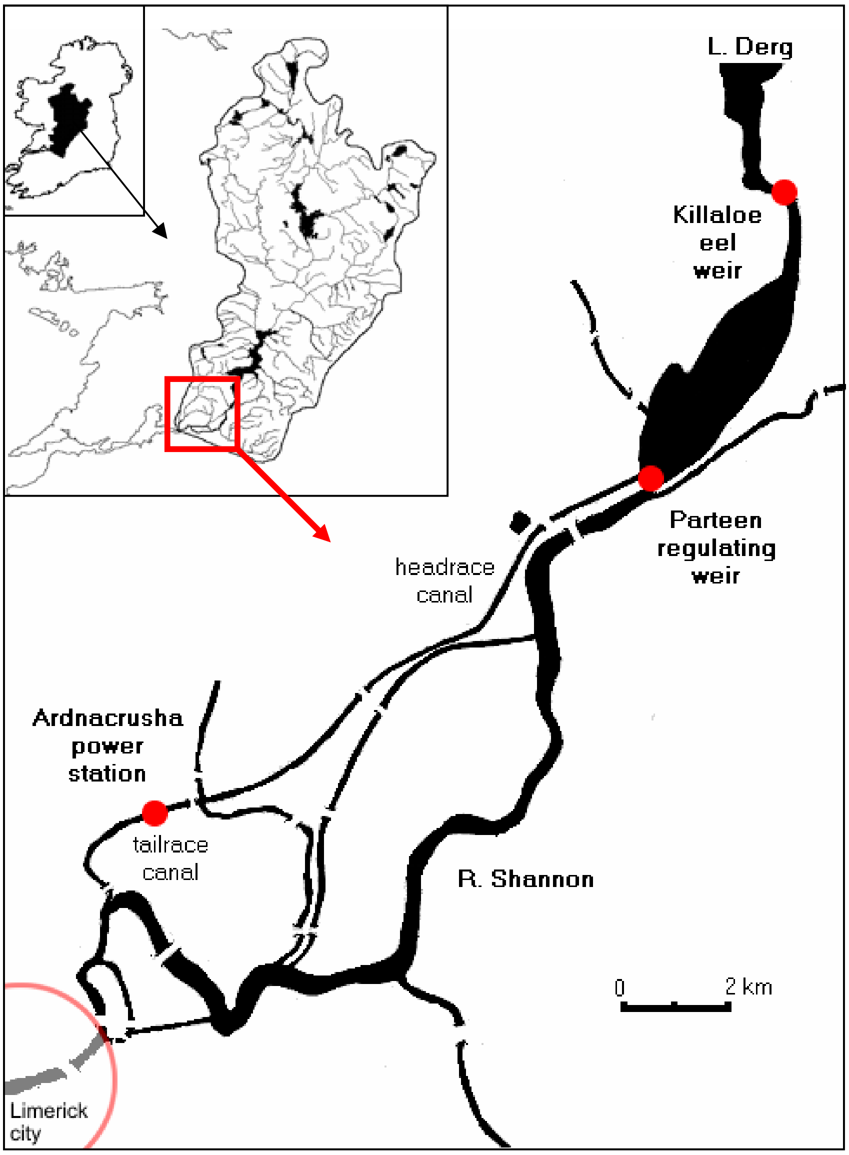

Figure 1 Map of the lower River Shannon, key locations mentioned in this paper are highlighted. *Insert:* The River Shannon and it's catchment area, the location of the area detailed in the main figure is highlighted.

The Ardnacrusha generating station (86 MW), constructed between 1925 and 1929, is located 3km upstream of the tidal limit of the river at Limerick city (Fig 1) and it harnesses 10,400km^2 of the catchment area upstream. The Ardnacrusha station is equipped with three vertical shaft Francis turbo-generators (installed in 1929, refurbished in 1990s) and one vertical shaft Kaplan turbo-generator (installed in 1934, refurbished in 1990s) operating under an average head of 28.5 m and supplied via 6m diameter penstocks. A 12.6km headrace canal supplies the power station with the up to 400m^{3}sec^{-1} water supply needed for maximum generation levels. A 2.4km 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 is located immediately upstream of the regulating weir. A statutory $10m^3sec^{-1}$ compensatory flow must be discharged to the main river channel. Since the 1980's the bulk of this water passes through a 600kW 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 33.56m, excess water is allowed down the river channel through any or all of the set of three 18m 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 3km upstream of the regulating weir, is $186m^3sec^{-1}$. The mean summer discharge is 99 m^3sec^{-1} and the mean winter discharge is 274 $m^3sec^{-}1$. However, flows may be as low as 10-15 m^3sec^{-1} in dry summers or over 700 m^3sec^{-1} in major floods.

