Biology and Management of European Eel
(*Anguilla anguilla*, L) in the Shannon Estuary, Ireland

**Chapter 1**

Introduction
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1.1 Background to the current study

The European Eel (Anguilla anguilla, L.) is a fish of significant commercial and ecological importance (Sinah & Jones, 1975). It is one of only 15 native fishes present in Ireland’s freshwater ecosystems and is perhaps the most recognisable of all our fauna. In recent decades, this species has undergone a dramatic decline throughout its range (Moriarty, 1986a, 1996a, 1996b, 2000). This decline is threatening the long-term sustainability of European eel fisheries, including those on the River Shannon in Ireland (Moriarty & Dekker, 1997; McCarthy et al, 1998). The European Eel is a unique indicator of the environmental health and integrity of our oceans, estuaries and freshwaters, and its recent decline is seen as a serious environmental matter (Castonguay et al, 1994). This thesis focuses on eels in the River Shannon, and is particularly concerned with the biology and management of juvenile stocks.

The River Shannon is the largest river system in Ireland and has a catchment area of 11,700Km² above Limerick City. Including its estuary, the catchment area is 16,865 Km². The river has traditionally been regarded as an important river for eel fishing in Ireland (Went, 1974, McCarthy, 1994a). A hydroelectric scheme was constructed on the river during the period 1925-1929, and this impeded eel natural recruitment to 89% of the catchment area of the river. To mitigate this effect the Electricity Supply Board (ESB), who own and manage the fisheries of the River Shannon (O'Callaghan, 1999), has implemented a juvenile eel trapping and overland transport programme since 1959 (McCarthy, 1994a, Reynolds et al, 1994). A Borland fish-lift (Clay, 1995) was also constructed at this time to improve fish passage (O’Farrell et al, 1996). Although the stock enhancement measures were initially effective (Quigley & O’Brien, 1996), eel stocking levels progressively declined from the early 1980’s onwards mainly as a result of poor natural recruitment associated with the global decline of the species (McCarthy et al, 1994a).

From 1992 onwards, a major programme involving yellow and silver eel fishery development was funded by ESB (McCarthy et al 1994b; McCarthy et al 1994c; McCarthy et al, 1998). Moreover, a major effort has been made since this time to develop a comprehensive stock enhancement programme involving glass eels, elvers and fingerlings captured at numerous estuarine and downstream riverine locations (Reynolds et al, 1994, McCarthy et al, 1998). Experimental stockings of reared fingerlings and fingerlings collected by electrical fishing on the Lower Shannon have also taken place (McCarthy & Cullen, 1996).
In this thesis an intensive monitoring study of juvenile eel catches associated with the eel stock enhancement programme during the period March 1995 to April 1999 is described.

1.2 The European Eel

The European eel, *Anguilla anguilla* (L) is a native fish of Western Europe, the Middle East and North Africa. It is widely distributed in freshwater and brackish water environments, and occasionally occurs at marine sites. Its range extends from the Canary Islands and Morocco in the south-west to Iceland in the North. It is found throughout the Mediterranean Sea and its distribution extends west to the Azores. It is indigenous to Ireland and has been harvested here for many millennia. Archaeological evidence such as fishing spears has been found at several sites in Europe, including Ireland (Went, 1974, Aalen *et al*., 1997). Major, long established, commercial fisheries are still in operation on the Rivers Shannon, Corrib, Erne, and Bann/Lough Neagh (Went, 1950, McCarthy *et al*., 1994a). Curiously, despite the history of eel fisheries in Ireland and its popularity as a food fish elsewhere, local Irish people rarely consume it.

![Plate 1 The European eel.](image)

The European eel is a member of the genus *Anguilla*, a member of the order *Apodes* and the only genus in the freshwater family *Anguillidae* which includes 16 species, all but two of
which occur in the Indo-Pacific regions of the world (Tesh, 1977). It is closely related and almost identical in appearance to the North American eel, *Anguilla rostrata* Le Suer. The members of this group of fishes, in addition to their typically elongated, slender, snake like bodies, tend to have spineless fins and narrow heads that enable them to burrow in soft substrates and enter crevices. Eels are smooth skinned with a tough, durable integument, with small embedded scales. This contributes significantly to their ability to survive in a wide range of habitats. Mucus production and other attributes of the integument are important adaptations that enable eels to migrate feely between marine and freshwater environments. The gills, which are important in respiration, also play a major role in osmoregulation. Due to the small size of their scales, eels can also uptake oxygen through their integument. The proportion of respiration through the gills is approximately 40%, and that through the integument is about 60% (Usui, 1991). The mucus produced by the skin prevents dehydration while allowing subcutaneous respiration, facilitating eels to survive out of water for a significant time. The internal organization of the eel corresponds to that of other teleost fishes (Tesh, 1977).

