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Research on migratory salmonids, eels and freshwater fish stocks and fisheries

A summary of research undertaken under the Department for Environment, Food and Rural Affairs (Defra) Salmon and Freshwater Fisheries Programme between 1990 and 2002

E.C.E. Potter and P.J. Dare

Science Series
Technical Report No. 119

CENTRE FOR ENVIRONMENT, FISHERIES AND
AQUACULTURE SCIENCE

SCIENCE SERIES TECHNICAL REPORT
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Defra Contract: SF0242

LOWESTOFT
2003

This report should be cited as: Research on migratory salmonids, eel and freshwater fish stocks and fisheries. Sci. Ser. Tech Rep., CEFAS Lowestoft, 119: 64pp.

Acknowledgement:
The authors would like to thank the various contractors who provided information and illustrations relating to the projects described in this report. We are also very grateful to Denis Glasscock, Irene Gooch and David Riches for their patience and attention to detail in preparing the camera-ready copy.

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1. INTRODUCTION

1.1 Sustainability of fisheries and ecosystems

Throughout their lives fish are exposed to a wide range of pressures from natural environmental factors and human activities. Understanding how these affect fish populations is fundamental to controlling their impacts and maintaining sustainable fisheries which, where appropriate, can support commercial and recreational exploitation. Salmonid species, in particular, require near-pristine freshwater conditions and are therefore important indicators of environmental quality. However, different species can be affected in a variety of ways by activities which directly or indirectly change the physical or chemical environment; thus, while salmonids require clean river gravel in which to bury their eggs, other species may depend upon good marginal weed growth for this life stage.

Inevitably we have greatest concern for factors which cause major losses or prevent the access of fish to important parts of their habitat. However, there is growing evidence that fish are affected in a range of more subtle ways. For example, some chemical contaminants have sub-lethal effects which impair communications between individuals by means of pheromones and thus affect their ability to breed. Furthermore, there are growing concerns about the wide range of factors which independently may have minor effects on fish but when operating in concert may have more serious consequences.

Migratory salmonids, Atlantic salmon (*Salmo salar*) and sea trout (*Salmo trutta*), and eels (*Anguilla anguilla*) have complex life-cycles, spending parts of the lives in freshwater and parts in the sea (see Sections 2 and 10). This increases the range of factors which impinge on stocks; furthermore, factors operating in freshwater may affect subsequent survival in the sea, or vice versa. Understanding the processes operating in the sea presents particular problems, and these are of particular concern because changes in the marine environmental are thought to have been partly responsible for the marked decline in returns of salmon and in the production of young eels in recent decades. While many of these factors may be difficult to modify or control, it is important to understand their effects so that appropriate management actions can be taken wherever possible.

1.2 Management of salmonid stocks

Stocks of Atlantic salmon have declined appreciably throughout much of their range during the last 30 years. In England and Wales, there has been an overall decline in salmon numbers (Figure 1.1) despite significant improvements in areas such as south Wales and north-east England where a number of river stocks are recovering following the removal of pollution or obstructions. Much of the decline has been due to falling numbers of multi-sea-winter fish, the most valuable component of the stock.

The Department for Environment, Food and Rural Affairs (Defra), or the Welsh Assembly Government (WAG) in Wales, and the Environment Agency (EA) each have roles in the monitoring and assessment of salmonid

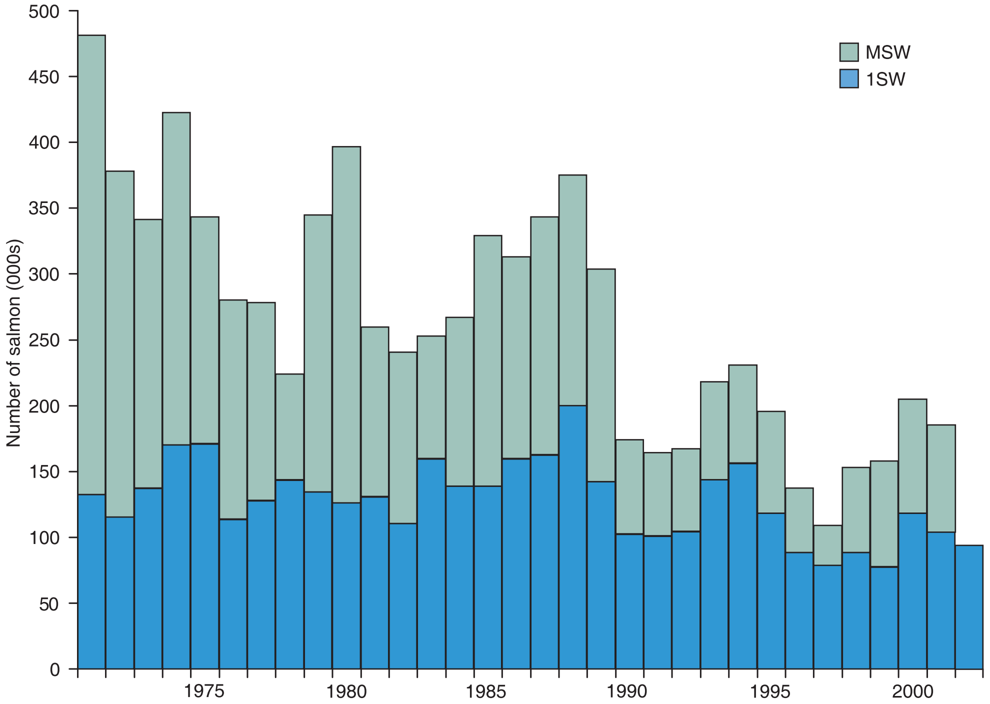

Figure 1.1 Estimated pre-fishery abundance of potential one sea-winter (1SW) and multi-sea-winter (MSW) salmon of English and Welsh origin between 1971-2000 based upon run-construction modelling. (note: MSW estimates not available for 2002) (Source: CEFAS)

and freshwater fish stocks and the management of their fisheries. Defra and WAG have overall responsibility for salmonid and freshwater fisheries within their areas of jurisdiction. They are jointly responsible for setting the statutory framework under which salmonid stocks and fisheries are managed, and the Secretaries of State have statutory responsibilities to consider the acceptability of all new fishery regulations and fishing licence duties proposed by the EA. The UK also has obligations to the European Union in this area, for example in relation to the European Habitats Directive, and in bodies such as the North Atlantic Salmon Conservation Organisation (NASCO) and the International Council for the Exploration of the Sea (ICES), to protect salmon stocks and to contribute to their management in international waters. Defra takes the lead on these matters, seeking support from the EA as appropriate.

Defra, together with WAG, works closely with the EA on the management of these fisheries and in the organisation of underpinning research, which is undertaken to support the formulation of policy and the development of advice that enables the government to carry out its statutory duties. Regular meetings are held between Defra and the EA on research priorities, and discussions are also held with the Scottish Executive, Environment and Rural Affairs Department (SEERAD) and the Department of Agriculture and Rural Development for Northern Ireland (DARDNI) on research issues relating to the UK's international and EU responsibilities. Defra has concentrated primarily upon funding research on issues related to its management obligations for salmon and sea trout at regional, national and international levels. A wide range of research projects on these two high-profile species is commissioned both internally, at the Centre for Environment, Fisheries and Aquaculture Science (CEFAS), and by extra-mural contracts to other institutes and organisations, particularly where they possess specialist skills in particular research areas. A small number of projects has been funded on non-salmonid species, most notably the eel, whereas most research on coarse fish species in England and Wales is funded by the EA.

1.3 Economic importance

Salmon and freshwater fisheries make major economic, social and recreational contributions within England and Wales, and some rural areas rely heavily on income from these fisheries. Two measures of this contribution are the capital value of the fisheries and the annual expenditure that they generate.

Salmon and sea trout stocks in England and Wales support recreational and commercial fisheries in rivers, estuaries and coastal waters that have a capital value of about £130 million (2001 figures), while recreational fisheries for non-migratory trout are valued at over £600 million. Eels also support commercial fisheries that, to a lesser extent, can be of importance to local rural communities; the value of these fisheries, mostly for export, has declined in recent years from £5 million in 1997/98 to around £1 million. Freshwater coarse fish species, on the other hand, are exploited almost entirely by recreational fisheries, which are estimated to have a capital value of about £2.3 billion.

Angling remains one of the most popular recreational activities in the UK, and the total annual expenditure by freshwater anglers on related goods and services in England and Wales is estimated to be around £2.5 billion, of which £545 million is spent by game anglers (2001 figures). British salmon stocks can also contribute to fisheries off West Greenland, around the Faroe Islands, and in the coastal waters of neighbouring countries.

1.4 Research areas

The commercial, recreational and ecological importance of salmonids, coupled with recent stock declines and the threats to their populations in many UK waters, have been the stimuli for research programmes commissioned and funded by MAFF (prior to June 2001) and (since June 2001) Defra. (Throughout this report we refer to these all as 'Defra' projects). The principal aims have been to improve our understanding of the biology of freshwater fish and assess anthropogenic impacts upon them. Although much of the research has been directed at salmonids, the programme is co-ordinated with that of the EA who take greater responsibility for studies of coarse fish species.

This report provides an overview of the 40 research projects (33 completed and 7 in progress) undertaken during the period 1990-2002. Information is also provided on a further two projects which are due to start shortly. Project codes and administrative details such as duration, costs and contractors are given in Annex 1. Contractors' names are those in current use; recent changes to institute names are explained in the glossary of technical terms and acronyms which forms Annex 2. The locations of the major field study sites where experimental work has been conducted are shown in Figure 1.2.

The research programme falls under the following main headings as described in the following sections:

- Freshwater ecology of juvenile salmonids
- Management of salmonid freshwater habitats
- Marine ecology of migratory salmonids
- Salmonid olfactory behaviour
- Sub-lethal effects of pollutants on salmonids
- Salmonid migratory behaviour
- Salmonid population genetics
- Assessing salmonid stocks
- Eels and coarse fish

This research supports Defra and EA responsibilities to promote conservation and management of salmonid, eel and freshwater fish stocks together with the riverine environments of England and Wales.

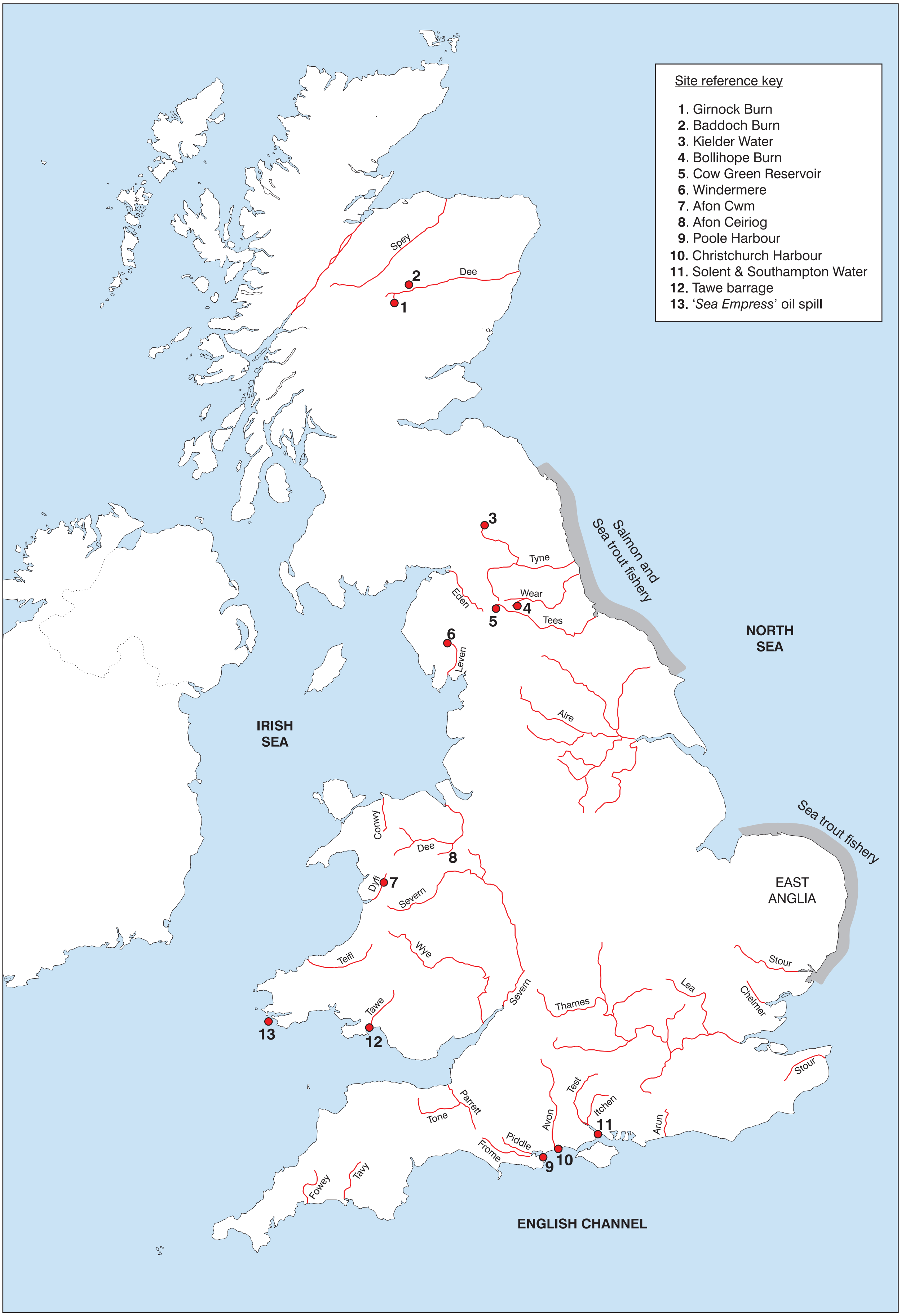

***Figure 1.2** Locations where research on salmonid and coarse fish species was undertaken for the projects described in this review*

2. FRESHWATER ECOLOGY OF JUVENILE SALMONIDS

The main projects addressed in this section are:

SF0205 Ecology of Young Salmonids (Centre for Ecology and Hydrology)

SF0215 Studies on Sea Trout and Brown Trout in a Stream in mid-Wales (Centre for Ecology and Hydrology)

SF0229 Habitat Utilisation in Wild Salmonids and the Impacts of Stocking (CEFAS)

SF0231 Habitat Selection and Distribution of Migratory Salmonids in River Systems (CEFAS)

Key features of salmon life cycle:

Atlantic salmon (Salmo salar) originate in rivers around the North Atlantic from Spain to Russia, in Iceland, and on the eastern coast of North America. They are found in the majority of rivers in England and Wales, ranging in character from steep spate rivers in Wales to lowland chalk streams in southern England. They spawn in freshwater but spend about half of their life in the sea, where they achieve most of their growth (a strategy known as 'anadromy').

Salmon spawn in the autumn and winter in excavations in gravel beds known as redds. After hatching in the spring, the 'alevins' remain in the gravel drawing nourishment from their yolk-sacs. When the yolk sac is depleted the fish emerge from the gravel as ' fry', disperse and begin to feed. At this stage, they set up territories, which they defend against competitors. In their first autumn and winter, the young fish, now known as 'parr', may redistribute themselves, possibly moving into deeper water or sheltering under stones. After one to three years residence in freshwater, the parr develop into 'smolts' and migrate to sea in the spring.

Little is known about the movements of our salmon in the sea, although they probably move into the Norwegian Sea in the summer and autumn of their first sea year, and some migrate as far as western Greenland during the following summer. The fish grow rapidly, returning to their home rivers as mature adults after one to three years at sea; different age groups may return at different times of year. Most salmon spawn only once, although a small proportion may survive to spawn again after a second sojourn in the ocean.

See page 20 for differences in trout life cycle.