For downstream migrants there are a number of options available depending on flow conditions. During times of headrace discharge the 10m navigation gate at the entrance to the headrace canal is typically lifted and fish may migrate via the 9m deep headrace canal to the powerstation. At this point they must pass through large trash screens (with 60mm 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 either 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 18m wide undershot gates.

The main silver eel fishery on the lower River Shannon is located at Killaloe. The Killaloe silver eel weir, described in more detail by McGrath *et al* (1976) and Cullen & Mc Carthy (2000), covers about 90% of the river width, and can be fished using up to 34 coghill nets (8m long, 10 m opening diameter). 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 currently transported overland and re-released downstream of the generating station to help boost spawner escapement levels from the system. Killaloe was the main capture point for eels on the River Shannon prior to the mid 1990s when a number of experimental fishing crews were introduced throughout the system. As a result the recent catches of eels at Killaloe have sharply declined, partly due to the decline in eel stocks, and partly due to the increased upstream fishing pressure.

Methods

In addition to data gathered by scientific observers as part of an ongoing Monitoring Programme on the River Shannon eel fisheries information on the daily eel catches at the Killaloe eel weir were obtained from Electricity Supply Board Fisheries Conservation. Data was available from the fishing seasons of 1981/1982 to 2005/2006. Data on the daily mean flow rates at various points on the lower River Shannon and spillage rates at the Parteen Regulating Weir were obtained from the station room records held at Ardnacrusha Power Station for the same period.

The eel tagging experiments made use of a variety of tags which are broadly referred to as a) anchor and b) internal. The anchor tags consisted of the conventional, individually numbered floy anchor tags and a selection of non-numbered anchor tags (referred to as tab tags) which could be identified by shape and colour. The internal tags were of an electronic type known as PIT (passive integrated transponder) tags. These tags consist of an integrated microchip bonded to an antenna coil and encapsulated in a glass tube 12mm long by 2mm diameter (Prentice *et al*, 1990). Each tag is coded with one of 550 x 10^9 unique 10-digit alpha-numeric codes and is activated by an external 400kHz signal. In these experiments a hand held scanning device (Trovan LID-500) was used which could identify a tag at a range of 30cm and showed the tag number on a L.C.D. screen. The tags were introduced into the body cavity of the eels by means of a modified syringe. Prior to tagging all eels were anaesthetised using chlorobutanol and measured , following tagging they were allowed to recover before release.

Results

Catch and flow data analyses

Previous analyses (Cullen and McCarthy, 2003) had highlighted the importance flow in determining the catch patterns at the Killaloe silver eel weir. Spearman Rank Correlation analysis highlighted the very highly significant relationship between flow and catch (rS 0.585, $p<0.001$) in the 25 year data set analysed. As can be clearly seen in Fig 2, where examples of a daily catches and flow rates are given for 4 fishing seasons (1987/1988, 1991/92, 199/95 and 2003/2004), there is a clear influence of flow rates on the pattern of catch at the Killaloe eel weir. With a view to further understanding the flow regimes in the lower River Shannon and to assessing how they might be utilized to manage the migration patterns of the silver eels and maximising spawner escapement particular emphasis was placed on an analysis of the spillage patterns in relation to the silver eel catches.

Table 1 Summary statistics on the flow rates at Killaloe for all fishing dates as well as the flow rates at Killaloe, the spillage rate at Parteen and the % of flow accounted for by spillage for all dates on which spillage occurred during the fishing seasons of 1981/82 to 2995/06 inclusive.

