Developing Guidelines for Best Practice in Stocking Eel For Enhancement Purposes

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Developing guidelines for best practice in stocking eel for enhancement purposes

A report for the Marine and Fisheries Agency prepared by Alan Walker, Panayiota Apostolaki, Mike Pawson, Joanne Walton, Joe Scutt-Phillips and Tisha Martin.

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The conclusions and views expressed are those of the Authors and not necessarily those of Cefas or the M&FA.

Users should note that neither Cefas nor the M&FA accept liability for model outputs if users alter the model source code or the parameter values.

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1. Executive summary

The European eel (*Anguilla anguilla*) population has declined to levels that are now considered to be unsustainable unless strong conservation measures are introduced. The European Union (EU) has proposed stocking as one possible management measure to enhance the production of adult (silver) eels, and hence contribute to compliance with a river basin's management target (≥40% of the silver eel biomass that would have escaped to the sea in the absence of anthropogenic influences). However, stocking with young eels is expensive, and the benefits will not be realised in terms of silver eel escapement for at least 5-10 years, so it is imperative that we adopt the most effective approach ('best practice').

Where stocking is considered to be an appropriate management option within national Eel Management Plans, it is necessary to estimate the quantity of juvenile eels that will be needed to meet a river basin's management target, the optimum size of eel to be stocked, their stocking density in relation to the carrying capacity of the habitat, and to identify the habitats that should be most beneficially stocked. None of the existing reviews on stocking of eel provides a quantitative tool with which to conduct cost-benefit analyses comparing stocking with other stock-enhancement approaches, or to guide the practicalities of an effective and efficient stocking programme.

This project was initiated to provide managers with an Eel Stocking Assessment Tool (ESAT) to support rapid decision making for stocking to enhance eel populations, to update knowledge on concepts and best practice for stocking with eels, and to identify indicative value ranges that can be used to parameterise population processes in a quantitative model that can be applied from the glass eel/elver through to silver eel stages.

This report contains an up-to-date review of the scientific literature and unpublished information on stocking with eels and eel production processes, identifying key factors that govern the success of, or need for, stocking. The review covers the status of the European eel stock and need for management, scientific advice on stocking with eels, where to source eels for stocking and where to stock most effectively in relation to a river's carrying capacity and habitat suitability, density effects on eel production and the risks associated with stocking.

A separate review deals with the biological processes to be incorporated in a 'simple' model of eel population dynamics and the values of their parameters that are available in the literature and are appropriate for its application to UK waters. This review identifies limitations due to gaps in knowledge and suggesting studies that could be conducted to address these knowledge gaps.

The main output of this project is a quantitative tool that can be used to calculate the number of eels that need to be stocked in a basin in order to satisfy a certain level of non-compliance with the eel management target, in terms of silver eel escapement or equivalent values for yellow eels (as numbers or biomass). The model takes eels from the glass eel stage, when they recruit to the estuary of the river, or eels of a larger size, and models their development and survival through differentiation into male and female yellow eels until they metamorphose into silver (maturing) eels and leave the basin to return to the ocean to spawn. Eels stocked after artificial on-growing (aquaculture) can also be included in the model, and estimates of the initial eel stock in the river system can be made.

The MS-Excel®-based model allows various stocking scenarios to be tested quantitatively, and incorporates eel production processes of growth and mortality applied according to eel length. The key processes of sex differentiation, silvering and escapement take place when the length of eels is within specific ranges, and gender-specific probability functions are used to represent how plausible it is for an eel to undergo each of these processes at a given length, based on values of biological processes appropriate to the UK (published values vary within and between basins, and a technical manual provides information on why the proposed values were chosen). Although it is likely that processes in the population dynamics of eels are affected at high densities, qualitative knowledge is lacking, and therefore we assume that there are no density-dependent effects on eels in the areas in which enhancement stocking takes place.

The probability functions are given in terms of length frequencies that are converted to numbers at age by appropriate age-length-keys. Corresponding length-weight relationships are used to calculate biomass at age or life stage. Thus, running forward, the model can be used to estimate an equilibrium population of yellow eels, or an annual biomass output of silver eels from a given level of stocking, spread over several years according to growth rates, sex ratios and lengths at which male and female eels silver and leave the system. Running the model backwards (minimisation) will, therefore, provide an estimate of the annual input of stocked eels required to produce the additional population of yellow eels or biomass of silver eels required to comply with the management target.

The model can be used for either stocked or naturally recruited eels, separately or together, in so far as the density of the eels does not approach levels that will trigger density-dependent effects. It is also possible to simulate the impact of other causes of mortality by increasing the natural mortality values used in the model, and to use the model to predict the effect on yellow eel populations of specific stocking events, which can be validated by subsequent monitoring. Whilst the model does not cover the impacts on eel production of such issues as parasites, diseases, pollution, etc, it is able to accommodate putative changes in survival due to these factors, providing quantitative information was available.

This quantitative tool is accompanied by a User Guide, Technical Manual and Review of Current knowledge of eel processes and model parameterisation, which explain the biological and evidence base for its operation, and a full set of source references.

2. **Introduction**

Note that some sections of this final report are intended to stand alone as guides to model use and parameter choice. Therefore, some texts are repeated between sections.

The European eel (*Anguilla anguilla*) population has declined considerably since the 1970s to levels that are now considered to be unsustainable unless strong conservation measures are introduced (ICES 2008). As part of an Eel Recovery Plan (ERP: EU-COM-1100 2007), the European Union (EU) proposes stocking as one possible management measure to enhance the production of adult (silver) eels, and hence contribute to compliance with a river basin's management target (≥40% of the silver eel biomass that would have escaped to the sea in the absence of anthropogenic influences). Article 7 of Regulation EU COM 1100/2007 requires that 35% of the catch of eel <12 cm must be made available for enhancement stocking each year after the implementation of national Eel Management Plans (EMPs) in 2009, and that this percentage should increase to 60% by 2013. At 2008 market prices, fisheries providing eel for stocking will require significant funding, and the benefits of stocking with young eels will not be realised for at least 5-10 years, when the growing yellow eels begin to transform into silver eels. Given the relative scarcity of glass eels throughout Europe, it is imperative that we adopt the most effective approach (‘best practice’) to maximise the benefit of stocking in terms of silver eel escapement.

Stocking of eel has been the subject of several reviews, which discuss and outline frameworks for best practice in assessing stock status, identifying habitat and biodiversity characteristics conducive to eel production, identifying potential risks associated with stocking, planning stocking programmes, and evaluating their success or failure (Knights and White 1997; Williams and Aprahamian 2004; Symonds 2006; Williams and Threader 2007). However, none of these reviews provide the quantitative tools necessary to conduct cost-benefit analyses comparing stocking with other stock-enhancement approaches, or to guide the practicalities of an effective and efficient stocking programme within an EMP. Draft EMPs for England and Wales, submitted to the EU Commission in December 2008, include assessments of the status of the eel population within a river basin and an evaluation of whether or not stocking is an appropriate option to meet the management target (see http://www.defra.gov.uk/marine/freshwater/fishman.htm#emp). A number of fundamental quantitative questions remain for managers:

- what weight of juvenile eels will produce the weight of silver eels necessary to enhance production from a river basin above its management target?
- will the enhanced production of silver eel in the stocked population exceed the putative loss (from glass eels caught and used for stocking) in production from the donor population or, indeed, will production in the donor population increase because of reduced density-dependent mortality?
- what habitats should be most beneficially stocked, and how often?
- what is the optimum age or size of eel for stocking, and is it better to rear eel for a period before stocking?
- what is the optimum density of stocking in relation to the carrying capacity of the habitat and the desired sex ratio of silver eel?

This project aims to provide managers with best practice guidelines for stocking European eel in river basins with the aim of increasing spawning escapement of silver eel from England and Wales towards targets set by the EU. We have developed an Eel Stocking Assessment Tool (ESAT) to support rapid decision making for stocking to enhance eel populations, which includes a quantitative model that can be applied from the glass eel/elver through to silver eel stages.

This report also presents a review of published and grey literature, and discussions with scientists and aquaculturists engaged in stocking and rearing eel, to update knowledge on concepts and best practice for stocking, and to identify indicative parameter value ranges that can be used to parameterise the model. The review includes the results of re-analysis of some of the available data in order to elucidate particular features of eel population dynamics.

The Cefas staff involved in this project were Alan Walker (Project Manager), Yiota Apostolaki (Model Leader), Joe Scutt Phillips (Modeller), Joanne Walton and Tisha Martin (Research Assistants) and Mike Pawson (ex-Cefas) acted as overall Project Leader.

3. Aims and Objectives

The **objective** of this research is to develop best practice guidelines for stocking eel in river basins for enhancement purposes using quantitative assessment methodology. The study also identifies gaps in our knowledge of eel production processes relevant to stocking, and suggests how these might be addressed.

The project has five **milestones**, all of which have been met by the due dates. These are:

1. Review the literature on stocking eel, on eel production processes and unpublished information through engagement with eel scientists and those involved in eel culture, identify key factors that govern the success of, or need for, stocking and determine plausible parameter values to use for the parameterisation of the eel stocking assessment tool (end October 2008);

2. Develop a ‘simple’ model of eel population dynamics and production (ESAT) to enable various stocking scenarios to be tested quantitatively, in order to identify, if possible, a ‘best practice’ to satisfy a certain level of non-compliance with a river basin's eel management target, and appropriate documentation (by end December 2008);

3. Test realistic stocking scenarios through application of ESAT (end January 2009);

4. Identify limitations in quantitative assessment due to gaps in knowledge, and suggest experimental studies that could be conducted to address these knowledge gaps (end February 2009);

5. Deliver ESAT and the contract report to Customer and disseminate results and outputs through seminar hosted by the EA (end-users), and address comments before delivery of the final product (end March 2009).

At the initiation of this project, it was anticipated that the ESAT model would incorporate eel production processes of growth, mortality, sex differentiation and maturation applied from the glass eel/elver to silver eel stages, based on existing models and those being developed. Indicative parameter values that can be used to parameterise the model would be obtained from published and grey literature, and discussions with scientists and aquaculturists engaged in stocking and rearing eel. Any modifications to these aspirations in light of knowledge gained during this research have been reported to and agreed by the Customer. This quantitative tool is accompanied by a review of ‘best practice’ guidelines to provide the most comprehensive package of tools with respect to the requirements of the developing EMPs, based on our most up-to-date knowledge.

4. Update to Best Practice for stocking with eels

Before embarking on the two key elements of the project, which are to update best practice for stocking eel reviewed by Williams and Aprahamian (2004), and to develop a simple quantitative model of eel population dynamics to evaluate stocking scenarios, it is useful to remind ourselves of the life cycle of the European eel and particularly of the freshwater stages that the model represents. Leptocephalus larvae, believed to be derived from spawning in the Sargasso Sea, are carried eastwards by currents across the Atlantic Ocean (McCleave 1993) and, on reaching the continental shelf, metamorphose to the glass eel stage before migrating into freshwater. Major glass eel runs still occur into the Atlantic-facing estuaries of the UK (most importantly the Severn Estuary), where the glass eels change into pigmented elvers, and where there are fisheries that potentially provide a resource for stocking to enhance populations of yellow eels. These grow in both freshwater and coastal marine waters before transforming into silver eels, at which stage they migrate back to the oceanic spawning grounds. Age at transformation tends to correlate with latitude and the productivity of waters, ranging from 10-20+ years in cold northern oligotrophic waters to 2-4 years in warm southern eutrophic waters (Vollestad 1992), and is typically earlier for males than for females. The population dynamics of eels are discussed in Section 6, in relation to evaluation of processes in the ESAT model.

4.1. Status of stock & management need

Data complied by the Joint European Inland Fisheries Advisory Commission (EIFAC)/International Council for the Exploration of the Seas (ICES) Working Group on Eel (WGEEL) indicate a downward trend in the numbers of glass eels being recruited to European waters since the high levels of the 1970s, with no obvious sign of recovery (most recent data in ICES 2008). This decline in recruitment prompted ICES to advise the European Commission that the European eel stock is outside safe biological limits and that its fishery is not sustainable. A similar, but less strong, pattern of decline is also evident in UK coastal and estuarine fisheries, where reported mean catch rates in glass eel dip nets have declined from about 25 kg/net in 1980 to 2 kg/net in 2006 (Environment-Agency 2007).

One management option identified in the EU's ERP (EU-COM-1100 2007) is to restock inland waters with glass eels or elvers. Williams and Aprahamian (2004), updating the review of (Knights and White 1997), found that most information about stocking with eels relates to still waters, possibly because yellow and silver eels can be more efficiently exploited and monitored in lakes, and because historic stocking has primarily been aimed at supporting commercial fisheries in such environments. They noted that most of the information in the literature comes from empirically derived input-output models, i.e. where stocking strategies and rates are compared to fishery catch returns. For example, there are good data for the Lough Neagh fishery in Northern Ireland (Allen *et al.* 2006). There have been very few attempts to study and monitor stocking into rivers (e.g. Aprahamian 1986; Aprahamian 1987; Berg and Jorgensen 1994), and fewer still report long-term assessments of the production of eels in rivers (e.g. Vollestad and Jonsson 1988). Recapture rates of stocked yellow or silver eels appear to be low, often below 5%, unless silver eels can be efficiently trapped on their seaward migration (Vollestad and Jonsson 1988; Naismith and Knights 1990; Andersson *et al.* 1991) .

The WGEEL has discussed stocking and transfers of juvenile eel at length (most recently in ICES 2006; ICES 2007; ICES 2008), covering the principles and extent of stocking, stock transfer practices and their contributions to fisheries. To date, however, the effect of these activities on silver eel escapement has been discussed mainly from a conceptual and theoretical viewpoint, principally due to a lack of good quantitative data and the absence of a predictive model.

In 2006, WGEEL noted that scientific advice on stocking with eels has changed over the years, from being in favour (Moriarty and Dekker 1997) to a more precautionary stance reflecting potential risks associated with disease transfer and/or genetic impacts (ICES 2001). In light of the continuing decline of recruitment and poor stock status, however, WGEEL (ICES 2006) presented a more pragmatic argument for stocking, influenced by the realisation that the decline in glass eel recruitment was limiting the options for restoration of the stock. Most recently, WGEEL (ICES 2008) provides updates on stocking figures and practical information to support best practice in stocking, but noted that the recent European glass eel catch (circa 100 t) is less than that required (estimated at up to 1000 t) to supply the total potential productive habitat (about 40,000 km2) within the species' natural distribution range and that stocking alone is unlikely to achieve the EU's eel recovery objective in the medium term. This lack of glass eels for stocking is less likely to apply to the UK, however, where glass eel catches are much less reduced than in the rest of Europe, and where other management options (e.g. reducing exploitation, by-passing upward and downward barriers) probably provide less scope to improve production and escapement of silver eels. Nevertheless, the priority for managers is to make best use, in stock enhancement terms, of a scarce resource, and it is imperative that eel stocking is performed in the most efficient manner.

The availability of sufficient quantity and quality of stock European eel and suitable methods of transportation were considered by ICES (2006, 2007) and by Williams and Aprahamian (2004), and for American eel (*A. rostrata*)(Symonds 2006; Williams and Threader 2007). With relevance to the present project, the meat of Williams and Aprahamian's (2004) report is in the section (2.2.7) that deals with developing a successful stocking strategy. This considers issues such as: source of fish, health of the stock, handling and transportation of fish to stocking site, stocking densities, age or size of stock, timing of stocking and mechanisms of release, all of which must be taken into account when trying to maximise the benefits and minimise potential risks (Cowx 1997).

Williams and Aprahamian (2004) also considered the need to evaluate the outcome of a stocking programme, and whether there are alternatives to stocking. For the purposes of this project, it is assumed that the main ecological and practical aspects of planning and implementing a stocking programme have already been addressed (for the basin in question) within the development of EMPs. That is, it has been demonstrated that a basin is not meeting its management target (a minimum of 40% escapement of silver eel biomass compared to what would be produced under “undisturbed” conditions), and that the cause of this shortfall is sufficiently well known that stocking appears to be an appropriate option to ameliorate the situation. The questions are: where to source eels for stocking, where should eels be stocked, what are the risks of stocking, and how many need to be released to achieve the required output (the management target)?

4.2. Where to source eel for stocking

WGEEL (ICES 2006) warned that, at low stock levels, removal of glass eel from any site to stock another should only be done with a full assessment of the effect on recruitment into the productive areas dependent on that donor site. In addition to the direct effects on the size of the local population, a reduction in natural recruitment/density may lead to a reduction of dispersal of juvenile eel to upstream habitats, and possible alterations to sex ratio of silver eel.

WGEEL (ICES 2008) summarises information on how managers might assess whether a surplus of glass eel exists (and can be taken for stocking without detriment to the yellow eel population and silver eel escapement in the donor basin), and quantification of this surplus.

Upstream migration may be driven by intra-specific competition and higher densities downstream. For example, the construction of an estuarine dam on the River Vilaine (W. France) prevented recruitment of eels for 25 years, but the installation of an eel pass resulted in a density-dependent migration behaviour in which the periphery of the high-density area (about 0.8 eels m^{-2}) extended further upstream in successive years (Feunteun 2002). Ibbotson et al. (2002) suggested that upstream migration of eels in the River Severn was mainly through diffusion. Therefore, removal of stock from downstream areas may reduce the propensity for colonization of upstream areas.

Although the physiological mechanisms for gender differentiation in eels (reviewed by Davey and Jellyman 2005) are still unclear, there is strong evidence that it is density driven. There is a risk that removing glass eel from estuaries will affect subsequent gender differentiation and sex ratio of yellow and silver eels. Transporting undifferentiated eels from high to relatively low density habitats may well influence ultimate sex ratio of the silver eel output, and by association, the weight and distribution of escapement through time. From a UK perspective, it may be sufficient to know that the glass eel fishery in the Severn Estuary does not appear to have had any measurable negative impact on stocks of eel in the lower and reaches of the Severn basin (Environment Agency, unpublished).

Because the contribution of stocked eels to the yellow eel population (and silver eel escapement) is governed largely by their survival and growth, the option to maximise both by on-growing glass eels/elvers before stocking may more than offset the extra costs of holding compared to immediate release of glass eels/elvers. However, Klein Breteler (1994) concluded that culturing of glass eels to juvenile size increases costs by 4-12 times compared to direct stocking, and that the advantages in survival and growth rates were only marginal. White & Knights (1997) suggested that any initial growth advantage is lost after about 5-6 years.

