CM/2006/J:27

Not to be cited without prior reference to the authors

Modelling of *Anguilla anguilla* production and silver eel escapement for the River Severn, compliance with targets and development of management plans.

Alan M. Walker[1], Miran W. Aprahamian[2], Mike Pawson[1], Beth Williams[3], Anthony Bark[3], Brian Knights[3].

[1]Cefas, Lowestoft Laboratory, Pakefield Road, Lowestoft, Suffolk NR33 0HT, UK.

[2]Environment Agency, Richard Fairclough House, Knutsford, Warrington, WA4 1HG, UK.

[3]King's College London, Franklin-Wilkins Building, 150 Stamford Street, London SE1 8WA, UK.

Abstract.

The River Severn catchment supports the largest glass eel fishery in the UK, with a current annual catch of around 10 t. Since the 1980s, there has been a decline in the catch and CPUE (an index of recruitment) of glass eel of ~70%, with the main decline happening in 1983/1984. Yellow and silver eel fisheries in the Severn catchment are negligible. Comparison of the results of eel-specific surveys undertaken in the late 1990s and between 2002 – 2004 with those during the early 1980s indicates that there have been no significant overall changes in eel distribution, density, biomass or size structure of the eel population in the Severn. This suggests that escapement of silver eels is similar to that during the late 1970s and early 1980s, when the glass eel fishery was much larger (~40 t).

The European Commission Eel Recovery Plan requires that Member States develop management plans in order to ensure at least 40% of the potential escapement of silver eels *Anguilla anguilla* is achieved in a River Basin District (WFD). However, as eel production and silver eel escapement is not measured in most catchments, a modelling approach is required to estimate potential and actual escapement, and to assess the likely effects of management measures. Two modelling approaches have been applied to data for the Sveren catchment.

In this paper we describe the use of a Reference Condition Model, related to a 1950's baseline, which suggest that the current level of escapement from the Severn is probably not sufficient to meet the 40% management target. However, with this model, it is not possible to assess whether removal of the glass eel fishery would help to achieve compliance (through increased recruitment), or whether the main constraint of silver eel production is the perceived decline in the amount and suitability of habitat available to eels in the Severn since the 1950s. To address this, we have applied a Scenario-based Model for Eel Populations (SMEP) to model yellow eel populations and silver eel escapement from the Severn catchment. SMEP considers both the biological characteristics of the eel population and a number of potential anthropogenic influences on that population. Biological characteristics modelled include growth, natural mortality, sexual differentiation, maturation and migration, and the model can use site-specific data to calibrate the output. Since the Severn is relatively data-rich, we are able to assess the effects that changes in recruitment, habitat (quality and quantity) and/or accessibility have on mortality, production and eventual silver eel escapement through time.

The presentation will also discuss the need for an enhanced (over current) monitoring programme to complement the development of tools to set reference levels and assess compliance with the EU target, and to quantify the effect of remedial measures.

Keywords: *Anguilla anguilla*, SMEP, catchment, River Basin District, recruitment, silver eel, escapement, population, model.

Contact author:

Mike Pawson: Cefas, Pakefield Road, Lowestoft, Suffolk, NR33 0HT, United Kingdom, [tel: +44 1502 524436, fax: +44 1502 526351, e-mail: mike.pawson@cefas.co.uk].

1. Introduction

In October 2005, the EU commission presented a proposal aimed at establishing measures for the recovery of the European eel stock (COM(2005) 472 final). The objective of the proposal is to achieve a recovery of the European eel stock to historic levels of adult abundance and glass eel recruitment. The principal element of the Regulation is the establishment of national Eel Management Plans (EMPs), by means of which each Member State will achieve the objective of a 40% escapement of silver eel from each river basin, measured with respect to undisturbed conditions. According to the Commission Note produced in May 2006 (COM(2006)9427/06), this refers to the "best estimate of the potential escapement from the river basin in the absence of human activities affecting the fishing area or the stock". The subgroup on review of stocks of the Scientific, Technical and Economic Committee for Fisheries (STECF) - EEL MANAGEMENT recommended that, for the purposes of the development of EMPs, the undisturbed situation should reflect glass eel recruitment at a normal historic level, and the physical habitat conditions should include the full productive extent of eel habitat, given the absence of barriers to migration and no mortalities from fishing, turbines or pollution (SGRST-06-02).

Since eel production and silver eel escapement is not measured in most UK or European catchments, a modelling approach is required to estimate potential and actual escapement, and to assess the likely effects of management measures. In this paper, we report on the application of two modelling procedures to inform the development of an EMP for the River Severn catchment, which supports the largest glass eel fishery in the UK.

2. The Severn catchment

The River Severn rises in Wales and flows 350 km to its estuary downstream of Gloucester, where it widens into the Bristol Channel (Figure 1). The funnel shape, the high tidal range (13.2 m mean spring at Avonmouth) and the south westerly orientation of the estuary all combine to promote strong glass eel recruitment. Tewkesbury is taken as the upstream limit of tidal influence. In the past, the marshes and creeks bordering the estuary would have provided nursery areas for young eels, but the construction of flood-control tidal flaps since the 1950s on these streams and run-offs is considered to have reduced access to these areas.

Major tributaries that join the Severn include the Vyrnwy, the Stour, the Teme and the Warwickshire Avon. This catchment (10,000+ km^2) drains a large part of the English

Midlands, which include large urban centres, and mid-Wales which is predominantly rural in character. The main river has been impacted by eutrophication, but nutrient loading from point sources such as industry and sewage treatment works has been greatly reduced in the last 20 years. However, diffuse pollution is still an issue and persistent chemicals from a range of sources are known to impact on fish stocks.

The main river is navigable to motorised craft by locks and weirs as far as Stourport, 30 km upstream from Tewkesbury (Figure 1). These are major barriers to eel migration and have been in place since the 1800s (White & Knights, 1997a). Older mill weirs are found in many tributaries (Figure 2). The river has also been extensively managed to control flooding, particularly in the lower and tidal reaches where low-lying land has been reclaimed for agriculture.

3. The fishery

There are commercial eel fisheries on the lower and tidal River Severn, carried out under licence granted by the Environment Agency. In 2005, there were 413 licence holders: 402 for using dip nets for glass eel, 10 for winged traps and fyke nets to catch yellow eels, and one for a weir trap to catch silver eels. Note, however, that a license can allow the use of several instruments, so the number of licences is not necessarily a direct indicator of fishing potential or activity.

3.1 Glass eels

The Severn glass eel fishery operates on spring tides from the mid-February near Sharpness through to mid-May as far upstream as Tewkesbury. During the flood tide, which lasts for only 2 hours, the elvers are dispersed across the whole width of the river; on the ebb tide (9-10 hours) the elvers seek the slack water at the sides. Fishing usually takes place during the first four hours of the ebb tide at night. The nets are hand-held against the bank, with the mouth facing downstream or upstream depending on the direction of movement of the elvers in relation to the tide.

Glass eel catch records are collected either at regional or the UK national level and,, at present, they do not provide data for the Severn fishery alone. However, it is considered that this fishery accounts for at least 95% of the national catch of glass eels and that the national data are a good indicator of the trends in catches from the Severn. Annual catches varied widely over the period 1972 to 1983 (Figure 3), but a declining trend is apparent in subsequent years, with minimum annual catches of ~5 t in 2001 and 2002 (Pawson *et al.*, 2006). In the last 30 years, the yield of elvers from the Severn is estimated to have declined by ~70%, with the main decline happening in 1983/1984. The largest catch of recent history was 100 t, in 1979, whilst the smallest was 4 t in 1976 (Peter Wood, UK Glass Eels, personal communication).