**Plate 2** Diagram of the life cycle of the European eel (redrawn from White and Knights, 1994)

The life cycle of the European eel (table 1.1) has only been understood in relatively recent times, and recent advances in our understanding of this matter continue to be made (Volkaert et al, 2000). The discovery of the breeding grounds in the Sargasso Sea by Danish oceanographer Johannes Schmidt was one of the most significant steps forward in the understanding of its life history (Schmidt, 1922). The European eel is now known to exhibit a catadromous life history, reproducing in the Sargasso Sea 6,500Km away from Ireland, but feeding and growing in European brackish or fresh waters. The European eel uses a
reproductive strategy more typical of marine than freshwater fish, producing very large numbers of small ova that hatch into larvae that must feed and grow in the plankton before metamorphosing into the next life stage. High fecundity is necessary to compensate for variable and potentially high natural mortality during the oceanic, estuarine and freshwater stages. The European eel has until recently been considered a panmictic species, consisting of a single spawning population (Wirth & Bernatchez, 2001), although some hybridization with the American eel, *Anguilla rostrata*, was reported (Avise, 1990). However, recent investigations using analyses of highly polymorphic genetic markers (microsatellite DNA loci) have concluded that the genetic structure implies non-random mating and restrictive gene flow among eels from different sampled locations (Volkaert *et al*, 2000; Daemen *et al*, 2001). Volkaert *et al* (2000) have concluded that the continental life phases of the European eel include an introgressed Icelandic population, a central/northern population and possibly a southern population. Daemen *et al* (2001) reported that their analyses suggested close similarity between British and Irish glass eel populations, and weak differentiation among British/Irish, Atlantic Moroccan, Italian and Swedish Baltic populations respectively. Although Daemen *et al* (2001) point out the limitations in their data analysed to date, they concluded that the paradigm that the European eel constitutes a panmictic population is now difficult to maintain. Wirth & Bernatchez (2001) analysed 13 samples from the north Atlantic, the Baltic Sea and the Mediterranean Sea basins and found that there was global differentiation. They concluded that the genetic structure implied non-random mating and restricted gene flow among eels from different sampled locations, therefore refuting the hypothesis of panmixia.

The larval stage of the eel is called a ‘leptocephalus’. Eel larvae are carried by Ocean currents from the spawning grounds in the Sargasso Sea to the European/North African coast. The leptocephali increase in size as they undergo their transoceanic migration reaching approximately 45mm as they approach the coast of Europe (Fig 1.2). It was originally thought that the transoceanic migration of the leptocephali took three years (Schmidt, 1922). However it is now known that the journey period lasts around one year (Boetius & Harding, 1985a; Lecomte-Finiger & Yahyoui, 1989). On completion of their oceanic migration, the leptocepali metamorphose into transparent glass eels, which migrate towards and into estuaries using passive tidal transport (Deelder, 1970; Tesh, 1977). This metamorphosis is accompanied by a decrease in the length and girth of the body. A threshold temperature of about 4-6 °C is required to influence entry of glass eels to estuaries (Tesh, 1977). Glass eels have been recorded arriving on Irish shores from November onwards (McGovern and McCarthy, 1992).
Progression of glass eels through estuaries is thought to involve active tidal stream transport mechanisms with glass eels swimming in the upper layers during flood tide and keeping to the bottom during ebb tide (Creutzberg 1961; McCleave & Klecker, 1982; Gascuel, 1986). It has been widely reported that greater densities of eels are present in the water column during flood tides that coincide with dusk or darkness and that tide height and temperature are the main factors influencing the swimming behavior and vertical distribution of glass eels in the water column (Tesh, 1977; McCleave and Klecker, 1982; Moriarty, 1982). The relative predictability of glass eel movements is of considerable significance to continental commercial fishermen.

Plate 3 River Shannon elvers.