2.1 Background

The distribution of juvenile salmon and trout, both migratory and non-migratory forms, in streams and rivers depends upon factors affecting both the spawning behaviour of the adult fish and the growth and survival of the juveniles. Key factors are the quantity and distribution of suitable habitat for the fish at different stages of their life cycle. For example, the habitat required for good survival of eggs and alevins differs from that for parr, and so the fish must be able to find suitable habitat as their needs change. Understanding these requirements is fundamental to the conservation and management of stocks. It is also central to our use of biological reference points (e.g. conservation limits) to determine the status of stocks and regulate exploitation, because these values are related to the capacity of the system to produce fish.

Defra has funded a range of basic ecological studies on factors affecting juvenile salmonid production and the implications for river management, in addition to investigations of factors limiting production at specific stages in the life cycle ('production bottlenecks') and mitigation measures (addressed in Section 3). Studies are also being undertaken on the habitat requirements of salmonids, the interactions between salmon and trout, and the habitat utilisation by migratory and non-migratory components of populations.

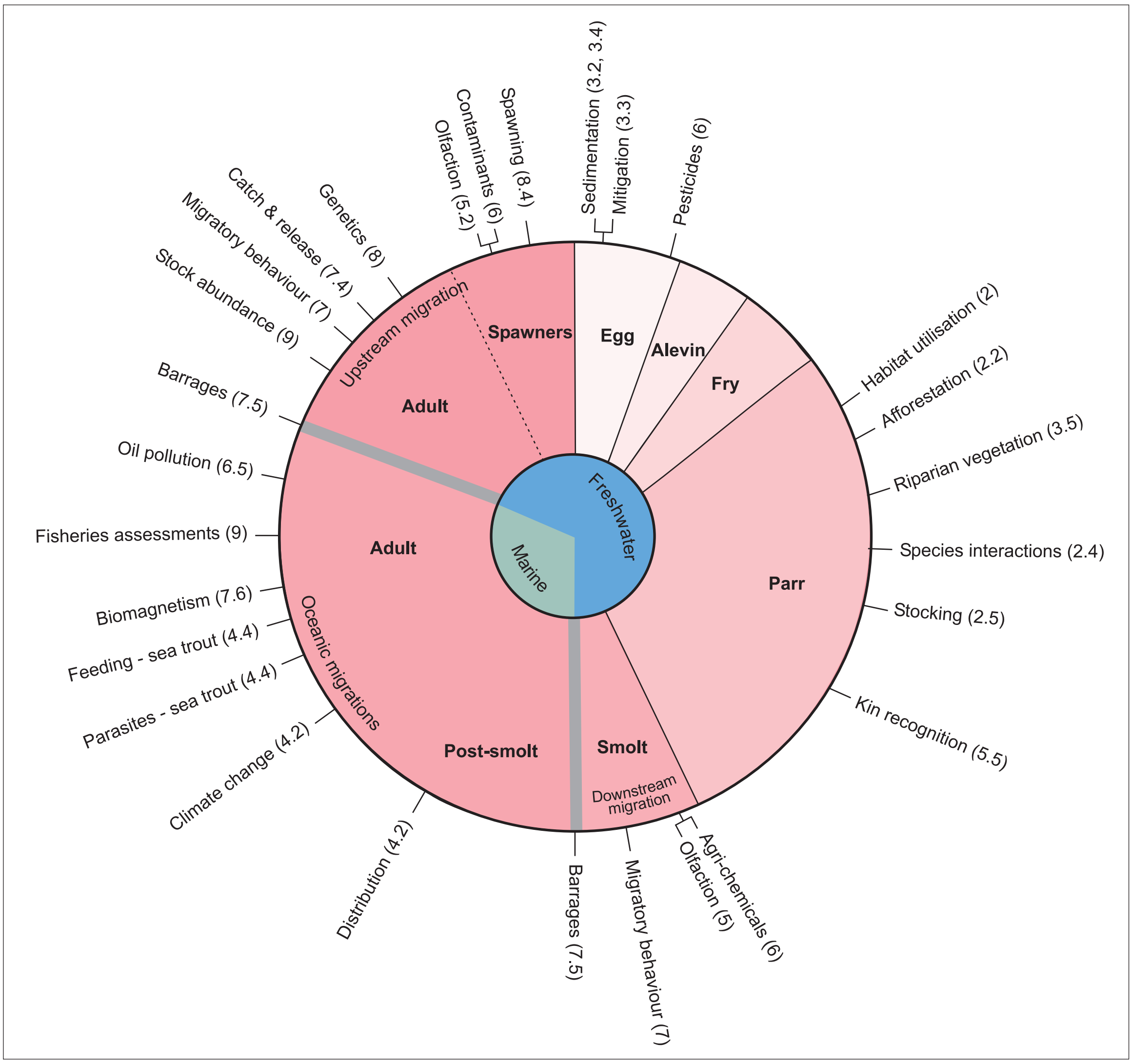

Figure 2.1 ***Schematic diagram of the life cycle of the Atlantic salmon, showing the biological topics and impacts of human activities that are being studied with Defra funding. Figures in parenthesis refer to sections of this report***

2.2 Ecology of juvenile salmonids

Effective conservation and management of salmonids in freshwater depends in large measure on understanding the biological and environmental processes that together interact to govern the production of young fish in a given river. To gather such information, funding support was given to two existing long-term ecological studies of trout being undertaken by the Centre for Ecology and Hydrology (CEH) at streams above Cow Green reservoir in upper Weardale, north-east Pennines (Figure 1.2, Site 5) and on the Afon Cwm in mid-Wales (Figure 1.2, Site 7). The work involved comparing the number of eggs laid with the resultant numbers, population density, growth and survival of alevins, fry and parr produced in relation to river conditions and other environmental factors, including changes in land use. For example, trout populations in upland streams can be threatened by alterations to hydrological regimes resulting from changes in use of moorlands, such as intensive afforestation with conifers.

The studies (**part of SF0205**) in Bollihope Burn (Figure 1.2, Site 4) and neighbouring Pennine streams revealed changing patterns of survival through the early swimming stages of trout. Losses of intra-gravel stages (eggs and alevins) were generally high, due probably to wash-outs during spates. The swim-up fry also experienced high losses (due to mortality and down-stream dispersal) such that only ~10% survived *in situ* irrespective of the initial numbers emerging from the gravel redds; thus, their survival was not related to their population density. Among the resultant parr, however, growth and survival did depend on the initial numbers of parr per unit area of stream bed, i.e. they were density-dependent. Thus, higher initial numbers of parr showed proportionately higher percentage losses and slower growth than did lower numbers of parr. This relationship was attributable to the strongly territorial behaviour displayed by parr which defend individual foraging areas. At higher densities (more than ~4 fish per square metre in the studied stream) the consequential increased levels of encounters led to more widespread dispersal of the parr. These results indicate that each stream may have its own optimum density ('carrying capacity') for sustaining a parr population. They also have important implications for the management and possible enhancement of trout stocks in sub-optimal habitats such as these Pennine streams.

The Welsh trout study (**SF0215**) was supported in order to improve the management of upland streams through a better understanding of how trout populations may be affected by large-scale land-use changes. On the Afon Cwm, some 87% of the catchment had been afforested, mainly with Sitka spruce, during 1983-86 at the start of the CEH long-term study.

Afon Cwm is an important spawning and nursery stream for sea trout, but its output of juvenile fish (fry and parr) is usually low (less than 0.6 fish per m^2). Both resident (brown) trout from tributaries of the Afon Cwm and migratory (sea) trout returning from the sea enter the stream to spawn, with most of the egg production coming from the larger migratory fish. In dry years, however, few sea trout are able to reach the spawning areas above a weir. The numbers of spawners thus varied widely between years, as did annual recruitment and the numbers of juveniles less than one year old present each September. Whereas the numbers of these juveniles appeared to be controlled by abiotic factors, most notably losses over the weir downstream of the nursery ground, there was evidence that survival of older juveniles was controlled by density-dependent factors (as in Bollihope Burn).

This long-term study provided base-line information on the trout population and water quality of Afon Cwm before and during the early stages of afforestation. Up to 1998, no apparent effects had been detected either upon water discharge parameters during the trout egg incubation season or upon annual recruitment. However, these data will continue to be used to identify any future changes that may develop after full canopy closure has occurred beside the stream since this may lead to over-shading (see also **SF0220**) and possibly also to acidification.

2.3 Movements of juvenile salmonids

Relatively little is known about changes in habitat utilisation by salmonids during certain critical stages in their lives. In particular, the over-winter survival of parr can be poor where suitable habitat is lacking, but these habitat needs and the seasonal movement of juvenile salmonids between different habitat types are poorly understood. A study has therefore been started on habitat usage by young salmon (**SF0229**). This work has involved the development of remote monitoring systems to study the movement and habitat use of individual wild and stocked salmon marked with passive integrated transponder (PIT) tags in an experimental section of the River Itchen, a southern chalk stream (Figure 1.2). The system (Figure 2.3) comprises fixed PIT antennae, which continuously monitor movements of tagged fish into and out of the study site, and portable PIT antennae arrays, which record habitat use within the study area (Figure 2.4). The PIT antennae emit a low frequency electromagnetic field, which energises any PIT tags passing within range. The tags then respond by transmitting a unique code back to a reader. Juvenile salmonids down to 6cm in length can be tagged. Tag detections are recorded automatically by computerised data loggers (Figure 2.3(b)) together with various environmental data. A similar system has been set up on the Afon Ceiriog, an upland spate tributary of the Welsh Dee (Figure 1.2; Site 8).

Initial studies have investigated the movements of juvenile salmon within the study stream and the

Figure 2.2 A typical upland trout stream in moorland habitat in Wales; note spruce afforestation beside the stream

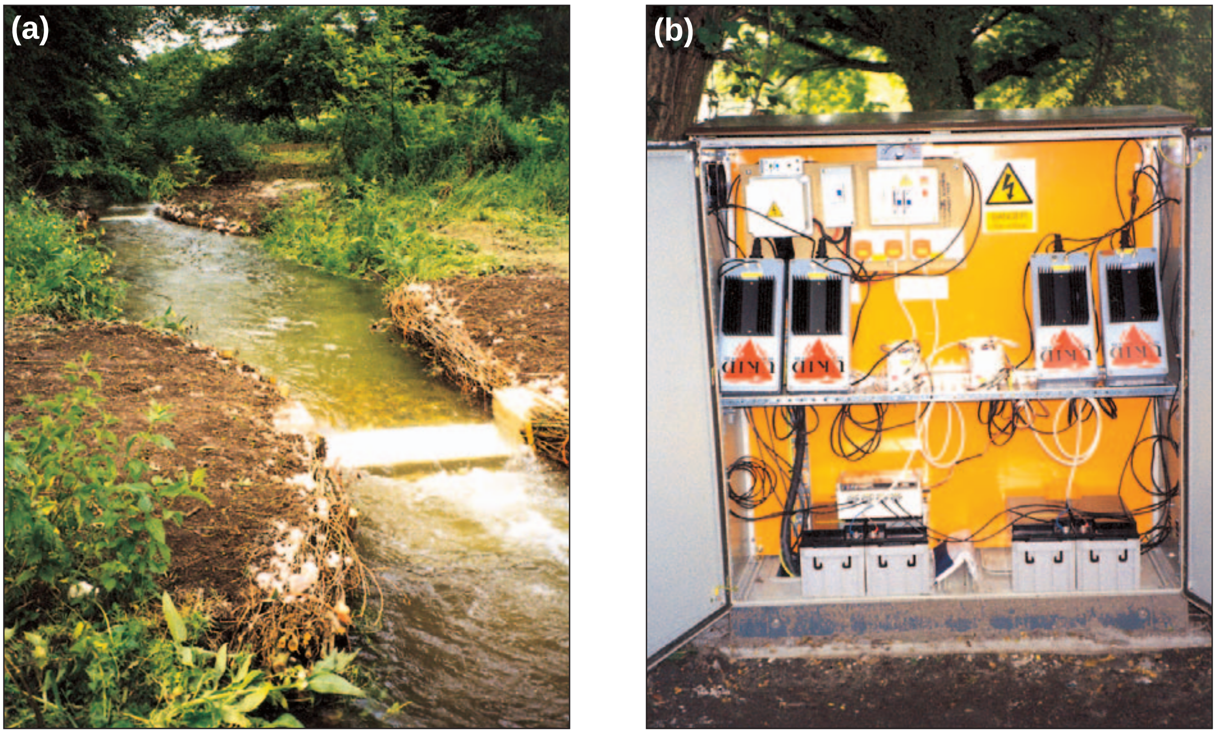

Figure 2.3 ***Study stream on the river Itchen, Hampshire, showing (a) the fixed PIT antennae system in position; (b) bank-side installation showing the PIT tag decoders (at top), data logger (bottom left) and emergency backup batteries (bottom right)***

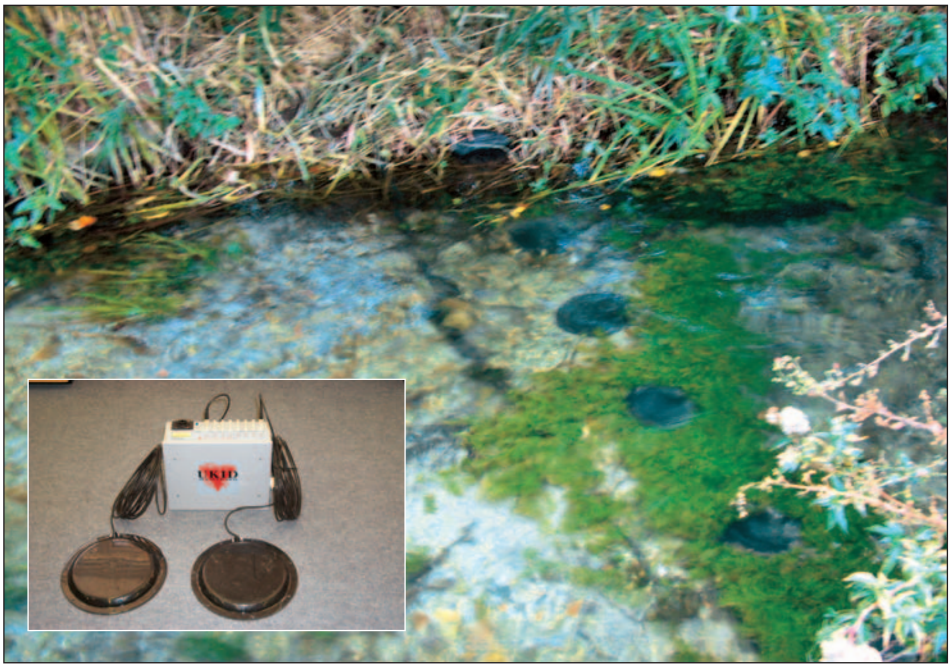

Figure 2.4 ***A mobile PIT antennae array set across a side-stream of the river Itchen; inset: demonstration close-up of two antennae linked to a multi-point decoder***

emigration of fish from this nursery throughout the year. Preliminary results show little movement out of the area before autumn, but significant changes in the behaviour of the fish between summer and winter. Movements of smolts, in April, were significantly correlated with the onset of night, and with time of maximum daily water temperature. However, despite this preferred time of migration, and unlike results reported from traps, the results showed no evidence of the smolts departing in shoals.

2.4 Interactions between salmon and trout

Trout and salmon are known to have different habitat preferences but this does not satisfactorily account for the large differences in the relative abundance of the two species in different river systems. The occurrence of co-existing (sympatric) populations of salmon and trout has the potential to lead to over-estimation of potential stock sizes for either or both species and therefore has implications for determining appropriate management measures. Studies are currently underway (**SF0231**) to investigate factors that are thought to be associated with the different population distributions in river systems, including the habitat requirements during upstream migration and spawning of both salmon and trout.

This area of research will provide a scientific basis for improving the estimation of biological reference points and also enhance the understanding of the ecology, dynamics and requirements of salmonids in river systems in England and Wales.