	All dates	**Spillage dates only**		
	Killaloe flow	*Killaloe flow*	*Spillage*	*% of Killaloe flow*
Mean	263.61	500.92	138.62	26.23
Standard Error	2.16	3.49	3.57	0.55
Median	252.30	491.96	126.05	25.81
Standard Deviation	142.23	81.68	83.55	12.92
Minimum	10.00	278.46	12.00	2.72
Maximum	826.16	826.16	385.50	100.00

During the 25 years of data analysed spillage occurred in all but 5 of the years, over varying periods of time ranging from 2 days (1.3% 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 the earlier years there was extended fishing, with the silver season often starting in September and lasting for 6 months. In comparison fishing in more recent years is carried out on a more limited basis, with the fishing season lasting usually up to three

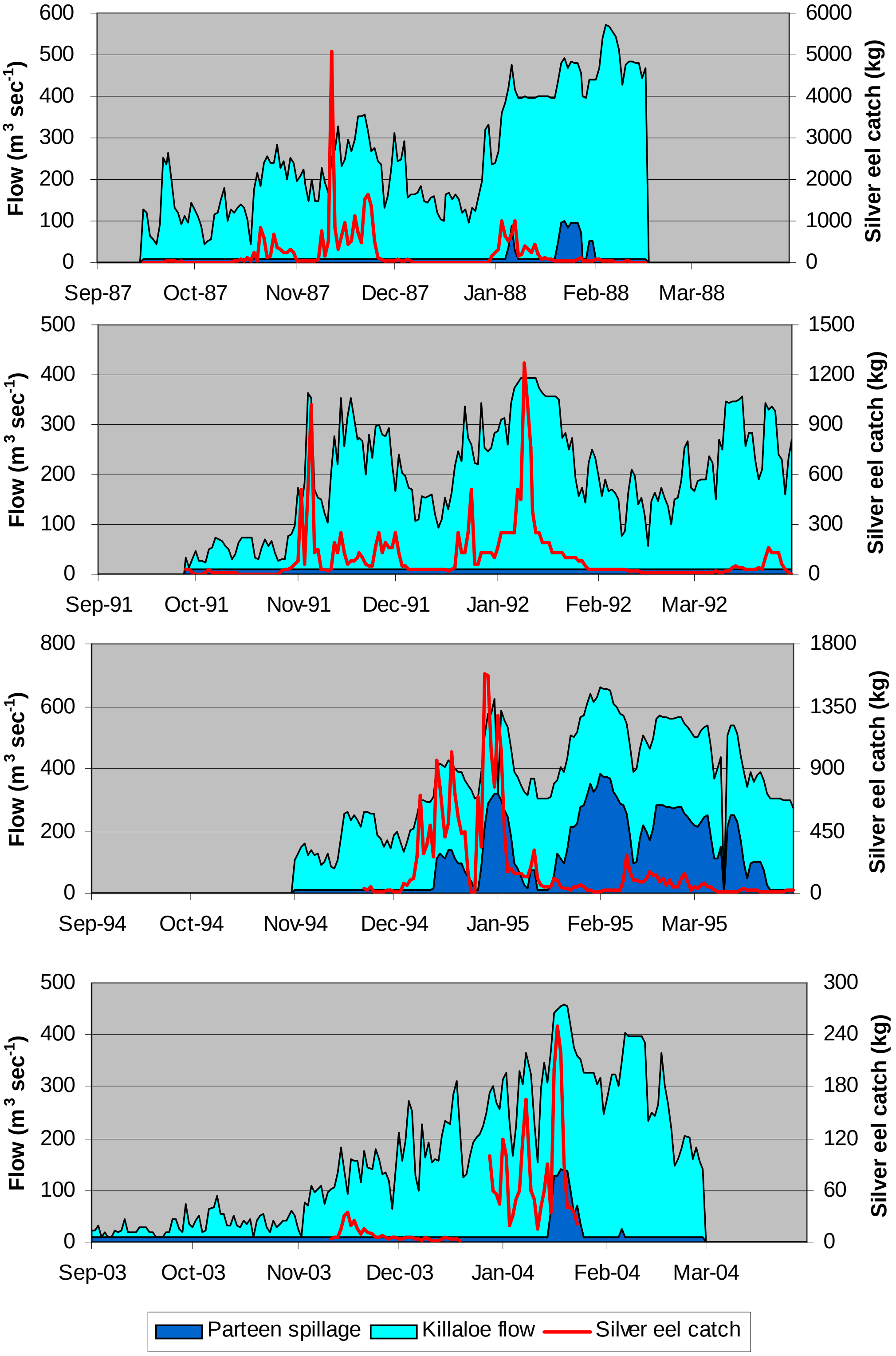

Figure 2 Patterns of daily eel capture and flow rates at the Killaloe eel weir for the fishing seasons of 1987/1988, 1991/92, 199/95 and 2003/2004, highlighting the influence of flow on the pattern of eel migration. The contribution of spillage to the overall flow rate at Killaloe is indicated.