The method used to catch Severn glass eels confers a relatively high survival rate in comparison with elvers caught by trawling elsewhere in Europe. As a consequence, the Severn is a good source of glass eels for stocking (subject to health check and consenting considerations) and they have been stocked at a number of sites in the Severn in recent years (Figure 4) and in other rivers and in lakes in the UK and Europe (Knights and White, 1997). However, demand for glass eels/elvers as seed-stock for eel aquaculture increased greatly in the 1990s, and high prices have inhibited purchases for stocking (Knights, 2001).

3.2 Yellow and silver eels

Yellow and silver eel fisheries in the River Severn were relatively small in the 1980s (around 20 fishermen catching a total of about 5 t per annum) and primarily existed for home consumption. In 1984, 13 licences were issued for putcheons, set with the mouth parallel to the bank in the tidal reaches to catch yellow eels, but placed facing upstream in fresh water to intercept the silver eels migrating downstream. There were also 16 licences for fyke nets between Gloucester and Tewkesbury, and two eel racks on the Warwickshire Avon were worked regularly in the mid-1980s. The bulk of the silver eel catch on the Severn was taken in wing nets stretched from bank to bank. From 1982 to 1984, 7 men took a total catch of 2 t compared with 13 operators catching about 9 t in 1976.

Fyke nets and traps are still used for yellow and silver eel on the lower river, but catches are minimal: in 2005, the reported yellow eel catch was 61 kg and the reported silver eel catch was 6 kg. There is one fixed eel trap on a weir on the River Avon, operated recently (2005 onwards) on behalf of the Environment Agency to collect silver eels for monitoring purposes.

The catch data for all life stages of eels declared to the Environment Agency are sparse and considered to be unreliable (Knights, 2001). Aggregated declared catch returns for the Severn in 2004 are 577 kg of elvers/glass eel and 569 kg of yellow/silver eel. In recent years, HM Custom and Excise nett export data suggest that the declared glass eel catch has been under-reported by a factor of between 3.4 and ~15 times, and that the true catch of glass eel is in the region of 10 t per year (Pawson *et al.*, 2006). Similarly, it is estimated that official catch returns underestimate the true combined catch of yellow and silver eel by a factor of between 2.4-7.2 times (2002-2004 data, in Pawson *et al.*, 2006).

4. Status of stocks based on survey methods

4.1 Glass eel recruitment

There is no fishery-independent monitoring of glass eel recruitment in the Severn, and catch per unit effort (CPUE) has been used as a recruitment index. The CPUE data derived from HM export estimates indicate that recruitment in the last decade has been at about 30% of the peak values of the early 1980s, but with some recent increases towards historical levels (Figure 5).

4.2 Yellow eel populations

An extensive investigation of yellow eel distribution, abundance, age and growth was carried out during 1983 and 1984 at a total of 109 sites (Aprahamian, 1986, 1988). In 1998, 24 of these sites were resurveyed, 16 of which were resurveyed in 1999 (Knights *et al*. 2001). Ten sites of those fished in 1983, 1998 and 1999 have been resurveyed annually since 2002. The sites were grouped into zones as indicated below, and illustrated in Figure 6:

Zone A – Outer Severn Estuary tributaries;

Zone B – Inner Severn Estuary tributaries;

Zone C – Tributaries between Gloucester and Tewkesbury;

Zone D – Tributaries between Tewkesbury and Worcester off the non-tidal river (excluding the Warwickshire Avon and the River Teme catchments).

Currently, eel are well distributed throughout the Severn catchment, although few appear to penetrate the source streams arising from the Cambrian mountains, and eel are also absent from rivers draining the Birmingham conurbation (Figure 7). The surveys between 2001 and

2005 found eels at all the sites where they had been present in the early 1980s, but also at some sites where eels had previously been absent.

The eel population downstream of Worcester was considered to be at carrying capacity during the 1980s: both eel density and biomass varied by up to an order of magnitude between sites, but there was no significant difference in growth rate (Aprahamian, 2000). In contrast, the density and biomass of eel in the middle reaches of the Severn and Avon catchments are low (Aprahamian, 1986 & 1988) and likely to be below carrying capacity.

The density and biomass of eel at the 10 sites common to all surveys are shown in Figures 8 and 9, respectively. Overall (all zones), there is little evidence of any change in either density or biomass over the period, though there is evidence of a systematic change in certain zones. In those sites sampled from rivers draining into the outer estuary (Zone A), the biomass in 1983 was much lower than has been recorded subsequently. This may represent a change in productivity or sampling variability, as Knights *et al.* (2001) have a reported a variation in mean density of eel at common sites of ~25% between years. The improvement in the status of the eel population in Zone D (Queenhill Brook) has been attributed to habitat improvement following the discontinuing of channel dredging.

Overall, there are no statistically significant differences (Kruskal Wallis test) in the densities of eel <150 mm (age 1 – 3 years) or >450 mm in 1983, 1999 and 2004, but there were significant changes within zones. The density of eel >450 mm in Zone A showed a small decrease in 2004 in comparison to 1983 and 1999, whereas there was a marked increase in Zone B. Eels >450 mm were absent from Zone C in 2004. In Zone D there was an increase from 1983 to 1999 with a small decrease from 1999 to 2004.

Comparison of the results of eel-specific surveys undertaken in the late 1990s and between 2002 – 2004 with those during the early 1980s indicates that there have been no significant changes in eel distribution, density or biomass or in the size structure of the population in the Severn. This suggests that escapement is similar to that during the late 1970s and early 1980s, when the glass eel fishery was much larger (~40 t y^{-1} and as high as 100 t y^{-1}) and before the major decline in glass eel recruitment to Europe (Moriarty, 1990; Dekker, 2000).

5 Status of stock in relation to Reference Condition Model

It has been shown for a number of UK river systems that eel density declines with distance from tidal influence in a systematic manner and can be effectively modelled (Knights *et al.*, 2001; Ibbotson *et al.*, 2002). The Reference Condition Model (RCM) aims to describe the eel population (density/biomass) in a given catchment as it would appear in the absence of anthropogenic influences, and to compare the current situation with this reference position. The instantaneous rate of decline in eel density was calculated for 12 catchments in England and Wales (selected data from Knights *et al.*, 2001; Ibbotson *et al.*, 2002) and compared with a number of catchment variables, of which catchment gradient explained 55% of the variability (for further details see Section 4.2.2 in ICES, 2004). It is important to note that the data from which the Reference Condition was derived, were from surveys conducted during the late 1970s to early 1990s and do not necessarily represent the 'undisturbed' conditions as defined at the beginning of this paper. However, these data do provide for a reference condition prior to, or at least during the early part of, the recent significant decline in recruitment of glass eel to Europe.

The River Severn data from the 1983/4 eel-specific survey provided the widest coverage across the catchment and were used to assess compliance with reference conditions. These data resulted in an observed instantaneous rate of decline in eel density in an upstream direction from the Severn Estuary (bold line in Figure 10) that was faster than might be expected under reference conditions (dotted line in Figure 10). Comparison of the 1983/4 situation (area under the curve) with that estimated under reference conditions suggests that the production of silver eels from the Severn in 1983/4 represented 41% of the catchment's potential. If this production estimate is weighted according to the amount of habitat available to eel at various distances from the tidal limit, at that time, then the decline is estimated at 34% of reference conditions. The current situation (2000s) is considered to be similar to that observed in 1983/4 as the evidence suggests there has been no overall change in density and biomass and distribution over the last 20+ years. Therefore, it would appear that recent recruitment to the River has been adequate to maintain the eel population to at least its 1983 level. This suggests that silver eel escapement is similar to that prior to 1980, assuming the same amount and quality of habitat (though note the presence of a 40 t glass eel fishery at that time).