2.5 Stocking

Stocking of hatchery-reared salmon and trout has been widely practiced in many rivers and other waters in England and Wales despite little being known about the true efficacy of such activities, or of their effects on resident wild fish, for example through increased competition for resources. Studies have therefore been undertaken and are planned on the efficacy of stocking, on release methods and on interactions between stocked and wild fish.

Releases of salmon and brown trout in chalk streams (**part of SF0212**, see Section 3) produced valuable information for stocking programmes, relating to stocking densities, choice of stocking stage, and protocols for fish release, in addition to data on juvenile population dynamics. For example, higher smolt production was achieved by stocking with hatchery-reared fry that had been fed for a time before release ('fed-fry') rather with newly emerged swim-up fry ('unfed-fry'). The ecological and stocking studies showed that enhancement attempts would be sensible biologically only for stocks below the carrying capacity of their stream, such that density-dependent mortality would be reduced. Enhancement stocking is best undertaken by rearing of eggs obtained from local wild stocks and then releasing the fry in their native streams.

A further study (**part of SF0205**) was made comparing the effects of 'point stocking' and 'scatter stocking' of salmon in Bollihope Burn, Co. Durham (Figure 1.2; Site 4). Fry stocking took place in spring and early summer, usually using fish that had just absorbed their yolk sacs and had not been fed in the hatchery. The distribution, numbers and weight of survivors to September were examined by electrofishing census. Scattered parr survived better (27%) than point stocked fish (~17%). The scattered fish also showed relatively little spatial variation in population density or body weight, unlike those that had been point released. Some of the latter group moved up to 50 m upstream or 500 m downstream from the release point but most stayed nearby, indicating that, where this approach is used, release points should be not more than 500 m apart.

It is also important to determine how released and wild juveniles interact and, especially, whether wild fish are displaced by introduced fish to less suitable habitats where survival may be reduced. The study stream on the River Itchen, described above (**SF0229**), is being used to investigate the effects on the behaviour and distribution of the wild stock of introducing artificially reared fish into this stretch using individually PIT tagged parr, hatchery reared from local spawners.

2.6 Uptake of the results of studies on salmonids

The ecological research outlined above has contributed to a better understanding of the behavioural and environmental processes which govern the numbers of young salmonids that a stretch of river can support. This is fundamental to the conservation of stocks and the day-to-day management of factors affecting them, including fisheries (see also Section 3). Salmon stocks in England and Wales are now being managed to attain 'conservation limits' which therefore requires an understanding of stock dynamics obtained from such investigations.

Studies of stocking practices have led to a greater awareness, especially among fisheries managers and other interest groups, that many earlier stocking exercises were often not well conceived and may have posed a threat to the viability of wild trout and salmon populations, for example, through the risk of stocked fish displacing and/or interbreeding with native fish (see also Section 8.3). The results of this work have been used in the development of national strategies on stocking of salmon and trout, by the Environment Agency, and the development of guidelines to control the number and size of fish which may be stocked into different waters without undue risk of a deleterious impact on wild stocks.

2.7 Publications and other outputs

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3. MANAGEMENT OF SALMONID FRESHWATER HABITATS

The main projects addressed in this section are:

SF0203 Salmonid Ecology and Stock Enhancement (CEFAS)

SF0206 The Efficacy of Manual Gravel Cleaning as a Means of Improving Salmonid Spawning Grounds (Centre for Ecology and Hydrology)

SF0212 Improving Natural Production of Juvenile Salmonids (CEFAS)

SF0220 Restoration of Degraded Salmonid Habitat (CEFAS)

SF0225 Modelling Sediment Levels in Salmonid Spawning Gravels (University of Southampton)

SF0227 Sediment Dynamics in River Catchments (CEFAS)

3.1 Background

Studies undertaken by CEFAS in the 1980s showed that habitat degradation, partly resulting from changes in land use, was creating 'bottlenecks' in the production of juvenile salmonids in many rivers in England and Wales. One problem that appeared to be increasing with the development of more intensive agricultural practices, was the deposition of fine sediment ('fines') in salmonid spawning gravels. A number of factors, mostly anthropogenic, are known to contribute to increases in sediment loads in streams. These include enhanced erosion of land surfaces caused by certain farming operations, bank erosion by farm livestock and reduced river flows resulting from factors such as water abstraction and increased weed growth.

Spawning salmon and trout require areas of clean gravel in which to excavate redds and lay their eggs, in order that the developing embryos receive a good supply of oxygenated water. Undue deposition of sediments at the spawning sites prior to or during spawning and incubation was thought to block the water flow and thereby cause partial or complete failure of spawning, and this might also deter fish from using these spawning sites. A research programme was therefore initiated to examine the effects of sedimentation on salmon and to evaluate methods for reversing or mitigating any harmful impacts on salmonid populations.

3.2 Sedimentation of salmonid spawning gravels

Sedimentation was identified as a potential problem affecting salmonid populations in many rivers in England and Wales, but the chalk streams in southern England were thought to be particularly susceptible to sedimentation problems because of their fine gravel substrates and lack of flushing flows to keep the gravel clean. Studies were therefore conducted in the River Itchen (Figure 1.2) to investigate the effects of sedimentation on the production of salmonids (part of **SF0203**). Levels of sedimentation were assessed by freezing gravel cores in the river bed and then removing them for particle size analysis (Figure 3.1).

Natural survival of embryos within the gravel was investigated by placing perforated boxes containing eggs in artificial redds and by using fine-mesh traps to catch salmon fry emerging from natural redds, having first estimated the number of eggs deposited. Survival of the embryos varied from 2% to 17% during the three years of the study. The lowest survival rates occurred in spawning gravels with the largest proportions of fine sediment and where a concreted sub-surface layer, in which stones were bound together with calcium carbonate deposits, was present at a depth between 5 and 10cm. In some cases the siltation was so severe that no oxygenated water could get to the eggs. It was estimated that, in the absence of any exploitation on the returning adult stock, an embryo survival rate of 8% would have been required to prevent the further decline of the stock levels. Siltation was therefore considered to be a major contributor to the marginal status of this stock.

3.3 Mitigating the effects of sedimentation

In order to find an immediate solution to the severe bottleneck in juvenile production caused by sedimentation, a range of field trials was conducted on the River Itchen to investigate the use of techniques to mitigate the effects on the salmon population. These studies included the use of stream-side incubators, to bypass the egg-to-alevin stage in the natural environment, and the investigation of various methods to remove silt from the spawning gravels.

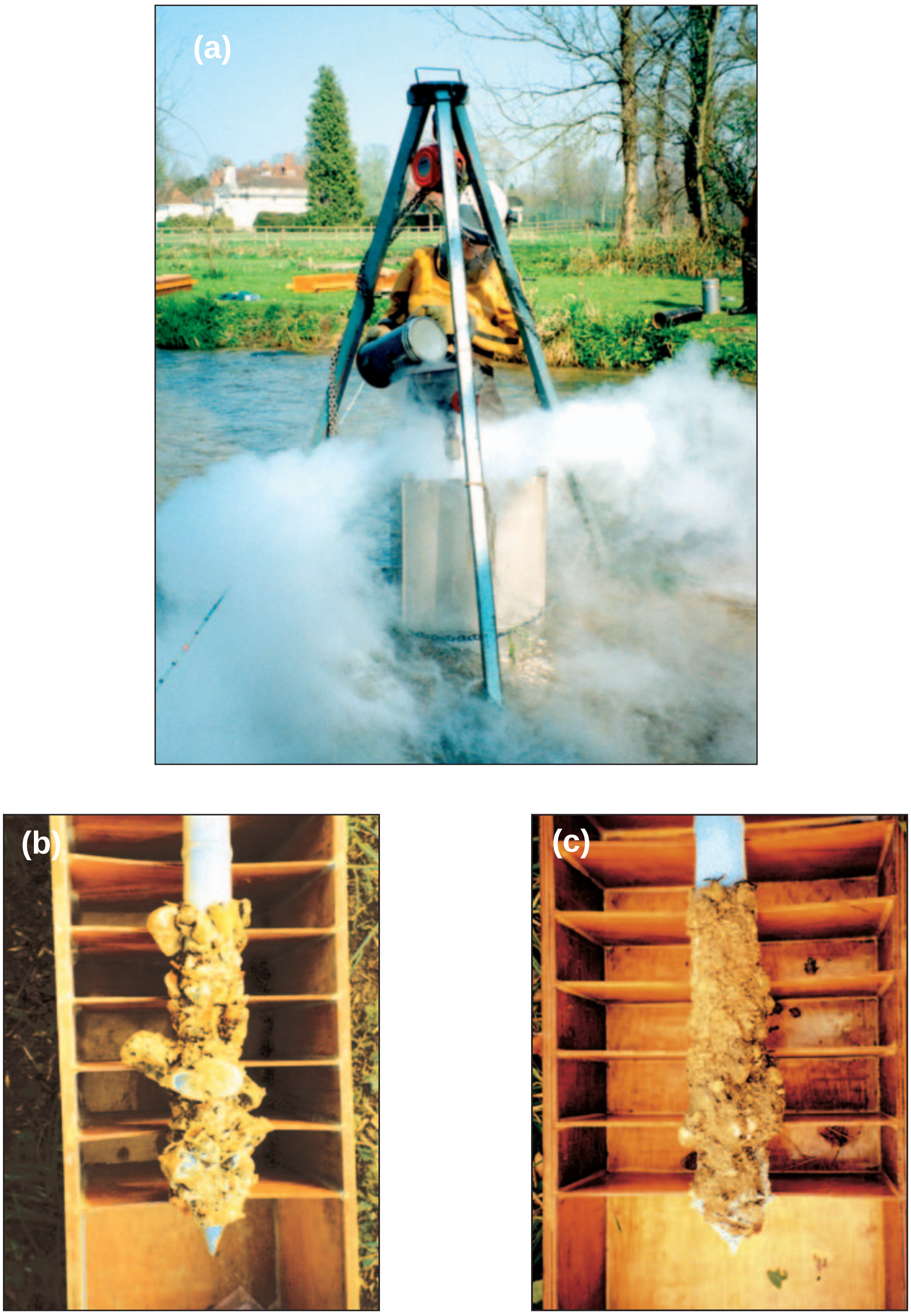

Figure 3.1** **Sampling the composition of salmonid spawning gravels on the River Itchen: (a) freeze-core sampling using liquid nitrogen; frozen samples of (b) clean gravel and (c) silted gravel placed on sorting boxes

3.3.1 Bankside incubators

Artificial incubators had previously been shown to increase the survival and quality of fry that are reared in hatcheries, and they provide a means to bypass the problem of reduced embryo survival in the wild without resorting to hatchery rearing. Bank-side incubators enable eggs stripped from wild fish to develop in a sediment-free environment and to emerge naturally. In field trials (**parts of SF0203 and SF0212**) the eggs were placed in coarse gravel in boxes sited in the stream margin, and river water was supplied to the boxes by a gravity feed supply (Figure 3.2). Embryo survival in the incubators was 80-91% compared with 2-19% observed for eggs buried in the river gravel. In addition, both the lengths and weights of alevins produced were greater than for the fish produced in the degraded natural habitat.

The boxes required regular inspection to ensure that they had not become blocked or damaged, although they were easy to use and proved remarkably resilient to reduced flows. The incubator methodology was subsequently adopted by the EA (Southern Region) on a number of rivers in southern England, as well as by many hatcheries.

Figure 3.2 A stream-side incubator containing gravel with salmonid eggs in operation; the gravity-fed water flows up through the box to aerate the eggs

3.3.2 Gravel cleaning

With mounting evidence that siltation of spawning areas could be a significant cause of declining salmon numbers in chalk rivers, methods were also sought to treat the problem in the short-term. Studies (**SF0206, SF0212**) were therefore undertaken during 1991-94 to assess the benefits of gravel cleaning as a means of improving the quality of spawning substrates and thus enhance salmonid stocks in areas where sedimentation was known to be a problem. Two reaches of the River Itchen, Hampshire, were selected for the field trials. Many fisheries organisations, particularly on southern chalk streams, historically cleaned salmonid spawning gravels by raking or other form of disturbance. A range of such approaches was therefore examined, along with a method using high pressure water jets, which wash the sediment out of the gravel thereby allowing the current to carry it further downstream.

Gravel core analysis showed that the water jet cleaning was the only method which significantly reduced silt loads in the spawning gravels. However, although the test areas remained significantly cleaner for more than two years, they gradually silted again. The cleaning of spawning gravels also significantly increased intra-gravel survival, from 2-6% to 40-66% in the first two years, but survival was reduced to 6-20% in the third year showing that the benefits deteriorated as sediment levels built up again.

3.3.3 Channel modification

The previous investigations had shown that, although gravel could be cleaned effectively, this could be expensive and the benefits might be relatively short-lived. Field trials were therefore undertaken (**SF0220**) to investigate the effectiveness of modifying stretches of a river in order to increase the water velocity, and thereby increase the sediment mobility and extend the effectiveness of the gravel cleaning. During 1996/97 stretches of the River Itchen were narrowed and wing deflectors were installed to guide the current in a meandering course, creating deeper and faster flows (Figure 3.3). Such higher energy flow, and associated increased turbulence, was designed to reduce the deposition of fines and provide a mechanism by which infiltrated fines would be flushed from the river-bed. The pattern of change in the gravel composition and salmon embryo survival rates, following cleaning, were then monitored and compared to that in unmodified reaches.

At unmodified sites, cleaned gravel beds quickly reverted to a fines content similar to that seen before cleaning. A similar deterioration in gravel quality was initially observed in the cleaned gravel beds where the channel had been modified. However, the fines content and sand indices at these sites subsequently declined indicating that appropriate channel modifications appeared to extend the improvement seen in salmon spawning gravels.

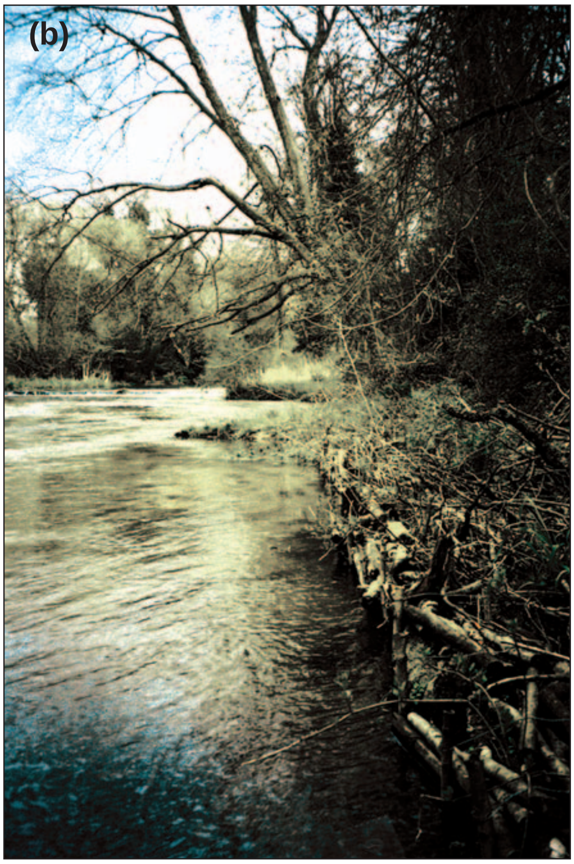

Figure 3.3 The river Itchen at Shawford: (a) looking upstream towards a river bank deflector section installed to increase current speed and reduce sedimentation; (b) close-up of a section of bank modified to deflect the flow

Excessive siltation of salmon spawning areas can also be caused by dense growths of aquatic weeds which reduce flows and thus provide areas for sediment deposition. Clearance trials in the River Itchen have demonstrated that salmon parr production could be greatly increased where weed densities were controlled by cutting and removal.