months maximum. Figure 3a highlights the overall variation in flow rates and spillage rates that have occurred during the silver eel fishing seasons for the 25 years of data analysed. In Figure 3b the percentage of the Killaloe flow that results from spillage is shown for the occasions on which spillage was recorded during the silver eel fishing seasons. There has been considerable variation in both flow rates and spillage rates, but the overall summary statistics on flow and spillage data are presented in Table 1.

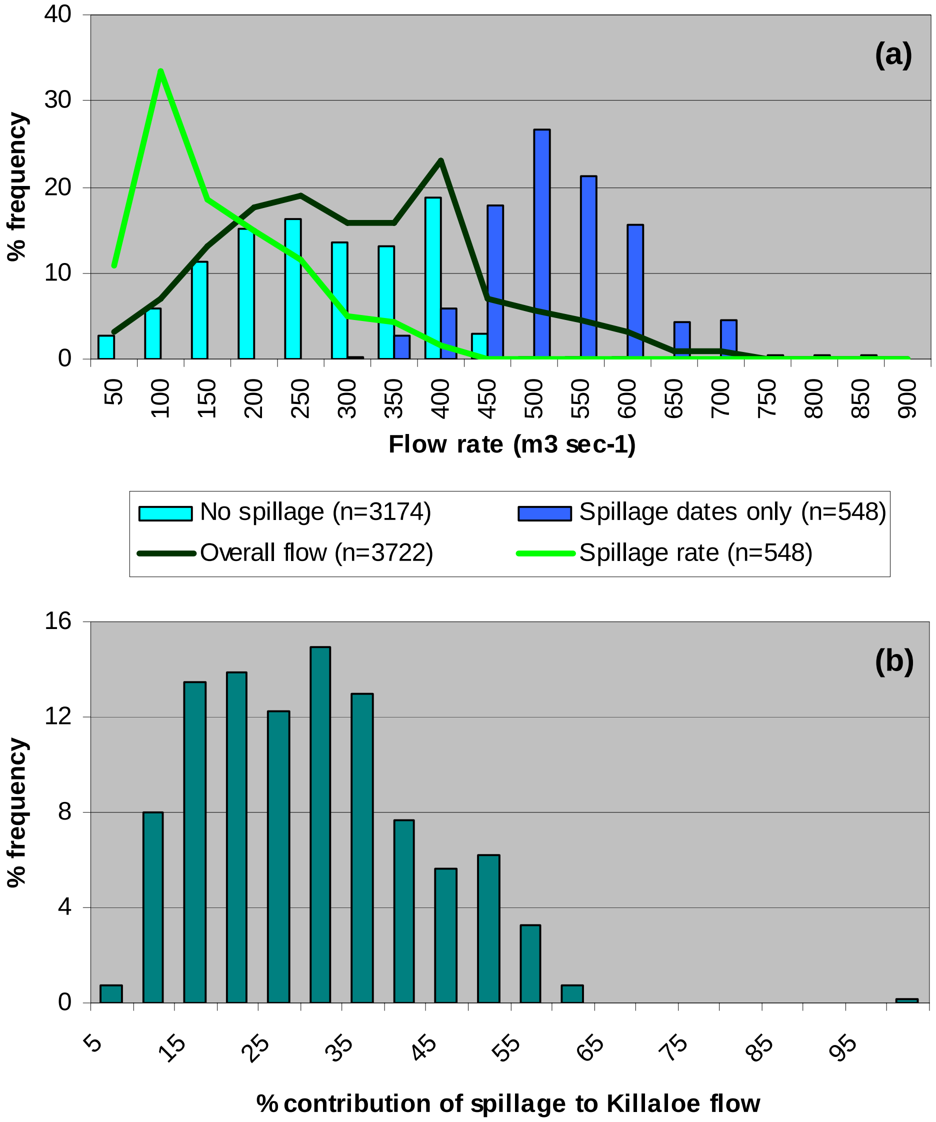

Figure 3 Frequency distributions describing (a) the variation in flow at Killaoe during the fishing seasons of 1981/82 to 2005/06 inclusive in addition to a breakdown of this information to account for dates on which spillage did or did not occur. Information on average spillage rates is also provided. (b) The proportion of the Killaloe flow that is accounted for by spillage for the same time period.