The estuarine migration stages of glass eels and the freshwater migration of elvers and older eels need to be considered separately. At the tidal head, tidal transport is less effective. This means that water temperature will have a relatively greater influence on recruitment. Tidal transport will be less efficient at high river discharges. This has important implications for recruitment of elvers to the tidal head of rivers, and their subsequent escapement or commercial interception. As the tidally assisted migration stage ends and before some will resume active migration into freshwater, glass eels need to feed and metamorphose into pigmented elvers (Tesh, 1977). Delays caused by high discharge and/or low temperatures may confine a glass eel cohort near the tidal head for extended periods, where they may suffer increased natural mortality (Jessop, 2000). McGovern and McCarthy (1992) noted
that elver ascent in the River Corrib system occurred when temperatures were greater than 11°C and it is generally thought that water temperatures in this range are required for active upstream glass eel/elver migrations. The upstream migration of elvers and small juveniles into river systems usually takes place in late spring and summer in countries such as Ireland, Britain, France, and Spain (Moriarty, 1986a; Naismith & Knights, 1988; Lara, 1994; White & Knights, 1994; Legault, 1996). This upstream movement is primarily influenced by water temperature (Tesh, 1977). It is known that water temperatures play a key role in regulating fish migrations (Banks, 1969; Jensen et al, 1986; Jonsson, 1991; Prignon et al, 1998). When the minimum temperature for eel migration is reached early in the season, the role of water temperature appears to be secondary to the influence of time of year (Baras et al, 1996; Moriarty, 1996a), and other environmental stimuli (Martin, 1995).

On entry into estuarine waters glass eels undergo several stages of pigmentation (Tesh, 1977, Ellie et al, 1982) after which they are called elvers. The successive development stages of the eel are given in table 1.2. Elvers migrate into European river systems, although some individuals remain in the estuarine and brackish waters and in some cases marine areas. The total distances traveled by the upstream migrating eels can be quite substantial. For example, elvers ascending the Rhine can reach the falls at Shaffhausen, about 1,000km from the estuary in a few months. The yellow eels establish themselves in rivers and lakes where they spend a number of years feeding and growing. As the eel is spawned in subtropical waters it prefers warmer waters if available, but the colder waters of northern Europe do not deter colonisation by eels. Eels are by nature burrowing creatures, and so prefer habitats where a suitable substrate is present. They are often found in significant numbers under bridges where crevices and rocks provide cover. Eels are generally nocturnal, active and feeding from dusk onwards (Helfman, 1986). They will eat a wide variety of food which generally depends largely on size and availability (Deelder, 1970). The activity of eels is related to temperature and eels become noticeably less active as water temperatures drop below 11°C (Tesch, 1977).

The temporal extent of the eel's freshwater life cycle phases varies greatly throughout the range of the species. Growth is affected by water temperature and in northern waters eels tend to be much slower growing and older than those in the warmer waters of more southern regions (Tesh, 1977). Boetius & Boetius (1967) established that the optimum temperature for metabolism of the European eel was 25°C to 26°C. In more southern waters, where these temperatures can occur for several months of the year, eels can attain lengths of 60 – 70cm in four to six years. In more northern regions where water temperatures may seldom exceed 20°C, lengths of 60-70cm may only be attained after as much as 15-20 years. Eels may attain quite advanced ages if migration upon maturity is prevented. The oldest age reached is reported to be 55 years, reached in a well in Denmark (Tesch, 1992).
Figure 2.1 Map of the Ireland with the location of the Shannon catchment and other hydrometric areas indicated.
The female sex is heterogametic in the case of the Anguilliformes (Wiberg, 1983). It is thought that this phenomenon may be a result of the influence of the environment on the phenotype of the eel rather than the genetic influence (Beeckman and Olievier, 1987; Colombo and Grandi, 1996; Roncarati et al, 1997). Although male and female eels can live together there is often a preponderance of one sex over the other. Where densities of eels are high (i.e. in the lower reaches of a river), males are often dominant. However, females often dominate lower density stocks deeper in the catchment. This has been shown for the Shannon catchment by McCarthy et al (1998). Parsons et al (1977) reported how changes in sex ratios appeared to be related to variations in stocking densities in Lough Neagh.

Towards the end of the feeding phase of the lifecycle, yellow eels mature and change into silver eels and commence the downstream and transoceanic, migratory phase in the eel lifecycle. Male silver eels are smaller, and generally younger, than female silver eels. In general silver male eels do not exceed 45cm in length, maturing at lengths above 30cm. Female eels generally do not change into silver eels at lengths less than 45cm. The sex ratio of male to female within the populations throughout Europe also varies, with some rivers supporting populations that are predominantly females, whereas other populations are predominated by males. During the transition to silver eels, yellow eels undergo both physiological and morphological changes. The most conspicuous of these changes is in the colour of the skin and pectoral fins (Tesch, 1992). The pectoral fins also become more lanceolate, the snout becomes narrower and more pointed and the eyes more enlarged. The skin and subcutaneous tissue increases in thickness due to fat accumulation. It is this high fat content which leads to the high commercial value of silver eels. Other changes include an increase in the number of clariform cells and the number of chloride cells in the gills. These increase the osmoregularity capacity of the eel facilitating the transition from fresh to salt water (Sinah and Jones, 1975).