3.4 Sediment dynamics

The growing understanding of the potential serious impacts of sediment upon salmonids emphasised the need for better dialogue and co-ordination between groups involved in research on sedimentation problems. A review (**SF0227**) was therefore undertaken on work related to the impacts of sediments on fish that was being conducted or funded by various agencies, in order to help formulate Defra's future research priorities in this area. The review summarised existing knowledge and current research in order to provide Defra with a clear statement on the impacts that sediments can have on river ecology.

Efforts were also made to bring together available data from freeze-core sampling of the structure of gravel beds in different rivers in the UK (**part of SF0219 and SF0229**). Data were supplied by EA and other agencies and then incorporated into a database and distributed on CD to contributors and groups co-operating in Defra and EA studies. A preliminary review of the substrate information identified a lack of historical data as a critical deficiency, making it difficult to identify any temporal trends in sediment levels. In 2001, it was possible to add Defra information on land use to the database, and a combined sediment and land use database CD was issued by CEFAS.

Sediment levels in a river are clearly affected by both the amount of sediment entering the river and the rate that it passes through the system. Previous studies had identified mitigation measures, but there remained a need to find sustainable methods for reducing the impact of sediment on salmonid populations. A project (**SF0225**) has therefore been initiated, at the University of Southampton, to develop a model of in-river sediment dynamics that may be used to predict the effects of land use practices (i.e. sediment input) and river management on sediment levels in salmonid spawning areas. An equilibrium state may arise when the amount of the sediment fractions that are washed out of a stretch of river equals the amount that enters it. The study is combining laboratory and field studies of sediment movements to model these processes and will attempt to explain how factors such as river hydrology and river topography affect the quantity of sediment that remains in the gravel in this equilibrium state and its distribution between different areas.

A review has been conducted of existing land-use models, describing sediment delivery from land surface or river bank erosion, to find one that can be coupled with the existing UK in-river siltation model of Sediment Intrusion and Dissolved Oxygen (SIDO-UK). The final coupled model will display the output graphically with the data being saved in spreadsheet-suitable format. Flume tank experiments are being used to study the movements of sediment in different types of channel and the infiltration of different size fractions of sediment into an artificial redd. The data will provide robust calibration and validation for further refinement of the sediment models. To complement flume and model developments, a fully integrated study is also being made of sediment dynamics, silt intrusion, dissolved oxygen, egg survival and alevin emergence in salmonid spawning gravels and redds in the field. Initial studies have been undertaken on the River Test and its Blackwater tributary, in southern England (Figure 1.2), and have shown that high rates of deposition of fine sediments (<720 µm particle size) on the Test appear to have a more detrimental effect on intra-gravel flows than larger sediments (mainly >720 µm) sampled in the Blackwater. Moreover, a high organic content found in Test sediments appears to exert an oxygen demand that further reduces the potential oxygen available to incubating salmon progeny. These studies are being supplemented by further investigations in other UK rivers.

3.5 Management of riparian buffer zones

One management approach designed to reduce the input of contaminants, including sediments, into rivers and to protect river banks from erosion has been the creation of buffer zones, and funding was made available to farmers under MAFF's Habitat Improvement Scheme (Water Fringe Habitats) to employ these protective measures. These zones also encourage the growth of bankside vegetation, including overhanging bushes and tress, which provides both shelter and food items, such as terrestrial invertebrates, for juvenile salmonids. However, there were concerns that, without effective management, growth of riparian vegetation could also damage fish stocks, by creating excessive shading and thereby reducing production.

A small, long-term study (**part of SF0220**) was therefore instigated to investigate the need to manage tree growth on river banks. The study aimed to mimic the creation of a riparian buffer zone by removing the tree canopy from two wooded stretches of stream and then allowing it to regrow. These wooded sites had previously been found to have significantly lower in-stream densities of large aquatic weeds and lower abundance of invertebrate fish prey.

Monitoring of the sites over the two years after canopy removal indicated that the shading had been greatly restricting production. Where the canopy was removed, weed cover increased from <1% to >50% and the quantity of invertebrate prey increased to become comparable with that in unshaded areas. The salmon and brown trout responded more slowly to the vegetation changes, and densities of young parr in the cleared sites did not increase to match those in control sites until the second summer after canopy removal. Studies of these sites are continuing as the canopy re-grows in the experimental stretches, but the results already suggest that it should be possible to enhance the production of juvenile salmonids through careful management of closed-tree canopies along river banks.

3.6 Uptake of the results from salmonid habitat management studies

The work on sedimentation has confirmed the serious impact that silt input to rivers can have on the survival of salmonid eggs and alevins and has also demonstrated the value of various mitigation measures in the short to medium term. In particular, cleaning spawning gravels with power hoses and the use of stream-side incubators were both shown to be valuable remedial measures for countering habitat degradation and for stock enhancement and they have been adopted by workers on other rivers. The results generated a greater national awareness of siltation problems in the mid-1990s and have provided the basis for advice on ways to limit harmful effects of agriculture on fish populations, and on methods to improve riparian management. However, it is hoped that the modelling studies currently underway will provide a means to identify the most effective longer-term solutions to these problems. Studies are continuing into the adverse effects that uncontrolled riparian vegetation may have on salmonid production. The results already suggest that management of closed tree canopies along river banks may be required in some situations. This will be important in managing the increasing lengths of river where buffer strips have been developed.

3.7 Publications and other outputs

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4. MARINE ECOLOGY OF MIGRATORY SALMONIDS

The projects addressed in this section are:

SF0104 The Structure of Trout Populations: Inventory of Migratory Types by Pigment Analysis (University of Aberdeen)

SF0204 Growth and Survival of Sea Trout in the Sea (CEFAS)

SF0216 A Climatological Study of Sea Surface Temperature and Salmon Habitat (Alliance for Marine Remote Sensing, Canada)

SF0221 Diet of Sea Trout in the Sea (CEFAS)

SF0230 **(part)** Salmonid Migration and Climate Change (CEFAS)

SF0237 Modelling the bioenergetics of Salmon migration (CEH, Wallingford)

Key features of the trout life cycle:

Populations of our native trout (Salmo trutta) co-exist with salmon and have similar life-cycles. Nearly all trout undertake seasonal migrations, but variable components of local populations adopt different migratory life styles. Thus, some individuals are fully resident in their natal stream or only migrate within their river ('classic' brown trout), while others undertake a smolt transformation and emigrate to sea to grow. However, all return when sexually mature to spawn in their natal areas. Those that migrate to the sea are distinguished as sea trout and are mainly females; residents are predominantly males. Genetic population structure is sustained by the accurate homing of migratory trout before they spawn.

4.1 Background

Both salmon and migratory trout spend a significant part of their lives in the sea, but very little is known about the factors affecting the fish during this phase in their life-cycles. Estimates of the numbers of adult salmon in the sea suggest there has been a general decline in stocks in both North America and Europe in recent years. The patterns of decline in England and Wales (Figure 1.1) are broadly consistent with the changes in marine survival observed for a small number of monitored stocks in Europe, although there has been considerable variation between different rivers. Most of these monitored stocks showed a drop in the proportion of smolts for the 1989 smolt year class surviving to return as one-sea-winter salmon, but while return rates have remained low for some stocks, they have increased again for others. Reductions in marine survival were also recorded for many sea trout stocks during the late 1980s, but while some stocks recovered quite quickly, those in north-west Scotland and western Ireland continued to decline dramatically.

These events highlighted the need for research into the factors affecting the survival and growth of salmon and sea trout in the sea, and this was identified as a high priority both nationally and internationally. Studies of salmon in the sea are particularly difficult because of the long migrations undertaken by the fish and the great uncertainty about their behaviour and distribution. Early studies funded by Defra have therefore concentrated upon investigating methods to collect data on salmon in the sea and efforts to model their behaviour from the limited data that are available.

As a background to studies on trout, work was undertaken on methods to discriminate between migratory and non-migratory components of these populations. In addition, of particular concern for migratory trout were suggestions that the observed declines might be associated with infestations with the salmon louse (*Lepeophtheirus salmonis*) derived from salmon farms, or with industrial fisheries exploiting their prey, particularly sand-eels (*Ammodytes* spp.). The absence of salmon farming in England and Wales provided the opportunity to obtain baseline information on levels of infestation by sea lice to assist international investigations of this problem. Baseline studies were also undertaken into the diet of sea trout during their marine migrations.

4.2 Oceanic distribution of salmon

The ability of salmon post-smolts to migrate across wide regions of open ocean (Figure 4.1) and there find favourable areas for growth is a crucial determinant

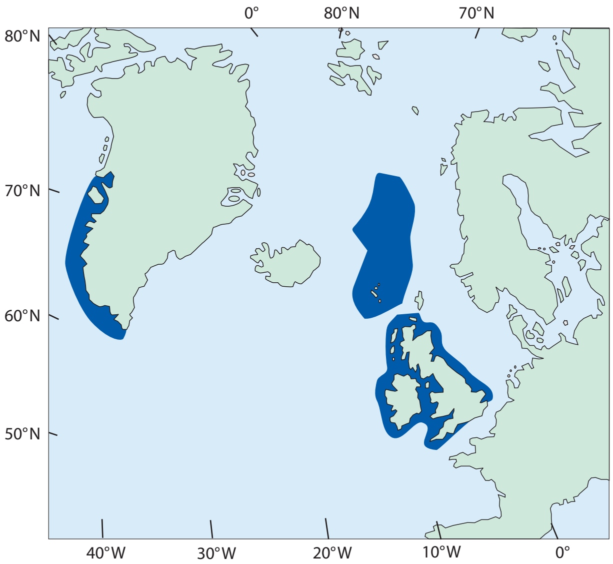

Figure 4.1 ***Main regions of the North Atlantic where tagged salmon from England and Wales have been caught by commercial or research Þsheries. Occasional recoveries have been recorded elsewhere. Migration routes between these areas are poorly understood***

of spawning stock abundance. It has been suggested that favourable conditions may exist where sea surface temperatures (SST) are between about 6-9°C, and annual fluctuations in the location and extent of such areas ('preferred salmon habitat') may be a major factor influencing the migration routes, abundance, growth, survival and run-timing of salmon in the sea. Since patterns of SST are likely to be affected by predicted climatic changes, this may therefore affect salmonid abundance in the future. As an extension of its migration studies (see Section 7) CEFAS has therefore **(part of SF0230)** assessed the potential consequences of changing ocean conditions on salmonid migrations and stocks, so as to ensure appropriate management measures can be taken to conserve salmon in the future.

Preliminary work to investigate the availability of new data on the oceanic habitat of Atlantic salmon was undertaken, by the Alliance for Remote Sensing, using sea surface temperature data for the entire North Atlantic collected by polar orbiting earth observation satellites during 1982-95 (**SF0216**). A colour-coded time-series of SST maps was constructed for each month or season defining optimal (6-9°C) and sub-optimal (2-6°C and 9-13°C) salmon habitats, as well as potentially adverse or non-optimal (<2°C and >13°C) regions of the ocean for salmon (Figure 4.2). These showed considerable and

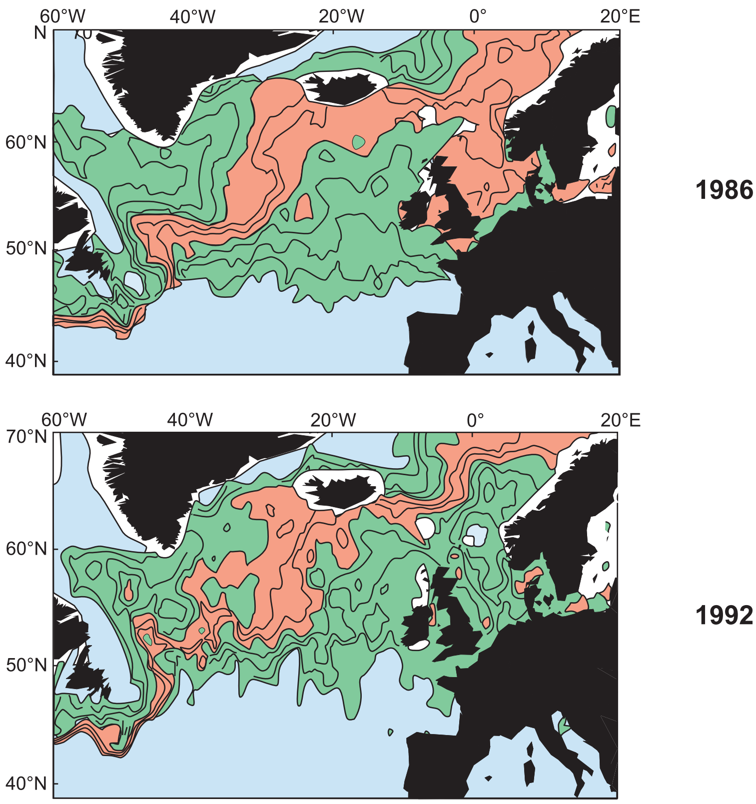

Figure 4.2 ***Two examples of sea surface temperature variability across the North Atlantic showing the distribution of optimal 6-9°C (red), sub-optimal 2-6°C (green) and non-optimal <2°C or >13°C (blue) thermal regions for salmon growth and survival in spring (April - June). White areas denote lack of data. Smolts entering the sea off British coasts would have encountered favourable conditions in 1986 but not in 1992. (based on satellite imagery from Alliance for Remote Sensing, Canada)***

unpredictable variability in the location and extent of the patches of both favourable salmon habitat and regions of adverse conditions. This work informed the subsequent use of a wider range of data sets on sea surface temperature, marine currents and plankton distribution which are now being applied to a number of modelling studies on salmon in the sea (**see SF0230 and SF0237**).

The potential for using new archival or data storage tags (DSTs) to study the ocean movements of salmon has also been investigated (**parts of SF0219 and SF0230**). DSTs, such as the type developed by CEFAS for Defra as part of its marine fisheries research programme, record a range of environmental parameters, including temperature, pressure and light. Light measurements may be used to estimate the location of surface swimming fish by recording changes in day length and time of midday as the fish change latitude and longitude. The use of these tags on salmon smolts is still constrained by the tag size and cost, since recovery rates are likely to be low, but the potential for studying the behaviour of adult fish that spawn for a second time is being evaluated.

4.3 Migratory structure of trout populations revealed by pigment analysis

The management of trout fisheries and conservation of stocks is complicated by the co-occurrence of resident and migratory forms in the same populations. A project (**SF0104**), at the University of Aberdeen, was set up as a first step towards finding a method for estimating the migratory and non-migratory structure of brown trout stocks. It investigated the possible value of using tissue pigments as an indicator of migratory status. Carotenoid pigments impart the red/orange colour to the body tissues and eggs (Figure 4.3) of salmonids and are of dietary origin, being synthesised by phytoplankton and passed up the food-chain to the prey species of salmon and sea trout. The variation in carotenoid pigment composition was examined among sea-migratory and river-resident trout and in their eggs and progeny. High performance liquid chromatography (HPLC) was used to resolve and quantify carotenoid pigment components found in dorsal muscle and eggs taken from redds and then incubated in a hatchery.

The differences in the profiles of muscle carotenoids in migratory and non-migratory adult trout were sufficient to be diagnostic of their migratory status, and there were also indications that pigment profiles of brown trout varied between freshwater habitats (rivers or lakes) and regions. Among female trout, differences in the muscle pigment profiles of sea or brown trout were reflected in differences in the pigment profiles of eggs and in developing alevins until four weeks post-hatch, when monitoring ceased. The parental type of

Figure 4.3 The pink colouration of salmon and sea trout eggs is imparted by carotenoid pigments of dietary origin

single eggs could be classified without error, and the differences were sufficiently great to suggest that they were likely to remain detectable for much longer. In both sea- and brown trout, muscle and egg pigment profiles differed for individuals, suggesting differential mobilisation of pigments from body tissue to ovary.