Summaries of the annual variations in spillage rates and the proportion of the silver eel catch recorded at the Killaloe eel weir during times of spillage are presented in Figures 4 and 5 respectively. Although there is considerable variation between years, a correlation analysis between catch and spillage information indicated that the total catch of silver eels is significantly correlated to both 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 is recorded during the spillage period (rS 0.516, p=0.021). The importance of spillage is also indicated by the relationship between the proportion of the catch that is captured during spillage periods and the percentage of the total flow that is accounted for by spillage (rS 0.475 , p=0.035).

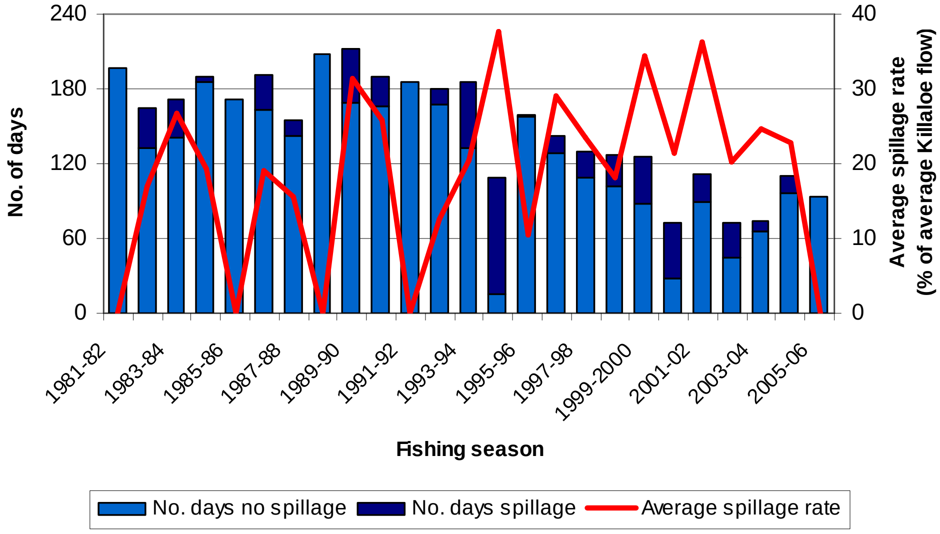

Figure 4 A breakdown of the occurrence of spillage for each of the fishing seasons from 1981/82 to 2005/06 inclusive, in addition to information on the average annual spillage rate

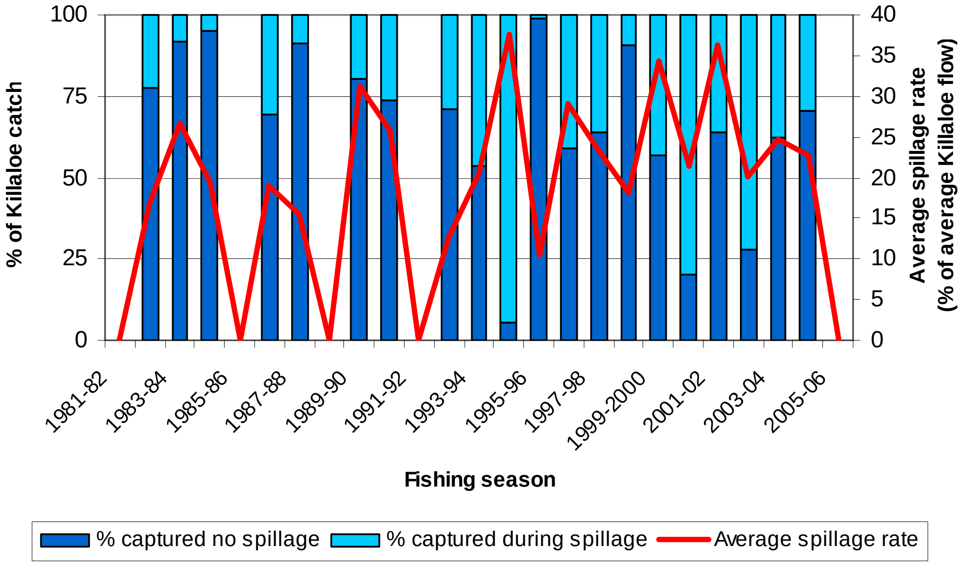

Figure 5 Variation in the capture rate of silver eels at the Killaloe eel weir during periods when spillage occurred vs no spillage occurring for each of the fishing seasons from 1981/82 to 2005/06 inclusive. The average spillage rate is also included.