If the decline in the glass eel CPUE (Figure 5) reflects a decline in recruitment of some 70%, and the potential current output is similar to that in the early 1980s, this suggests that there has been a decline in density-dependent mortality. Analyses of glass eel pigmentation-stage and body size data led White & Knights (1997b) to conclude that estuarine migration of glass eels/elvers was slow and that natural mortality was probably very high. This suggests that the glass eel fishery has not been having an impact on escapement of silver eels over the last 20-25 years. Similarly, the lower recruitment since the 1980s does not appear to be reflected in changes in the densities of eels in the middle and upper reaches of the catchment, and has not led to a decrease in upriver migration. However, the RCM suggests that the yellow eel population may be ~60% lower than would be expected under reference conditions, though such conditions in the Severn might not have existed since well before the start of the 20th Century.

The use of the RCM to assess current compliance with the 40% escapement target has a number of limitations. It is not possible to assess the biomass of silver eel migrating from the catchment, and yellow eel data have been used to assess compliance with the target. This is considered justified as the silver eel fishery is currently small, certainly <1 t, and the only other known anthropogenic losses might be from power station intakes in the estuary which are similarly inconsequential (Knights *et al*., 2001). The stock, as measured in 1983, would reflect the preceding 20-25 years of relatively high and consistent glass eel recruitment. The decline in recruitment of glass eels to the Severn Estuary would appear to have started in 1983/4, when the glass eel catch fell to 50% of the average catch observed in the previous 10 years (P. Wood personal communication). Comparison of the 1983/4 data with the reference state identified by the RCM suggests that the silver eel output from the Severn may be just meeting the 40% escapement target. However, the reference condition used in the RCM was derived from rivers still in the presence of anthropogenic influences, though the fisheries were relatively small. Thus, the reference state densities should decline at a slower rate than identified by the model, which would indicate that the Severn may not be complying with the 40% escapement target. Because sampling on the Severn is confined to sites that can be fished effectively by electric fishing (mainly shallow tributary sites), densities in the main river may differ from those predicted by the RCM. It is not possible from the RCM to identify whether the short fall relates to fisheries or other causes.

This assessment has not taken into account the loss of habitat during the second half of the 20th century, when the amount of physical habitat available to eel in the Severn catchment is considered to have reduced, particularly in the lower reaches. This deterioration will have had a concomitant impact on escapement. It is thus considered very unlikely that the 40%

escapement target is being met when compared with undisturbed ('pristine') conditions, i.e. the conditions pertaining prior to the 1950s, but in the absence of any water quality problems.

6. Quantifying the target

In order to derive a quantifiable target against which to evaluate compliance and management actions, it is necessary to be able to estimate silver eel production at various levels of recruitment. To estimate the theoretical output, information is needed on the amount of habitat available to eel in the absence of anthropogenic influences and the expected density and biomass of eel in various reaches of the Severn catchment. For this purpose, a Scenario-based Model for Eel Populations (SMEP, unpublished) has been applied to data for the Severn catchment. It is important to note that both the modelling procedures of SMEP and the method by which it is applied to catchment data remain areas of active development. Therefore, the following application is intended to illustrate the potential of SMEP to inform assessment and management decisions, but must not be considered as a definitive assessment of eel production from the Severn.

SMEP was designed to model eel populations based on the assumption that the principles of growth, sexual differentiation, migration and maturation would be similar throughout the catchment, and that production is tempered by productive area and saturation (in relation to carrying capacity). It is, nevertheless, based on defined "reaches" within the catchment, within each of which the eel population is considered to be homogeneous and between which eels migrate.

6.1 Model conditions

6.1.1 Catchment description

The reaches defined for the SMEP modelling of the Severn catchment are illustrated in Figure 11, and were selected to reflect areas of similar habitat type (gross comparisons) and the availability of suitable reference eel survey data. Note that they do not necessarily match with the area of eel habitat modelled with the RCM. Reach 1 is classed as estuarine, Reach 2 as tidal and Reach 3 as the lower section of the main river. Reach 4 was defined by the upstream limit of available historic eel data and Reach 5 covers the remaining, uppermost area of the system, incorporated in the model to allow for the expected eel movements up the entire catchment and production from the whole catchment.

Reach lengths were measured as the total stream length. Reach wetted surface area was calculated either as length*average survey site width, length*average width from measurements made with Google Earth, or the sum of areas for sub-sections of Reach 1 (from Google Earth), where the main river width varies from approximately 71 m to 1700 m. This procedure is appropriate because SMEP calculates productive capacity as the product of reach length and width.

6.1.2 Model biology parameters

SMEP uses the Von Bertalanffy L_{∞} (cm) and K values for modelling growth, and default parameter values for 'UK eel' were applied (values taken from scientific literature). Sexual differentiation and natural mortality were set according to SMEP default parameter values: the model determines what proportion of undifferentiated yellow eels will become male or female according to density-dependent relationships.

The α and β values for the length/weight regression ($W = \alpha L^{\beta}$) were derived from a power function of length vs. weight using data from yellow eels electro-fished from the River Severn between 1983 and 2004. Carrying capacity was set at 2604 g 100 m^{-2}, as this was the maximum biomass of yellow eels recorded by river surveys in 1983, and is similar to the maximum biomass (2524 g) observed in sections of the lower river when the eel population there was thought to be at carrying capacity (Aprahamian, 2000). The mean length ± SD at recruitment into the catchment was set at 70 ± 20 mm. The maximum migration rate for yellow (undifferentiated, males and females) eels was set at 20 km y^{-1}, and that for silver eels at 75 km y^{-1}, which is just shorter than the shortest reach (a formulaic requirement of the modelling procedure). The tendency to migrate was set at 0.8 for yellow eels migrating upstream, i.e. 80% of migrating yellow eels move in an upstream direction, and at 1.0 for silvers migrating downstream.

Glass eel recruitment to the Severn estuary has never been quantified in absolute terms. However, in anticipation of the lack of such data for most of the eel populations that would be modelled, SMEP includes a function, or minimisation procedure, by which to estimate (back-calculate) the minimum recruitment level that would produce a reference yellow eel population, given a defined trend in recruitment. At present, the reference population is described according to the proportion of females in one reach, although this is an area for future development of the model. For present purposes, the average proportion of female yellow eels across survey sites in Reach 3 in 1983 was selected as the reference condition, since this was the year with the most extensive set of sex ratio data. Recruitment of elvers to the modelled part of the catchment was treated at a constant level, given the suggested effects of density-dependence (above) and high levels of natural mortality in the estuary (White & Knights, 1997b). Note, that for present purposes, SMEP modelled the eel population based on trends in the recruitment of elvers into the river, and not on trends in the recruitment of glass eels from ocean to the estuary.

6.1.3 Population reference data

A length-sex key was derived from all those eels sampled in the Severn in 1983, where length and sex had been recorded. A length frequency distribution was calculated for the eels caught in Reach 1 in 1983, and the length-sex key applied to that distribution in order to calculate the overall proportion of females in the sample. The proportion of females and the length frequency distribution for each reach (except Reach 5) were calculated as above. Reach density was estimated as the average of sample densities from the various sampling sites in rivers included in each reach (data from 1991 to 2005), weighted according to the relative area of each tributary within the reach.

6.1.4 Other user-defined conditions

As noted above, the model application reported here is intended to illustrate the potential of SMEP, at its present stage of development, as a management tool. Therefore, the modelling was based on a very simplified scenario both for the eel population and for the catchment itself. Although the Severn eel population is subject to fishing mortality of yellow and silvers eels, reported catches are small and, even after taking into consideration the likely under-reporting, are not expected to have a significant impact on eel production. Therefore, no yellow or silver eel fishing pressures were modelled. Similarly, although stocking has occurred in some parts of the catchment, most recently in the River Avon tributary since 1990 (Figure 4), the River Avon was not included within the reaches modelled and the effects of stocking on the remainder of the catchment were not considered in this application.

Barriers to migration and issues of environmental/habitat quality occur within the catchment (Figure 2), and both would be considered in a full model application. However, in the absence of data providing the spatial distribution and proportional effect of these barriers (given the simplified nature of the catchment as input to the SMEP model), and the lack of information regarding the relative effects of these potential impacts on migration and production, neither was incorporated in the present model application. Rather, the productive area of the catchment under 'pristine' conditions was reduced by 2/3 in order to model the combined effects on eel production of barriers and habitat quality.