On this basis, pigment typing of alevins appears to be a robust means of establishing maternal provenance (to either sea- or brown trout females) prior to, during and for some time after swim-up and emergence.

4.4 Trout in the sea

In England and Wales, the only substantial marine fisheries for sea trout have been located off the north-east coast of England and off East Anglia (Figure 1.2). Tagging studies have shown that the East Anglian coast is an important feeding area for post-smolts bred in the rivers of north-east England. These post-smolts appear as a by-catch in small meshed nets operated off East Anglia about two months after leaving those north-eastern rivers. Licensed fisheries operating off East Anglia have also targeted sea trout that have spent at least one year at sea and which are maturing to spawn in the following winter. These fish are exploited later along the Yorkshire and Northumbrian coasts on their return migration to rivers in the north-east.

These fisheries therefore offered a good opportunity to investigate sea trout throughout much of the marine phase of their life cycle. In two studies (**SF0204 and SF0221**) samples were collected to assess the growth of trout in the sea and changes in their diet during the year, in addition to changes in infestation by sea lice.

4.4.1 Marine diet of sea trout

The diet of the sea trout sampled was predominately fish and, of the identifiable fish remains, the vast majority were sandeels, including both lesser and greater sandeels, *Ammodytes marinus* and *Hyperoplus*

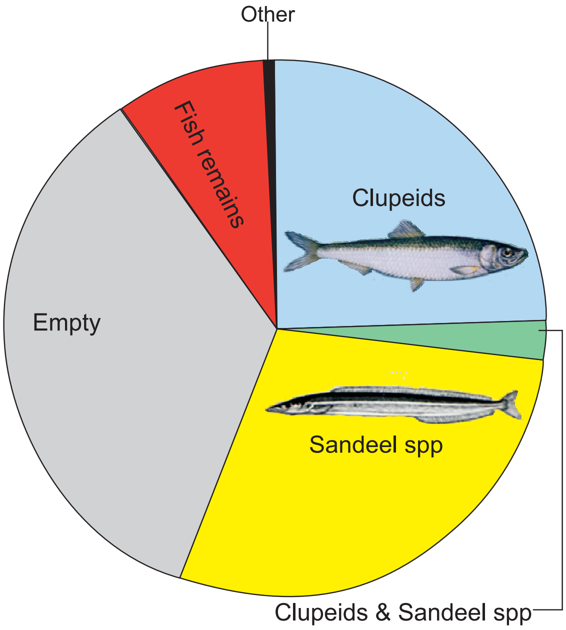

Figure 4.4 The marine preys of immature sea trout taken in the East Anglian fishery, showing the predominance of sandeels and clupeid fish in the diet

lanceolatus (Figure 4.4). There was a distinct seasonal pattern in the feeding on sandeels, with peak consumption in the spring and summer months, although the results also showed some inter-annual variation in timing. In summer, the larger trout fed mainly on sandeels, while the smaller trout took mostly small clupeids such as sprats (*Sprattus sprattus)*, which, in winter, became a major prey item. Various marine invertebrates were found in the trout stomachs, but rarely in any numbers, and some terrestrial insects were found on one occasion. Thus, sea trout in the southern North Sea appear to be opportunistic feeders making use of the most abundant prey, sandeels and sprats, of the appropriate size at different times of the year. The preponderance of sandeels in the diet, irrespective of sea area, supports the view that they can be an important food resource for sea trout around the coasts of England and Wales. Thus there is potential for sea trout to be affected by local depletions in sandeel abundance or availability, especially if suitable alternative prey species are unavailable.

4.4.2 Sea lice infestation

The infestation of sea trout by the external parasitic copepod *Lepeophtheirus salmonis*, which is specific to salmonids (Figure 4.5), and by the non-specific copepod *Caligus elongatus* were also studied. The statistical frequency distributions of both species conformed to an aggregated distribution typical of most parasites. In the southern North Sea the levels of infection for *L. salmonis* were typically low, with an overall average abundance of a little above three parasites per host. Monthly averages were also low, never rising above six lice per host. Infestation levels for *C. elongatus* were considerably higher, at about 42 per host on average. Both species of lice showed seasonal patterns of infestation with population size increasing during the late summer and autumn. *C. elongatus* tended to show larger annual differences in abundance than *L. salmonis*.

Salmonid-specific lice (*L. salmonis*) have been implicated as potentially harmful to migratory salmonid populations, particularly when post-smolts are carrying more than about 30 to 50 lice per fish. These studies demonstrated low baseline levels of sea lice infestation for marine-phase sea trout on the English east coast compared with observations in parts of western Scotland and Ireland. The low infestation therefore suggests that their effect upon east coast stocks is minimal, and this is particularly highlighted by the rarity (<1%) of fish carrying more than 20 lice.

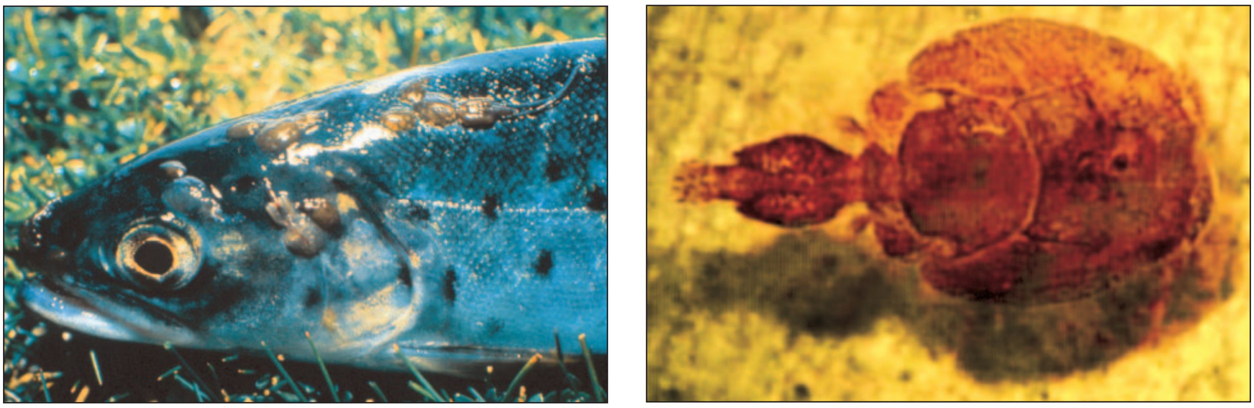

Figure 4.5 Salmon lice Lepeophtheirus salmonis (a) attached to a fish, and (b) a female in close-up

4.5 Uptake of the results of studies on marine ecology of salmonids

The current poor survival rate of salmon during the marine phase of their lives remains a major concern for the conservation and management of salmon stocks. However, research on these problems is inevitably complex and costly. NASCO has therefore formed the International Atlantic Salmon Research Board to co-ordinate research activities and to seek additional funding for international programmes. The studies currently being funded by Defra (**SF0230**, **SF0237**) will play an important part in this programme.

The pigmentation study confirmed that demographic analysis of trout spawning populations - at least, with respect to sea- and brown trout types - is possible and practical, using HPLC methods to examine carotenoid pigment profiles in eggs, in alevins and possibly in fry.

The results from the sea trout studies have been used in the provision of advice to Defra, the EA and ICES. Data collected on the Anglian Region sea trout fishery were used as a basis for proposed new byelaws and orders to regulate fishing activities. The base-line data collected on age, growth and diet of trout in the sea will provide a reference for comparison with other regional populations and for the identification of temporal changes. The overall state of health of the sea trout populations on the east coast of England were considered to be satisfactory, with sea lice infestations within normal recorded ranges and no evidence of other disease problems. These results were used to provide baseline information on lice infestation rates and to advise in international discussions about levels of lice infestations at other sites. The study was also used to advise a Co-ordinator of Fisheries Research and Development workshop on standardising methods for measuring sea lice infestations.

4.6 Publications and other outputs

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5. SALMONID OLFACTORY BEHAVIOUR

The projects addressed in this section are:

SF0201 Physiology of Salmonid Migratory Mechanisms (CEFAS)

SF0209 Olfactory Responses in Salmonids (CEFAS)

SF0213 Pheromone Reception in Salmonid Fish (Centre for Ecology and Hydrology))

SF0214 Pheromonal Control of the Behaviour and Physiology of the Atlantic Salmon (University of East Anglia)

SF0217 Role of the Major Histocompatibility Complex (MHC) in Kin Recognition, Mate Choice and Homing in Atlantic Salmon (Institute of Zoology, London)

SF0228 Impacts of Agricultural and Aquaculture Contaminants on Wild Salmonids (CEFAS)

5.1 Background

Many fish have evolved highly developed chemosensory and chemical signalling systems, which are mediated via olfaction (sense of smell), for communication in the aquatic environment. These systems serve various functions including own-species and kin recognition, predator warning, orientation, and for promoting reproductive synchrony. Consequently, any factor that limits the ability of the fish to detect and respond to these chemical signals could have direct, and possibly deleterious, effects on the status of the stocks.

By the 1990s, research had indicated that internal sex hormones and their metabolites could also function as external sex pheromones for signaling between individual fish (as in mammalian communication). These substances, which are excreted into the water, have distinct and fundamental roles in controlling the reproductive physiology and behaviour of fish. In Atlantic salmon, the olfactory system had long been thought to play a role in home-stream recognition by adults, but little was known about this process or the role of olfaction at other stages in the animals' life cycle.

Research was therefore proposed to investigate the role of chemical communication in salmonids as a basis for determining whether anthropogenic effects on water quality could disrupt those processes. Consequently, a research programme was initiated by CEFAS, in 1990, to study how salmon communicate with one another using olfaction.

5.2 Pheromone identification, functions and responses

The research began with studies on the identity and function of pheromones in the Atlantic salmon (**SF0201**). A range of steroids was tested and electrophysiological studies demonstrated that precocious (i.e. sexually mature) male parr showed strong responses to testosterone, but did not appear to be responsive to other steroids reputed to have pheromonal properties in other fish species. Interestingly, the olfactory epithelia of the parr were only responsive to testosterone for a limited period of the year (around October), suggesting that the response might be associated with reproductive behaviour. Behaviour studies then demonstrated that testosterone was also a potent attractant to mature male parr and stimulated strong upstream movements.

Studies were also undertaken on the role of urine as both the medium of release of pheromones and in chemical communication among Atlantic salmon (**SF0209**). Electrophysiological studies showed that the urine from an ovulated female salmon was required to prime the olfactory receptors of male salmon before they could detect a sex steroid (17,20ß-sulphate). Radio immunoassay of urine, sampled from adult and juvenile Atlantic salmon using miniature catheters, demonstrated that the urine was the principal mode of release of this sex steroid to the environment.

These studies also identified the F-series prostaglandins, ($PGF_{1\alpha}$ and $PGF_{2\alpha}$) as the chemical substances involved in priming the physiology of male salmon prior to spawning. The PGFs were found to have all the attributes of 'pheromones': they are released to the environment within the urine of female salmon that are preparing to spawn; they are detected by the olfactory system of the males; and they result in elevated levels of sex steroids in the blood and increased sperm production in the males. This was the first time that a 'pheromone' had been demonstrated in Atlantic salmon.

A number of other prostaglandin series were studied to investigate whether they were also priming pheromones and had a role in salmon reproduction (**part of SF0218,** also see Section 6). The A, B, D, E and I series of prostaglandins did not produce an olfactory response from the male salmon or result in a priming response in terms of elevated levels of plasma steroids or sperm production. Further studies, at the University of East Anglia (**SF0214**), found that other chemicals released by female salmon, either in urine, bile or across their gills, also did not consistently stimulate males. Such compounds included testosterone and sulphated testosterone. Thus, the F-series prostaglandins are the only identified salmon reproductive pheromones.

Finally, studies were conducted to determine whether the same olfactory mechanisms are found in brown trout (part of **SF0228**). Four of the F-series prostoglandins previously tested on salmon were studied together with female urine and ovarian fluid. Similar olfactory responses to reproductive pheromones were found in male brown trout; their olfactory epithelium was very sensitive to these substances at concentrations as low as 10^{-11} million (less than 1 part per billion). Thus trout respond to the same pheromones as salmon, which may be one reason that hybridisation occurs between these species.

5.3 Identification of putative steroid receptor sites in olfactory tissue

Studies were undertaken with trout to identify and characterise a possible olfactory receptor of the steroid hormone testosterone that was also capable of responding to external signals. The project (**SF0213**) involved electrophysiological studies on the olfactory tissues of 3-year old brown and rainbow trout reared at the CEH laboratory at Windermere. The aim was to locate and identify the specific binding sites, within the olfactory tissue, of molecules which may function as receptors of pheromonal substances.

The studies found that olfactory tissue of both trout species contains at least three specific binding sites for testosterone. They are located within the cell nucleus (nuclear fraction), the remaining cell contents (cytosolic fraction) and in the membrane fraction. Binding of testosterone in the nuclear and membrane fractions shows characteristics typical of binding to specific steroid receptors. No marked differences were found between the species or sexes in the affinity or capacity of testosterone-binding sites in the nuclear extract or membrane fractions. However, cytosolic testosterone-binding sites are 3-4 times more numerous in rainbow trout than in brown trout. They are also more abundant in female rainbow trout than in males, but show a lower affinity than male sites for testosterone.

The results indicate that the olfactory tissue of salmonids is capable of responding to testosterone present in the water. The intracellular sites of testosterone-binding show characteristics common to testosterone receptors in other fish tissues. This suggests that the development and/or function of salmonid olfactory tissue may be open to influence by endogenous testosterone. This is the first report of an androgen binding to olfactory tissue in fish, and of a membrane-associated androgen binding-site in fish.

5.4 Structure of the olfactory organs

A Scanning Electron Microscope study (**part of SF0201**) was undertaken on the development of the olfactory rosette in the Atlantic salmon (Figure 5.1) in order to investigate critical stages in the development of the olfactory sense in salmon. Of particular interest was the possibility that critical developmental stages might provide insights into the role and operation of olfaction in salmonids. The study indicated that olfactory receptor cells were evident in alevins within 1-2 days after hatching (Figure 5.1). Folding of the basal cells into discrete lamellae occurred within 3-4 months and the number of lamellae increased over the following 4 months. The rosettes developed rapidly in precocious male parr during the autumn, and the structure of the rosettes was identical to those of mature adult fish sampled on their return spawning migration. Histological analysis of the olfactory rosette in juvenile salmon also demonstrated rapid anatomical development of the olfactory epithelium during smoltification (**part of SF0209**). The number of secondary lamellae increased significantly at the

***Figure 5.1** Scanning electron micrograph of part of the olfactory rosette of a salmon parr showing basement membrane and ciliated cells (x 2300 magnification)*

smolt stage, which may be important in the process of home-river imprinting. The study showed that there were significant differences in the development of the olfactory rosette between wild and hatchery-reared fish; this may have implications for the behaviour of reared fish later in life.

5.5 Chemical recognition between individuals

Kin recognition can play an important role in competitive interactions, homing and reproduction and thus provides a further means by which the disruption of olfactory processes may affect populations. The role of chemical recognition between members of an individual brood (siblings) was therefore investigated by rearing separate family groups of salmon (**part of SF0209**). Electrophysiological recordings from the olfactory system demonstrated that siblings could distinguish between the urine derived from sibling and non-sibling fish. Behaviour studies indicated that fish were attracted towards urine derived from siblings but moved away from the urine of non-siblings.

This urine recognition may play a role in reducing inbreeding among adult salmon and in the territorial behaviour of juveniles, which are less aggressive towards siblings than non-siblings. It might also provide a mechanism for use in homing; returning adult salmon may orientate towards odours produced by related juvenile fish which are resident in the home-stream. Such an odour-based recognition system closely resembles a kin recognition and mate choice system found in mammals, which is based on genes of the Major Histocompatibility Complex (MHC) linked to the immune response mechanism. Essentially, in this system individuals with a similar MHC genotype (and odour) are recognised as kin, while those with a dissimilar genotype/odour are recognised as non-kin.