From these observations, Williams and Aprahamian (2004) concluded that the most cost-effective source of stocking material is the glass eel stage, which might give returns equivalent to stocking with yellow eel. Glass eels are commercially available, and the Regulation (EU-COM-1100 2007) requires that fisheries make at least 35% of eel <12 cm available for stocking from their implementation in July 2009 onwards. Because it is unlikely that local EMPs will be implemented before the end of the UK glass eel fishing season in 2009, they will not effect a reduction in glass eel fishing effort that year. However, if EMPs are not approved, the Regulation requires a 50% cut in fishing effort. Since the glass eel fishery is the most lucrative part of European eel exploitation, it's effort is unlikely to diminish where its impact can be shown not to be detrimental to local yellow eel populations.

4.3. Where to stock

Reviewing various sources (Williams and Aprahamian 2004; ICES 2006; Symonds 2006; ICES 2007; Williams and Threader 2007), WGEEL (ICES 2008) noted that, in some circumstances, stocking with eels was carried out to mitigate or compensate for depleted stocks, upstream of hydro-power dams for example, whilst in other cases stocking has been done mainly to enhance local stocks in order to improve or provide a profitable fishery. Thus, stocking should enhance local eel populations in waters with free access to the sea, with the ultimate goal to increase the European stock's reproductive potential and the abundance of recruiting glass eels. To this end, stocking could also occur in new water bodies, or areas where eel are absent, in order to produce additional potential spawners where there is access to the sea.

The ERP requires that enhancement of yellow eel populations and silver eel escapement in individual basins contribute to achieving the management target set for the respective River Basin District (of which there are 11 in England and Wales, including the trans-boundary Solway and Tweed shared with Scotland). Stocking will therefore be most effective if aimed at those parts of basins that will support high survival and growth rates, i.e. where eel densities are currently well below the carrying capacity of the habitat or its potential production, or can be shown to be depleted compared to historical or expected levels.

In general, eel density declines with distance away from the sea (Aprahamian 1986; Naismith and Knights 1993; Lobon-Cervia *et al.* 1995; Knights *et al.* 2001; Ibbotson *et al.* 2002; Feunteun *et al.* 2003), and sites more than 25-30 km above the tidal influence are likely to be below their carrying capacity (see below) for eel (Aprahamian 1988). The reduction in eel density as one travels upriver is likely due in part to physical obstructions to upstream migration and distance (migration time) from the oceanic source of recruiting glass eels. It is also manifest as a negative relationship between river gradient and eel density (Aprahamian *et al.* 2007), in which steeper gradients reduce the distance of upstream migration and densities of yellow eels and hence the production of silver eels. Thus, sites upstream of obstructions and in the upper reaches of rivers would be expected to have a low density of eel, making them potentially suitable areas for stocking. These effects are magnified when recruitment is low (as now), such that only the lower reaches of a basin may have eel populations approaching “normal” densities. Naismith & Knights (1993) and Knights (2005) suggest that the River Thames is a case in point.

4.4. Carrying capacity and density effects on eel production

WGEEL (ICES 2006) discussed the concept of the carrying capacity of a water body in relation to deciding whether to stock eel. Carrying capacity is defined as the maximum density or biomass that the habitat can sustain under average conditions. Carrying capacity as a concept in which eel production is maximal in terms of density (numbers) or biomass is difficult to quantify because of the plasticity of eel production, in terms of numbers vs biomass and with sex-related growth and age/size at silvering. For example, a reach could produce high densities of eel that are mostly male and migrate at low individual weights, so biomass production might be lower than if the reach produced fewer but larger females. Whether a site is at carrying capacity is also linked to ease of access for colonisation and the productivity of the water.

In tributaries of the lower Severn, for example, Aprahamian (2000) found eel densities ranging from 0.12-1.14 m^{-2} and biomass from 2.56–25.24 gm^{-2}. As there was no relationship between growth and either density or biomass, across the sampled sites, the author suggested that these sites were close to or at their carrying capacity. However, studies reporting carrying capacity of a river or lake for eel are rare, possibly due in part to the difficulty in assessing density and/or biomass of eel accurately in a given body of water (Williams and Aprahamian 2004), and/or the lack of quantitative tools available with which to establish whether a reach is at or approaching carrying capacity.

Williams and Aprahamian (2004) suggested that a site is likely to be below carrying capacity for eel if the density of eel is < 2 eels m^{-2} and biomass < 2.5 g m^{-2}, or greater than 30 km from the tidal influence. These authors and WGEEL (ICES 2008) suggest that greater attention should be given to biomass when trying to assess whether a site is at carrying capacity; arguing that there is a smaller variation in biomass when compared to density both within and among river systems (Aprahamian 1986); biomass is more directly related to carrying capacity (Knights *et al.* 2001); and the ERP target is expressed in terms of silver eel biomass (EU-COM-1100 2007). However, stocking with elvers is aimed at restoring populations in the medium to long term (10-15 years, in the UK), and population structure and the densities of eels < 15 cm are probably of more relevance than absolute biomass.

For present purposes, we are primarily concerned not with estimating carrying capacity per se, but whether the stocking density or increased density of the recipient+stocked population can have a negative effect on growth and/or survival rates. In the absence of robust data on density thresholds for these life history processes, we can only suggest that one takes the densities or biomass of eel in reaches close to the estuary (<30 km), observed prior to the recruitment decline, as an indication of population size at which density-dependence may have had an effect. Clearly, this is a topic that requires significant further investigation. Wherever appropriate, therefore, we will refer to 'potential production' in terms of biomass, numbers, or density.

4.5. Habitat suitability for stocking

Lobon-Cervia et al. (1995) suggested that carrying capacity for eel may be limited by the availability of habitat and feeding resources and that the suitability of these resources may depend on fish size. Williams and Aprahamian (2004) discussed the elements of habitat suitability for eels, and observed that there is little quantitative data on the physical requirements of eels, though the species appears very catholic in its choice of habitat. They suggested that suitable habitats for stocking eel would be those where the eel density is low and thus likely below carrying capacity, e.g. upstream of major obstructions to their migration and in the middle and upper reaches of basins. Ideally, the sites should have a pH between 5 and 8 (Alabaster and Lloyd 1982), a high degree of physical heterogeneity, both within the water course and riparian zone, and provide a high amount of cover and a diverse food supply. Knights et al. (2001) suggested using sites with soft sediment, crevices and vegetation allowing the eel to burrow and hide. The trophic status of a given site mainly affects the density of eel that can usefully be stocked, but ICES (2003), for example, does not provide quantitative details of the relationship between production and trophic status.

Laffaille et al. (2005) demonstrated significant relationships between eel density and depth and water velocity in the Fremur Basin, and noted habitat preferences differed between eel size classes: large eels tended to be found in intermediate to deeper habitats with less aquatic vegetation, whereas smaller eels were mainly found in shallow habitats with an abundance of aquatic vegetation and were absent or rare in areas of deep water with a silty substrate.

The Habitat Suitability Model developed by WGEEL (ICES 2003) provides a Habitat Suitability Index (HSI) with a score between 0 (not suitable for a viable population) and 1 (optimal habitat). The model includes stage-specific components, of which the elver-yellow and silver eel components are most relevant for the present purposes. Whilst this model approach could be adapted to guide stocking site selection, the model described in ICES (2003) used habitat data averaged over regions, countries and basins, some of which might not be appropriate for eel populations in England and Wales. Furthermore, this model will only be of use to managers if appropriate habitat assessment data are available.

Growth of eels largely depends on temperature and food availability, the latter having inter-specific connotations. Optimum temperature for growth in eel is 20-26ºC, and growth ceases at temperatures below 10ºC (Tesch 2003). Thus, both the average temperature during the growing season, and the length of the growing season affect eel growth and the time taken to reach maturity, and the number of days when temperatures exceed 14º-16ºC is often considered critical (Deelder 1984; Wickstrom *et al.* 1996). These are probably the most important considerations (in addition to knowing that the local eel population is depleted) when deciding where to stock.

In considering where to stock, managers must also take into account the subsequent potential exploitation and other sources of mortalities of the eel, e.g. fisheries, turbines, etc. There may be a number of stakeholders who potentially benefit from stocking – fisheries, conservationists (particularly those promoting otters (*Lutra lutra*) or bittern (*Botaurus stellaris*), for example, (Knights 2002)) - who might be expected to help fund stocking.

Williams and Aprahamian (2004) reviewed the available data on stocking density and yield, and conclude that more detailed and long-term research is needed to determine the optimum stocking rates (hence the present project). Nevertheless, they propose that eels should be scatter stocked (to minimise density-dependent mortality) in rivers during the summer, when temperatures are high enough to encourage dispersal, at densities of between 1 and 2 eels m^{-2} in low productivity waters, rising to 4-5 eels m^{-2} in warmer waters with plenty of bottom cover and/or marginal vegetation and high macro invertebrate productivity. Though they suggested stocking in a minimum 5-year rotation programme, this did not take into account the deficit of eel production in any specific basin (in relation to the EU's ERP management target).

4.6. Risks associated with stocking

Williams and Aprahamian (2004) observed that each management option to restore silver eel escapement will have its associated costs, benefits and risks, and they outlined a risk analysis framework that included risk assessment and a means to manage the risks identified in relation to their biological and social consequences.

One biological risk associated with stocking eels is that they have long been considered to be a major predator of the eggs, parr and smolts of salmonids. Though Mann and Blackburn (1991) concluded that eel predation on salmonids was negligible, the perception persists, with the result that areas where conservation of juvenile salmonids is paramount may be out of bounds for stocking with eels. On the positive side, as noted above, piscivores such as the otter and bittern may well benefit from their introduction, and it is believed that eel may provide a biological control for non-native crayfish (Environment Agency, pers. comm.).

Another concern, that there may be genetic risks associated with transfer and stocking of genetically distinct sub-groups of eels (Wirth and Bernatchez 2001), is now considered to be minimal. More recent studies (Dannewitz *et al.* 2005; Maes *et al.* 2006) could find no evidence of spatial genetic variation in European samples of glass eel, and it is unlikely anyway that stocking in the UK will use elvers other than from west-coast estuaries in England and Wales.

ICES (2008) identified the risks attending the three main stocking options; with glass eel, young yellow eels and on-grown eel from aquaculture, noting that diseases, parasites, biased sex-ratios and genetic selection may best be avoided by stocking with eels that are as young as possible. Stocking with yellow eel caught in the wild carries the risk of their being contaminated with pollutants such as PCBs, flame retardants, pesticides and heavy metals, which have been reported as potentially limiting migration of silver eels to the spawning grounds and impairing reproductive success (Larsson *et al.* 1990; Robinet and Feunteun 2002; Palstra *et al.* 2006). Priority should therefore be given to sourcing stock from those sites where such contaminants are at the lowest possible levels, and information on such areas is available through the European Eel Quality Database (Chapter 6 of ICES 2008). If on-grown eels from aquaculture are considered for stocking, the main risks are spread of disease, reduced genetic fitness and skewed sex ratios. ICES (2007) considered that stocking with healthy on-grown eels will result in growth rates and mortalities comparable to the stocking of glass eels, although this was based on relatively few, and mostly Scandinavian studies (Vollestad and Jonsson 1988; Wickstrom *et al.* 1996; Moriarty and Dekker 1997; Svedang 1999) and some unpublished data presented to the WGEEL by Astrom and Rosell. Precautions must be taken, nevertheless, to ensure that the genetic integrity of the European eel is not compromised by stocking with aquaculture-grown eels that may contain *A. rostrata* (they have been found in Germany, (Frankowski *et al.* 2008)), nor that rearing practices render the eels less fit for survival in the wild.

In the proceedings of a workshop held in Montreal (Canada) in 2007, Williams and Threader (2007) addressed the risk of disease transfer when stocking eel. Symonds (2006) described several parasites, viruses, bacteria and fungi that have been found in eel communities in North America, whilst studies in Europe indicate that stocking and transfers have been responsible for spreading eel parasites and diseases (van Ginneken *et al.* 2004). The rapid spread of the debilitating swim-bladder parasite *Anguillicoloides crassus* throughout Europe (Kennedy and Fitch 1990; Kirk *et al.* 2000) indicates that eel transfer or stocking done without screening can be detrimental for both the eel population and the associated aquatic community. Screening of eels for parasites, viruses and pathogens takes place in England and Wales, but not in Scotland or Ireland, nor in France where the largest part of the European glass eel catch is taken.

Given these concerns, and the absence of data, WGEEL (2008) advised stocking in high quality upstream habitats with glass eels from estuaries or neighbouring river basins as a priority or, where there is no recruitment, from the same main hydrographical region (i.e. Northern Europe in the case of the UK). In all cases, ICES suggest that the most important issue is to preserve the total genetic diversity to allow adaptation to a changing environment, and that keeping the highest level of biodiversity in phenotypic and genetic traits is crucial for the survival of the species. This cannot, as yet, be quantified, and it is therefore impossible to evaluate the balance between maintenance of genetic diversity/integrity and the need to maximise spawner escapement from a severely restricted source of recruits.

Correspondence with scientists and those engaged in eel culture, to collate unpublished information.

Six nations: Germany, Spain, Sweden, UK, Estonia and Denmark, reported to ICES (2008) that they had stocking protocols. The format of these protocols varies between nations, with some containing rules or guidance on where to stock eels, whereas others require screening of donor stocks for diseases and parasites. Scientists from each of these nations were contacted and asked to provide these protocols, if they were published, and any unpublished source materials, where possible. A summary of the findings is presented below:

UK: stocking by the Environment Agency in England and Wales is guided by Williams & Aprahamian (2004). Movements of live fish must be registered with the EA, and are only approved after a sample of the stock has been checked for diseases and parasites.

Germany: No single, formal protocol document is available, but a regional guideline document from the North Rhine Westfalia federal state has been provided. This document gives some basic rules that should be followed when stocking eels.

Sweden: No single, formal protocol document is available. However, general principles of stocking are that the eels are stocked in fairly productive waters where eels were historically abundant, at stocking densities of about 100 "elvers" per ha in productive waters and rather lower in more oligotrophic ones.

No protocols have been made available from Spain, Estonia or Denmark.

In addition, Poland, the Netherlands, Belgium, Finland, Latvia and Lithuania all reported eel stocking. No information was available on stocking protocols from these countries.

5. Model overview

The main aim of this project is to develop a tool that can be used to guide the eel stocking process, by calculating the number of eels that need to be stocked in a basin in order to meet the management target in terms of silver eel escapement. It is assumed that the EMP for a specific basin includes a management target (expressed in terms of biomass of silver eel leaving the river each year) and an estimate of actual silver eel escapement, or equivalent values for yellow eels as a surrogate for silver eels. The latter is the case for current English and Welsh EMPs, which are based on sampling information that does not precisely represent the underlying eel population structure (selectivity effects). This needs to be borne in mind when applying the model, which essentially deals in population numbers.

The model takes eels from the glass eel stage, when they recruit to the estuary of the river, as pigmented elvers or eels of a larger size, and models their development through differentiation into male and female yellow eels (at sex-specific sizes) until they metamorphose into silver (maturing) eels and leave the basin to return to the ocean to spawn. Throughout their freshwater residence, the yellow eels grow and are subject to mortality. Mortality can vary with age and stage. This allows the user to account for elvers having higher mortality that older eels. The model calculates the size of the eel stock in terms of number of eels (population wide or age-specific) as well as the biomass of escaping silver eels. Eels stocked after artificial on-growing (aquaculture) can also be included in the model, and estimates of the initial eel stock in the river system can be made.

Key processes such as sex differentiation, silvering and escapement take place when the length of eels is within specific length ranges. We use probability distributions to represent how plausible it is for an eel to undergo each of these processes at a given length. As the length range at which silvering and escapement occur depends on the sex of eels, the model uses gender-specific probability distributions to describe these processes. For the purpose of this study, we assume that density-dependent effects only take place when the density levels of eels are high enough to affect the role that key processes play in their population dynamics, and the model assumes that there are no density-dependent effects in the areas in which stocking takes place (which should be chosen to maximise eel production from stocking). However, density-dependent rates/probabilities could be included in the quantitative formulae we use to describe these processes if the user has such information.

This is an age-based model, but one in which the probability distributions are given in terms of length frequencies at a particular time after stocking and for which biomass at any given time or life stage can be calculated using a length-weight relationship. Thus, running forward, the model estimates the population of yellow eels or an annual biomass output of silver eels from a given level of stocking, spread over several years according to growth rates, sex ratios and ages at which male and female eels silver and leave the system. Running the model backwards (minimisation) will, therefore, provide an estimate of the annual input of stocked eels required to produce a given population of yellow eels or of silver eels (numbers or biomass). In either case, steady state dynamics have to be assumed (i.e. recruitment/stocking, growth, mortality and size/age at stage changes remain constant through the time period considered).

The model can be used for either stocked or naturally recruited eels, separately or together, in so far as the density of the eels does not approach levels that will trigger density-dependent effects. To include density-dependent effects in the model, the user will need to modify the model and that would require some level of programming experience. Whilst the model does not include the impacts on eel production of such issues as parasites, diseases, pollution, etc, it should be able to accommodate putative changes in survival due to these factors by increasing the natural mortality values used in the model. Fishing mortality could also be treated similarly, but the EMPs' aim of maximising silver eel escapement would be best served by stocking only where eels are unlikely to be exploited.

In its end-user form, the model is initiated with parameter values that are appropriate to the UK (published values vary within and between basins, and Section 6 provides information on why the proposed values were chosen). The main inputs will be the (additional) numbers or biomass of yellow or silver eels required to meet the management target and the size/age at which eels are stocked.

6. Current knowledge of the processes to be incorporated in the model framework, and model parameterisation

The mathematical expressions used to describe the dynamics of an eel population are provided in Technical Manual (Section 7). Here, we review the information available from the literature that can be used to decide on the values of the parameters used in those expressions. We consider the relevant information from eel studies in Europe, primarily, and then focus on the information we deem most appropriate for informing the ESAT model in it's application to UK waters. Whilst we have attempted to deal with a particular process in each sub-section, they are inextricably linked and some overlap is unavoidable.

6.1 Sexual differentiation

6.1.1 Age/length at differentiation

The biological mechanism by which individual eels elect to become male or female in not well understood, though it appears to be quite plastic and may be influenced by density and growth rates (which are inter-related, see Davey and Jellyman 2005). The model requires a description of the age/length at which an eel could differentiate and of the probability of it doing so. There is a scarcity of relevant information in the literature, but the available data for UK eel populations has been examined and analysed by Cefas (Walker and Apostolaki, unpublished data) as detailed below.