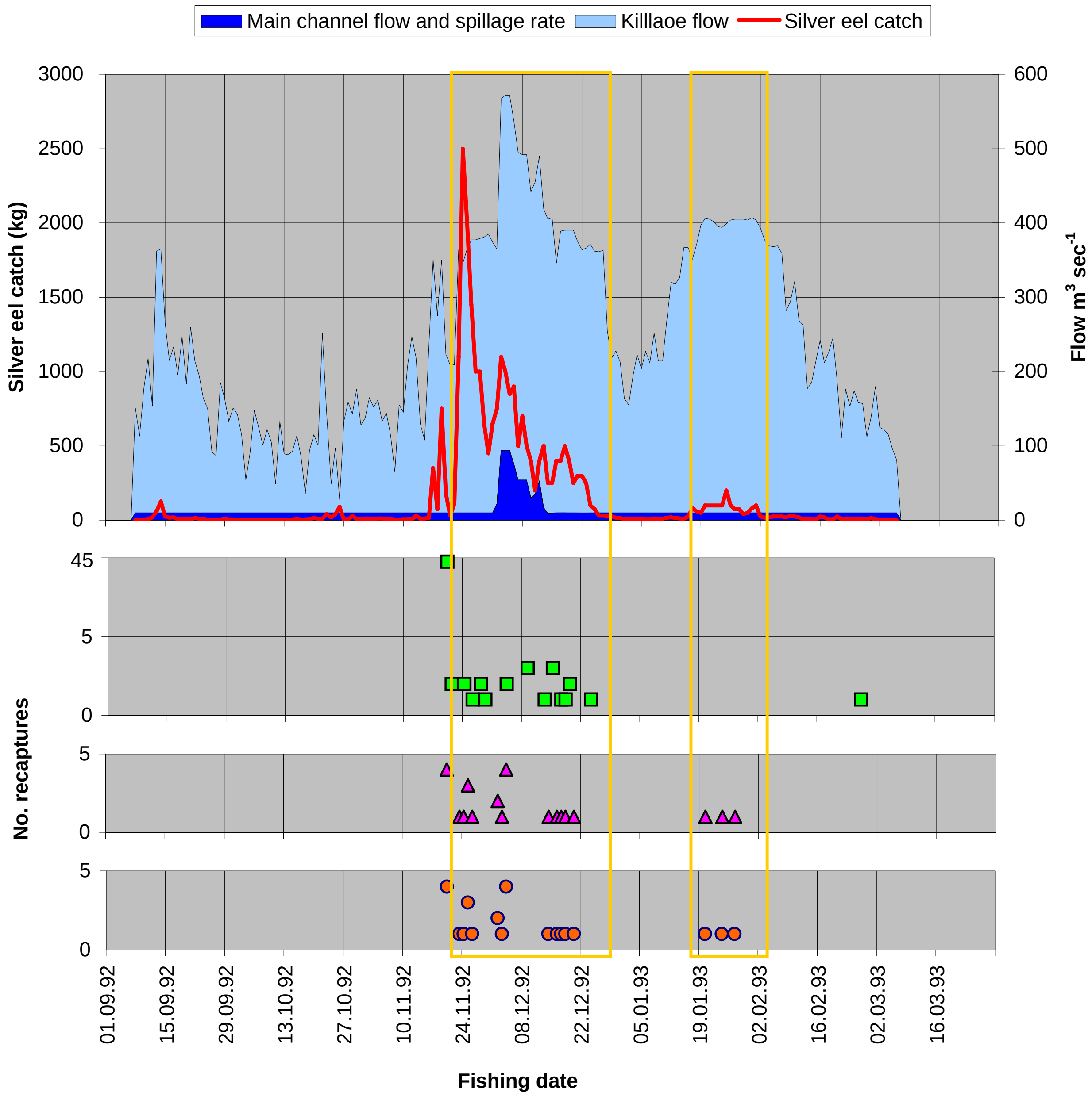

Figure 6 Variation in the capture rates of tagged eels released upstream of the Killaloe eel weir during the 1992 fishing season. The data is presented in relation to the daily catch and flow rates at Killaloe for the 1992/93 fishing season. The contribution of spillage at the Parteen regulating weir to the flow rate at Killaloe is highlighted. Occassions of high flow and related high capture are indicated by the yellow boxes.