Studies were therefore initiated by the Institute of Zoology, London to investigate the function of MHC in Atlantic salmon and, in particular, its role in kin recognition **(SF0217)**. The overall aims of this project were to identify the MHC polymorphism in salmon and then to test for the association of MHC alleles with odour-based kin recognition between family groups, using experiments with artificially-reared full sibling families. Urine and tissue samples were collected from sibling groups in order to examine the role played by the 'family' of MHC genes in sibling recognition. Studies were also instigated to characterise the components of urine that siblings distinguish. If MHC is involved in kin recognition, it may also provide a novel genetic marker for discriminating between salmon stocks. It was therefore hoped that it would be possible to develop a rapid method for screening MHC variation and to evaluate its application as a tool that fishery managers could use for the discrimination of salmon stocks in the management of mixed stock fisheries.

It soon became apparent, that Atlantic salmon MHC is considerably more complex than was foreseen. Despite biological and technical problems, considerable progress was made with estimating the number of MHC genes, understanding their organisation, and with identifying those MHC genes which are functional and those which are non-functional. A method was developed for rapidly screening MHC variation which will allow assignment of a MHC genotype to individuals used in kin recognition and mate choice experiments. However, it appears that many of the MHC genes in Atlantic salmon are of relatively recent origin, and are therefore closely related and very similar at the DNA level. As a result, it was not possible to design strategies to examine variation in single MHC genes. Attempts to rapidly screen variation at several genes simultaneously produced patterns which are too complex to interpret reliably.

5.6 Uptake of the results of salmonid olfaction studies

Olfaction may be the most important sense controlling many aspects of the life cycle of the Atlantic salmon. Pheromones detected through its olfactory system are important in controlling both behaviour and physiological processes and they also play a role in synchronising reproduction and social interactions. This research on how salmon communicate with one another using olfaction was undertaken as a baseline for determining how these processes may be disrupted by the presence of chemical contaminants known to be present in many U.K. freshwaters. These follow-on studies are described next, in Section 6. At a time of declining salmonid stocks and often poor water quality, the results from these studies should improve general understanding of salmon physiology, thereby enabling Defra to protect stocks through clearer assessment of risks from existing background pollution levels or from future acute contamination incidents.

5.7 Publications and other outputs from olfaction projects

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6. SUBLETHAL EFFECTS OF POLLUTANTS ON SALMONIDS

The projects addressed in this section are:

SF0209a Marine Oil Pollution and Salmon (CEFAS)

SF0218 Ecotoxicological Factors affecting Salmonids CEFAS)

SF0228 Impacts of Agricultural and Aquaculture Contaminants on Wild Salmonids (CEFAS)

SF0241 Impacts of intensive in-river aquaculture on wild salmonids (CEFAS)

SF0303 Oestrogenic Consequences of Trace Organics (CEFAS)

6.1 Background

The studies described in Section 5, identified a pheromone that is involved in priming the reproductive system of male salmon just prior to spawning. The pheromone is released by the female in her urine and, when detected by the olfactory system of the male fish, results in an increase in plasma reproductive steroids and the levels of expressible milt. These studies have been used as a basis for investigations of the effects of environmental levels of persistent aquatic contaminants on Atlantic salmon and sea trout. The research has focused primarily upon the impact of agricultural pesticides on sensitive stages in the life history of salmonids, in particular embryo survival and development, the parr-smolt transformation and marine survival and reproduction. Both the olfactory and endocrine responses to the pheromone have been used as sensitive bioassays to assess the impact of four generic pesticides on olfactory mediated reproduction in the salmon. More recently, the studies have been expanded to examine the impact of mixtures of pesticides on these sensitive stages in the life cycle and also on the migratory behaviour of emigrating smolts

A further area of concern about the sub-lethal effects of chemical contaminants stemmed from the presence in rivers receiving sewage effluents of substances (oestrogenic chemicals now termed endocrine disruptors) capable of inducing the female reproductive process of vitellogenesis in immature and male fish. Vitellogenesis involves the production of an oestrogenic chemical, vitellogenin, which is a component in egg yolk. Its induction in male fish could clearly have serious impacts on the reproductive success of populations. The oestrogenic substances in rivers were known to derive from at least two sources, a constituent of the most commonly used contraceptive pills (17α-ethynyl estradiol), and alkylphenolic detergents used in wool factories. A major programme of research was therefore undertaken to measure the sublethal toxicological effects of these pollutants upon salmonid and coarse fish species, and to assess the risks posed to wild fish stocks.

6.2 Disruption of olfactory sense by acidification

The natural acidity index of salmonid rivers normally varies between pH 8.0 in highly calcareous waters to around pH 6.0 in acidic moorland streams (neutrality = pH 7.0). However, some waters may become more acidic through the afforestation of river banks with conifers. An electrophysiological study (**part of SF0201**) was therefore undertaken to see whether acidification adversely affects olfactory discrimination in Atlantic salmon. Recordings from precocious male parr indicated that olfactory responses to both testosterone and urine were significantly reduced when water acidity increased to pH 5.6, and were eliminated at pH 4.6. Similarly, at pH 5.6 and pH 6.6 significantly higher concentrations of testosterone and urine were required to produce the same amplitude of responses as that found in control fish in non-acidified water (pH 7). Acidification of streams may therefore significantly affect the olfactory ability of the Atlantic salmon and hence both its reproductive behaviour and physiology, and ability to home to their natal rivers.

6.3 Disruption of olfactory sense by pesticides

The responses of sexually mature male salmon to female pheromones have also been used as sensitive bioassays to assess the impact on salmon reproduction of four common pesticides (diazinon, carbofuran, atrazine and cypermethrin) that were known to be contaminants of both ground and surface waters in the UK. Routine monitoring had shown that these chemicals occurred in a number of rivers and tributaries supporting spawning salmon at critical periods during the freshwater life history (**parts of SF0209, SF0214, SF0218, SF0228**). A summary of the measured biological effects of these contaminants upon salmon is given in Table 6.1.

Diazinon is an organophosphate (OP) pesticide and one of the active ingredients used in dips to prevent and treat ticks, lice and scab on sheep. Diazinon has a proposed

Table 6.1 Sublethal effects of agri-chemicals found in rivers upon the reproduction of Atlantic salmon, in relation to water quality standards and monitored contamination levels (μg l^{-1} or parts per million)

	Diazinon Sheep dip	Cypermethrin Sheep dip	Carbofuran Insecticide	Atrazine Herbicide
Permissible Contamination levels:				
Annual average (EQS)[a]	0.01	0.0001-0.0002[b]	-	2[d]
Maximum (MAC)[a]	0.1[c]	0.002[b]	0.1[c]	10[d]
Environmental levels[e]	18.5-35	0.85	26	14
Threshold levels for harmful effects on salmon				
Olfactory disruption (males)	0.06[f]	>0.001[f]	1.0	0.04[f]
Sperm reduction/mortality		0.05	2.7	0.5
Embryo mortality/impairment	0.05	0.05		0.5
Smolt migration				0.5

[a] *EQS = proposed Average Annual Environmental Quality Standard*
MAC = Maximum Admissible Concentration
[b] *proposed levels*
[c] *general MAC for individual pesticides in drinking water, imposed by Water Act 1991*
[d] *joint with simazine*
[e] *maximum levels recorded in salmon rivers*
[f] *measured concentrations; other values are nominal*

Average Annual Environmental Quality Standard (EQS) of 0.01 μg l^{-1} and a Maximum Admissible Concentration (MAC) of 0.1 μg l^{-1}in the aquatic environment, but levels of diazinon within the range 18.5 - 35 μg l^{-1} have been measured in spawning tributaries. (Chemical formulations of pesticides are given in Annex 2).

This pesticide was found to have a sub-lethal effect on the olfactory system of the salmon, reducing the ability of the male fish to detect and respond to the priming pheromone that is important in synchronising reproductive physiology and behaviour in salmon. The olfactory system of the male was significantly affected by diazinon after exposure to concentrations of 0.4 μg l^{-1}, and endocrine response of the male to the pheromone was reduced after exposure to significantly lower concentrations (0.06 μg l^{-1}). Exposure of salmon embryos to environmental levels of diazinon (5 to 10 μg l^{-1}) resulted in significant mortalities, and other effects, including significantly increased levels of steroids and cortisol and reduced levels of the thyroid hormones, were also evident in the surviving embryos. These results suggest a significant effect on the growth and development of the embryos and may have implications when assessing effective egg deposition and determining whether spawning targets have been met in rivers.

Carbofuran is a water-soluble systemic insecticide used on winter crops. It has not been designated an EQS for the aquatic environment, but has been measured at concentrations up to 26 μg l^{-1} during autumn/winter. Effects similar to those observed for diazinon were recorded at concentrations as low as 2.7 μg l^{-1} (Figure 6.1). Carbofuran directly effected the olfactory system of the male salmon reducing the ability of the male fish to detect and respond to the female priming pheromone. Relevant plasma reproductive steroids were not elevated in the males and there was a significant reduction in the production of sperm.

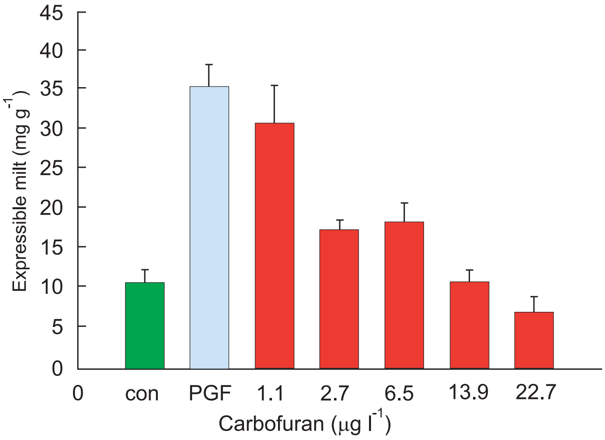

Figure 6.1 The impact of carbofuran insecticide on the priming response of salmon. Exposure reduces milt production in males by lowering their ability to detect the reproductive priming pheromone released by ovulated females. (Green bar shows milt production without priming; blue after normal priming; and red bars after priming in the presence of increasing concentrations of carbofuran)

Atrazine is a water-soluble pre- and post-emergence herbicide for the control of annual and perennial grass and annual broad-leaved weeds. It is known to have high mobility through soil and to be a contaminant of aquatic ecosystems in England and Wales. In 1992 and 1993, atrazine was one of the five agri-chemicals most frequently present in both ground and surface water at levels in excess of the MAC of 0.1 μg l^{-1} imposed by the Water Act 1991. Since 1993, the use of atrazine has been banned on non-cropped land and as a result there has been a decline in its detection in UK surface waters. However, its main use now is in the production of maize, particularly in SW England. Concentrations up to 275 µg l^{-1} have been detected in run-off water from agricultural land.

Exposure to environmental levels of atrazine (0.04 - 14.0 µg l^{-1}) resulted in a sub-lethal effect on the olfactory system of the salmon, reducing the ability of the male fish to detect and respond to the priming pheromone (Figure 6.2). Both plasma steroid levels and sperm production were significantly reduced at concentrations of 0.04 µg l^{-1} and above. Atrazine also had a further direct impact upon the testes of the male salmon, modifying the release of androgens, which suggests an additional toxic mechanism affecting reproduction. Previous studies on endocrine disrupting chemicals in UK rivers and streams have indicated that many are oestrogen mimics. However, it would appear that atrazine also modifies the production and metabolism of the androgens in the male which are involved in reproduction.

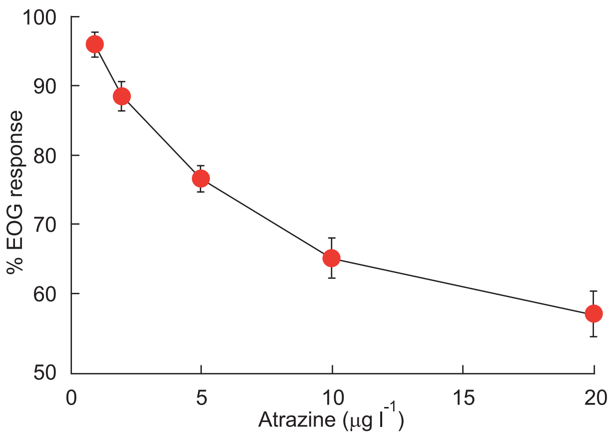

Figure 6.2 The effect of atrazine herbicide on the olfactory system of salmon. Exposure to increasing concentrations of this chemical reduces the ability of male salmon to detect PGF2α , the reproductive pheromone released by an ovulated female. (EOG = electro-olfactogram, a measure of olfactory cell activity)

The research on atrazine was further extended to examine its impact upon smolt physiology and the adaptation of juvenile salmon to saltwater. Smolts that were exposed to environmental levels of atrazine in freshwater were physiologically stressed at concentrations of 6.5 µg l^{-1}, as evidenced by increased plasma cortsiol, osmolarity and monovalent ion concentrations. Subsequent exposure of the smolts to seawater for 24 hours after prior exposure to sub-lethal levels of atrazine in freshwater, resulted in 14-28% mortality. Further studies (**part of SF0228**) undertaken by CEFAS in collaboration with the University of Stockholm have demonstrated that exposure of pre-smolts to low levels of atrazine inhibits migratory behaviour so that fish either do not migrate or there is a significant delay to the emigration. This has particular significance to the survival of smolts in the marine environment as there is believed to be a brief window of time for successful entry of smolts into the open sea.

Cypermethrin is a synthetic pyrethroid (SP) insecticide, which is increasingly being used as the active ingredient in sheep dips to replace the organophosphates (OPs). Although less toxic to humans than OPs, SPs are significantly more toxic to aquatic invertebrates and fish. Cypermethrin has a proposed EQS of 0.0001 to 0.0002 µg l^{-1} and a proposed MAC of 0.002 µg l^{-1} in the aquatic environment. However, levels of cypermethrin in excess of 0.85 µg l^{-1} have been measured during routine monitoring of surface waters.

Low levels of cypermethrin (>0.001 µg l^{-1}) were demonstrated to have a sub-lethal effect on the olfactory system of the salmon reducing the ability of the male fish to detect and respond to the female priming pheromone. As a consequence, there was a significant reduction in the sperm produced by the spawning male salmon. Exposure to 0.5 µg l^{-1} cypermethrin also reduced the motility and life of the sperm in water suggesting a secondary sub-lethal effect on salmon reproduction. Exposure of eggs and milt to cypermethrin during fertilisation within a hatchery had a significant effect on the subsequent development of the eggs. During exposure of the surviving eggs to the pesticide there was a significant decrease in egg weight and ionic content at all concentrations. A direct effect on fertilisation rates and embryo survival may have implications for salmon spawning targets and juvenile production in many rivers supporting salmonids.

6.4 Effects of pesticide mixtures

The research described above examined the effects on salmon of individual contaminants, but fish may also be exposed to mixtures of chemicals within rivers and tributaries. Where a mixture of pesticides occurs within the aquatic environment, the impact on the fauna and flora may be additive, antagonistic or synergistic.

Two pesticides that regularly occur together within watercourses are the s-triazine pesticides atrazine and simazine, both of which are herbicides used in the control of grasses and broad-leaved weeds. Short-term exposure of the olfactory epithelium of mature male salmon parr to either simazine or atrazine had the same effect on the ability of the male salmon to detect the reproductive priming pheromone released by females as combined doses of the two pesticides at the same overall concentrations. This showed that the effects of these two contaminants were additive and not synergistic. However, the two sheep dip insecticides diazinon and cypermethrin, which are commonly found together in tributaries during the salmon spawning season, acted synergistically. When environmental levels of the pesticides (Table 6.1) were combined, they had a greater disruptive effect on pheromonal mediated endocrine function in male salmon than did the individual compounds at the same total concentrations. A similar synergistic effect was seen on salmon embryos after a brief 2 min exposure of eggs and milt to mixtures of these pesticides during fertilisation. The contaminants had a greater impact on embryo survival when combined than when on their own.