The minimum and mean lengths at which eels differentiate into males and females can be determined from sub-samples of eels for which sex was recorded, from which the probability of differentiation (both sexes pooled) with length can be estimated by examining length-sex keys for the population. River- or population-scale parameters have been calculated for the eight populations from the Defra-Kings data set (collected as part of development of Defra contract SF0236, Bark et al., unpublished) that included sex-length data, and for the Severn and Dee data provided by the Environment Agency (Table 6.1).

The Dee and Severn datasets from the early 1980s indicates the sex of individuals as F, M or ‘*’. The ‘*’ may denote an absence of data on sex, rather than undifferentiated eels, since some eels up to 40-50 cm are designated *. For present purposes, however, we have assumed that, where the length is <30 cm, the ‘*’ symbol indicates an undifferentiated eel. Despite the provision of sex information for far greater numbers of eels per length class, compared to the Defra-Kings datasets, there are no females in the first 8 and 6 cm of the differentiated length ranges of the Dee and Severn samples, respectively. Therefore, we did not use these datasets in the analyses.

Information from Sinha and Jones (1967) for three rivers in Wales is also included in Table 2. This study provides one of the most detailed descriptions of proportion of females at age that is available for UK rivers, and the results of the analysis are shown in Figure 6.1. It is also worth mentioning that a study of ~200 eels >29 cm from a basin in Norfolk did not find any undifferentiated eels (Jespersen circa 1920).

Table 6.1. Information on the length (cm) of differentiated eels for rivers in England and Wales.

River	No. eels sexed		Minimum length of:			Maximum length of undifferentiated eels (age)
	Max	Mean	Differentiated eels	Females	Females only	
Wnion	12	5	10	28	>41	22 (12)
Gara-Start	20	7	21	21	37	26 (11)
Hull	15	8	18	25	44	20 (4)
Essex	12	7	20	27	41	21 (8)
Tadnoll '03*	13	11	15	17	40	
Ellen	12	10	20	22	41	24 (8)
Darent***	13	6	20	20	39	
Blyth	23	13	17	22	38	20 (8)
Dee**	769	169	16	24	41	
Lower Severn '83	251	100	21	27	48	
Ffraw	~500			30		35 (5 or 6)
Rhyd-hir	~300			26		36 (5-7)
Glaslyn	~300			29		37 (5-7)

** - these are the only data on sex from the Piddle-Frome sampling, and include only 5 undifferentiated eels; dataset not included in analyses.*
*** - assumes that unlabelled sexes are undifferentiated, even up to 36 cm.*
**** - lengths for only 5 males and 3 undifferentiated eels; dataset not included in analyses.*

The information in Table 6.1 shows that differentiation has been observed at lengths as small as 10 cm and could last for several years in a single year-class cohort. However, we do not have information about the factors that could influence the length or age at which an eel becomes differentiated or the time it takes for all eels from a single cohort to differentiate.

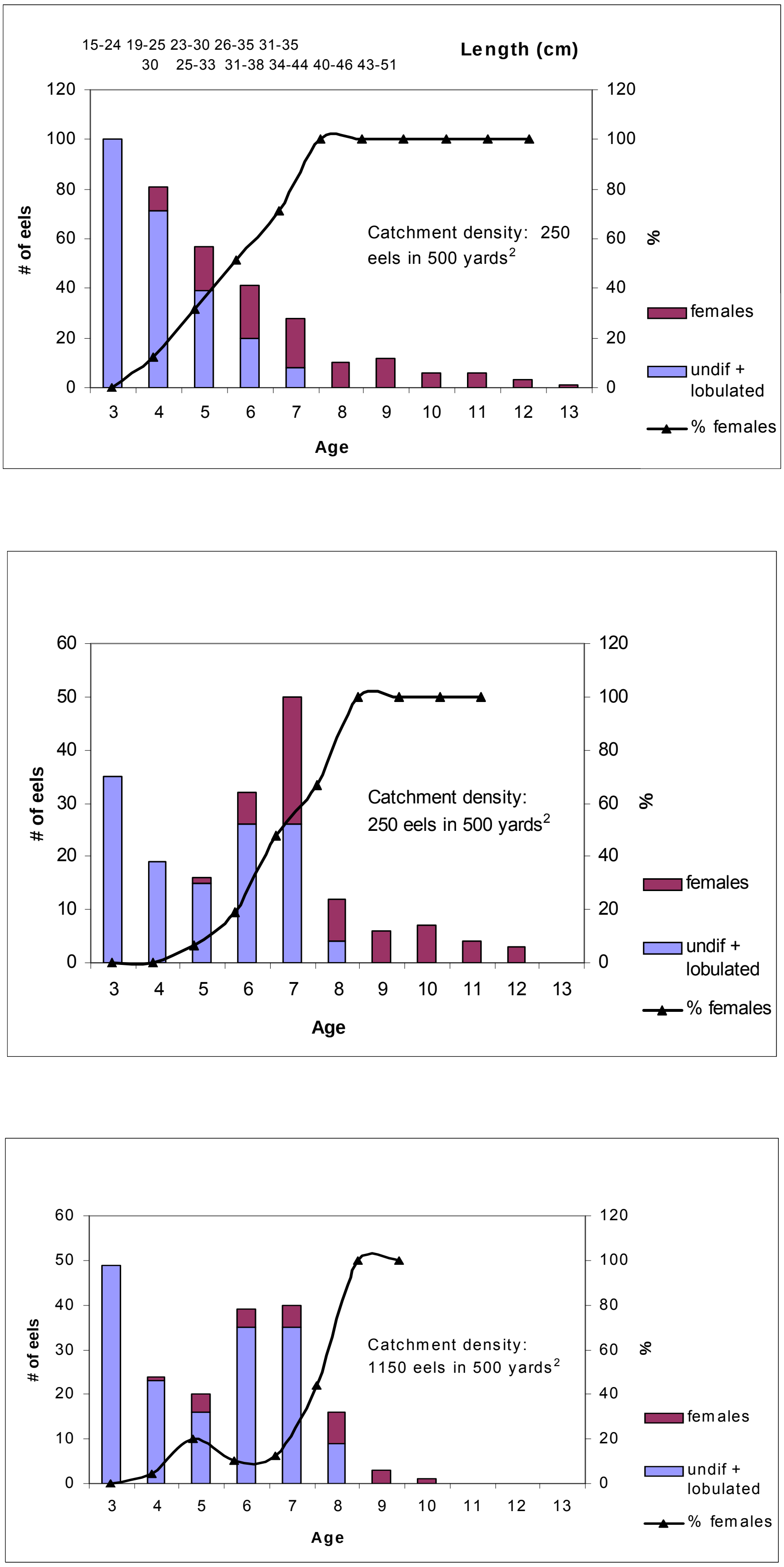


Figure 6.1. Number and proportion of females eels at age for three rivers in Wales: upper, River Ffraw; middle, River Glaslyn; lower, River Rhyd-hir. The corresponding length ranges at age for the River Ffraw are also provided. The length ranges that correspond to each age for the other two rivers are similar to those shown for river Ffraw. Data from Sinha and Jones (1967).

The results from the Welsh rivers (Sinha and Jones 1967) indicate that eels can start differentiating to be females at 4 years of age or at a length of approximately 25 cm. However, the proportion of eels at a given age that become females differs among the samples from the three rivers. It is not known whether the sex ratio shown in these figures represent the sex ratio for the whole river, since the authors did not provide information on the parts of the river from which the eels were sampled.

Based on this information, it appears that eels could differentiae at any length between 10 cm and 40 cm, with differentiation being more likely to occur at lengths between 20 and 30 cm. So, values between 20 and 30 cm appear to be a good choice for representing the length at which there is the highest probability that eels will differentiate (i.e. the mean of the normal distribution we use to describe length at differentiation).

6.1.2 Probability of becoming male or female

A number of studies have suggested that conditions of high eel density favour a male-biased sex ratio. However, there are a number of factors that make it difficult to understand this process, or to derive the data required to describe and model the effects of density on 'choice' of sex. First of all, the number of observations is limited because the methods to determine sex of eel require destructive sampling. Also, studies on sex ratio often report their findings by sampled river reach, and it is difficult to extrapolate these results to the whole basin. Even if we are able to do so, and density information is available, linking sex ratio to density is not straightforward, because the density at the time of the observations might not be representative of the density when the process occurred. Given that eels may spend more than 10 years in a river (and females could spend much more than that), and could differentiate during the first few years in the river, there might be a gap of several years between the time when the eels differentiated and that when density is calculated. One option could be to calculate the sex ratio using eels of only a certain size (e.g. >20 cm but <30 cm) to increase the chance that an eel has differentiated and reduce the chance that density has changed considerably since the time they differentiated, but that also has problems. For example, most eels within that length range will need to be killed to identify their sex, and a proportion of the study eels might still be undifferentiated, both of which will limit the power of the study (under present day circumstances). Furthermore, given the typical reducing trend in density and increasing trend in proportion of females with distance from the sea, the calculation of whole-river average density statistics is likely to be biased by the choice and distribution of survey sites. Ideally, the spread of sites should provide robust local population estimates that, by suitable weighting, are representative of the river population as a whole.

Reviewing some French, Spanish and Norwegian studies, Robinet et al. (2007) suggest some relationships between whole-river eel density and sex-ratio of emigrating silver eels: rivers with densities higher than 500-1000 eels/ha or 90-170 kg/ha produce mainly male silver eels (>90%); whereas rivers with densities lower than 300 eels/ha or 45 kg/ha produce mostly female silver eels (>80%). The authors suggest a density threshold of 500 to 1000 eels/ha around which the sex ratio of silver eels swaps from being dominated by one to the other sex.

This method relies on estimating whole-river production of yellow eels, based on long-term monitoring of a large number of sampling sites. Furthermore, since male and female silver eels migrate at different ages, and because the conditions that resulted in some eels becoming male might have been different from those that resulted in other eels becoming female, the method relies on relative production of both sexes being stable over time.

A study in 1982 to 1983 in the Rivers Severn and Dee also showed that the sex ratio varied with the part of the river sampled (Aprahamian 1988). The sex ratio for the whole river was 58% females to 42% males for the Severn and 59% females to 41% males for the Dee. The densities observed in the River Severn ranged from 500 eels.ha^{-1} (in the upper basin) to 32,000 eels.ha^{-1} (max. value in the lower basin). These values are much higher than those indicated by Robinet et al. (2007) as the density limit that would produce mainly male silver eels. Although the two results are not directly comparable, since the Aprahamian study refers to yellow eels, they do provide some information about the range of density values that can be associated with a considerable proportion of females in the population. For the reasons discussed earlier, these results would be of more value if sex ratio at age or length has been reported. Also, information on eel density in the River Dee is not provided.

In a study on the River Thames, Naismith and Knights (1990) suggest that their results show that high densities are associated with high male to female ratios. However, the results show a male to female ratio of 11:3 for eels of length between 30 and 32 cm in a site (Becton) with a “high” density, while this ratio is 18:3 in another site (Inner reaches) with a lower density. It is not clear how the authors reach their conclusion, and the presentation of the results leaves many questions unanswered (e.g. they claim that they use the average CPUE for eels of length>30 cm per site as the number of eels of length between 30-32 cm, but the results only present a relative number of males and females in each site).

Although we cannot derive the sex ratio for the whole of the River Thames, results presented in Naismith and Knights (1990) give male to female ratios for eels of length 30-32 cm that range from 1:9 to 12:1, depending on the part of the river sampled. Naismith and Knights (1993) present a further analysis of these data that indicates densities of eels of 0.06 eel.m^{-2} (600 eels.ha^{-1}). It is important to note that the sex ratio for eels <35 cm is male dominated everywhere in the river except in the outer reaches. Unfortunately, it is not clear what proportion of eels at each length range are classified as undifferentiated.

In the absence of silver eel data for most UK rivers, the threshold suggested by Robinet et al. (2007) cannot be tested for UK eel populations. An alternative approach, therefore, is to explore relationships between density and sex ratios in yellow eels, for which we have used data from a recent study carried out by Kings College London under Defra contract SF0236 (Bark et al., unpublished). The Defra-Kings dataset provides length and weight for 5774 individual eels, and numbers and biomass for samples from a total of 128 sites across 8 basins (Wnion – Blyth in Table 6.1 above). However, as sex was recorded for only a few eels per site (max. 23, means of 5 to 13 across rivers), there are insufficient data from which to derive robust estimates of sex ratios or % females for individual sampling sites. In the absence of site-specific information, we have derived whole-river sex-at-length probabilities (sex-length keys) from combined site data. We applied the river keys to site-specific length-frequency distributions, for all sites where lengths were recorded for >10 eels, in order to predict the number of females at each length class, and calculated the proportion of females within the differentiated population.

A further potential bias in calculating sex ratios is the emigration of silver eels, especially males, since the ratio measured across the observed length range may be biased towards females if males have already begun to silver and leave the site. Therefore, the sex ratio should be calculated for eels shorter than the length of the smallest male silver eel. Given the lack of silver eel length information for most rivers, we cannot use a river-specific upper limit of immature eels, so we have chosen to set the limit based on the limited UK silver eel data available to the study. The shortest male silver eel observed from the rivers Severn (1983-1984: Environment Agency) and Piddle (Kings-Defra) was 30 cm, so this limit is applied in our analyses.

Furthermore, although differentiated eels were observed in the Wnion from 10 cm and longer, no females were observed at lengths less than 28 cm. Because of this, we have excluded the datasets for the Wnion, Hull, Tadnoll Brook and Essex rivers from our analyses.

A study by Rosell et al. (2005) on eels in Lough Neagh in Northern Ireland links the relative lower elver numbers in the Lough since 1989 to an increase in the proportion of females in the silver eels caught more recently. Based on estimates of elver densities in the period that are linked to high male proportions in silver eels, the authors suggested that their data provide indicative elver densities that can lead to male or female dominated silver output.

Generally, the information we have about the process of sex differentiation in eels is fragmented and sometimes contradictory. Because of the difficulties in studying this process in the wild, scientists have tried to study it in a controlled environment. One good example of such a study is presented in Roncarati et al. (1997), in which elvers were separated into three groups and kept in tanks at densities of 800 g.m^{-3}, 1600g.m^{-3} and 3200 g.m^{-3} or, approx. 1780 eels.m^{-3}, 3650 eels.m^{-3} and 7200 eel.m^{-3}. The three densities resulted in male to female ratios of 2:1, 3.5:1 and 25:1 respectively. It is not clear whether more undifferentiated eels became males at the higher density, or whether the same proportion of males and females was produced but males were able to survive much better in the high-density environment. Survival was much higher for eels in the tank with the lowest density, and the change in the sex ratio between the tanks was mainly because of a reduction in the number of female eels rather than an increase in the number of males produced (the total number of eels produced was almost the same for the three density levels).

Although the densities reported by Roncarati et al. (1997) are much higher than those observed in English or Welsh rivers, the proportion of females produced is considerable even at densities of 1780 and 3650 eels.m^{-3}. However, these eels were kept under much more favourable conditions that those in the wild (no shortage of food, constant temperature, etc.), which is reflected in the sizes the eels attained in the 450 days of the experiment (~52 cm for females and 42 cm for males). Consequently, these results cannot be used as indicative wild values for the model, though they do suggest that, under favourable conditions, a high proportion of females could be produced at higher densities than in the wild.

The information in Table 6.1 indicates that the smallest females that have been observed are of length of 17 cm or greater. However, a length of 25 cm appears to receive more support by the observed data as the length at which differentiated eels might become females. Given that the smallest length of differentiated eels is less than 17 cm, we assume that eels that differentiate at very small lengths have a higher probability to become males. In order to parameterise our model we need to understand at what length the probability that an eel that will differentiate will become male is the same as the probability that it will become female. From Fig 6.1 we see that such a ratio could occur at ages as young as 5 years or at lengths between 25 and 35 cm (based on length at age information from the same study (Sinha and Jones 1967). Therefore, a length within that range could be a representative value for the length at which eels have the same probability to become males or females.

6.2. Silvering

Production in relation to recruitment or stock density of fish populations is conventionally expressed in terms of the biomass gain over all ages (i.e. a function of each cohort's growth and natural mortality), and as yield to fisheries by age group. In calculating eel production in relation to spawning escapement, however, we must also take into account the age and size at which male and female yellow eels become silver and emigrate from the freshwater (and coastal) growing environment.

Pedersen (1999:cited by Frost et al. 2001) reported that Danish wild male and female silver eels had mean weights of 98 +/- 17.7 g (standard deviation) and 829 g +/- 285 g respectively, whilst Frost et al. (2001) assumed that silvering starts at average weights of 100 g and 500 g respectively, based also on Danish eel data provided by Pedersen. WGEEL (ICES 2006) reported that male eels have an average size of 37 cm at silvering, whilst female eels averaged 67 cm. Tesch (2003), in reviewing published data on this topic from different rivers in Europe, showed that silver male eels are of length 35-45 cm and females >45 cm (mean between 55 and 60 cm).

Because there are differences in growth a size at silvering throughout Europe, the assumptions of our model are based on information from studies on UK rivers as much as possible. A few studies are available that provide such information. One of the earliest is by Jespersen (circa 1920), in which all males in a sample of 198 eels between 29 and 65 cm in length from a river in Norfolk were < 45 cm.

A study in the River Severn (Aprahamian 1988) suggested that males leave the system at lengths ranging from 29 to 44 cm, while females start to migrate at bigger sizes (length ranged observed: 35 to 81 cm). The age frequency distribution for male silver eels ranged from 4 to 20 years (mode at 11-15 years), and for females 9-27 years (mode 13-22 years) (Figure 6.2).