The downstream migration of silver eels is well known. These migrations usually begin during autumn (Deelder, 1970, Tesch, 1977), and may last for several months. It is however possible to observe silver eels migrating somewhere during the whole year (Deelder, 1970). The greatest migration of silver eels generally coincides with the occurrence of the last lunar quarter (Deelder, 1970, Tesch, 1977). In the lower River Shannon silver eel migration appears to be more greatly influenced by flow and weather conditions, with greater numbers of eels migrating during stormy flood conditions, than by lunar phase (Cullen, 1994). Other environmental factors, which are thought to have an influence of silver eel migrations, include temperature and wind, with high winds in the direction of a lake outlet increasing the migration rate out of the lake (Frost, 1950; Sinah & Jones, 1975; Moriarty, 1990). The migratory routes taken and behavior of silver eels at sea has not been
documented in any detail. Silver eels are captured frequently at locations where they become concentrated due to the effects of coastal outlines. Records of silver eels from the deep sea are even more sporadic, but are sometimes reported from the stomachs of marine species. The spawning area for silver eels is the Sargasso Sea and eels are presumed to die after spawning (Tesh, 1977).

In recent years, European eel stocks have undergone a dramatic decline throughout the range of the species (Moriarty, 1996a & b). This is threatening the sustainability of eel fisheries such as those on the River Shannon. The cause of this decline is unknown but is thought to include factors such as the following; Climate change, changes in oceanic conditions, over fishing, habitat loss, introduction of exotic parasites such as Anguillicola, pollution, changes in the food supply for larvae stages, and barriers to migration. Factors affecting recruitment could be exerting effects on one or a combination of the stages of the unique catadromous life cycle of the European eel, i.e. reproductive success in the Sargasso Sea; trans-oceanic migration of leptocéphali; metamorphosis to glass eels on the continental shelf; initial recruitment to estuaries and freshwaters; migration deeper into freshwaters; yellow eel growth stages; downstream migration of silver phase eel; trans-oceanic migration of mature silver eel to Sargasso sea. Recent advances in the knowledge of the genetics of eel populations have raised concerns for the conservation of the species (Volkaert et al, 2000).

1.2.1 Glass eel and elver fishing in Ireland

Rivers with significant glass eel/elver fishing potential have estuaries with some or all of the following characteristics; Narrow physical nature; Physical barrier(s) in the vicinity of tidal head; Large freshwater discharge; Large range local tidal stream; and are relatively unpolluted (McCarthy et al, 1994a). Fishing for pigmented elvers in freshwater using a variety of fixed traps and, in some cases, active hand netting has been carried out since at least the 1950’s (McCarthy et al, 1994a). This harvesting has been carried out mainly on the Rivers Shannon and Erne by ESB, and on the Lower Bann. There is no history of glass eel fishing in Ireland prior to 1993, although since this time experimental glass eel fishing has been carried out in the Shannon, Erne and Bann (Mathews et al, 2001). Although some limited transfer of elvers has occurred, it is clear that prior to the 1990’s, elver harvesting in general was only carried out on rivers where statutory obligations regarding fish passage applied (i.e. ESB dams), and areas with considerable potential were not developed due to the non existence of significant within catchment yellow and silver eel fisheries, and the non existence of a glass eel/elver internal or export trade in Ireland.
Although ESB was engaged in elver harvesting since 1959, records for Ardnacusha and Parteen are available only since 1979. Records for the period 1959-76 are patchy and only the final estimated number/weight of juvenile eels stocked into the Shannon Lakes is recorded. McCarthy et al (1994a) reports that calculations of the relationship between weight and numbers of juvenile eels recorded was not carried out on a regular basis.

1.2.2 The Future of the Irish Eel Fishing Industry

A marketing report on Irish eels was recently prepared by Anon (1999). This report assessed the current trends in the European Eel market and recommended the future strategy for expansion of Irish eel exports. However, eel prices have fallen drastically in recent years due mainly to increased production from aquaculture units in Europe and Asia and it is now proposed that there is a need to process wild eel catches in Ireland to provide value added products in the future. The supply of glass eel for ranching and aquaculture in Ireland is currently limited due to the existence of legislation preventing the development of glass eel fisheries. This shortage of restocking material is currently restricting the development of Irish Eel Fisheries (McCarthy et al, 1994b, McCarthy et al, 1998).