Further studies were undertaken on the combined effects of the oestrogenic chemical 4-nonylphenol (4-NP) and atrazine. Exposure of salmon smolts in freshwater to environmental levels of 4-NP (Table 6.1) during the peak migration period had no significant effects on gill Na^+K^+ATPase activity, plasma vitellogenin levels or osmoregulatory performance. However, where smolts were exposed to mixtures of 4-NP and the pesticide atrazine at such concentrations, there were significant differences in the gill activity and plasma Cl^- and Na^+, and increased mortalities when the fish were transferred to seawater.

These studies highlight the need to take account of combinations of contaminants that may occur in the aquatic environment.

6.5 Marine oil pollution

In 1996 the grounding of the oil tanker ‘Sea Empress’ at the entrance to Milford Haven, in south-west Wales (Figure 1.2, Site 13), resulted in a major spillage of Fortes crude oil into the sea. Among many serious environmental and wildlife concerns raised was that of the possible effects on adult salmon and sea trout, returning to local rivers, of both the oil residues and the dispersants used in the clean-up operation. A particular concern was whether exposure to these chemicals would affect the salmonids’ ability to orientate and home to their natal rivers. An *ad hoc* electrophysiological study (**SF0209a**) was therefore initiated by CEFAS to determine whether exposure to the oil residues and dispersants affected the ability of Atlantic salmon to detect biological odorants (a reproductive pheromone and an amino acid).

Because it was not possible to obtain sufficient numbers of adult salmon to carry out the study at the time of the emergency, the effects of oil residues and dispersants were studied using mature male salmon parr in freshwater. The ability of the parr to detect the biological odorants was greatly reduced or eliminated after exposure of the olfactory epithelia to the water soluble fraction (WSF) of Fortes crude oil and the two dispersants used during the ‘Sea Empress’ clean-up operation. However, since information was not available on the concentrations of these contaminants in the sea during the clean-up, it was not possible to determine how severely fish may have been affected in the wild. Nevertheless, it was evident that the salmon parr were able to detect the WSF and dispersants at the concentrations likely to be present in the environment, and returning adult fish may therefore have been able to avoid the contaminated waters.

Exposure of smolts to hydrocarbons might also have disturbed their mechanism of olfactory imprinting. This might have a greater effect on sea trout smolts because they remain longer in coastal waters than do salmon, which migrate rapidly away from the immediate coastal environment. Any effect on imprinting is also likely to have an impact on the behaviour of homing adults.

6.6 Oestrogenic consequences of trace organics

Studies of the effects on fish of oestrogenic contaminants were initiated in the late 1980s. Research was commissioned (**SF0303**) to identify the extent of river contamination by oestrogenic chemicals present in sewage effluents, and to clarify the nature of the resulting biological effects on fish populations. Field studies, using caged rainbow trout, were conducted in six rivers, five in south-east England (the Stour in Kent, Arun in Sussex, Chelmer in Essex, Stour in Suffolk, Lea in north London) and one in the north (the Aire in West Yorkshire) (Figure 1.2). These showed that the magnitude of oestrogenic effects varied widely, and in at least two of the rivers (Lea and Aire), oestrogenic responses were detected to at least 5 km below the sewage discharge points. In the river Aire maximum stimulation of vitellogenin synthesis occurred at all sites tested. This was accompanied by reduced testicular development, and similar effects were seen also in the testes of fish placed in the river Lea.

Subsequent studies in the river Aire, after the introduction of an effluent treatment process designed to remove the high concentrations of alkylphenolic detergents, which were known to have oestrogenic effects, indicated that there was little reduction in the stimulation of vitellogenin in the caged fish. This negative result suggested that a mixture of other oestrogenic chemicals may have been present in Aire water and/or that the industrial treatment process was incomplete.

Laboratory experiments were conducted in which roach (*Rutilus rutilus*) were exposed to two other known oestrogens, 17α-ethynylestradiol and nonylphenol. The results indicated that this coarse fish species may be less sensitive than rainbow trout to oestrogenic stimulation by these chemicals, although roach are still able to respond. In zebra-fish (*Brachydanio rerio*), life-cycle studies have demonstrated that extremely low concentrations (1 ng/l or 1 part per billion) of 17α-ethynylestradiol can produce cessation of egg laying. Further work is needed to determine the mechanism by which this occurs and to test other known oestrogens for similar activity.

It was concluded that many chemicals from domestic and industrial sources that are found commonly in sewage effluents will act as oestrogenic mimics. The long term implications for fish populations exposed to such effluents are as yet unknown.

6.7 Uptake of the results of ecotoxicological studies

It is apparent that a range of physiological processes that are mediated through olfactory mechanisms may be disrupted by reduced water quality and that some contaminants can have adverse effects at very low concentrations. The research has shown that the impacts of environmental levels of contaminants can operate throughout the freshwater life cycle particularly at sensitive stages such as embryo development, reproduction, smoltification and entry into the marine environment. It is also evident that the freshwater and marine phases of the life cycle cannot be considered in isolation, and the exposure of juvenile salmonids to aquatic contaminants while in freshwater may be critical to their subsequent survival in the marine environment.

It therefore appears that the present permissible levels of certain pesticides in the aquatic environment may be too high, and as such may impose a significant biological risk to salmonid populations. The results of these studies are therefore being examined in this context and they have already been used in the USA to challenge permitted levels of pesticides because of their potential effects on populations of Pacific salmon. To obtain approval to use a new pesticide in the UK under The Control of Pesticide Regulations 1986, manufacturers submit a large quantity of data to the relevant Government Department. Approved pesticides may also be designated an Environmental Quality Standard, indicating the concentration of the substance which must not be exceeded in the aquatic environment. The standards are specific to individual pesticides and depend upon their toxicity, persistence and potential to accumulate in fish, plants and animals. However, the assessments are based mainly upon gross mortality studies, and as a result may underestimate the actual biological impacts of the pesticides on fish populations. The risk assessments undertaken when licensing pesticides for use within the environment may therefore need to be modified. One possible area for improvement is a change in the type of basic scientific toxicological data which is taken into account during final approval. More sensitive toxicity tests based on the sub-lethal effects of the pesticides on biologically sensitive life history stages of fish (e.g. reproduction and embryo survival) might provide a better indication of the levels that will not present a risk in the aquatic environment.

While the studies on agricultural pesticides have revealed a range of sub-lethal impacts, there are greater concerns about the potential effects of such contaminants on fish that may be exposed for longer periods, such as spring-run Atlantic salmon, non-migratory trout and coarse fish. In addition, contaminants may have a wider range of effects on the physiology of the fish. For example, since atrazine is known to have a direct effect on kidney structure and function in freshwater salmonids, it may affect the release of pheromones within the urine of the female fish even if there had been no initial effect on reproductive status.

This research is currently being extended (**SF0241**) to investigate contaminants emanating from intensive in-river aquaculture facilities. The range of substances found in aquaculture effluents includes pesticides, antibiotics and hormones/pheromones, and these may affect the reproduction and migration of the local wild salmonids. For example, chemicals used in fish farms for parasite and disease control may have similar effects on salmonid migration and reproduction as agri-pesticides but they raise particular concern because of their direct release into rivers.

The early studies (above) on oestrogenic contaminants formed the basis for an expanded programme (not covered by this report), funded by a consortium of four agencies including Defra, to assess the scale of this problem in both freshwater and marine environments. Current knowledge on the impacts of such endocrine disrupting substances on fish, including salmon and sea trout kept experimentally in contaminated estuaries, has been published recently (in 2002) by this consortium in their report, *Endocrine Disruption in the Marine Environment (EDMAR).* Results from the field exposure experiments, over realistic periods, suggested that endocrine disruption in salmonids in estuaries is not widespread, and it is unlikely that such exposure is a major factor regulating their populations in England and Wales. However, the results reported above suggest that there is a potential for endocrine disruptors to operate in combination with pesticides in estuaries to affect adversely the ability of salmon smolts to adapt to marine conditions.

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7. SALMONID MIGRATORY BEHAVIOUR

The projects addressed in this section are:

SF0201 Physiology of Salmonid Migratory Mechanisms (CEFAS)

SF0202 Migratory Behaviour of Adult Salmonids and Smolts (CEFAS)

SF0208 Biomagnetic Navigation in Salmon (CEFAS)

SF0211 Movements of Salmonids around Obstructions (CEFAS)

SF0216 A Climatological Study of Sea Surface Temperature and Salmon Habitat (Alliance for Marine Remote Sensing, Canada)

SF0219 Movements of Salmonid Smolts in Coastal Waters (CEFAS)

SF0230 (part) Salmonid Migration and Climate Change (CEFAS)

SF0232 Impact of Catch-&-Release, and Identification of Spawning Areas in the River Eden (EA)

SF0237 Modelling the Bioenergetics of Salmon Migration (Centre for Ecology and Hydrology)

7.1 Background

Atlantic salmon, and to a lesser extent sea trout, are renowned for their migratory behaviour and homing abilities. Most fish spawn in upland streams and their offspring spend the first half of their lives in freshwater before emigrating to the open ocean, where they rapidly grow and mature before returning to their natal rivers to spawn. This migratory strategy enables a large biomass of spawning fish to exploit a freshwater habitat in upland rivers which paradoxically contains insufficient food to sustain their offspring beyond the first few years. Any factors disrupting or preventing the movements of smolts down to the sea, or the upriver passage of returning adults to their spawning areas, can therefore have catastrophic effects on salmonid populations. Most harmful factors nowadays result from human activities and include the construction of physical barriers in rivers and estuaries, and the discharge of various pollutants which may deter the fish or interfere with the olfaction sense used to locate their natal streams (see also Section 6).

The emigration of salmon and sea trout smolts into the marine environment is thought to be a particularly critical stage in the life cycle. These fish may be especially vulnerable to marine predators and changes in environmental conditions, which may affect the availability of food. It is believed that mortality during the first few weeks or months at sea may be both high and variable between years and locations. Consequently, the relative strength of salmonid year-classes may be set early in the 'post-smolt' phase, and changes in the factors that influence emigration may therefore have adverse effects on both stocks and fisheries.

The behaviour of adult salmonids returning through coastal waters and estuaries is also critical to our understanding of how they are affected by net fisheries and other anthropogenic factors. For example, there have been a number of proposals to build tidal barrages across estuaries in England and Wales for amenity purposes or to generate hydro-electricity. Information is thus required on the behaviour of returning adult fish so as to advise on methods to minimise the impacts of these activities.

The broad remit for a succession of projects beginning in 1990 was therefore to describe the migratory behaviour of juvenile and adult salmonids in rivers, estuaries and coastal waters together with the natural factors (biological, physical and environmental) affecting and controlling their behaviour. This research required the development of acoustic and radio tracking equipment and methods for studying fish behaviour. This was followed by tracking studies on individual juveniles and adults in rivers, estuaries and the sea. Studies were also made of potentially harmful anthropogenic influences on salmonid migration, such as barrages and dredging activities.

7.2 Tracking technology and methods

Conventional tags and marks simply label a fish so that it can be identified at a later date, and such tags have been widely used to study fish movements. However, they provide no information on the detailed behaviour of individual tagged fish between the points of release and recapture. More detailed studies of fish behaviour have depended upon the development of a range of sophisticated electronic equipment which permit individual fish to be followed or which record their movements. In the 1980s, CEFAS developed a range of tracking systems that permitted the active and semi-automated tracking of adult salmonids in both salt water and freshwater environments. These systems were widely used in the UK for studying salmonid behaviour, but our ability to study smaller fish, such as smolts, was constrained by the size of the available tags. In the 1990s, the further rapid advance of electronics permitted the continued miniaturisation of tags and the development of more sophisticated tracking equipment.

7.2.1 Miniature smolt tags

It is essential that the attachment of transmitters to fish should have minimal effects on their behaviour. As part of the programme to track salmonid smolts (**SF0202**), CEFAS therefore continued their tag development programme to produce a 300kHz acoustic transmitter which was small enough for use on fish down to about 12 cm in length (Figure 7.1). This tag has permitted a range of novel investigations on wild fish and, after nearly 10 years, is still the smallest acoustic transmitter suitable for use on smolts. However, before field experiments began it was necessary to determine the most appropriate attachment method. Tags can be placed in the stomachs of smolts, but experience has shown that they are likely to be regurgitated quite quickly. External attachment also has disadvantages because it impedes movement, affects growth and may cause irritation or infection at the point of attachment. The study therefore investigated the effects of implanting the tags within the body cavity of the smolts. A procedure was developed which takes about 2.5 to 4.5 minutes and is achieved with a small ventral incision, which is sealed with two stitches after the tag is inserted. The fish recovers quickly and their growth, general behaviour, swimming ability and feeding are unaffected. Approval has been obtained from the Home Office Animals Inspectorate for use of this method in authorised tracking studies, and it has also been adopted by various other research groups.

7.2.2 High resolution tracking

Normal telemetry, using hand-held receivers, permits the position of fish tagged with radio or acoustic transmitters to be fixed with a precision of 10-50 m, while automated systems normally record the passage of fish past fixed positions along rivers or estuaries. However, in order to study the detailed movements of fish, for example in the vicinity of obstructions, there was a need to develop a system that could record the position of the fish more precisely and over extended periods. CEFAS therefore developed a high resolution tracking system that employed up to 10 acoustic receivers positioned around the experimental site. When a tagged fish moved into the array of receivers, acoustic signals ('pings') from a transmitter were received at a slightly different time by each buoy depending upon the distance from the tag. By comparing the time that the different signals were received it was possible to estimate the position of the fish with an accuracy of about 1m. This system was deployed in studies of the movements of adult salmonids and smolts around the Swansea barrage on the estuary of the River Tawe (**SF0211**) (see Section 7.5).

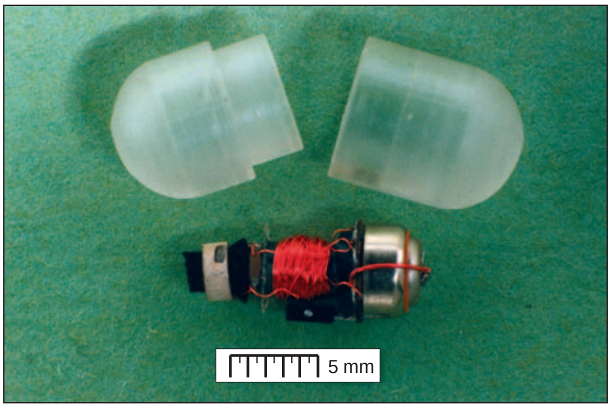

Figure 7.1 The CEFAS miniature 300 kHz acoustic tag used for tracking the movements of smolts in estuaries and coastal waters

7.3 Salmonid smolt migration in rivers and coastal waters

Salmon and sea trout smolts migrate to sea in the spring, usually in April or May as the river warms up. A series of telemetry studies has been undertaken in the estuaries of the Rivers Avon, Test and Fowey in southern England and the River Conwy in north Wales (Figure 1.2) to describe the normal migratory behaviour of smolts and the effects of environmental factors upon them (**parts of SF0202, S0219 and SF0230**). These estuaries were selected, in part, to provide a range of different conditions such as freshwater flows and estuary length. Fish were captured in freshwater and tagged with miniature acoustic transmitters as they began their seaward migration. Smolt movements within each river and estuary were then monitored using acoustic signal relay buoys located at intervals down the river and estuary. These buoys detect the signals from the acoustic tags and retransmit them to a series of dedicated radio listening stations. The offshore migration of smolts was investigated by detecting individual tagged fish passing through the lower estuary and then actively following them from a small research vessel as they moved out to sea.