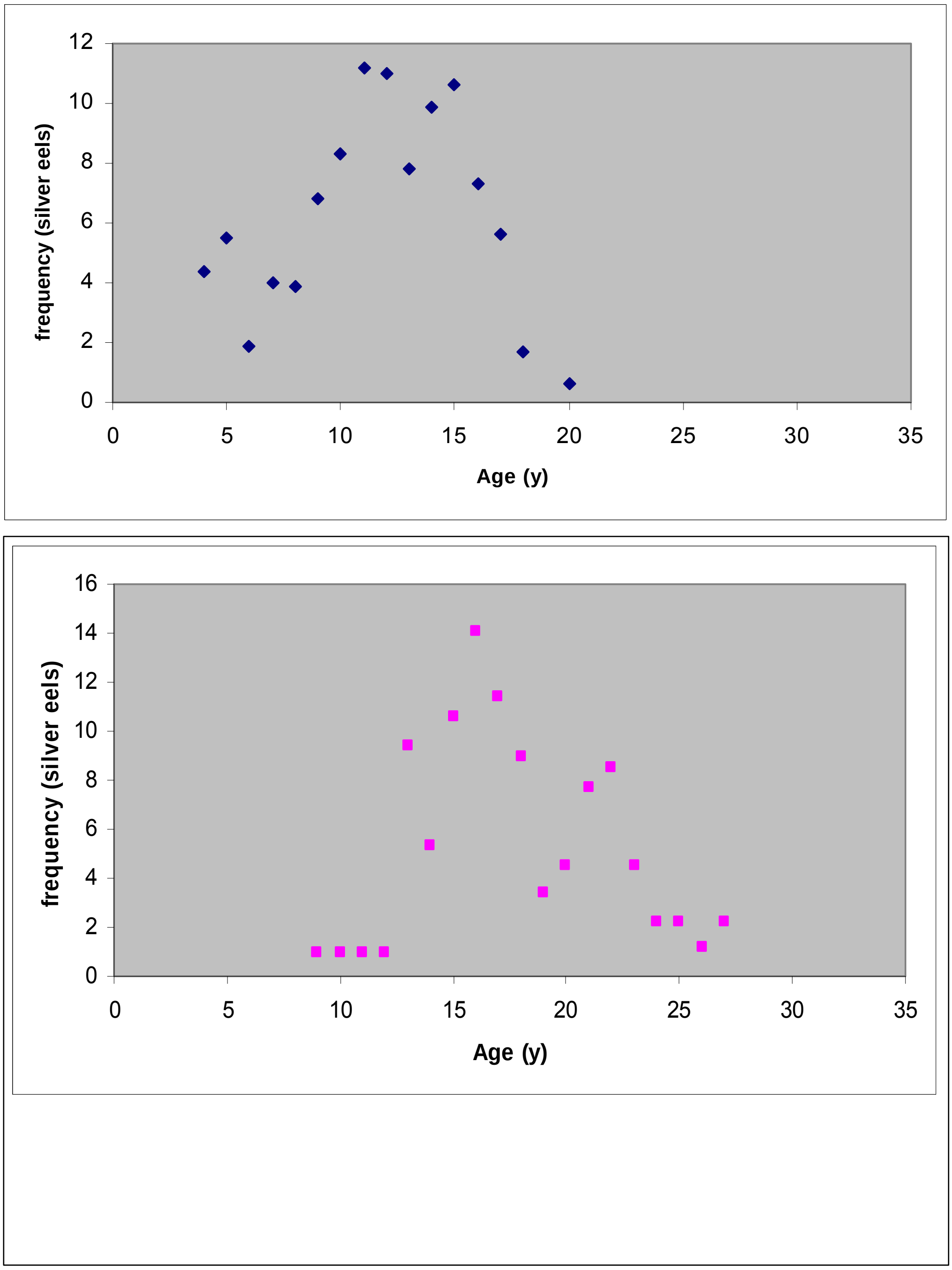


Figure 6.2. Proportion of silver eels from each age class in the River Severn, males (upper) and females (lower) (after Aprahamian 1988).

Length at age data for silver eels trapped migrating downstream in the River Severn in 1983 (Aprahamian, 1988), and in the Rivers Piddle and Frome from 1997 to 2003 (Knights et al., 2001, Kings-Defra unpublished data) so show that males migrate at smaller lengths (and ages) than females.

Naismith and Knights (1990) also discuss this process for eels in the River Thames and suggest that males silvered mainly between 33 and 40 cm, at about 4 to 8 years (mode at 5 years) and that the majority emigrated before attaining 41 to 45 cm. Females matured at about 36 to 60 cm (8-11 years), the majority silvered at >46 cm. Very few eels were found to exceed 60 cm.

Based on the information above it seems appropriate to assume that the most probable length values (i.e. the mean of the probability distribution we use to describe this process) at which male eels will become silver are in the range between 30 and 40 cm while the relevant values for females appear to be between 45 and 55 cm. However, the range of plausible lengths is wider for both genders and appears to extend between 37 and 45 for males and 35 and 60 for females.

6.3. Growth rates

Growth of eels largely depends on temperature and food availability, the latter having inter-specific connotations. Optimum temperature for growth in eel is 20-26ºC (Tesch 2003), and growth ceases at temperatures below 10ºC (Elie and Daguzan 1976). Thus, both the average temperature during the growing season, and the length of the growing season affect eel growth and the time taken to reach maturity, and the number of days when temperatures exceed 14ºC-16ºC is often considered critical (Deelder 1984; Tesch 2003).

WGEEL (ICES 2006) reported growth of eels to vary between 14 and 62 mm.year^{-1} within its distribution range. At this rate, it will take 5-21 years for males to reach the average size of 35 cm at silvering, whilst female eels will take much longer since they appear to silver at greater lengths. For glass eels stocked in 2009, the effects on silver eel escapement could be expected from 2014 (at the earliest) to approximately 2050, depending partly on stocking location, sexual differentiation and growth. Eels stocked in suitable habitats may well grow faster than if left where they had recruited naturally and may, therefore, mature earlier (Aprahamian 1988). There are a number of studies that have used length at age data to construct a formula that will link age to length. For example, Sinha and Jones (1967) used data from three rivers in Wales and showed that the variance in the length at age is considerable and that growth patterns vary among rivers: age 2 ranged from 12 to 20 cm; age 3 from 16 to 24 cm; and age 4 from 20 to 26 cm.

The authors also found that the females in a specific age group were of greater length that those eels with lobulate organs of the same age (Sinha and Jones 1967). Their studies provided different length-at-age formulae for males and females. However, the results of the two formulae for the same age were very similar. Barak and Mason (1992) analysed length at age data from two rivers in East Anglia and reported an almost linear increase of length with age for all ages up to 10 years.

An alternative approach that scientists have followed is to calculate growth rate at length and also the total growth of eels from glass eels to a predefined stage in their life. For example, Pedersen (1999: cited in Frost et al., 2001) calculated the growth of farmed eel, as a function of eel size and time, and showed that growth declines with age up to an average weight of about 150g after 18 months.

*Table 6.2. Intrinsic growth and survival rates for farmed eel (from Pedersen, 1999. Intrinsic growth and mortality rates were smoothed using: Intrinsic daily growth = -0.0037*LN(size)+0.022 and Natural mortality = 0.06*size^(-0.94).*

Size (g)	Intrinsic growth rates (% day)	Cumulative survival rate (%)	Natural mortality rates (% of initial intake of glass eel, observed values)
Glass eel	3.0	30	12.1
1 – 5	2.0	10	9.1
5 – 20	1.3	5	3.8
20 – 60	1.0	0.5	1.6
60 – 100	0.8	0.20	0.6
100 – 130	0.5	0.10	0.3
130 – 160	0.3	0.10	0.1

A cohort model showed that 1 kg of glass eel grows to 385 kg of yellow eel at 150 g per eel, while use of the observed natural mortality rates in % of intake (27.6%) shows that 1 kg glass eel grows to approximately 330 kg.

With respect to growth in biomass, Bisgaard and Pedersen (1991) provided information on a weight at length formula using data from a river in Denmark. The formulae they constructed differed for stocked and wild eels and were:

Wild eels: $W\ (g)=L(cm)^{3.88} \times 10^{-4}$ Size range: 13-31 cm (r=0.97)

Stocked eels: $W(g)= L(cm)^{3.22} \times 7.8 \times 10^{-4}$ Size range: 13-31 cm (r=0.99)

Vollestad and Jonsson (1988) also constructed a weight at length formula using data from a river in Norway:

$\mathrm{Log}_{10}W(\text{in g})= 3.073*\log_{10}TL\ (\text{in mm}) - 5.971$

Growth studies indicate that length at age varies throughout Europe. For this reason we have used growth data from only English or Welsh rivers to parameterise our model. Analysis of available data carried out under a different project has provided information on length-at-age and the variation of length at a given age for different rivers. For the parameterisation of this model we have used data (Defra-Kings) from rivers Blyth, Ellen, Essex, and Hull to construct a length-at-age relationship. A number of length-at-age formulae were considered including von Bertalanffy and linear functions (Figure 6.3). In all cases we considered the linear equation has either the best fit in the data or was very similar to the one that achieved the best fit. Given that the linear growth function is the simplest one and concerns about the paucity of information on the growth of eels above a certain length, we have chosen to use a linear relations to describe eels growth. The formula we use is:

$$L\ (mm)= 63 +22*a \qquad (6.1)$$

where L is the length at age *a* (in years). For most ages, the range of lengths that corresponded to a given age were included between +- 30% of the value found with the length-at-age formula. So, a 30% variation in the length-at-age can be seen as an upper limit in the value the user chooses to describe the variation in the length at age found from Eq 6.1.

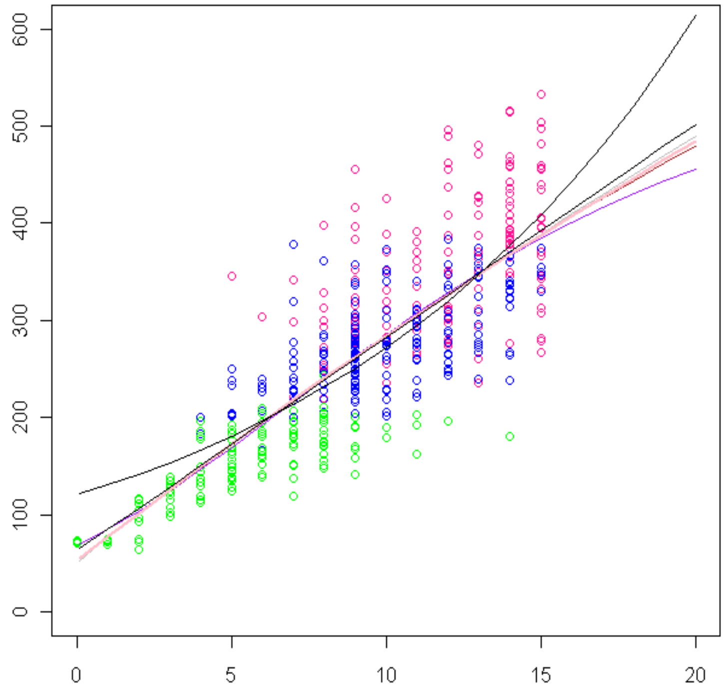


Figure 6.3.1. Fit of different growth models to length at age data from 4 rivers. The red line corresponds to the linear model

6.4. Mortality

Calculating mortality for eel is an area of research that still requires much study. A study from Denmark suggested a daily mortality rate of stocked elvers of 0.01-0.02 day^{-1} which corresponds to 2% survival per year (Berg and Jorgensen 1994). However, it has been said that this is up to 10 times higher than mortality reported elsewhere. Vollestad (1992) reported survival of wild eels of length smaller than 15 cm is less than 20% per year (Bisgaard and Pedersen 1991). However, the survival for the same length of cultured eels was much smaller. Survival remains below 40% for lengths smaller than 30 cm but increases quickly to above 60% for greater lengths. Longer-term Z values for stocked eels appear to be between 0.36-0.65 for a Danish stream (Rasmussen and Therkildsen, 1979), and 0.5-0.7 for the River Thames (Naismith and Knights, 1997). However, neither migration nor natural recruitment were accounted for in either of these studies. Dekker (2000) reports that 75% of eel recruits die from natural causes, equivalent to an annual mortality rate of 0.1-0.2 with a life span at 14 - 7 years respectively.

Whilst Williams and Aprahamian (2004) also considered the cost-benefit analysis of stocking for commercial fishing purposes, which does not concern us here (since our remit is to guide measures to effect stock recovery), their examination of evidence for survival rates of stocked eel is useful. There are few data available in the literature on mortality rates, even from long-term studies, because of unknown losses to migration and to unrecorded fishing mortality (Knights *et al.* 1996).

Because of the variation in the values found in the literature and the high number of factors that can affect eel survival it is very difficult to choose values for survival at length. We have opted for mortality values that result in 30% survival at small lengths and changes to above 70% survival for eels of length of 35 cm or above. However, because the results of the model are very sensitive to the choice of these values we would advise users to repeat their calculations with more than one set of mortality at length values so, they have a good idea of the range of results that one can get by using plausible (but different) set of mortalities at length.

7. Technical Manual for ESAT

7.1. Model overview

The Eel Stocking Assessment Tool (ESAT) is a tool to assist management of European eel (*Anguilla anguilla*) stocking programmes. It can be used for estimating the number of glass eels that should be stocked in a river or basin annually in order to reach a given yellow eel population target, as well as exploring the predicted population structure and silver eel escapement.

ESAT uses an age-structured stock dynamics model, and allows users to modify inputs and parameters to suit the needs of their basins and management plans. Constructed in Excel, ESAT uses the worksheet format to show output as well as providing a user interface, whilst the model is implemented using Visual Basic for Applications (VBA) and imbedded into the document as VBA modules.

This document contains the methods, mathematics, and assumptions used in the ESAT model.

7.2. Model structure

An age-structured population dynamics model constitutes the main part of the ESAT model (hereafter called “the model”). The model can project the population forwards from a given state (initial population structure and size) using annual time increments (but see discussion about time steps in the section entitled “Use of smaller than annual time steps”). It can also be used to calculate the number of eels that need to be stocked every year to achieve production of a target number of yellow or silver eels under equilibrium conditions, based on a minimisation routine.

The dynamics of the eel population in the model are stage-dependent. Four stages are used in the model (each based on important life stages), each of which determines its dynamics and the appropriate biological parameters. These stages are undifferentiated eels, male eels, female eels, and silver eels. Undifferentiated eels are those that have not yet differentiated into either sex (as far as current understanding allows). Eels that the user might class as glass eels, elvers, and yellow eels smaller than those designated as either male or female, are all classed as undifferentiated within the model. Male and female (yellow) eels are those that have differentiated their sex, but have not become silver eels.

Silver eel is the last stage modelled in the system.

Other than at time=0 using the length defined stock structure option, length is determined from age using a growth function and information on the variance in length values. The formulae that describe eel mortality, sex ratio and transition from one life stage to the next are expressed as functions of length, since this is how they are usually described in the literature. The model then uses the length range that each age class covers to link the different processes to the age class (i.e. find the values for natural mortality, differentiation probability, etc. that correspond to each age class).

Stocked eels are added to the eel population each year, or as required, and a proportion of all eels die due to natural mortality. A proportion of the remaining eels could also change their life-stage group, based on their individual lengths and current life-stage (Fig. 8.1). Finally, eels that have become silver are removed from the system, and the remaining eels are added to the age group one year above their present age. This process is then repeated for each year until the model reaches its final iteration.

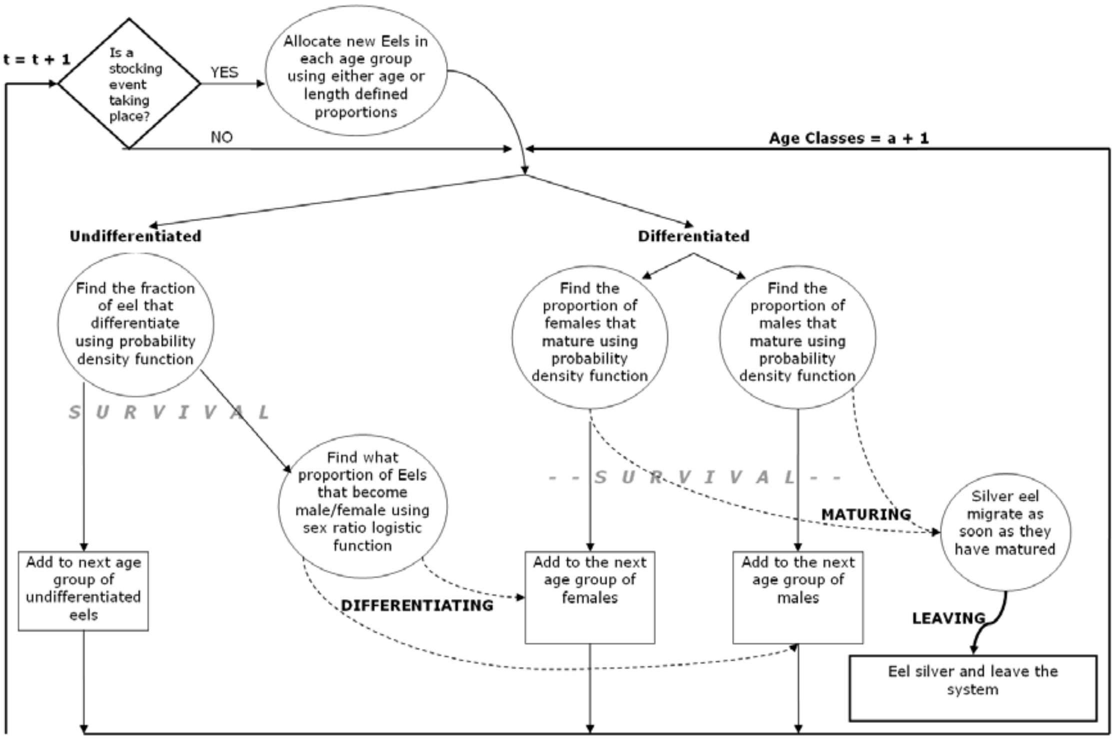


Figure 7.1. Schematic of the eel production processes applied in one year increments in the ESAT model.

7.3. Detailed description of processes

7.3.1. Number of eels at age

The main equation that the model uses to describe the number of eels that survive from one year to the next is given by:

$$N_{t,a} = N_{t-1,a-1} * e^{-M_{a-1}} \qquad (7.1)$$

Where $N_{t-1,a-1}$ is the number of eels of age a-1 at time t-1, $N_{t,a}$ is the number of eels from that age that remain at time t and M_{a-1} is the annual mortality at age a-1.

The model calculates the mortality that eels in each age class experience, as the average of the mortality at the lower, mean and upper lengths of the length distribution of each age class. The mortality at length values are given in the Mortality Table shown in the worksheet called "***Parameters***".

7.3.2. Growth

A von Bertalanffy growth equation is often used to describe the growth of fish. However, research on growth of eels indicates that such a model might not be the most appropriate one to describe eel growth (see Section 6.3 for a detailed discussion). For this reason, we have chosen to use a linear relationship to define growth in ESAT. Thus, the equation used to describe eel growth is:

$$L = 63 \text{ mm} + 50a \qquad (7.2)$$

Where 'L' is the length in mm and 'a' is age in years. The values of the parameters of this formula are based on analysis of growth data from representative rivers in England (based on Defra-Kings data). The model allows the user to add variation in the length values predicted using Equation 7.2. Eels are assumed to be uniformly distributed over the length range defined by the upper and lower length of the given age class.