6.2 Outputs

The minimisation procedure, based on the proportion of female yellow eels observed in Reach 3 survey sites in 1983, predicted the minimum equilibrium recruitment of elvers to the river to be around 31 million. Given this level of recruitment, the model simulated a yellow eel population under present-day conditions which was similar to that reported from survey data. For example, yellow eel densities predicted by the model for Reach 3 (52 eels 100 m^{-2}) are similar in magnitude to those measured at sites in the lower Severn during 2002 to 2004, when observed densities ranged from 4 to 214 eels 100 m^{-2}. Likewise, the mean densities predicted for Reaches 4 and 5 (12 and 1 eels 100 m^{-2}) are close to those observed at upper Severn sites in 1999 (<1 to 4 eels 100 m^{-2}), the most recent survey data available.

Assuming a present-day recruitment of 31 million elvers and a productive area of catchment that has been reduced by 2/3 due to barriers and the impact of habitat/environmental quality, the model predicts an average annual silver eel production of about 80 000 eels, and that about 20% of these would be female. Given a similar historic recruitment, complete access to the entire catchment and no habitat quality impacts, SMEP predicts that average annual silver eel output would have been about 95 000 eels, but that about 94% of these would have been females. The considerable change in sex ratio in favour of males is likely to be the result of reductions in available habitat coupled with constant recruitment, resulting in increased yellow eel densities in each reach (2x to 5x).

In contrast to the RCM model, this output suggests that present-day production of silver eels may be as much as 80% of potential production, given no anthropogenic impacts on the population. However, the SMEP model application is based on a gross simplification of the

Severn eel population and spatial description of the catchment, and on speculative assessments of potential changes in habitat availability. As noted above, therefore, these results are presented as an illustration of the potential application of SMEP and do not reflect any management assessment of stock status. The latter will require appropriate quantification of the productive catchment and the locations and impacts of both physical and water quality barriers.

Given further developments in the model application procedure and the availability of appropriate catchment and eel population data, it would be of interest to managers also to model the effects of increasing the productive area of the catchment, to simulate improvements to habitat quality or the removal of migration barriers, with or without any improvement in recruitment to the system. Such simulations would be possible with the 'barriers to migration' or 'habitat/environment quality' input options in SMEP, but it is not possible to run such simulations at present.

7. Conclusions, management implications and monitoring

The results of modelling using the RCM indicate that the Severn currently may only just be complying with a 40% escapement target. However, the similarity between yellow eel density and biomass values at sites surveyed across 20+ years suggests that the fisheries are not having a major impact. Perhaps, therefore, the major constraint on yellow and silver eel production is limited access to the middle and upper reaches because of weirs. However, these have been in place on the main river for well over a century, and it may be that the Severn historically had densities lower than would be predicted from the RCM. It is thus concluded that access is the most likely factor preventing the Severn complying with the 40% escapement target, the assumption being that improving access will reduce density-dependent mortality in the lower reaches and lead to a greater production of silver eel.

Given this conclusion, it is proposed that a two-pronged remedial approach is considered, first to achieve increased silver eel production and then to improve the monitoring programme to underpin compliance assessment and to better focus management actions.

The main options available to increase the silver eel output from the Severn catchment are: to reduce the size of the glass eel fishery; to improve access to the middle and upper reaches (and Warwickshire Avon) catchment; to increase the amount of habitat in the lower reaches; or to stock glass eel in suitable habitat that is under-utilised at present.

Without further developments of the SMEP model, it is not possible to quantify the benefits of these management options in increasing silver eel escapement. Closing the glass eel fishery without increasing the amount of habitat or improving access is likely to result in an increase in density-dependent mortality and no long-term increase in silver eel output. However, it is essential that glass eel exploitation is sustainable and capable of delivering the 40% escapement target.

Increasing the amount of available habitat through improving access to habitat and habitat quality, especially but not only in the lower reaches, should provide benefits in the medium to long term (8 – 20 years), by reducing density-dependent mortality. It is essential that those eel passes that do exist on a number of obstructions are maintained in an operative condition (or altered to maximise their effectiveness), as well as to construct additional passes where most appropriate.

Aprahamian (1986, 1988) suggested that the most immediate benefits could be gained from stocking glass eels/elvers in to the middle reaches of the Severn and Avon catchments where eel densities are low but the habitat is suitable. There is evidence from the Severn that glass eel stocked in the middle reaches did grow substantially faster than those in the lower reaches (Aprahamian, 1987). However, there have been no assessments of what the production of eel might have been if the glass eel had been left *in situ*.

Monitoring is key to understanding the potential and actual escapement of silver eels, and there are substantial gaps in our current monitoring outputs that need to be addressed. The Environment Agency intends to produce an enhanced monitoring programme, because the above analysis has been based on very few samples and these are mostly from the lower river, which would be expected to be the last to show any impact of declining recruitment. It must also be noted that surveys are conducted in the shallow parts of rivers and the data may not represent the production from deeper sections. It is also imperative that any monitoring programme supports development of tools (e.g. SMEP) to estimate the 40% silver eel escapement target and assess compliance of the yellow eel population against this target. These tools could also be used to quantify the impact of the glass eel fishery on escapement and the impact of other anthropogenic factors.

For the Severn catchment, it is recommended that:

1) a habitat inventory be collated, most likely using GIS data and software;

2) the amount of suitable habitat for eel lost since 1950 be quantified, and qualified as habitat that can or can not be recovered (cost/benefit analysis);
3) SMEP is used to develop reference points and assess compliance for the Severn;
4) eel-specific monitoring undertaken since 2000 be continued;
5) the benefits and costs of an additional eel-specific monitoring in the middle and upper reaches of the Severn (and Warwickshire Avon) catchment be determined;
6) the benefits and costs of an index trapping of eel in the main river and estuary using fyke nets, fixed traps and other survey methods be determined;
7) catches of emigrants at obstructions be monitored;
8) commercial catch statistics be improved (made more reliable).

Acknowledgement.

This study was funded by Defra and the Environment Agency. We would like to acknowledge the work of Heidi El-Housani (King's College London) and Geoff. Kirkwood (Imperial College) in building and developing SMEP as part of a project funded by Defra at Kings College, London.

References

Aprahamian, M.W. (1986). Eel (*Anguilla anguilla* L.) production in the River Severn, England. *Polskie Archiwum Hydrobiologii*, **33**: 373-389.

Aprahamian, M.W. (1987). Use of the burning technique for age determination in eels (*Anguilla anguilla* (L.)) derived from the stocking of elvers. *Fisheries Research*, **6**: 93-96.

Aprahamian, M.W. (1988). Age structure of eel (*Anguilla anguilla* (L.)) populations in the rivers Severn (England) and Dee (Wales). *Aquaculture and Fisheries Management*, **19**: 365-376.

Aprahamian, M.W. (2000). The growth rate of eel in tributaries of the lower River Severn, England, and its relationship with stock size. *Journal of Fish Biology*, **56**: 223-227.

Dekker, W. (2000). The fractal geometry of the European stock. *ICES Journal of Marine Science*, **57**: 109-121.

ICES (2003). Report of the ICES/EIFAC Working Group on Eels. *International Council for the Exploration of the Sea*. ICES C.M. 2003/ACFM:06.

ICES (2004). Report of the ICES/EIFAC Working Group on Eels. *International Council for the Exploration of the Sea*. ICES C.M. 2004/ACFM:09.

Knights, B. (2002) Economic Evaluation of Eel and Elver Fisheries in England and Wales. Environment Agency Technical Report, No. W2-039/TR/2, 44 pp.