Silver eel tagging experiments
A number of tagging experiments were carried out to assess the movements of silver eels in the vicinity of the Killaloe eel weir as part of a larger tagging and monitoring programmes carried out during the fishing seasons of 1992/93 to 1994/1994 inclusive. In 1992 several batches of eels were tagged and released at points upstream of the Killaloe eel weir. The recapture rates of these eels at the Killaloe eel weir were monitored and a summary of the results of three such batches of eels are presented in Fig 6. As was typical with these tagging experiments there is an initial period of relatively concentrated recapture, followed by a more gradual recapture rate over the reminder of the season. Recaptures were generally concentrated at periods of increased silver eel capture – which were usually at times of increased flow.

Discussion

The level of decline in eels stocks throughout their range is now a matter of major concern and there is more and more focus on assessing the impact of dams, hydroelectricity power stations and other such obstacles on both the up- and downstream migration of eel stocks (e.g. Larnier, 2001, Haro *et al*, 2003, Richkus and Dixon, 2003, Durif *et al*, 2005). However while many of the studies to date have focused on the behaviour patterns of eels in the vicinity of such obstacles to their migration, or on the impact on the eels (e.g. turbine damage), there has been less of a focus on potential measures for maximizing escapement.

On the Shannon system it is probable that the normal flow management system is already helping to increase escapement rates. The importance of flow to silver eel migratory patterns has clearly been demonstrated on the lower reaches of this system both here and by Cullen and McCarthy (2003) and McCarthy *et al* (in press). Spillage is an important indicator of high water levels and high flow in the Shannon system. Spillage rates up to 385m^3 sec^{-1} have been recorded in past years, although this is the exception rather than the norm, with spillage rates generally less than 200 m3 sec-1 (77.6% frequency). Spillage may contribute to escapement of silver eels from the Shannon system as during spillage periods eels have the chance to travel down the original river channel, without having to pass through the Ardncrusha generating station where they may incur turbine related damage.

Although spillage rates vary on the Shannon it is likely that they are sufficient to attract migrating silver eels. A study by Gosset *et al* (2005) showed that a bypass with 2-5% of the discharge rate of the turbines was partially efficient for migrating silver eels. Likewise, a simulation study of the effects of spill and flow at a North American power plant indicated the potential for reducing silver eel mortality in rivers dammed for hydroelectricity generation (Haro *et al*, 2003). In the case of the Shannon the ratio of spillage rate to discharge via the power station is higher (averaging approximately 25%) and the spillage it is therefore more likely to act as an effective attractant to the migrating silver eels. The nature of the spillage mechanism at the Parteen weir is also likely to act as an attractant to migrating eels. Eels are known for their preference for migrating in the deeper waters of the channel and indeed Gosset *et al* (2005) also found that a bottom bypass was preferable to a surface bypass. As the regulating gates at the Parteen Weir are undershot gates (i.e. the gates are lifted to allow bottom waters to "spill" down to the main river channel they are likely to have a relatively high attractant level to migrating eels especially when the spillage level is high. It would therefore seem highly probable that during times of spillage on the Shannon system a percentage of the migrating population is utilising this alternative migrating route.

Past studies and limited fishery investigations on the main river channel downstream of the regulating weir (Cullen 1999, McCarthy and Cullen unpublished data) have indicated that this portion of the channel is dominated by high-density stocks that mature into predominantly male silver eels. Analysis of the limited commercial records have indicated that on occasions larger silver eels have been captured indicating that perhaps some eels are accessing this alternative route to migrate out of the Shannon system. Although it has not been possible to positively link the occurrence of such larger eels to periods of spillage this is largely due to the very limited fishing carried out and as a result the limited data available. Also when fishing had occurred on this stretch of the river during the period studied it was generally suspended or discontinued during and immediately following periods of spillage due to operational difficulties.