7.3.3. Age structure of stocked eels

Although glass eel are typically considered to be age 0 at time of capture, this age is based on time after arriving in estuaries, where they become susceptible to fisheries. In fact, the age of eel when they transform from leptocephali to glass eel is the subject of considerable debate, with estimates ranging from less than 1 year (Lecomte-Finiger 1992) to perhaps 3 years (McCleave and Kleckner 1987; Kettle and Haines 2006). The age-at-length growth curve we use in ESAT, and associated variation, represents a typical glass eel measuring 7 cm to be about 0.4 years old.

The age of stocked eels can be defined by the user or calculated by the model. In the former case, the user provides the proportion of the stocked eels that should be placed in each age-class, and the model allocates the number of eels in each age-class accordingly. In the latter case, the model uses information on the range of lengths of stocked eels, and the range of lengths that each age class covers to calculate the proportion of the stocked eels that go to each age class. If this option is chosen, the following information will be used in the calculation:

The following values are calculated from the growth equation (Eq. 7.2)

Upper length for each age class i = L_i^{upp}
Lower length for each age class i = L_i^{low}

The information that the user needs to provide in the ***Inputs*** worksheet of ESAT

Minimum length of eels that are added = L^{min}

Maximum length of eels that are added = L^{max}

Figure 7.2 shows the logical calculations that the model uses to find what is the probability, $prob_i$, that stocked eels will be allocated to an age-class, i. Note, that if the variance in the length at age values is not zero, the range of lengths that each age class covers will overlap with the range of lengths that adjacent age-classes cover. For this reason, even if the range of length of stocked eels fall within one age-class the proportion of stocked eels that will be in that class is not unity. The proportion of stocked eels, P_i, that will be allocated to each age class, $_i$, will be given by the following equation:

$$P_i = \frac{prob_i}{\sum_i prob_i} \qquad (7.3)$$

The contribution of eels from each age class to the yellow eel population (i.e. the proportion of eels from each age class that is above the survey selection length (given by the user in the **Inputs** worksheet)), is determined in the same way.

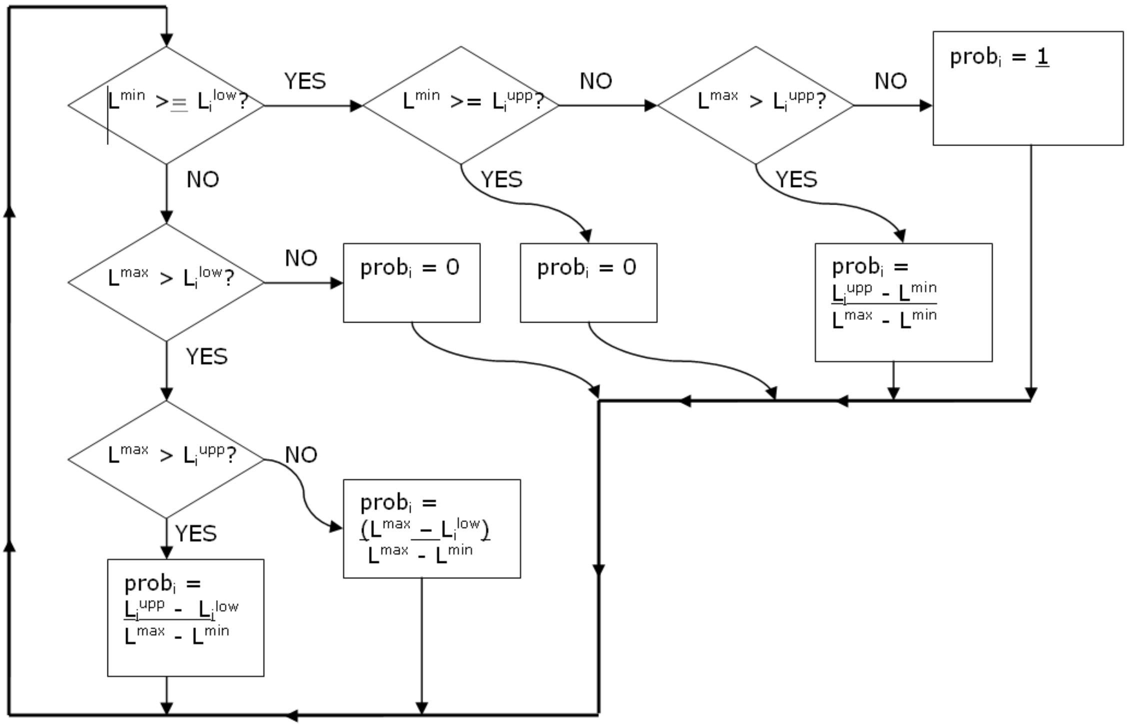


Figure 7.2. Logic operator diagram demonstrating how eels are assigned to age class from length

Note that the outcome distribution of stocked eels to age classes may appear counter-intuitive (i.e. not all eels stocked as glass eels will appear as age 0 in the first year in the river), but this is an essential property of the model given the need to replicate the dynamics of an eel population.

The following assumptions are inherent in the model calculations:

- The distribution of length of eels in each age class follows a uniform distribution.

- Similarly, the distribution of eels in the new eel stock over the length range provided follows a uniform distribution.

7.3.4. Life stage methods

Sex differentiation is modelled using a probability density function (p.d.f) to describe the length at which eels will become either male or female. A normal p.d.f is used to describe this process. The user sets the mean and standard deviation of the p.d.f externally. The probability that eels in each age class will differentiate is calculated using the normal pdf to calculate the probability that eels in the length range that corresponds to each age class will differentiate. The next step is to calculate the probability that eels in each length range will differentiate if they did not do so at smaller lengths (conditional probability). It is the conditional probability that the model uses in the calculations.

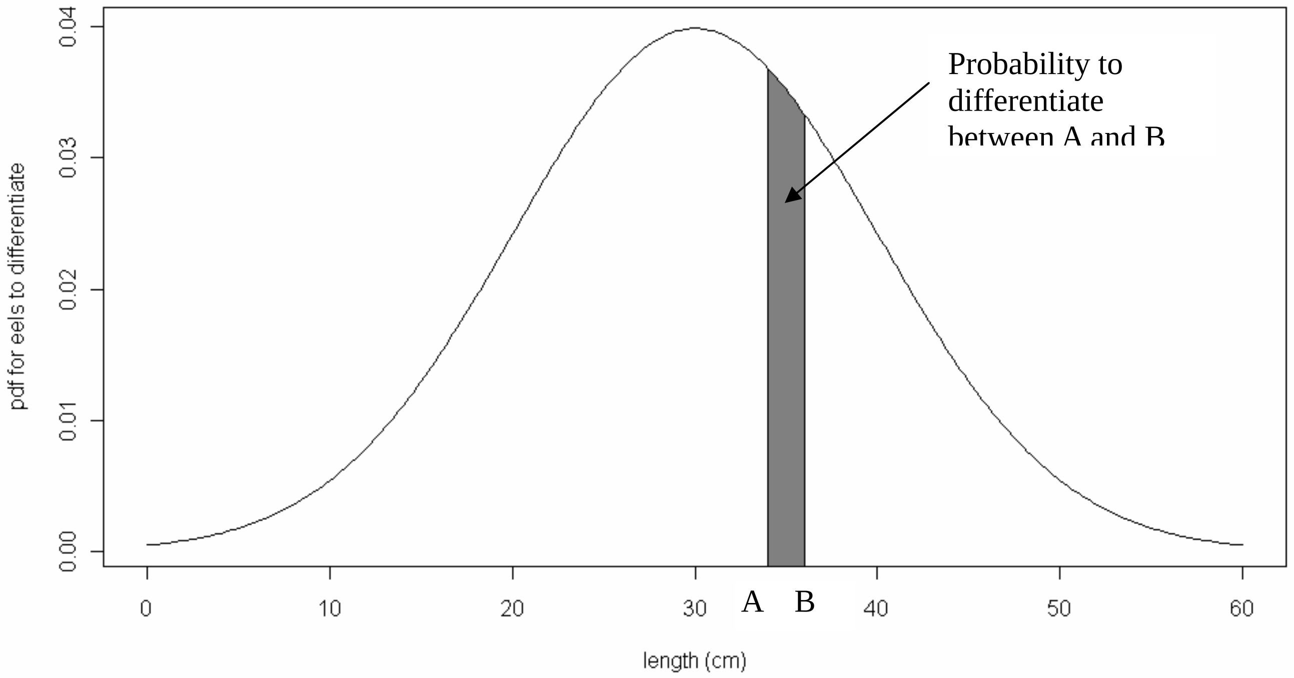


Figure 7.3. Example of normal 'p.d.f.' that describes the length at which eels differentiate into males or females

Once an individual eel has differentiated, then the probability of whether it becomes male or female is controlled by a logistic function. The standard logistic curve starts with low values at small values of the parameter in the x axis which increase as we move to higher values. In this case, a one minus logistic function is used to create a function that gives the proportion of differentiated eels that become male:

$$prop_{males} = 1 - \frac{1}{1 + e^{-(l - l_{50})/c}} \qquad (7.4)$$

where l_{50} is the length at which 50% of the eels that differentiate are males, and c is a constant that determines the steepness of the curve for values close to l_{50}. The proportion of eels that become females at any given length is equal to 1 – $prop_{males}$.

This method produces a higher proportion of male eels at lower lengths, and favours an increasing proportion of females as length increases. Therefore, Equation 7.4 assumes that the fraction of eels that turn male or female at a given length is length dependent.

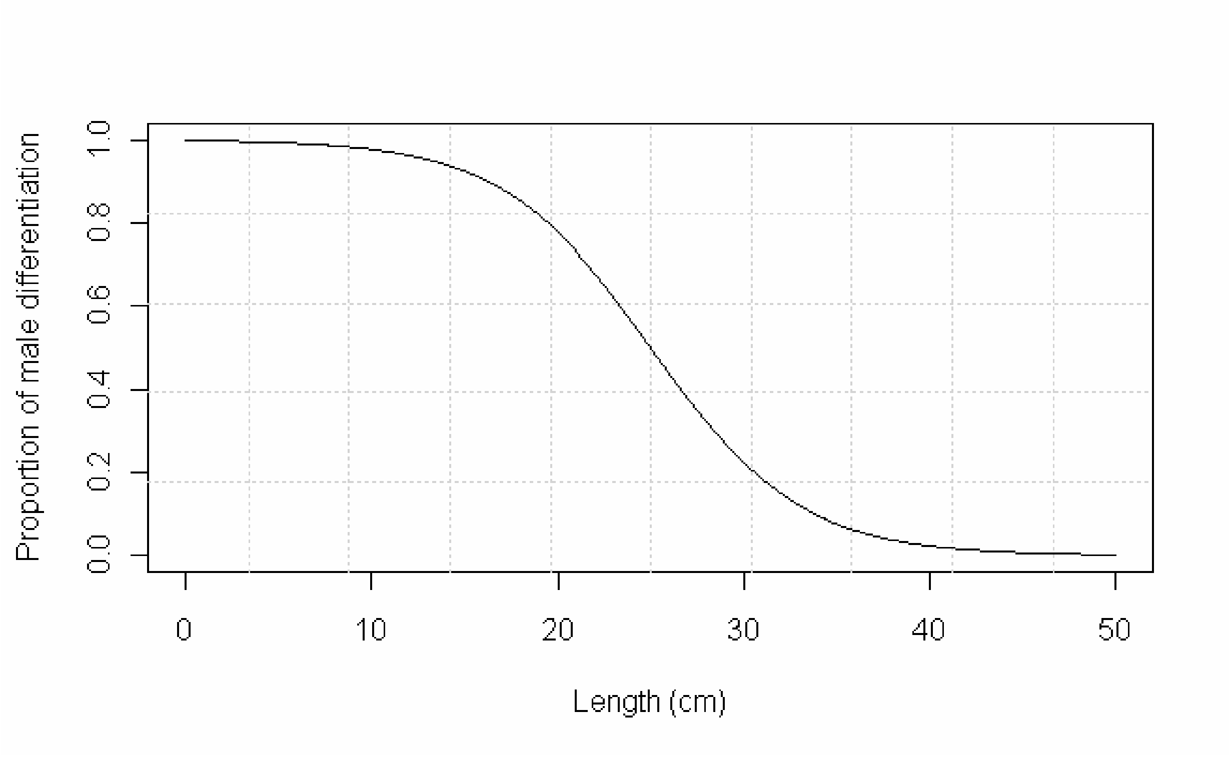


Figure 7.4. Proportion of eels that become males at length

To summarise, calculation of the number of eels that differentiate is done in the following manner.

For each age group:

1 The length at age is found using the parameters for the length at age relationship. The upper and lower length that a given age class covers (taking into account variation in length if it applies) are denoted A and B respectively;

2 Using the p.d.f. that describes the length at which eels differentiate, the probability for an eel to differentiate at lengths between A and B is found: P(diff A-B);

3 The probability for an eel to differentiate at lengths smaller than A is then determined: P(diff 0-A);

4 Based on that the conditional probability that an eel will differentiate between length A and B, and given that it did not differentiate at a smaller length (i.e. length A or smaller), the proportion that differentiate is:

P(diff A-B|not diff 0-A) = P(diff A-B)/(1-P(diff 0-A))

5 The result of this calculation is assumed to be the proportion of undifferentiated eels, at the relevant age class, which will differentiate;

6 From the male to female ratio logistic function, the proportion of eels that turn male at length A, L (mean length for each age class), and B are found (the 3 different values must be used, since we are using a frequency curve, not a p.d.f.). The mean of these three values is used to give the fraction of eels that become male. The proportion of eels that become females is given by 1 – this fraction.

A table of probabilities of differentiating (proportion of undifferentiated eels that will differentiate) at age, and a table of the proportions of these eels that become male or female, is calculated from the above procedure.

7.3.5. Representation of eels of different lengths in a survey (yellow eel population)

One of the eel stage classes used in the calculations is that of yellow eels. For the purpose of this study, a yellow eel population is defined as the number of eels with length equal or greater than the minimum survey length (see **Inputs** worksheet). The minimum survey length is provided by the user and represents the minimum length above which the eel population is fully selected by the gear used in the survey. To calculate the total yellow population the model uses the minimum survey length to determine what proportion of eels in each age class will have a length greater than the survey one.

7.3.6. Silvering

Normal probability density functions are also used to describe the probability of eels of each sex becoming silver at a given length. An illustration of these functions is shown in Figure 7.5.

Again, for a given length range (determined from age class) A to B, the proportion of eels that become silver is calculated as the conditional probability:

$$\text{P(mature between A-B| not mature by length A)}$$

$$= \frac{\text{P(mature between A-B)}}{\text{1 – P(mature by the time it attains length A)}}$$

Once an eel has silvered, it is assumed to have migrated and left the system in the same year. This assumption links the yellow eel population (most likely to be monitored) to silver eel escapement (the EU management target) in the most simple way, and there is a lack of evidence that silver eels do not migrate to the sea in the year of silvering in UK rivers.

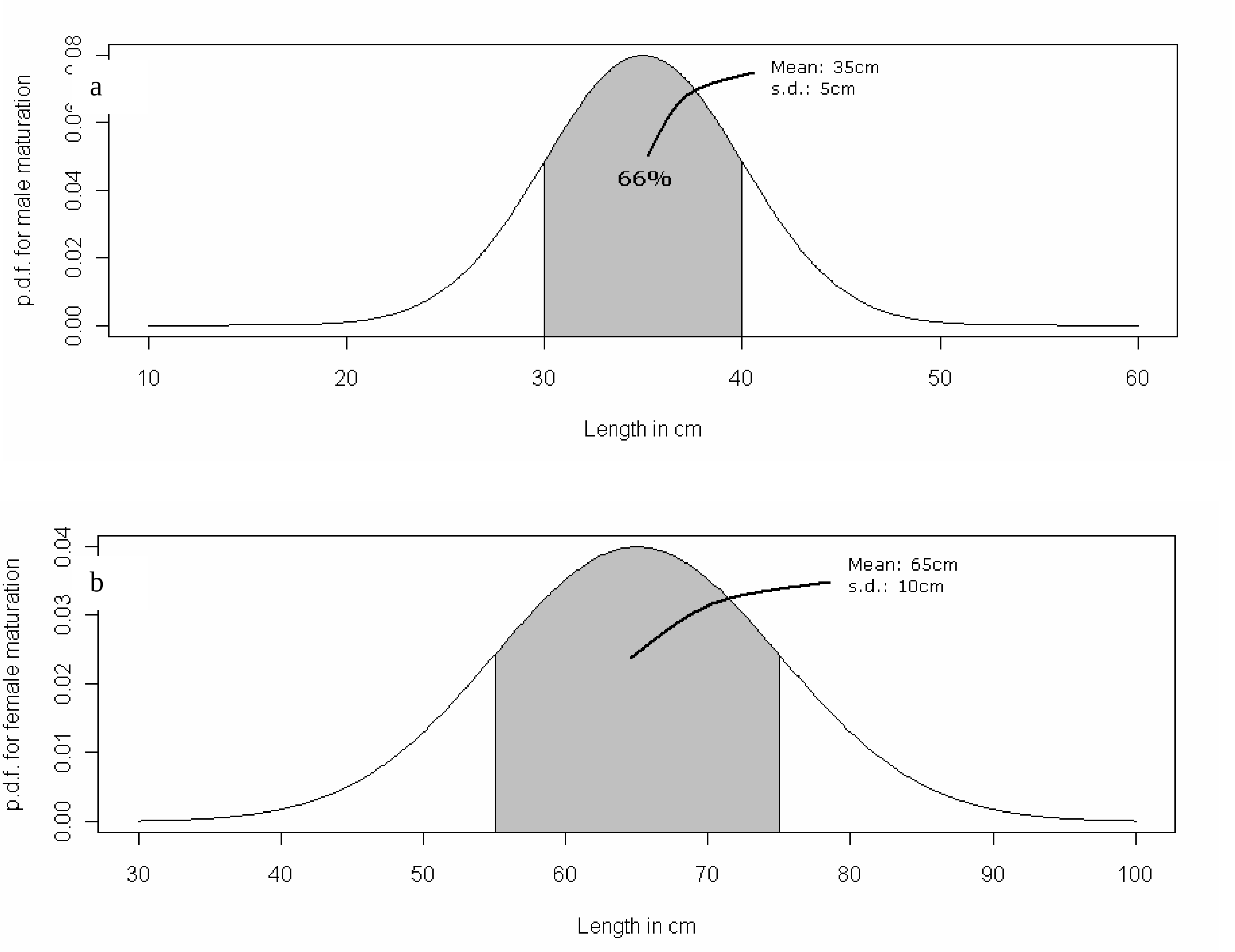


Figure 7.5. Probability density functions used to describe the length at which an eel becomes silver, for (a) male and (b) female eels

7.3.7. Silver Eel Biomass

A weight at length relationship is used to calculate silver eel escapement biomass. The formula used is described below and is based on weight at length data from several rivers around the UK (data from Defra-Kings, Environment Agency and Cefas).

$$\mathrm{Ln}(W) = \mathrm{Ln}(a) + \mathrm{Ln}(l)^{*}b \qquad (7.5)$$

Where l is in mm and weight is given in g, a and b are constants with values

$\mathrm{Ln}(a) = -7.0270$
$b = 3.1750$

The weight of eels in each age class is calculated using Eq. 8.5 and the mean length that corresponds to each age class which is calculated as:

$$\acute{L}a = (L_{a,\,lower} + L_{a,\,upper})/2 \qquad (7.6)$$

The weight at length relationship in Eq 8.5 is based on data from eels within river systems, and may not be representative of silver eels that have migrated back to the ocean. However, since the model assumes that eels migrate and leave the system as soon as silvering occurs, these discrepancies in silver weight will not affect the model outcome.