Knights, B. (2005) A review of the status of eel populations in the River Thames and its tributaries. *Report to Environment Agency Thames Region* (including presentations to Thames, Anglian & Southern Regions).

Knights, B. & White, E. (1997) Stocking strategies for the European eel, *Anguilla anguilla* L. In *Stocking and Introduction of Fish*, ed. I. Cowx, pp. 121-140. Fishing News Books, Blackwell Scientific, Oxford.

Knights, B., A. Bark, M. Ball, F. Williams, E. Winter, and S. Dunn (2001). Eel and elver stocks in England and Wales – status and management options. *Environmental Agency, Research and Development Technical Report* **W248**. 294 pp.

Moriarty, C. (1990). European Catches of Elver of 1928-1988. *Internationale Revue des gesantes Hydrobiology*, **75**: 701-706.

Pawson, M., B. Knights, M. Aprahamian, R. Rosell, A. Bark and E. Williams (2006). National Report on Eel Stocks & Fisheries in the United Kingdom and Northern Ireland. *Working Paper to the ICES/EIFAC Working Group on Eel*, January 2006.

SGRST (2006). Report of the second meeting of the subgroup on review of stocks (SGRST-06-02) of the Scientific, Technical and Economic Committee for Fisheries (STECF) – Eel Management. Ispra, Italy, 21-24 March. 13 pp.

White, E.M. & B. Knights (1997a). An analysis of environmental factors affecting upstream migration of the European eel, *Anguilla anguilla* L., in the Rivers Severn and Avon. *Journal of Fish Biology*, **50**: 1104-1116.

White, E.M. & B. Knights (1997b). Dynamics of upstream migration of the European eel, *Anguilla anguilla* L., with special reference to the effects of man-made barriers. *Fisheries Management & Ecology*, **4**: 311-324.

Figure 1. The River Severn and neighbouring catchments.

Figure 2. Distribution of obstructions in the Severn catchment

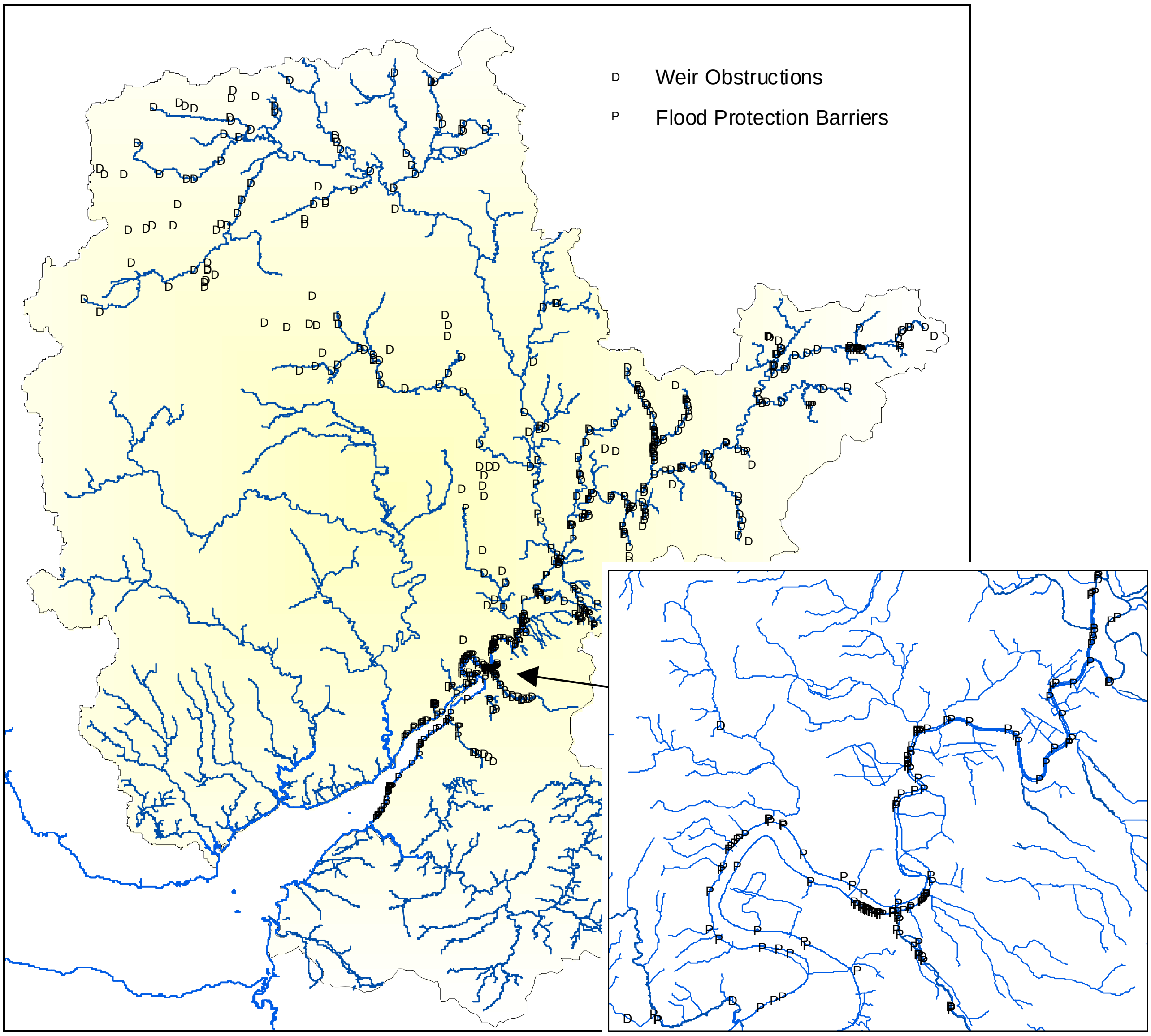

Figure 3. Annual catch of glass eel (tonnes) for England and Wales between 1972 and 2005, from MAFF (now Cefas)/Environment Agency (MAFF/agency) and HM Customs & Excise nett export estimates (Import/Export) (from Pawson *et al.*, 2006).