1.3 Estuaries

1.3.1 European Estuaries and Fish Conservation

The definition of an estuary as adopted by the Habitats Committee on 25 April 1996 under the Habitats and Species Directive (European Council Directive, 1992 (92/43/EEC) is given as ‘Downstream part of a river valley subject to the tide and extending from the limit of brackish waters. River estuaries are coastal inlets where, unlike ‘large shallow inlets and bays’ there is generally a substantial freshwater influence. The mixing of freshwater and seawater and the reduced current flows in the shelter of the estuary lead to deposition of fine sediments, often forming extensive intertidal sand and mud flats. Where the tidal currents are faster than flood tides, most sediments deposit to form a delta at the mouth of the estuary’ (Romao, 1996).

Estuaries have long been regarded as important sites for fish, both as nursery and over-wintering sites, migration routes and areas which naturally support large numbers of fish (Elliot & Hemingway, 2002). However, severe anthropogenic impacts on the fish and fish habitat of estuaries have occurred throughout the world, particularly during the last 100 years (Elliot et al, 1988). These impacts include canalization, riparian drainage, pollution, barraging, water abstractions, and over fishing. Estuaries are regions where marine and
diadromous fish are in intensive contact with anthropogenic water pollution and other forms of environmental degradation. This is of particular importance for sensitive juvenile fish in the estuarine environment, such as the glass eel stage of the European Eel. Ireland contains 4.7% (871 km\(^2\)) of the estuarine habitat of Western Europe (Davidson et al., 1991). This is much lower than that in Britain (28.5%), Germany (20.4%), Netherlands (17.1%) and France (14.7%) but similar to Spain (5.7%) and more than Portugal (3.4%). Estuaries consist of a complex continuum of many distinct habitat types with physical, biological and chemical interrelationships. Pihl et al. (2002) lists nine estuarine habitats in Europe that are used by fish. These are; Tidal freshwater; Reed Beds; Saltmarsh; Intertidal soft substratum; Intertidal hard substratum; Subtidal soft substratum; Subtidal hard substratum; Subtidal sea grass beds (subtidal vegetated habitats), and Biogenic reefs.

The pelagic part of the water column is considered to be a component of each of the above habitats. The extent and location of each of these habitat types has not been quantified for estuaries in Ireland. Nor has the utilization of these habitats by migrating (glass eels and silver eels) and resident yellow eels been investigated in detail to date. In recent decades, there is an increasing focus on the protection, conservation and surveillance of estuaries. To this end, studies such as the current investigation, increase our knowledge of the requirements of estuarine fish and provide information which will assist in the development of estuaries as a habitat and biological sustainable resource.

1.3.2 Tides and tidal currents

Tides are caused by the gravitational pull of the moon and the sun, which act on the world's oceans (Brown et al., 1997). As the earth rotates, a tidal wave moves around it. The moon, being nearer, provides most of the energy input driving the tides, so the frequency at which tides rise and fall at any one point on the earth relates primarily to the position of the point in relation to the moon. The net result is that in a period of 24 hrs and 51 minutes, a fixed point experiences two high tides and two low tides (i.e. tides occur roughly twice each day but are later each day by a period of 51 mins).

The height that the ocean rises and falls over a tidal cycle (the tidal range) varies significantly due to its dependence upon the relative position of the earth, moon and sun. When all three are lined up, the tidal range is largest and these tides are termed ‘Spring Tides’. When the forces exerted by the moon and the sun are in opposition tidal range is low and ‘Neap Tides’ occur. The tidal range is also dependent on the physical nature of a coast. Tides in the open sea do not usually have a range of >2.5m, however in funnel shaped estuaries such as the Bay of Fundy in North America, and the Severn in southwest England,
the tidal amplitude can be greatly magnified by the natural resonance period of the inlets (Little, 2000). The Shannon estuary is also funnel shaped and this results in a relatively high tidal range in this estuary. As tidal range increases, higher volumes of water move into and out of areas such as estuaries, so that tidal currents increase. Flood tide currents produced as the tide rises are usually stronger than those when the tide falls (ebb tide currents). Glass eels exploit this feature of tides and move up estuaries using selective tidal transport mechanisms (McCleave & Klecker, 1982).

1.4 Objectives of this study

The principle aim of this study is to improve the understanding of juvenile eels in the Shannon estuary area, through an assessment of estuarine glass eel immigration and upstream riverine migrations of elvers. Ancillary appraisals of bycatch, trapping methods, fishway passage efficiencies, electrical fishing, and predator-prey interactions will also be undertaken. The study will review the study area of the River Shannon, and provide a description of the Shannon hydroelectric scheme. Historical elver and juvenile catch data for the period 1959-1994 will be considered and will be used to set the context for the current investigations.

Plate 4 Parteen Regulating Weir on the Lower River Shannon.