7.3.8. Use of smaller than annual time steps

Users can choose to shorten the time that each of the early age classes covers to less than one year, in order to better monitor any rapid changes in the dynamics of the population that can take place during the first years after stocking. In this case, Eq. 7.1 will continue to describe the number of eels in each age class that survive to the next age class, but the natural mortality that will be used for the calculation will not be represent the mortality that the population experiences in one year, but rather the natural mortality that the relevant population experiences in the length of time that each sub-age class covers. The information on the annual mortality at length that the user defines in the excel spreadsheet will still be used for the calculations.

7.3.9. Calculation of required number eels to stock

As described above, the model can be used to calculate the number of eels that one needs to stock on an annual basis to achieve a target productions of yellow or silver eels. The model allows the user to define that target either in terms of the number of yellow or silver eels, or in terms of silver eel biomass. The model assumes that the chosen target represents the size of yellow or silver population the user wants to achieve under equilibrium conditions. To determine the stocking requirements, ESAT uses an optimisation routine to iterate model runs until the results under equilibrium converge to the target number or biomass. A one-dimension minimisation algorithm is used which employs a combination of a ‘golden section’ search and success parabolic interpolation. The search is bounded by the upper and lower limits that are given by the user in the ***ESAT MAIN*** worksheet.

8. Model scenario testing

We have conducted scenario testing in order to assess how sensitive the model is to variations in the model processes (Sensitivity Analysis), and to demonstrate how managers would apply the model (Model Application). The methods and results of both are reported here.

8.1. Sensitivity Analysis

Preliminary testing revealed that the model outputs are sensitive to the choice of mortality values and growth rates. The model was tested under different scenarios about the mortality of a cohort of eels that is stocked and how quickly they can grow, to provide an indication of the effects that each of these parameters has on the number of silver eels that a single stocking event might produce.

The growth model used has been developed as part of our work for the Environment Agency (Developing life tables for eel populations in England and Wales), and is based on observed length-at-age data for eels sampled from six river basins around England and Wales: Wnion, Ellen, Colne & Blackwater, Gara & Start, Hull and Blyth (Bark, Knights &

Williams, unpublished data). Statistical analysis of these data for undifferentiated, and male and female yellow eels, and knowledge of the potential for biases associated with sampling methods and emigration profiles, has highlighted the benefits of using a linear growth function to describe average growth rates of eels in rivers of England and Wales (Apostolaki, Readdy-Smith, Walker & Godard, in prep). Building on that experience, the ESAT model incorporates an average growth rate function, but will also allow for alternative functions (linear or otherwise) if river-specific data are available.

As there is considerable variation between individual eels in the length-at-age data, we have chosen to apply two growth scenarios which reflect the lower and upper ranges of growth rates, i.e. low = 2.2 cm, and high = 5 cm per year.

It has been suggested that mortality decreases with increasing size of eels (De Leo and Gatto 1995; De Leo and Gatto 1996; Lambert and Rochard 2007). We assume that this applies equally to wild and stocked eels, and therefore, ESAT has been designed to allow varying mortality rates with increasing length of individuals. It is reasonable to assume that stocked eels suffer a relatively higher mortality for some period after stocking, as they are subject to the stresses of capture and transport, etc, and become accustomed to their new environment.

Although a small number of studies have estimated mortality rates of wild or stocked eels at various times during their continental growth phase (Bisgaard and Pederson 1991; Jessop 2000; Graynoth and Jellyman 2002), only one study has reported annual mortality rates for a year class of eels as they grow from elvers to silver eels (Berg *et al.* 1994). Other studies have reported ‘lifetime’, i.e. elver to silver eel, mortality rates for various year-class cohorts, ranging from 50% to 84% (Vollestad and Jonsson 1988; Lobon-Cervia *et al.* 1995; Lobon-Cervia and Iglesias 2008).

We have designed ESAT to incorporate changes in mortality rate over time, as this will mean that the model is resilient to new data. For model testing, however, we have simulated three scenarios based on mortality rates reported in the literature (Bisgaard and Pederson 1991; Berg and Jorgensen 1994; Roncarati *et al.* 1997; Jessop 2000).

Mortality 1: Annual instantaneous rate of mortality decreases linearly from 0.7 (Roncarati *et al.* 1997) to 0.2 as the eels grow from a length of 8 cm to 40 cm, then remains at 0.2 for larger fish(Bisgaard and Pederson 1991);

Mortality 2: Mortality decreases quickly from 0.7 at length of 8 cm to 0.35 at 15 cm, and to 0.2 at lengths of 40 cm, then remains at 0.2 for larger fish. Under this assumption, the mortality of eels of length 13 cm or greater is half that of eels of the same length under Mortality 1;

Mortality 3: Mortality decreases linearly from 0.9 (Berg and Jorgensen 1994; Jessop 2000) to 0.2 as eels grow from length of 8 cm to 40 cm, then remains at 0.2 for larger fish.

The model was applied to the following six mortality/growth scenarios:

Scenario 1	Mortality 1 + Low growth rate
Scenario 2	Mortality 1 + High growth rate
Scenario 3	Mortality 2 + Low growth rate
Scenario 4	Mortality 2 + High growth rate
Scenario 5	Mortality 3 + Low growth rate

Scenario 6 Mortality 3 + High growth rate

The scenarios were each tested against a single stocking event of 170,000 elvers (see later), in year 0 and average lengths of 6 to 7 cm. Each scenario was simulated over a number of years sufficient to allow all of the stocked eels to have left the 'system', either because they became silver eels or because they died. The results are presented in terms of the decline in numbers of yellow eels, and the cumulative production of silver eels over time.

As would be expected, lower mortality rates during the first few years after stocking resulted in higher production of silver eels under both low and high growth conditions. However, almost all (>99%) of the eels in the low growth scenarios died before they could become silver eels (Figure 8.1). In comparison, up to 8% of the stocked eels survived to become silver eels under the high growth rate conditions (Figure 8.2). In most cases the population disappeared from the system within 7-11 years after stocking, either because the eels died or left the system as silver eels. However, under Scenario 3 (low mortality and low growth), the stocked eels continued to produce silver eels for 20 years. All these ages are representative of the variety in silver eel age structures from UK rivers.

Figure 8.1. Simulations of yellow eel decline due to mortality or transformation/emigration of silver eels, and cumulative silver eel production for the three mortality scenarios (1-blue lines, 2-orange lines, 3-purple lines) under low growth conditions (Scenarios 1, 3 and 5, respectively). See text for full details of mortality scenarios.

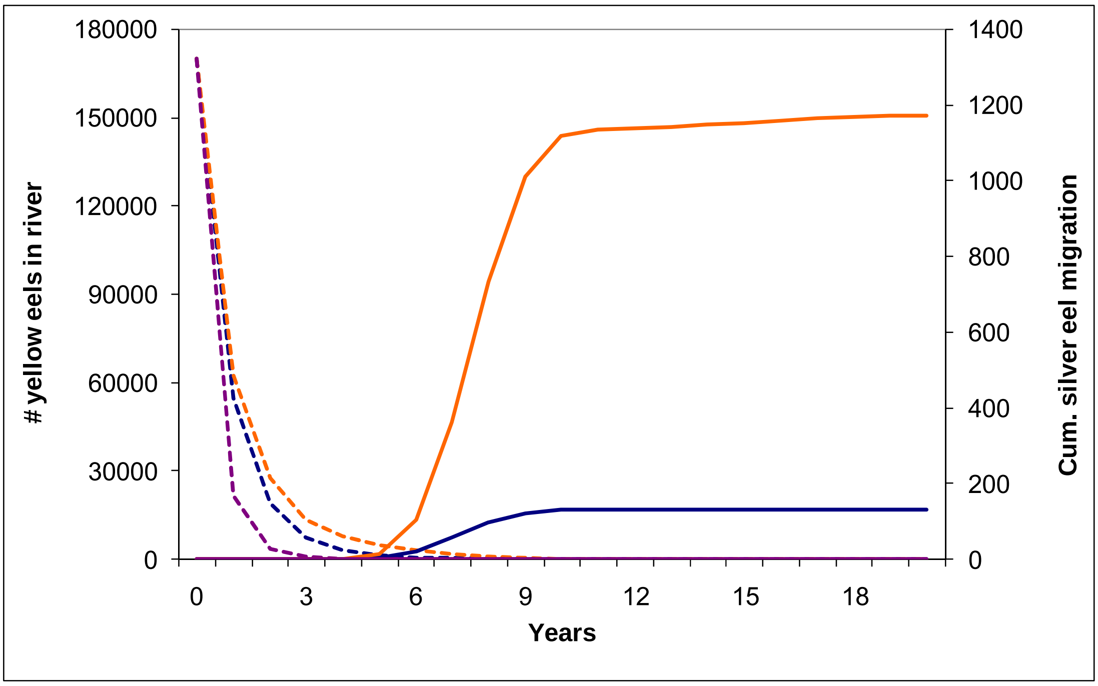
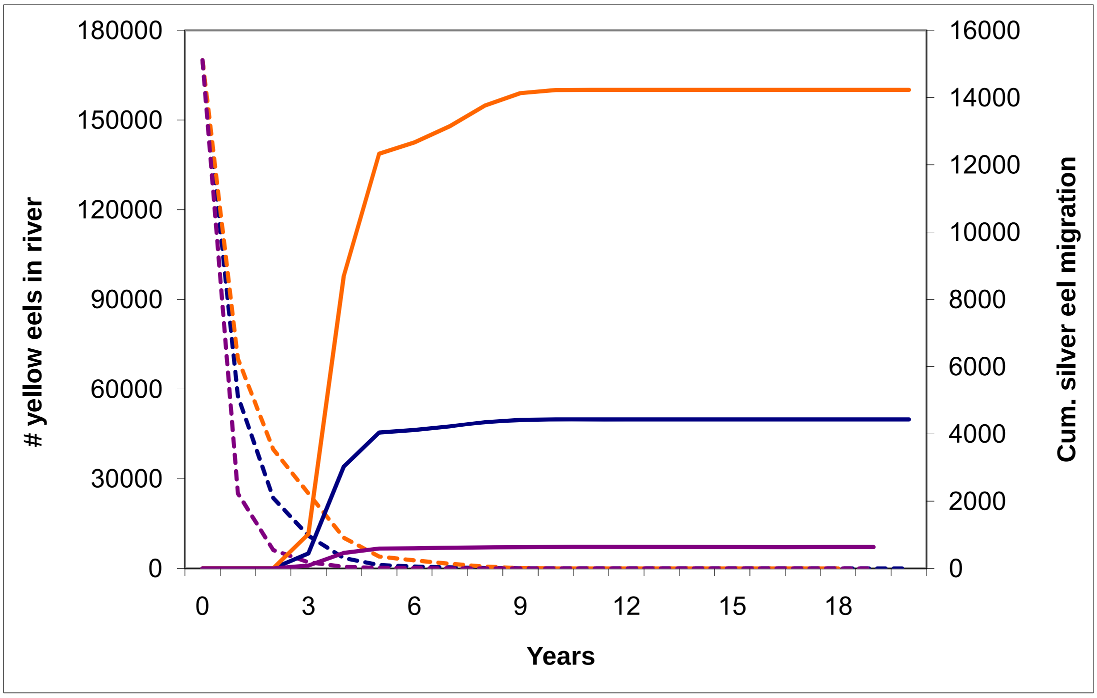


Figure 8.2. Simulations of yellow eel decline due to mortality and transformation/emigration of silver eels, and cumulative silver eel production for the three mortality scenarios (1-blue lines, 2-orange lines, 3-purple lines) under high growth conditions (Scenarios 2, 4, and 6, respectively). See text for full details of mortality scenarios (note the scale of the secondary y axis is different from than used in Figure 8.1).



Although growth and mortality rates are clearly important in determining the variation in silver eel production from a single stocking event, the results indicate that the model outputs are more sensitive to changes in growth rate than in mortality rate.

A comparison between the number of silver eels escaping under the two low growth rate Scenarios 1 and 3, shows that a decrease of 50% in the mortality of small eels (~13-20 cm) leads to an almost ten-fold increase in the number of silver eels produced under low growth conditions. Under high growth conditions, the difference is only 3-fold. In contrast, a similar reduction in the growth rate causes a 33-fold decrease in the silver eel production (e.g. Scenario 1 compared to Scenario 2).

The rate of growth in length is so important because it affects the mortality that an eel experiences at any given time (length). We have designed the model such that mortality tends to be higher at smaller lengths and becomes much lower as the eels grow longer. So, the longer time it takes for eels to grow in length, the higher is their cumulative mortality.

Clearly, changes in both parameters have significant effects on the model predictions. Some information on growth of wild eels in England and Wales is available to help us choose realistic values to describe growth in the model. However, this information also indicates that growth can be river-specific, so knowledge about the growth rates of eels in a specific river or region should not be used to describe eels in a different region without caution regarding the model outputs. Published information on mortality rates of wild or stocked eels is more limited and less easy to obtain than growth, which makes it less easy to choose realistic values for this parameter. Investigations of the potential of using anecdotal or qualitative information to formulate realistic assumptions about mortality might be the only solution in the short term, if such information exists.

8.2. Illustrations of model application

The key question for eel fishery managers contemplating stocking will be, "how many glass eel do I need to stock in order to achieve the required increased production of silver eels (or yellow eels)?"

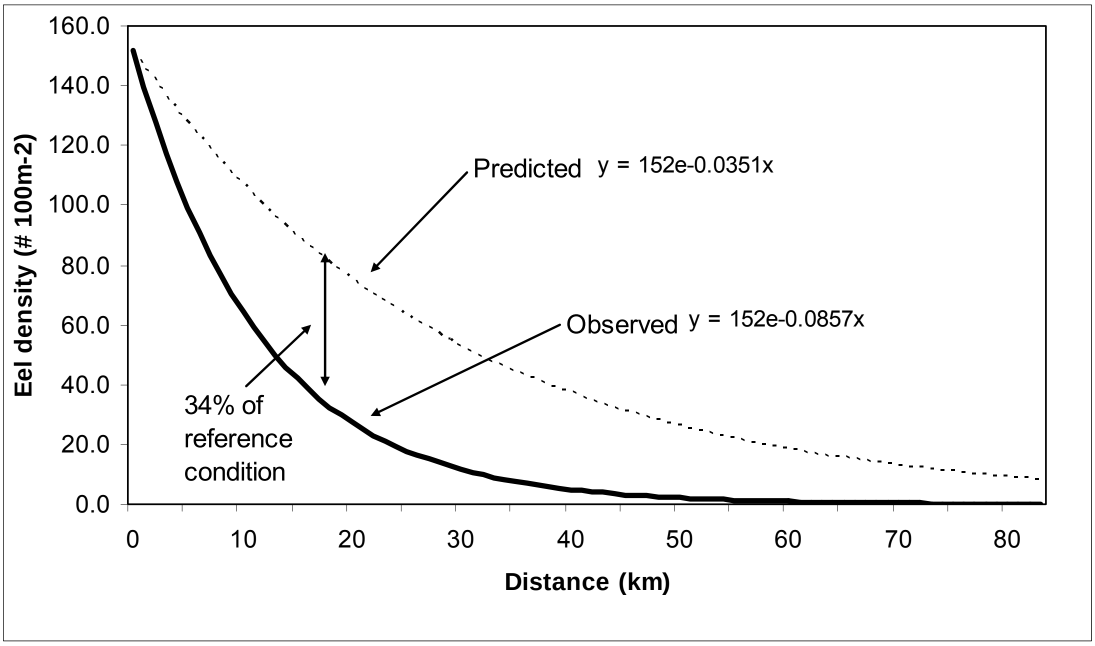
We have identified target rivers with which to trial ESAT, based on eel population data from previous Defra studies (Bark, Knights & Williams, unpublished data), and preliminary assessments of the additional eel production required to achieve the EU Regulation targets for these rivers. These assessments were made by the Environment Agency and reported in the UK EMPs that were submitted to the EU Commission in December 2008.

When this study was initiated, it was assumed that the EMP for any River Basin District not achieving its MT would include a target weight of silver eel production necessary to achieve compliance. However, the Agency does not yet have the methods to assess their river stocks in terms of silver eel production. Rather, the initial assessments in the published EMPs (give web-site) have been based on yellow eel density using the Reference Condition Model (RCM, see below), and assuming a linear relationship between yellow and silver eel status (Aprahamian *et al.* 2007).

In many rivers of England and Wales, the density of eel declines naturally with distance upstream from the estuary (Knights *et al.* 2001; Ibbotson *et al.* 2002). Data for 12 rivers surveyed in the 1970s and early 1980s have been used to create a model that predicts the yellow eel population (in terms of densities along the river) that would have been expected before the major decline in glass eel recruitment across Europe in 1983/84 (Aprahamian *et al.* 2007). The most significant factor explaining variation in density profile between rivers (assuming constant recruitment) was found to be river gradient. By plotting the upstream rate of decline in eel densities against the gradient for each of the 12 river catchments, it is possible to estimate the natural rate of decline for any river. This serves as the reference model. In its basic form, the RCM assumes that the habitat available upstream of the tidal limit is uniform. However, it can be weighted according to the amount of habitat available to eel at various distances from the tidal limit (due to barriers to migration, for example), in order to assess compliance with the 40% escapement target.

An example of the RCM assessment procedure is illustrated in the Figure 8.3, where the observed yellow eel population density (bold line) is calculated to be 34% of the reference condition (dotted line).