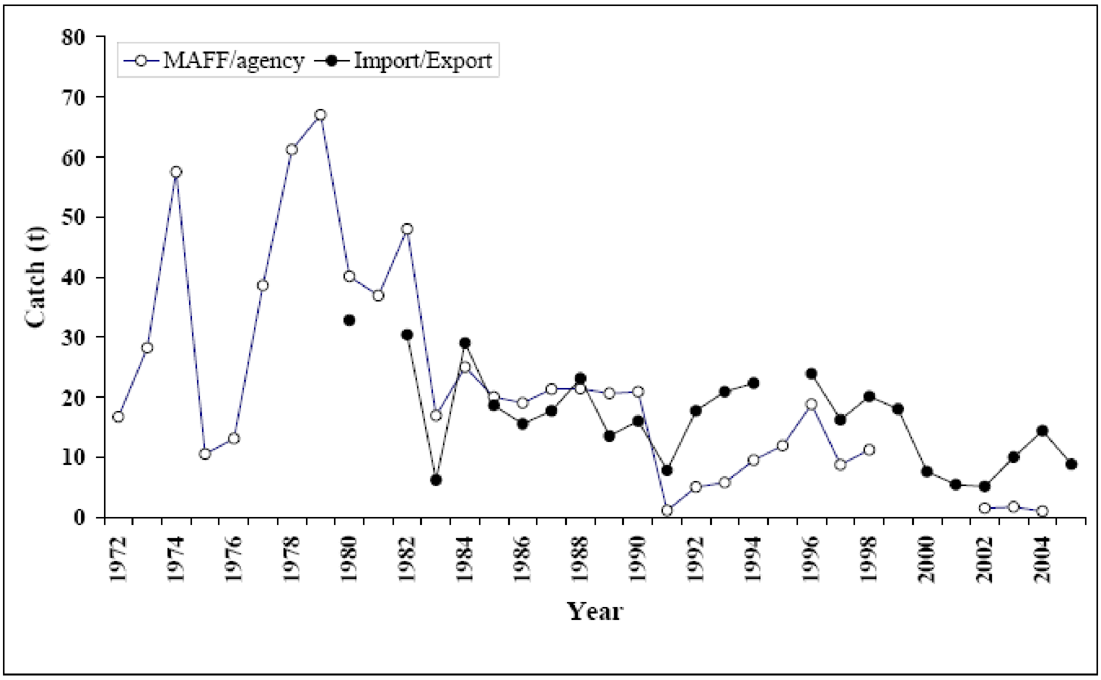

Figure 4. Location of elver stocking in the Severn catchment since 1990

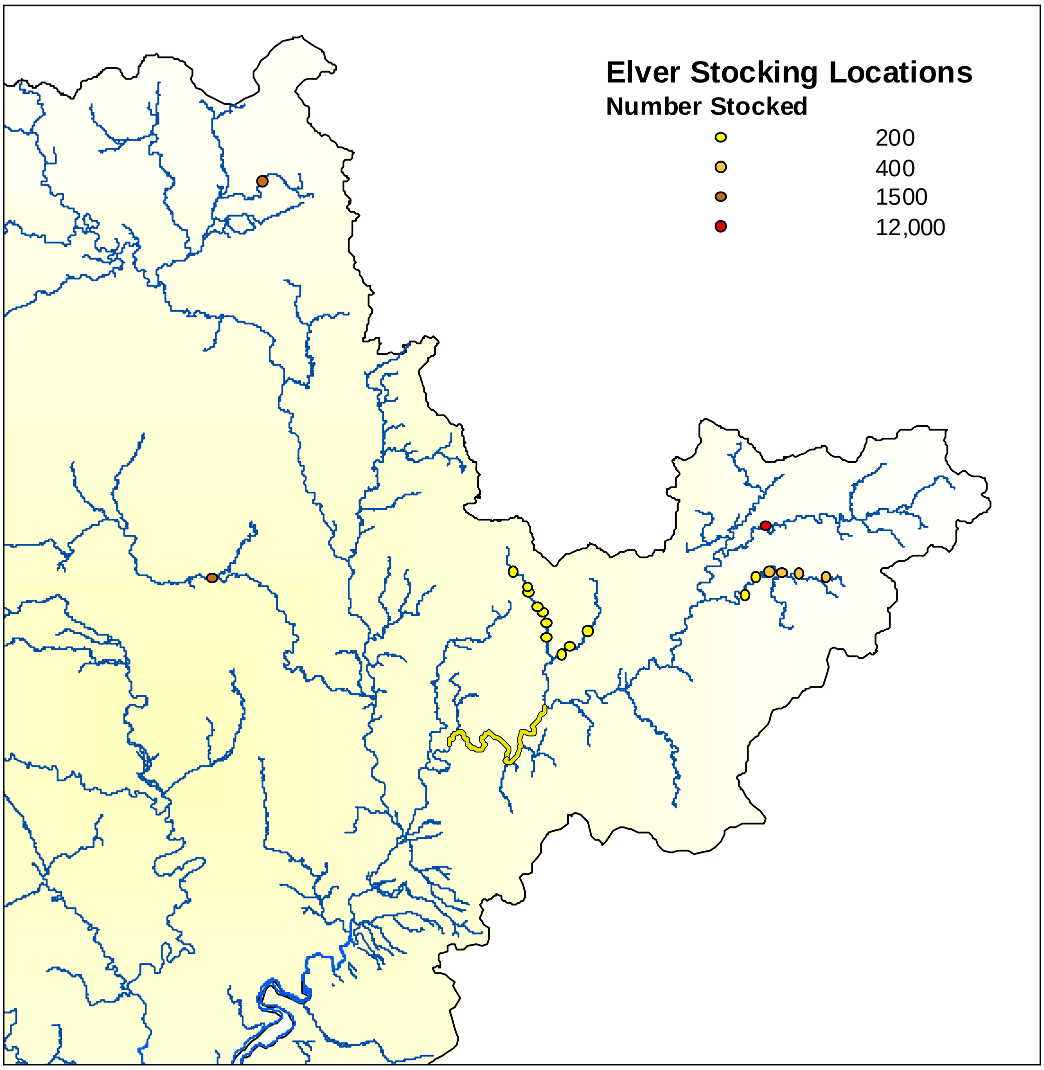

Figure 5. Glass eel catch per unit effort (CPUE) for England and Wales, from 1980 to 2005, based on HM Customs and Excise import and export data (from Pawson *et al.*, 2006).

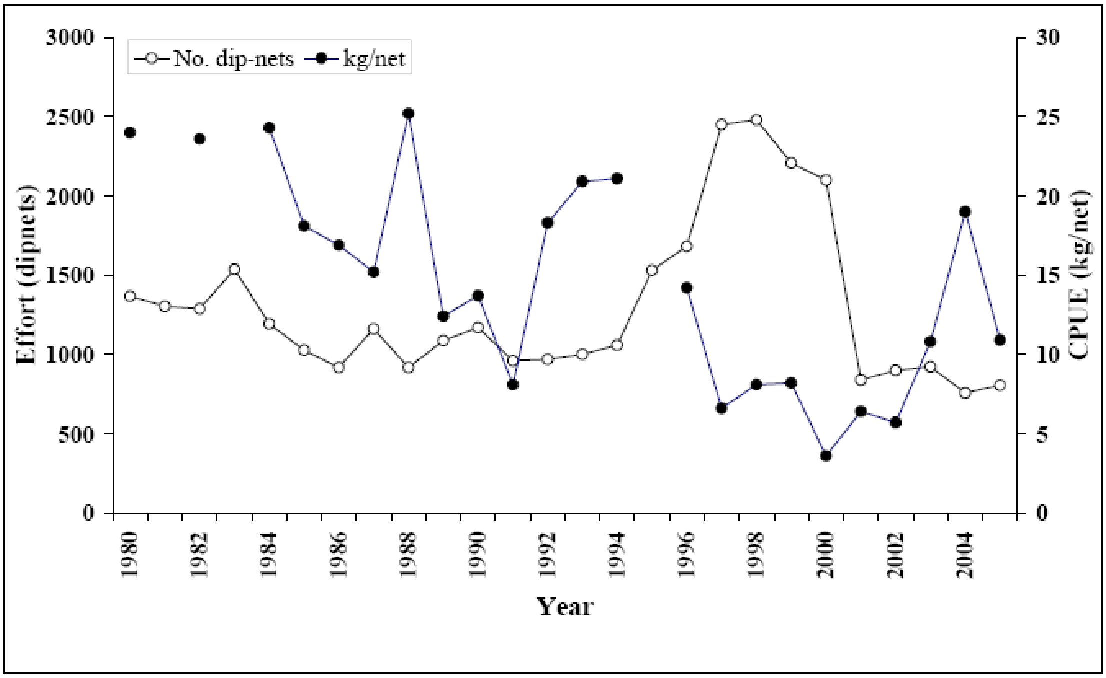

Figure 6. Eel survey zones on the lower Severn catchment (see text for details)