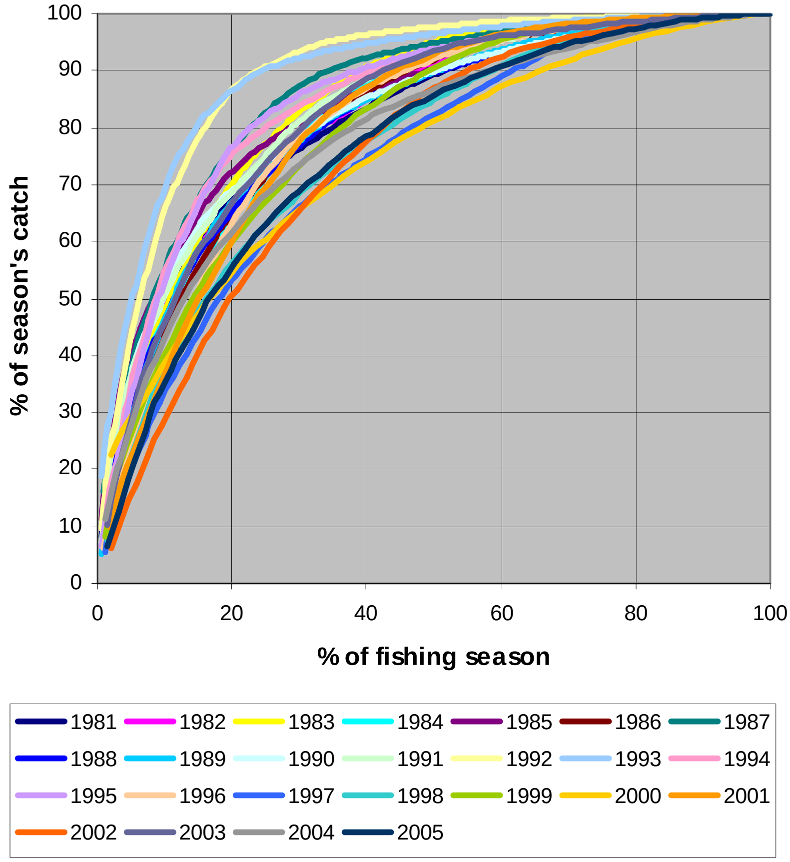

Figure 7 Capture rates at the Killaloe eel weir for the fishing seasons of 1981/82 (1981) to 2005/2006 (2005) inclusive.

The flow management system on the Shannon also offers the potential for future management of eels migratory patterns and maximizing the escapement rate. During salmon smolt migratory periods a series of monitoring traps are fished at the Killaloe eel weir. These allow for monitoring of the timing of the smolt runs and as information on the smolt migratory patterns become available the generating protocols at the Ardnacrusha power station are adjusted to maximize the benefit to the smolts. Such management practices may have to be considered with regard to ensuring eel escapement in the future. Although the eel fishing / migrating season on the Shannon system is often an extended one a large percentage of the catch / migration is often made over a short period of time. For example, as can be seen in Fig 7, in 1992 and 1993 over 80% of the silver eel catch for those seasons was made in less than 20% of the fishing season. In most of the years analysed over 80% of the catch was captured in 40% of the fishing season.

The potential exists therefore to monitor the silver eel migration patterns (as reflected in the silver eel catches at Killaloe) and where possible to mange generating and flow levels during times of increased catches to maximize the benefit to the eels i.e. with maximum diversion of flow to spillage and minimal / no diversion to the power station for limited periods of time. Indeed, a study on a New Zealand River system by Watene and Boubée (2005) has indicated that opening of spillway gates at a hydroelectric facility on the Patea River provided a simple but effective method for increasing eel escapements and the authors recommended maximizing spillage on such dammed rivers, especially at times of flooding and at night when eel are migrating.

Acknowledgements

Particular thanks to Electricity Supply Board (ESB) Fisheries Conservation and ESB Ardnacrusha Hydroelectric Generating Station staff for their help and for access to their records. Many thanks also to all the staff and students of the Zoology Department, National University of Ireland, in particular those who have participated in the ESB funded Shannon Eel Monitoring Programme from 1992 to date.

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