Figure 8.3. Application of RCM model to observed yellow eel density data (bold line) at various distances upstream from the tidal limit, and the predicted reference state of yellow eel densities (dotted line) obtained using the RCM. Adapted from Environment Agency Eel Management Plans, December 2008.

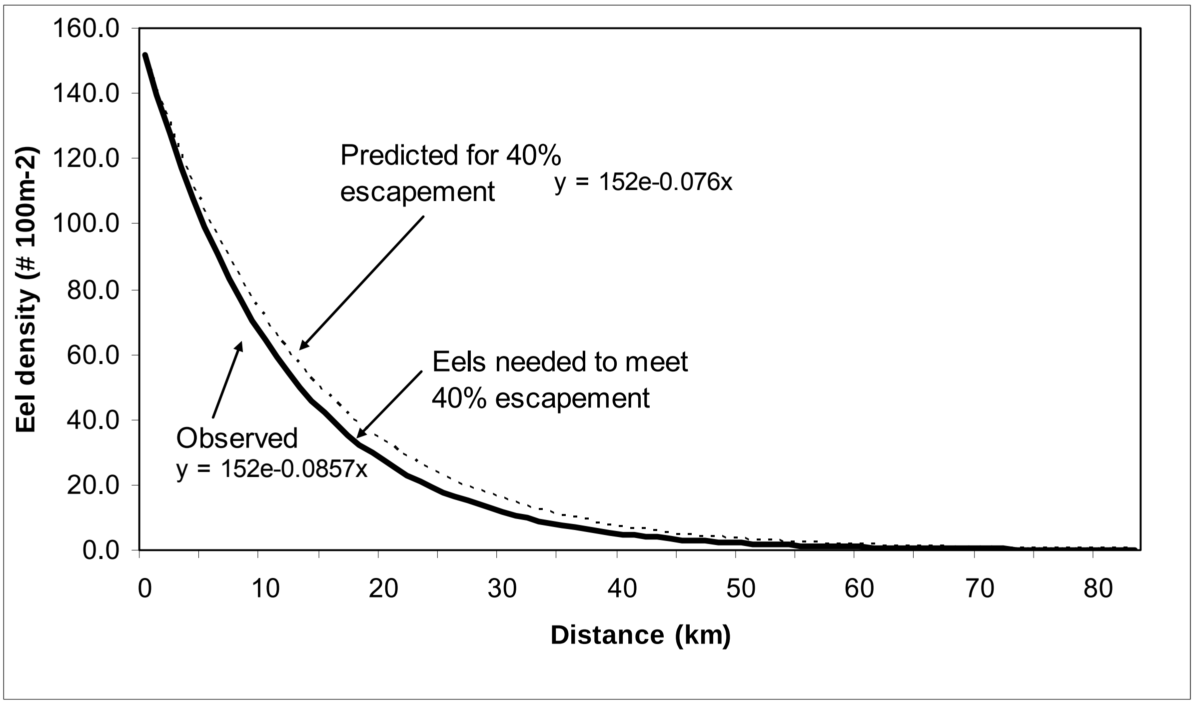


The area between the observed situation and the 40% surrogate target (i.e. 40% of RCM prediction, Figure 8.3) is the number of additional eels required to achieve compliance with the management target. These represent the total population, and are not necessarily distributed in relation to distance from the tidal limit. As a result, the stocking targets that we can use for this Scenario Testing part of this project are all expressed in terms of densities of yellow eels.

Cefas review of the UK EMPs provided six potential basins for testing stocking scenarios. Here, we report scenario testing based on the EMP target of 26,000 additional yellow eels.

As the Environment Agency density data are based on electric fishing surveys, and these are relatively inefficient for capturing small eels, we have assumed that the EMP target is for an increased production of eels > 20 cm in length. Therefore, we have included an option in the model output to report the total number of yellow eels > 20 cm in the ‘system’ in each year.

Figure 8.5. Use of the RCM model to derive yellow eel density targets for stocking, relative to the observed (bold, dotted line) and 40% reference (dotted line) profiles at various distances upstream from the tidal limit. Adapted from Environment Agency Eel Management Plans, December 2008.

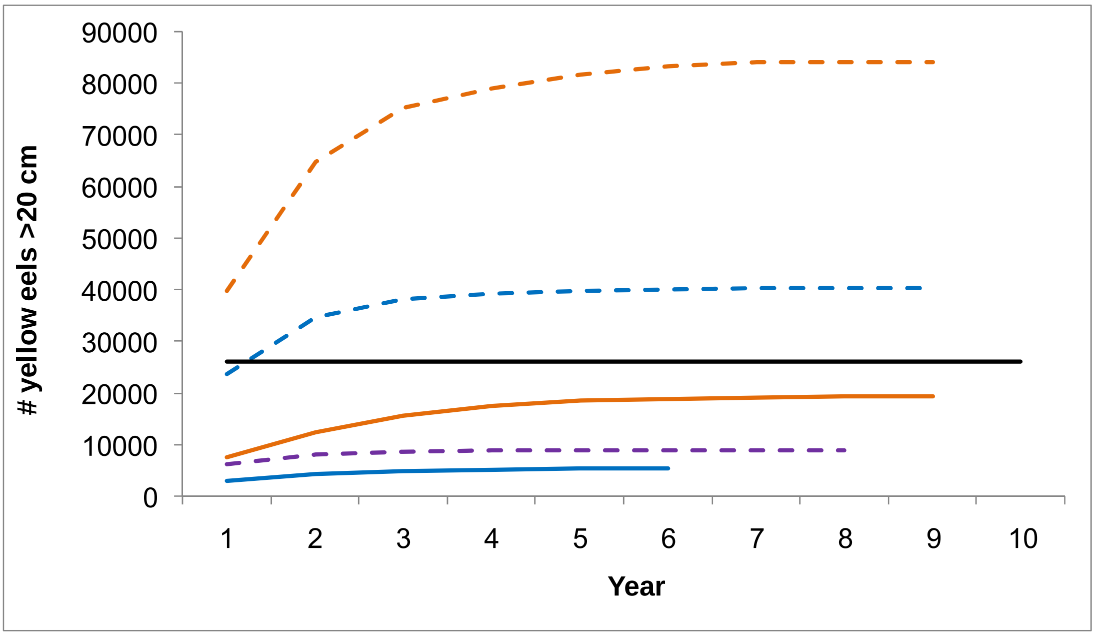


As the target is based on a range of lengths, and ages, of eels, we have assumed that stocking will be conducted every year. Simulating a single stocking event would be unrealistic because it would only produce a single cohort of eels in any one year, and therefore would overestimate the required quantities of stocked eel. As with the sensitivity analysis, above, we chose to simulate the stocking of 170,000 elvers per annum, which is based on the Agency's assumption of an 85% rate of mortality from elver to yellow eel.

We have run the model for sufficient lengths of time for the production of yellow eels at various ages to have reached a stable or equilibrium state, and applied each of the stocking scenarios listed above. The key output for comparisons is the number of yellow eels > 20 cm in the river in any particular year.

Two of the stocking scenarios (2 and 4) produced sufficient numbers of yellow eels to achieve the target (Figure 8.5). As noted above, growth rates significantly influenced this result, as these were both high growth scenarios. However, the highest mortality scenario resulted in a yellow eel production that was far short of the target.

Figure 8.6. Simulations of the production of yellow eel (> 20 cm) under high (dashed line) or low (solid line) growth conditions, and 3 mortality scenarios (1-blue, 2-orange, 3-purple). See text for full details of mortality scenarios. The black line represents the EMP target of 26,000 yellow eels. Note that the data for low growth/mortality 3 are not presented because these conditions resulted in fewer than 250 yellow eels.



While it would be possible and relatively simple to repeat the simulations with varying numbers of stocked eels, in order to establish the optimum number of stocked eels to achieve the target, a minimisation procedure within the model performs this function automatically. This runs backwards from the target (yellow or silver eels) to estimate the required number of stocked elvers.

9. Knowledge gaps and future research areas

A number of gaps in present knowledge have been highlighted in the text above, which limit the development and application of any quantitative modelling approach towards informing best practice in stocking eel for enhancement purposes. For purposes of clarity, a selection of these are grouped together and listed below:

- Density-dependent effects on eel production processes – both knowledge of the underlying effects and of the threshold densities above which these effects occur;

- Quantitative understanding of the factors driving sex determination, at the individual, site and populations levels, and comparisons between wild, stocked and aquaculture eels;

- Natural mortality rates across life stages and sizes of eel, the influence of the environment, and comparisons between rates for wild versus stocked eels in the same environment;

- What habitat and environmental factors influence eel production processes, and how do these effects vary between environments – what is productive potential and/or carrying capacity;

- Quantitative descriptions of eel production processes, based on robust amounts of data from within and between river basins, and environments.

In addition, there are several wider issues regarding information required for specific the application of ESAT to management of eel stocking in England and Wales, and these are briefly described below.

The use of the Reference Condition Model (Aprahamian *et al.* 2007), to estimate compliance with management targets in the Environment Agency's EMPs, requires the ESAT model to assess changes in yellow eel populations rather than silver eel escapement, as specified in the EC Regulation. However, we do not know the selectivity of the sampling gear being used by the EA to derive the RCM, and for surveys designed to post-evaluate the effectiveness of the stocking programme, and the model predictions. Research to estimate selectivity (by size) of eel sampling gear (both electric-fishing and fyke nets is indicated.

We have assumed that there are no density-dependent effects on eel production processes in the model, on the basis of uncertainties in the literature and presuming that stocking will mainly take place where the naturally recruited eel population is sparse or absent. Whilst this may continue to be difficult to include in a deliberately simple model, information on “threshold” densities to be avoided would be an important part of stocking best practice.

Though the model is intended for use as a predictive tool, it is important that every opportunity is taken to evaluate both the potential (with the model) and actual (by sampling) effects on yellow eel populations 2-5 years (say) after any stocking. This would enable managers to identify the parameters most in need of adjusting in the model, collect evidence that would enable this to be done with some confidence and, maybe, question the veracity of sampling techniques for eels (see 1, above).

The weight-at-length relationship is heavily biased towards measurements taken from yellow eels, whereas there are very few data available from silver eels. Personal observations suggest that silver eels have much greater muscle mass per unit length than yellow eels. As a consequence, silver eels may well be typically much heavier per unit length or age than yellow eels. Therefore, the weight-at-length relationship used in this present version of ESAT may underestimate the biomass of silver eels. Clearly, there is a need to collect length, weight and age data from representative samples of silver eel escaping from a number of rivers across England and Wales, in order to improve the accuracy of the modelled relationship.

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Annex 1. User Manual for ESAT

Eel Stocking Assessment Tool *(ESAT)*

User manual

Fisheries Challenge Fund project:
Developing guidelines for best practice in stocking eel for enhancement purposes

For use with model version 1.40

Developed by:
Joe Scutt Phillips, Panayiota Apostolaki, Mike Pawson & Alan Walker
Cefas Lowestoft
Fisheries Division

OVERVIEW

The Eel Stocking Assessment Tool (ESAT) has been designed to assist management of European eel (*Anguilla anguilla)* stocking programmes. It can be used to inform decisions on the number of glass eels (or older eels) that should be stocked in a river or basin annually in order to attain a given yellow eel population or silver eel escapement target. It also allows the user to explore changes in eel population structure and silver eel escapement under different stocking scenarios.

ESAT can be used to simulate the dynamics and production from either stocked or naturally recruited eels, separately or together. Given limited knowledge of the effects of density dependence on eel production processes, or of the density thresholds, the assumption inherent in this model is that the density of eels in the river remains at or below levels at which density-dependent effects on population processes are negligible. **Users should be aware of this assumption when designing eel stocking programmes in relation to management targets within Eel Management Plans (EMPs).**

ESAT uses an age-based stock dynamics model to simulate production through time, and allows users to modify inputs and parameters to suit the needs of their basins and EMPs. Default parameter values have been selected from an up-to-date literature review and stocking scenarios appropriate for England and Wales. These default values are based on our best knowledge at the time of writing (Section 6 of the Final Report). However, quantitative knowledge of some eel production process is very limited, and therefore, the model outputs should be viewed with caution. Furthermore, we recommend against users modifying model parameters except (1) where high quality, case-specific data are available, or (2) where the user is testing the sensitivity of the model to variation in parameter values.

A detailed description of the model is available in the Technical Manual. Constructed in MS-Excel®, ESAT uses the worksheet format to provide a user interface and show outputs. The model is implemented using Visual Basic for Applications (VBA), and embedded into the worksheets as VBA modules.

This document provides a guide to the use of ESAT and to help users understand the model that ESAT implements, so that it may be used appropriately and to the maximum benefit for decisions on stocking eels for enhancement purposes.

ESAT model overview

A detailed description of the model is available in the Technical Manual, and a critical review of the sources of default parameter values used in the model is provided in Section 6. Here we provide a brief description of the main assumptions and calculation blocks in the model used in ESAT.

The ESAT model is age-based, and moves forward temporally in yearly increments. Eels are divided into four distinct groups within the model, each based on important life stages: undifferentiated eels, male and female yellow eels, and silver eels. Undifferentiated eels are those that have not yet differentiated into either sex (as far as current understanding allows). Eels that the user might class as glass eels, elvers, and 'yellow' eels smaller than a particular length (default or user-defined), are all classed as undifferentiated within the model. Male and female yellow eels are those that have differentiated their sex, but they have not become silver. Silver eels have begun to mature and transformed into the "silver" stage, and are ready to leave the system. It is assumed that these eels migrate to the ocean in the same year that they silver.

Subsequent to initial, user-defined length at stocking, length is determined from age (i.e. time after stocking) by a growth function with variation to produce a length range for eels of a given age. These length ranges determine the level of eel mortality and when movement between life-stages occurs, and this allows the model to account for the fact that young, smaller eels have higher mortality than older, larger eels.

Each year, stocked eels are added within a certain length range. A proportion of all eels are removed based on mortality values found in the literature for differing length ranges. A proportion of the remaining eels then change their life-stage group, based on their individual lengths and current life-stage. Finally, those eels that become silver are removed from the system and the remaining eels are added to the age group one year above their present age for the next yearly step. This process is then repeated for each year until the model reaches its final iteration.

The processes of sex differentiation, silvering and escapement take place when the length of eel is within a specific range. Probability distributions are used to represent how likely it is for an eel to undergo each of these processes at a given length. The length ranges at which maturation begins and escapement occurs tend to be gender-specific, and so the model uses gender-specific probability distributions to describe these processes once sex differentiation has taken place.

Information in the literature indicates that the behaviour of eels and some biological processes may depend on eel density (numbers and/or biomass), and especially that high density levels may affect the role that key processes play in the dynamics of eels. However, very little is known about the quantitative effects of density on these processes, or on the threshold densities above which these effects occur. Therefore, and as this tool is for use in areas where yellow eel population is already well below 40% of that expected under "pristine" conditions (the management target), it is assumed that stocking density will have a limited effect on these processes and the quantitative formulae that have been used to describe them. The model, therefore, assumes that density-dependent effects do not take place in the habitats where stocking is planned.

ESAT is provided with parameters and inputs that have been selected from the literature, and stocking scenarios appropriate for England and Wales. The details and evidence for these values and assumptions are provided in the *Technical Manual*. These default values are based on our best knowledge at the time of writing, and the only input required from the user is information regarding the length range of stocked eels. However, different values for growth variance and sex determination ratios, for example, could be used if there is good evidence that these are more appropriate for local conditions. Growth itself can also be changed from the default general function provided with ESAT, to account for new or more river-specific data. In case of changing growth functions, the user would require some level of programming experience to modify the VBA modules of the model, and is recommended to ensure that the "new" values are actually more appropriate than the default values. Full details of these inputs and how to use the tool are provided in this *User Manual*.

The model can be used for either stocked or naturally recruited eels, separately or together. Running ESAT forwards with a given number of stocking events, produces an estimate of the yellow eel population and output of silver eels, spread over several years.

Running the model backwards will provide an estimate of the annual input of stocked eels required to produce a target yellow eel population or associated silver eel escapement. In the latter case, the estimation process aims first for the population or escapement to reach equilibrium, before the number of stocked eels needed to achieve the target is calculated. It is also assumed that biological processes such as growth, mortality and size/age at stage remain unchanged throughout the modelled time period (i.e. there is no scope for temporal variation in the quantitative description of these processes).

USER INTERFACE

ESAT is divided into four worksheets, each corresponding to different aspects or functions of the tool. As a MS-Excel® spreadsheet, inputs and outputs will be conserved between sessions whenever the file is saved. ESAT may, depending on your security settings, request permission to run macros. These macros drive the model that is embedded within the spreadsheet, and failure to allow them to run will result in ESAT failing to work properly (see *Troubleshooting*).

Note that this Manual has been written for users of MS-Excel 2003. The model will run in other versions of MS-Excel, but some of the Excel menu structures may be different.

The principal approach to using ESAT is to enter values into those cells that are coloured blue, green, or orange, whilst white cells contain outputs from the model. Parameters and inputs are changed by entering values into these coloured cells, and by selecting from the options check boxes within the worksheets. The function buttons that must be clicked, should values in these cells be changed, are also colour coded. So:

- Blue cells indicate inputs that require the model to be run again before affecting output;
- Green cells contain information that will require all the tables to be re-drawn and the model to be run again if they are changed;
- Orange cells are those that, when changed, update output instantly.

The different types of cell in the excel spreadsheet are represented in this Manual using the following font combinations:

- ***Worksheet name*** = italicised and bold;
- *<u>Box name</u>* = italicised and underscored;
- *Box contents* = italicised.

Note that, after new values have been entered into cells, the user must press enter or click away from the cell in order for Excel to register the change in cell value.

1. Using ESAT

The order of the **four worksheets within ESAT** has been arranged to ensure that all the appropriate parameters have been selected before a model run commences. These inputs and parameters are saved automatically between uses of ESAT, but to ensure that the tool is working correctly, users are recommended to adopt the procedure, and certainly each time ESAT is initiated (see *Troubleshooting*):

6. Within the ***Parameters*** worksheet

    7. Select the timescale (*Model Time*), and *Sub-year age class breakdown* (the user may configure the model to produce in-year outputs, for example to test against survey results several months after stocking), and other key parameters (see *Parameters*).

For circumstances where glass eel are to be stocked, and assuming that glass eel are all age 0, set the Upper Age of the Sub-year age class breakdown to 1 (model rules mean it cannot be 0).

    8. Then, click the *Draw Tables* button, and this will create a layout fitting to your requirements within the other sheets.