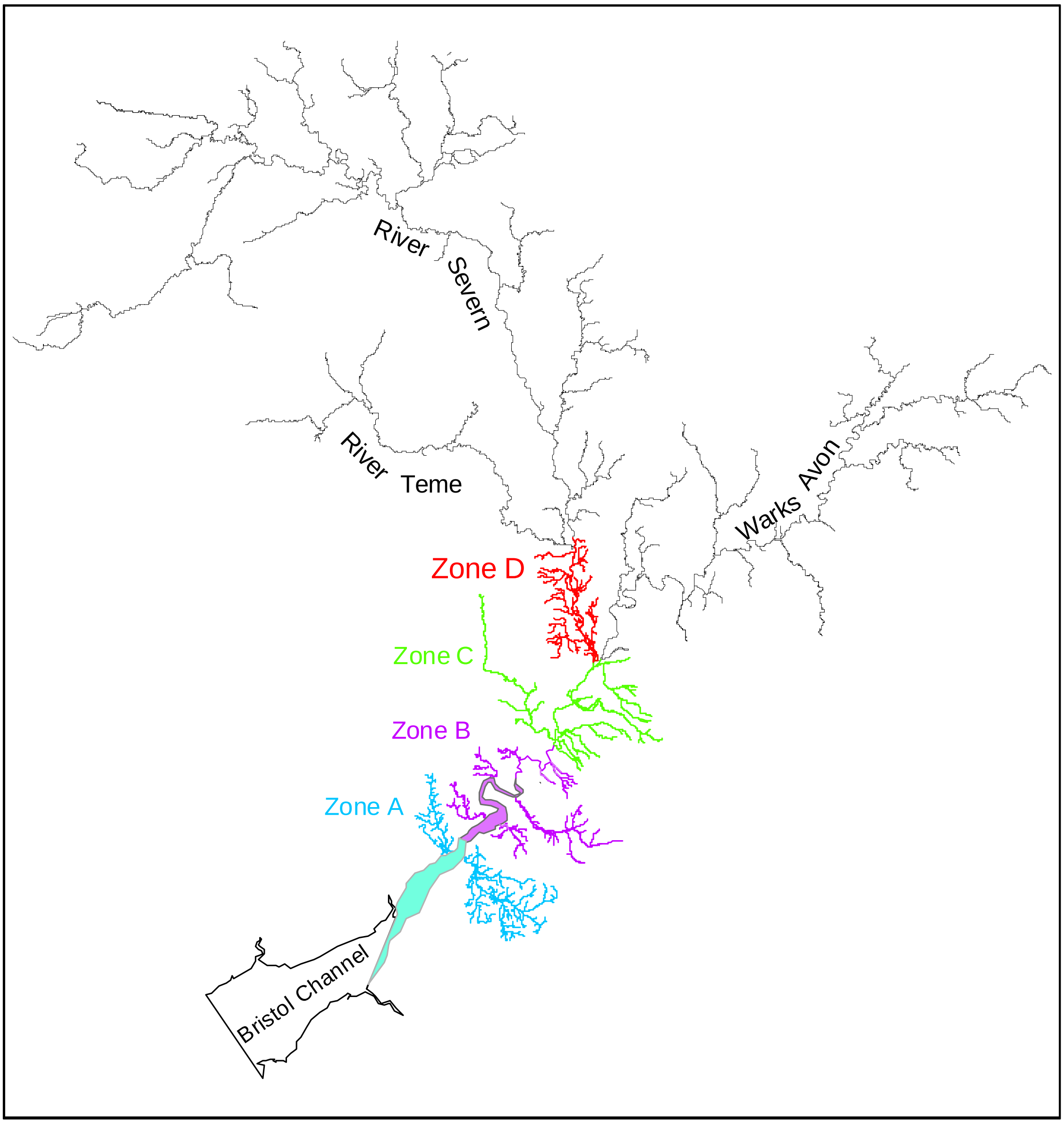

Figure 7. Distribution of eel in the Severn Catchment (2001-05 survey data combined)

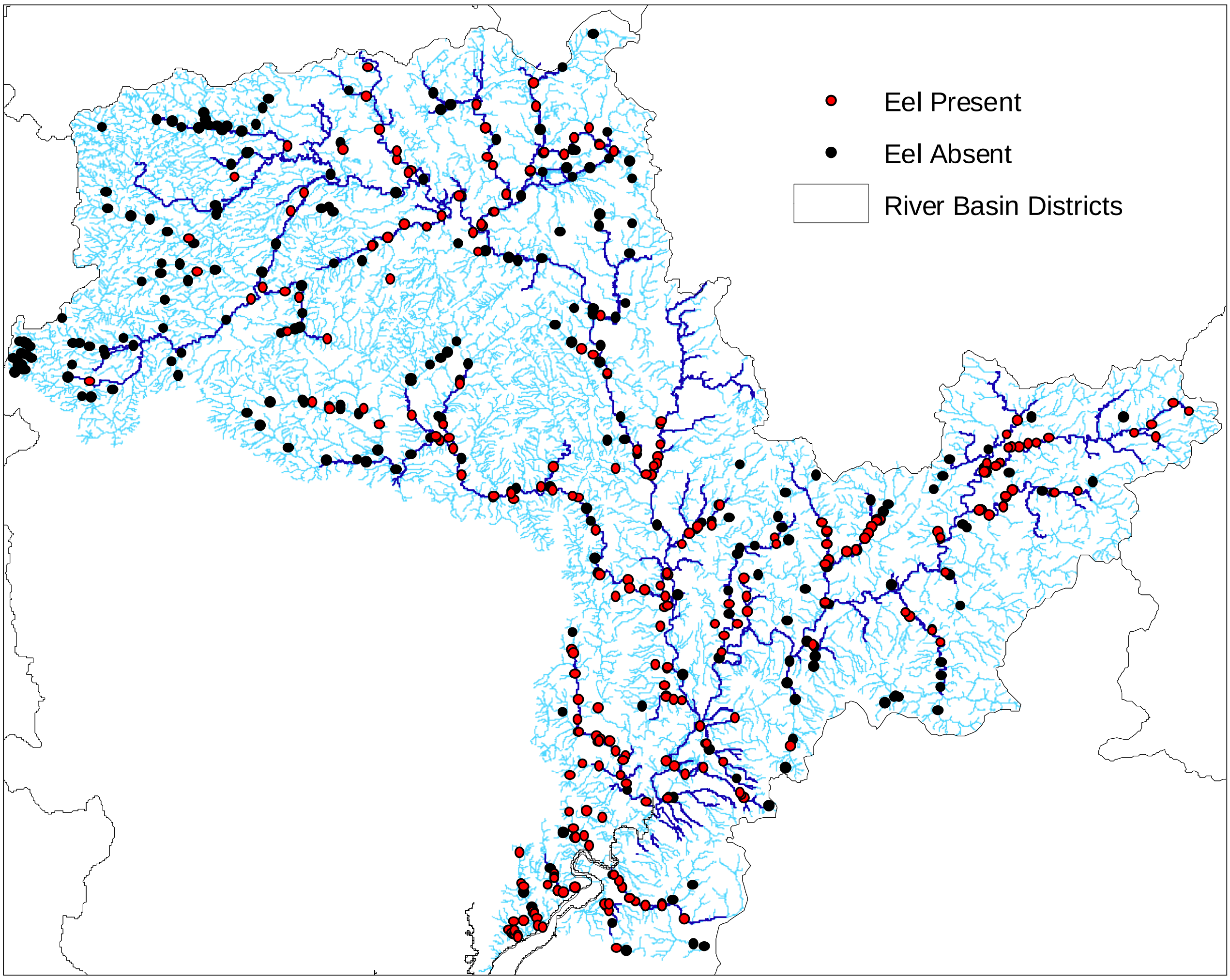

Figure 8. Density of eel at common sites between 1983 and 2004. See Figure 6 for survey Zone areas.