9. Change tab to the ***Inputs*** worksheet

    10. Select options regarding the length distribution of the stocked eels and other information about the population (see *Inputs*).

For circumstances where glass eel are to be stocked, and assuming that glass eel are all age 0, set the Proportion at Age 0 to be 1, and all subsequent proportions to be 0.

11. You are now ready to run the model and either:

    3a. Calculate stocking numbers in ***ESAT Main*** (see section 2), or

    3b. Project example stocking forwards from within ***Detailed Output*** (see section 5).

2. Worksheet: ESAT Main

The ***ESAT Main*** sheet is the first worksheet in the tool, and contains the key functions, inputs, and outputs. Once the user has configured the model appropriately (using the relevant cells in the ***Parameters*** and ***Inputs*** worksheets), then they will only need to provide a yellow eel population, silver eel escapement number or biomass target and this sheet will calculate the number of glass eels that one needs to stock annually to achieve the specified target.

The required eel targets are entered under the *TARGETS* menu:

- The *Yellow Eel Population* target represents the total number of yellow eels required once equilibrium has been reached in the population. The method and inputs used to calculate the proportion of the total eel population that constitute the sampled yellow eel sub-population are described below (see *Inputs (section 4)*).

- *Silver Eel Number* and *Silver Eel Biomass* refer to the annual target number or biomass (kg) of silver eel escapement, respectively.

To determine the stocking numbers required to meet the desired target, click on the appropriate check button in the *Stock Determination Functions* box, and then click the *Run Model – Determine Stocking (Backwards)* button.

The *OUTPUT* menu displays the number of eels that should be stocked annually to reach the given target. This value will also be automatically entered into every year in the *Total timescale data* table in the **Detailed Output** worksheet (see section 5). Note that the value will be that which was given after the last time the model was run, and if any parameters or options have been changed, then the output will not reflect this until the '*Run Model – Determine Stocking'* button is clicked again. Move this to section 5?

The *Minimisation Parameters* table contains parameter boundaries that must be defined, within which the model will search for the output required to produce the set target. The user does not necessarily need to modify the values that are provided for these boundaries in order to run the model. However, if the determined stocking number is equal or very close to either of the minimisation boundaries, then it is important to extend the range so as to ensure that the model is not restricted. Initially, the user may have no idea what this range is, but entering a very large range will only result in slower computation times. Restricting the range of these two parameters to somewhere near to the most likely value will increase the operating speed of the model.

3. Worksheet: *Parameters*

The ***Parameters*** worksheet contains all the parameters needed by the model, and information to configure the output tables. The user-defined parameters are described below. Once the values of these parameters are set, the user must click the *Parameter Functions Draw Tables* button to update the output tables.

The *Mortality* table displays the mortality values that are associated with length ranges. Each value marks the upper length of eel that will experience a given mortality. Thus, an upper length of 13 cm with a corresponding mortality of 1, means that all eels between the previous upper length and 13 cm will experience that mortality. These mortality values can be modified by the user, and both aggregated together or further divided to smaller length ranges. The values shown in this table correspond to annual mortality (units: yr^{-1}). For a more complete description of mortality and how it is used in ESAT, see the *Technical Manual*.

NOTE: Changing these mortality values has a great effect on system dynamics predicted by the model. Therefore, great care should be taken before editing this table, and only values for which there is good evidence should be used when ESAT outputs are used to assist management plans.

Life-stage Distributions contains the parameters that define the probability distributions ('pd') used in determining the proportion of eels that develop to various life-stages. A normal distribution is used to describe each of these developments. Each row corresponds to a life-stage development and contains values for the mean length in cm and the standard deviation, which describe the centre and spread of the distribution of probability. Figure A.1 gives an example of this kind of 'pd' distribution. If, after new studies, more specific data are established, then the user will be able change the parameters of these life-stage probability functions appropriately.

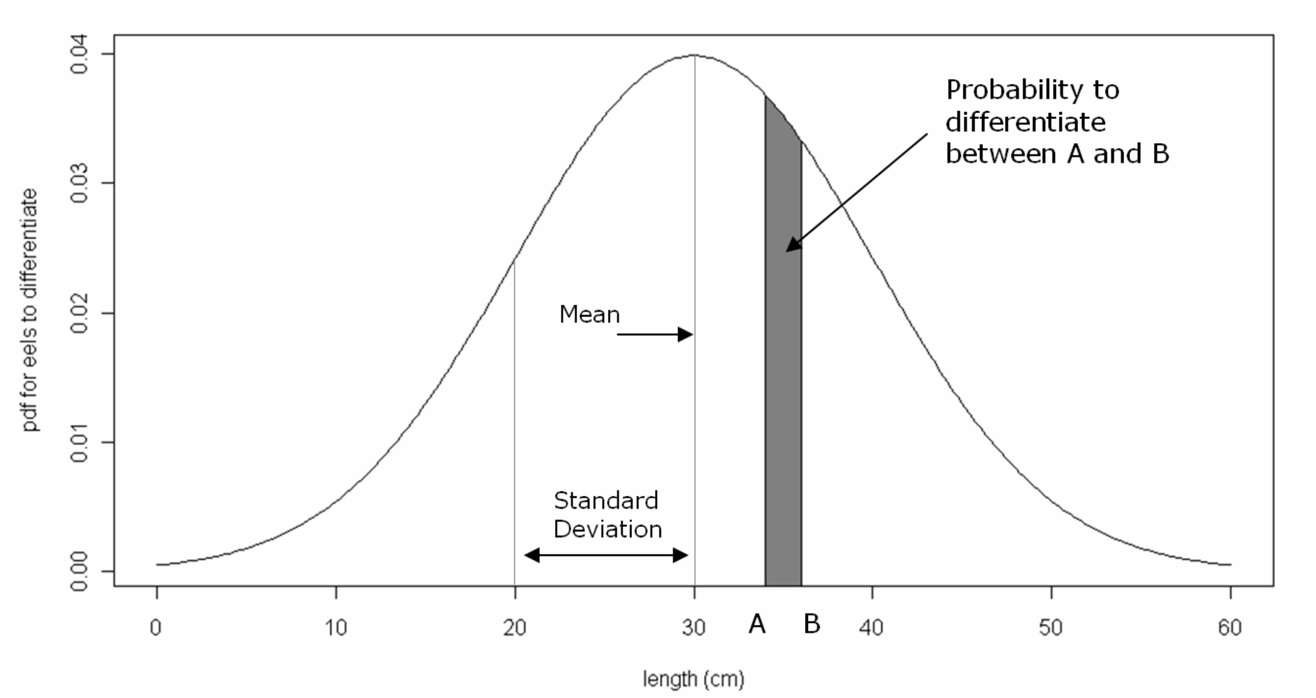

Figure A.1. An example of a normal probability function with mean of 30 cm, and standard deviation of 10 cm. The area under the curve between lengths A and B is the probability that an eel will develop into its new life-stage between those lengths, as shown by the shaded area.

Sex differentiation refers to the length at which an eel is first considered to be either male or female. Before this, eels are referred to as undifferentiated. So, the model requires information on the most probable length at which eels will differentiate (mean of the distribution), and also provide an estimate of the range of lengths at which eels could differentiate (in the form of a standard deviation). Default values have been supplied, but the user could use alternative values if appropriate. Once an eel has differentiated, its sex is determined by the sex ratio frequency function (see below).

The distribution for silvering eels describes the probability that a male or female eel will become silver at any given length. Males and females become silver at different length ranges, but for both it is assumed that, once an eel has become silver, it will migrate and leave the system in the same year. Again the model requires the Mean (cm) and Standard Deviation (cm) of the probability functions that represent this process for each gender.

For a complete description of the methods and assumptions used for life-stages in the model, see the *Technical Manual*.

The *Sex ratio frequency* is an inverse logistic function that gives the proportion of eels that differentiate at any length that would become male. The logistic curve takes its maximum value at the lowest allowable length and, through a mirrored, S-shaped curve, asymptotes to 0 with increasing length. In this way, most eels differentiating at a smaller length will become male, with this balance shifting in favour of females as length increases. However this balance can be changed by setting appropriate parameters.

In the *Sex ratio frequency* table, the *L50* value relates to the length at which the logistic curve inflexes and where the proportion of differentiating eels becoming either male or female is equal. The value of the *curve* determines the shape of the S-curve. For the full description and mathematics of the sex ratio logistic function, see the *Technical manual*.

ESAT enables the user to divide the early years of stocked eel into sub-year bins. This is configured using the *Sub-year age class breakdown* table. Yearly age classes (i.e. time after stocking) between *Lower Age* and *Upper Age* will be divided into the number of sub-year bins given by *No. of bins per year*. For example, a lower age of 0, upper age of 2 and a number of bins per year equal to 4, will result in the following sub-year breakdown:

0, 0.2, 0.4, 0.6, 0.8, 1, 1.2, 1.4, 1.6, 1.8, 2, 3, 4 ….. A -1, A

Where A is the final age class, defined within the adjacent *Age Classes* table. The maximum total number of age classes is 100.

Note: the *Lower Age* also represents the minimum age that the age-based model uses in the calculations.

The *Growth Variation* table describes the level of variation that will be applied to the results of the growth function used to describe eel length at age. The variation in the length (i.e. maximum and minimum length at age) calculated using the growth equation is found by multiplying the length by the *Lower* and *Upper Limit*. This means that setting both values to 1 will result in no variation between the lower and upper lengths that occur at a given age. The *Technical Manual* gives more information on how eel growth is modelled in ESAT.

Note: The range of lengths that each age bin covers are shown in worksheet ***Detailed Outputs*** in the *Age-Length Ranges* table.

Model Time sets the number of years that the model will run from the first stocking event (see ***Detailed Output***). The maximum timescale is 100 years.

4. Worksheet: *Inputs*

The ***Inputs*** page holds all the parameters regarding the stocked eel, any initial system stock estimates, and constraints for the yellow eel population. **Note** that the model will need to be run again (see ***ESAT Main*** or ***Detailed Output*** sections) if any values on this sheet are changed.

The *Initial System Stock* table can be used to enter the number of eels in each size or age class that are already present in the system. For each age bin, the number of estimated undifferentiated, male or female eels can be entered and included in the model at time 0. When these numbers are not provided, the system is assumed to be empty. If the user provides the number of eels that are already in the system, the model will add the newly stocked eels to the relevant part of the population and report the total number of eels in each age bin over time.

Two methods of determining the age of stocked eel are available in ESAT, and the details for each are found on this worksheet. There is also a *Stocking options* box, from which the user must select one of these options to be used in subsequent model runs: *Use age breakdown* or *length range to define stocked eel*. Using an age breakdown means that the proportion of stocked eel in each age class is explicitly given. Length range-defined stocking is when only the length range of the stocked eel is given to define the proportion of eels in each age class (bin).

In the event that the *Length Range* option has been selected to define the stocked eel ages, then a minimum and maximum length are set in the _Stocking Length Distribution_ table. ESAT will calculate the appropriate distribution of eels into age classes across this length range for all stocked eel, using the growth function and variation defined in the ***Parameters*** worksheet. Stocked eels are distributed to those age classes that most represent the length range defined by the user, ensuring that stocked eels are all a similar age class. **Note** that it is assumed that eel lengths are uniformly distributed across the defined length range.

If the *Age breakdown* option has been selected to define the stocked eels, then proportions must be entered next to each age class under the _Stocking Age Breakdown_ table (column entitled "*Proportions*"). This represents the proportions of each age class that will be present in any one stocking of glass eels, and must sum to 1 as checked at the bottom of the table.

The _Survey population_ table contains the value that defines the minimum length of eels that can be sampled effectively during post-evaluation surveys. This information is important because it allows the model to determine what part of the eel population will count against the set yellow eel target. **Note** that changing this variable can have great effects in determining stocking requirements, as it is directly responsible for the proportion of the total population of eels that are 'counted' by the estimation part of the calculations.

5a. Worksheet: *Detailed Output*

This worksheet contains more in-depth breakdowns of both total timescale eel data and specific year age breakdowns. It is also the sheet from which stocking events can be changed at the individual year level, and from where **the model can be run forwards to estimate the yellow eel population and output of silver eels**.

Total timescale data displays key information about the projected eel population across the model time that was set in ***Parameters***. Within the model, the *Time* years are integers beginning at t = 0 (first stocking), but in the total timescale data they are grounded by an actual year given in the orange _Start Year_ cell above the table. **Note** that in ESAT, all eels are stocked at the beginning of the year, but the information shown in _Total timescale data_ is data from the **end** of that year.

Restocked Eel displays the number of glass eel stocked for each year on each row. Once the _Determine stocking_ button (see ***ESAT Main*** section) has been clicked, the values in this column will be set to the determined annual stocking number to obtain a given yellow eel population or silver escapement target. However, these values can also be changed from year to year and the effects examined by running the model forwards (see **Running the model forwards** section below).

Yellow Eel Population refers to the number of eels that are considered yellow, as defined by the _Min survey length_ in ***Inputs*** worksheet. The *Total Eels in System* column is simply the total population in that year, including stocked glass eel (but not silver eels), and *Eel Mortality Over Year* is a count of the number of eels that have died from the total population over the course of the year. This value, plus the total population and all migrating silvers, is equal to the number of eels that were present at the beginning of the year after stocking. This number can be seen at the bottom of _Display Year Age Class Breakdown_ for that year (see below).

Male and *Female Silvers Migration* display the numbers of male and female eels that have silvered and left the system over the course of that year. Finally, *Cumulative Silvers* is a tally of the total number of silver eels migrating since the start year, and *Annual Silver Biomass* estimates the biomass that the total silver escapement from that year would produce (in kg). For more information about how this biomass is estimated, see the *Technical Manual*.

The total timescale data output from a particular model run can be quickly saved to a new sheet in ESAT by clicking the *Save total timescale data to new sheet* button. This will open a new worksheet and copy the results from the model run into it, along with the time and date for reference.

The table entitled *Display Year Age Classes Breakdown* is a useful indicator of the population dynamics within a single year. This table presents the numbers of eel in each individual age class at the start of a given year, as selected by the user in *Display Year*. The eels are further disaggregated into *Undifferentiated, Male, Female* and *Total Eels in System*. This table can be used to explore the actual age distribution of the population initially, as it approaches equilibrium, or the expected distribution after a stable population is estimated to been reached. To change the year that is displayed, enter the desired year into the orange cell marked *Display Year*.

This worksheet also contains a table marked *Age-length ranges*. This table holds the range of lengths that are associated with each age class, and is only a reference output. It will be affected by the age-class parameters and the growth variation, both of which are specified in the *Parameters* sheet. Note that the longer lengths are generated by the model, based on mathematical principles of the growth function, but it is understood that eels transform to the silver stage and emigrate to the sea before reaching such theoretical maximal lengths.

5b. Worksheet: *Detailed Output* - Running the model forwards

As well as determining the number of eels that need to be stocked to reach a given eel population and escapement targets, ESAT can also be run to explore the calculated population from given stocking numbers. By clicking the *Run Model – determine population (Forwards)* button, the values entered into the *Restocked Eel* column in *Total timescale data* will be used to project the model forwards and output the resulting population. **Note** that after a stocking determination model run has been made, subsequent population determination forward runs will give exactly the same output until the user changes some of these *Restocked eel* values from those generated by the stock determination run, or modifies any of the other parameters of the model, aside from some small changes due to rounding that may occur.

Using both stocking determination and population determination modes of ESAT can be a useful way of exploring different restocking options and timings, and generating interim stocking ‘targets’ which can be tested against during the process of post-evaluating the stocking programme.

6. Changing growth modelling in ESAT

Growth is modelled in ESAT using a growth function in a visual basic for applications (VBA) module. The details of this function are described in the technical manual, but here it is explained how the code can be modified to allow for a better growth function in the light of new data or research. Please note, however, that making changes to the parameters and functions provided with ESAT it is important to have both at least some understanding of programming in VBA, and well founded evidence with which to justify these changes.

Modules contain all of the functions and sub routines that run in ESAT. These code modules can be accessed by the Excel Tools > Macro > Visual Basic Editor menu, or pressing alt+F11 in the main Excel window. Within Module 2, locate the public function ‘getLengthFromAge’. This is the growth function that ESAT uses to predict lengths at age for all eels, and similarly to determine the ages of eels at a given length. ‘getLengthFromAge’ takes one parameter, age, as a variable of type double, and returns a double L, which is the length of the eel at age age. The length range for an eel of a given age is determined by multiplying this value L by the lower and upper coefficients that were specified in the ***Parameters*** worksheet, and this is performed in the functions ‘getLowerLengthFromAge’ and ‘getUpperLengthFromAge’ respectively. These two functions are located in Module 1.

The default, linear growth equation is given in the technical manual, but ‘getLengthFromAge’ also contains the non-linear equation in comments for reference purposes. When writing a new growth equation, be sure to comment out the default code and return the value of L in cm.

Troubleshooting

Issue	*Cause*	*To Solve:*
ESAT does not work. Cells contain no, or nonsense values, and clicking buttons has no effect	Macros have been disabled in Excel and so ESAT cannot run any of its code modules.	From within the Excel *Tools* menu, select *Macro* and then *Security…* Change the security level to low, or create a security exception for ESAT.
When I run the model from within ESAT, I get odd, unexpected or #VALUE! output in some cells.	Some parameters have not been set, or given inappropriate values.	Whilst there is some form validation in ESAT, it is still possible for unassigned or inappropriate variables to be used in the model. In this case, follow the three steps of entering information into ***Parameters*** and drawing the tables, completing the ***Inputs*** sheet (including re-selecting the desired stocking option), and then run the model again.
ESAT is not responding to changed parameters or values. It either does not seem to take them into account, or the buttons do not work straight away after I have entered a new value in a cell	The change of cell value has not been confirmed in Excel.	You may have entered some new values into cells, but you must press enter or click away from the cell in order for Excel to register the change in cell value.
When I copy values from a table, such as <u>*Total timescale data*</u>, and paste them to another sheet for further work or to create a graph, I get zeroes or #VALUE! in some of the cells.	Many of the cells in ESAT do not contain values, rather they contain calls to VBA functions that return a value to the cell. When these cells are copied, it is the function calls that are copied and subsequently may no longer work correctly in the new location.	Instead of pasting the values into your new area in the normal way, select *Paste Special…* from the Excel *Edit* menu. Then highlight the option marked *Values*, and click OK.

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Head office
Centre for Environment,
Fisheries & Aquaculture Science
Pakefield Road, Lowestoft,
Suffolk NR33 0HT UK

Tel **+44 (0) 1502 56 2244**
Fax **+44 (0) 1502 51 3865**
Web **www.cefas.co.uk**

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