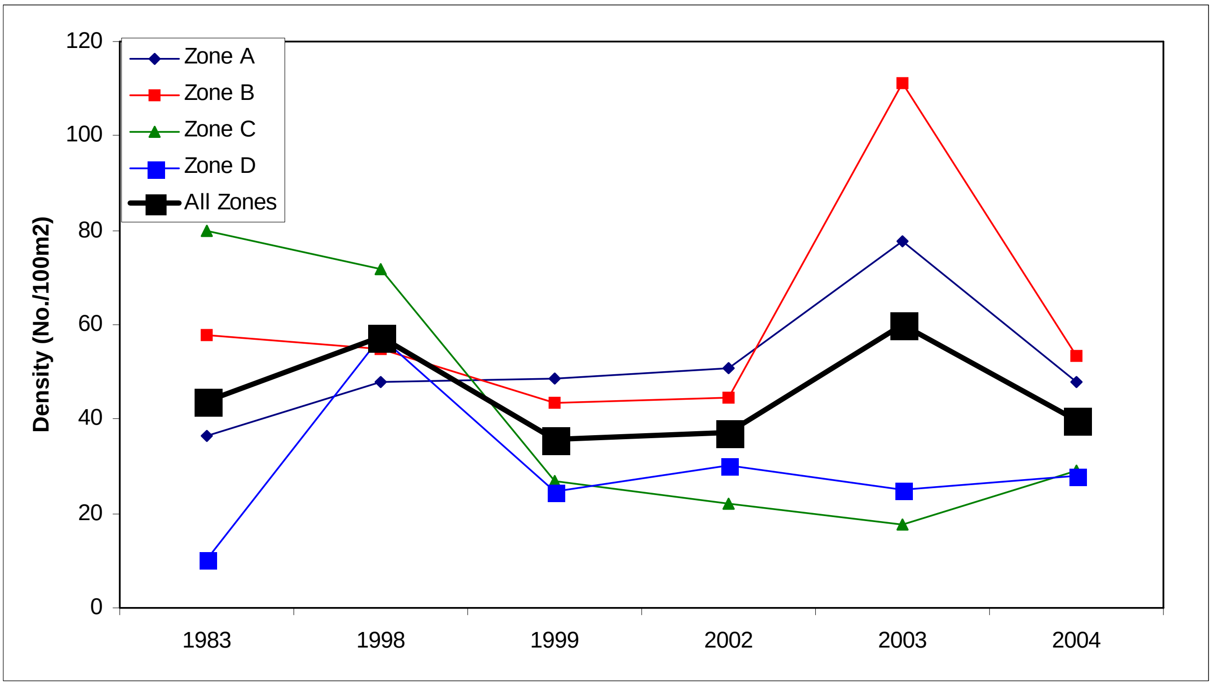

Figure 9. Biomass of eel at common sites between 1983 and 2004. See Figure 6 for survey Zone areas.

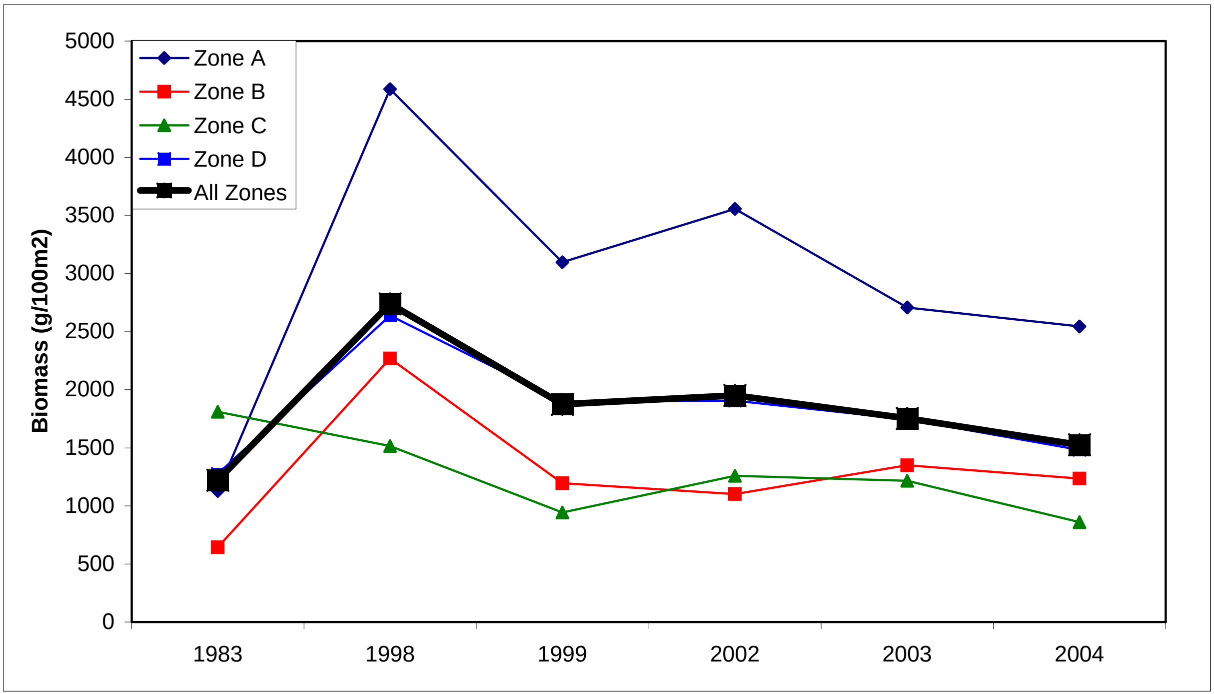

Figure 10. The predicted (dotted line) and observed rate of decline in eel density in 1983/4 (bold line) with distance upstream from tidal waters (from ICES, 2004).

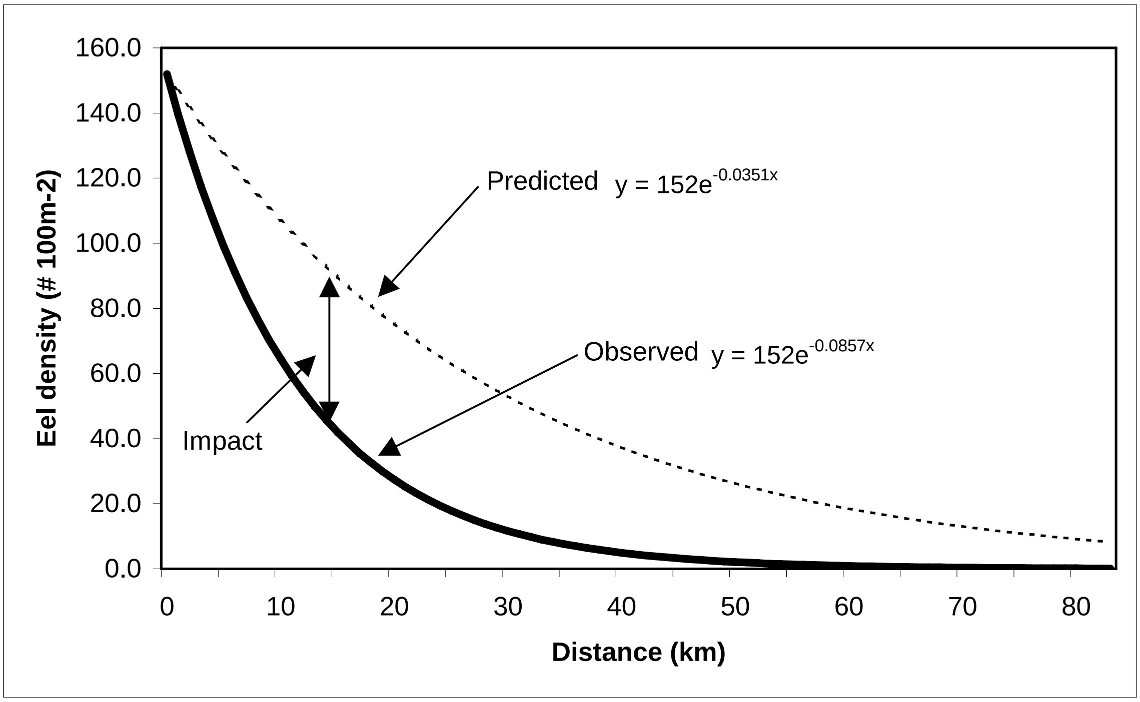

Figure 11. Map of the Severn catchment indicating the Reaches defined for the SMEP modelling