Initial studies (**SF0202**) were conducted to compare movements of salmon and sea trout smolts in the Avon and Conwy estuaries. These estuaries provided very different conditions, the Avon having relatively stable freshwater flows and a short open estuary, while the Conwy is a spate river with a much longer and narrower estuary. Smolts entering the Avon estuary took less than a single tidal cycle to reach the sea, whereas most Conwy smolts took longer to emigrate, some remaining in the central part of the estuary for several days. In the fresh water and upper estuary of both rivers the smolts tended to migrate by night, although towards the end of the season the smolts migrated during both day and night. Seaward movements through the estuary occurred during ebb tides or, on the Avon, during the periods of slack low and high water. Smolts continued to emigrate seawards through the lower estuary and into coastal waters during the ebb tide, although the diurnal pattern of movement was not evident, and smolt migration occurred during both day and night. There was also some seaward migration of smolts during the latter part of the flood tide, suggesting active directed swimming. In all cases the smolts emigrated rapidly and there was no apparent period of acclimation required when moving from fresh to salt water. Current measurements suggested that the fish were migrating in the part of the water column where the flow was fastest.

These tracking studies were supported by laboratory experiments which showed that nocturnal migration is controlled by an endogenous diurnal pattern of swimming behaviour. The fish tended to move down in the water column or to remain on the bottom during the day and then to swim up during the night. This is consistent with the patterns of movements seen in the wild.
Further studies have been undertaken (**part of SF0230**) to describe the behaviour of sea trout smolts. Investigations in the River Fowey, Cornwall, have shown that sea trout smolts behave similarly to salmon, migrating by day and night in both fresh and estuarine waters, with a significant tidal component to the direction of movements within the tidal river section and estuary. Smolts moved downstream with the ebb and upstream on the flood tide, resulting in some smolts remaining in these tidal sections for up to eight days. Physiological measurements showed that the sea trout smolts were already adapted to marine conditions before they left freshwater.

In conjunction with the studies on the Conwy and Avon (**part of SF0202 and SF0219**) smolts were also followed into coastal waters. This was a time-consuming exercise because it was necessary to wait for fish to emigrate under their own volition and then follow them one at a time. The tracking vessel had to remain quite close to the fish, which can be difficult at night, in bad weather, or if the fish moves close inshore. Similar studies were also undertaken on the River Test where smolts could be followed into Southampton Water (Figure 7.2), thus providing an opportunity to study their behaviour during the intermediate phase between estuary migration and true open sea migration. Salmon smolts have been tracked for up to 18 km in coastal waters. As they enter the sea, the smolts seem to swim rapidly in a directed manner although there is often a strong tidal component to the speed and direction of movement (Figure 7.2). In contrast to

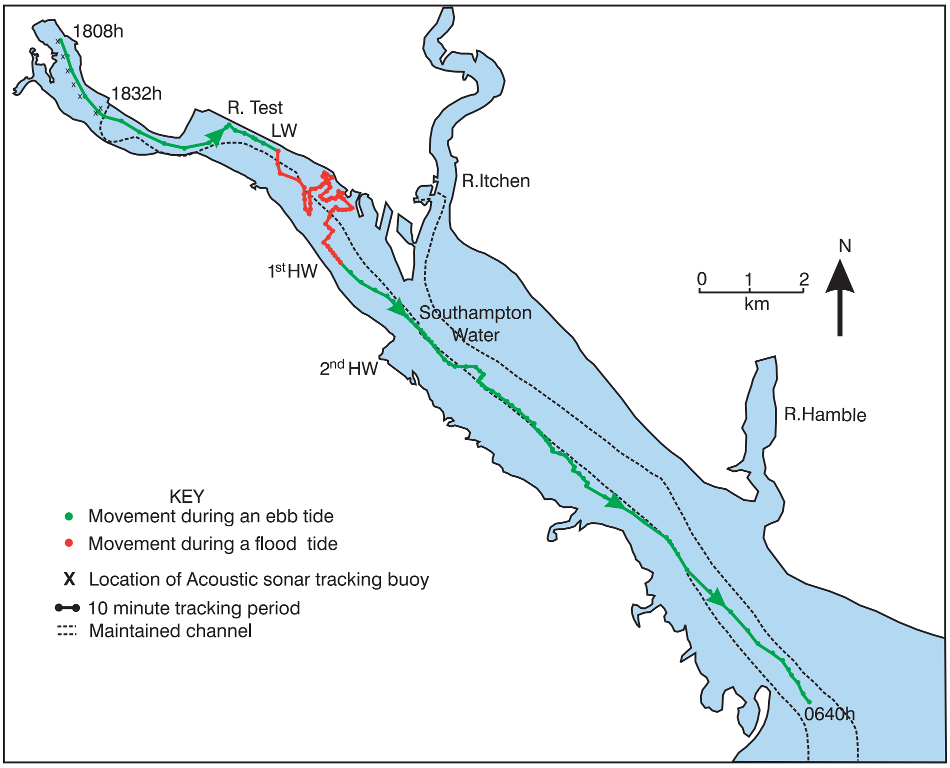

***Figure 7.2** The movements of an acoustically tagged salmon smolt through Southampton Water while emigrating from the river Test to the sea, as revealed by acoustic tracking. Seawards movements occurred during ebb tides*

the normal behaviour within the estuaries, movement occurs during both the day and night and the smolts remain close to the surface. These studies are on-going (**part of SF0230**).

7.4 Adult salmon movements in rivers and estuaries

Studies undertaken in the late 1980s had investigated the behaviour of adult salmon and sea trout in the Fowey estuary. These studies had shown that the fish have to wait for suitable river conditions, in particular elevated flows, before they could enter freshwater. In order to investigate this behaviour further, comparative tracking studies were undertaken on the River Avon (Hampshire) to see whether the fish would exhibit different behaviour in a river with more stable flows.

The study (**part of SF0202**) showed that adult salmon returning from sea and entering the Avon estuary usually moved quickly into fresh water, being delayed in the upper estuary only under exceptionally low flow conditions. The estimated proportion of salmon entering the river that appeared to be strays from other rivers was much lower for the Avon estuary (6.5%) than the Fowey estuary (27%), although some strays did remain in the Avon for more than 100 days. The two studies suggested that the behaviour of migratory salmonids in estuaries is strongly dictated by the topography, and fish may remain in the estuary for long periods if there are suitable holding areas. This has potential to significantly influence the effects of net fisheries upon stocks under different environmental conditions.

Tracking techniques have also been employed by the EA to investigate the effects of National Byelaws introduced in 1998 to protect spring salmon **(SF0232)**. These regulations require all salmon caught by rod before June 16th to be released alive, a practice (catch and release) that is also increasingly being adopted on a voluntary basis. Radio tracking was used to describe the movements, survival and spawning sites of spring-caught salmon ascending the River Eden in Cumbria (Figure 1.2). A total of 212 adult fish were caught, mostly by anglers, from different components of the spring and summer run and were radio-tagged and released; 134 of these fish were tracked to their spawning grounds using hand-held radio receivers and by a series of automatic listening stations located throughout the river catchment. Of the rest, 12 fish returned to sea, nine were known to have died while, for technical and other reasons, the others could not be tracked.

In the spawning season, radio-tracking showed that tagged salmon, and especially those from the spring run, were dispersed widely throughout the Eden catchment. Most spring-run fish were tracked to the Eamont catchment and to the River Lowther tributary, whereas later-run fish dispersed more widely. The importance of other parts of the Eden catchment for salmon spawning cannot yet be established, given the small numbers of salmon tracked to date. The study nevertheless showed that a high proportion of angler caught salmon that are released after capture can survive to spawning, and that catch-and-release angling can therefore be used as a viable conservation method for salmon.

7.5 Movements of salmonids around obstructions

Prior to about 1990, MAFF was required to advise on the design and siting of fish passes and to approve applications for their installation under the Salmon and Freshwater Fisheries Act 1975. The construction of estuary barrages presented a novel problem because salmonid behaviour in estuaries differs from that in rivers, for example in response to tides and currents. In order to learn more about the potential effects of estuary barrages on salmonids and to advise on mitigation, a study was initiated by CEFAS, in collaboration with the EA Welsh Region, to describe the behaviour of adult salmonids and smolts encountering the recently completed barrage across the River Tawe at Swansea (**SF0211**). This structure (Figure 7.3) is located 400 m from the sea and is a partial barrier, being over-topped by about one third of all high tides.

Adult salmon and sea trout were caught below the barrage, tagged with acoustic transmitters and then tracked as they approached and passed the barrage. The CEFAS High Resolution Tracking System was used to describe the movements of the fish close to the obstruction. Many of the fish were delayed in their upstream movements (Figures 7.4, 7.5), some making repeated approaches to the barrage on flooding tides, and only about one third of the adult fish tagged below the barrage were observed to move upstream into the river. Fish were attracted by the plume of water discharging from the fish pass, but few fish passing the barrage actually used the pass, most swimming over the weir while it was over-topped by the tide. Adult salmon were clearly disorientated and delayed by the restricted tidal movement close to the barrage and this may have resulted in greater mortality, for example from seal predation, and from expending more energy in order to enter freshwater.

Similar studies were undertaken on emigrating smolts. The construction of the barrage resulted in the formation of a largely freshwater impoundment along the 6 km length of the original estuary. This modified the tidal cycle and removed the strong ebb tide currents that the smolts would normally use to emigrate rapidly seawards. Emigrating smolts continued to move passively with the current, orientating to remain in the areas of maximum flow, but the reduced current in the

Figure 7.3 The Tawe barrage at Swansea at low tide; the stepped fish pass is visible on the left, between the lock and first weir

impounded area significantly increased the time taken to reach the position of the barrage compared with similar unobstructed estuaries. The smolts then held position immediately upstream of the barrage and were retained in this area for periods of up to 16 days. Salmon smolts spent significantly longer in this area than sea trout smolts, although both species appeared to move randomly and to show signs that they had difficulty detecting migration cues. These delays may result in them being subjected to greater losses, for example from increased bird predation, as they leave the estuary, and they may also enter the sea at a less favourable time.

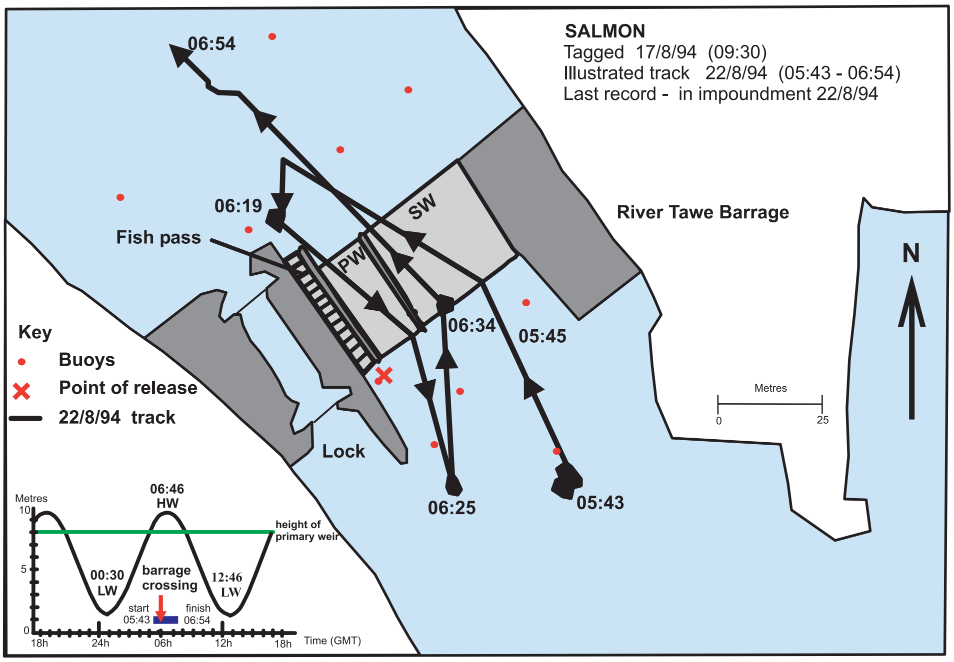

Figure 7.4 High resolution track of an adult salmon that showed quick upstream passage across the Tawe barrage on 22 August 1994. The fish approached the barrage fairly rapidly on a flood tide and crossed it over the secondary weir (SW) without significant delay about an hour before high water. It subsequently dropped back over the barrage, re-entered the impoundment about 15 minutes later (again over the secondary weir) before moving further upstream (out of detection range) fairly quickly. The horizontal bar on the graph indicates the duration of the track relative to the tidal cycle

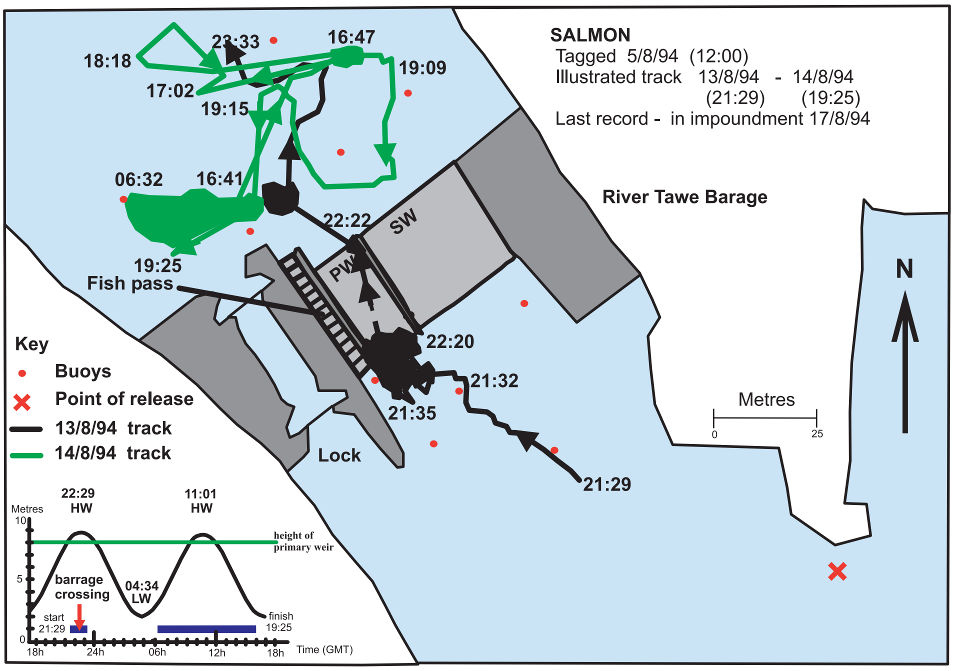

Figure 7.5 High resolution track of an adult salmon that was delayed at least two weeks during its upstream passage across the Tawe barrage in August 1994. The fish approached the barrage fairly rapidly on a flood tide (August 13), then held station adjacent to the plume from the fish pass for 45 minutes (black area) before crossing the primary weir (PW) at high water. It subsequently stayed within 50 m of the barrage for 71 minutes before moving further upstream, only to return close to the barrage for 13 hours on the next day (dark green area). Horizontal bars on the graph indicate duration of tracks relative to the tidal cycle

7.6 Biomagnetism and salmonid oceanic migrations

Very little is known about how salmon undertake their long marine migrations and return successfully to their natal rivers to spawn. Various mechanisms have been proposed including navigation by the sun, stars, or by magnetic or olfactory senses. Clearly, understanding these mechanisms might make it easier to predict the effects of anthropogenic and natural factors on salmon populations.

A CEFAS study (**part of SF0201**) was undertaken to determine whether Atlantic salmon possess biomagnetic particles which might assist them with orientation and navigation in the ocean. Magnetisation measurements with a superconducting quantum interference device (SQUID) magnetometer demonstrated the presence of magnetic material, particularly associated with the lateral line (Figure 7.6). The magnetic particles isolated from the lateral line and nerve had the characteristics of magnetite (Fe_30_4), were of a size suitable for magnetoreception

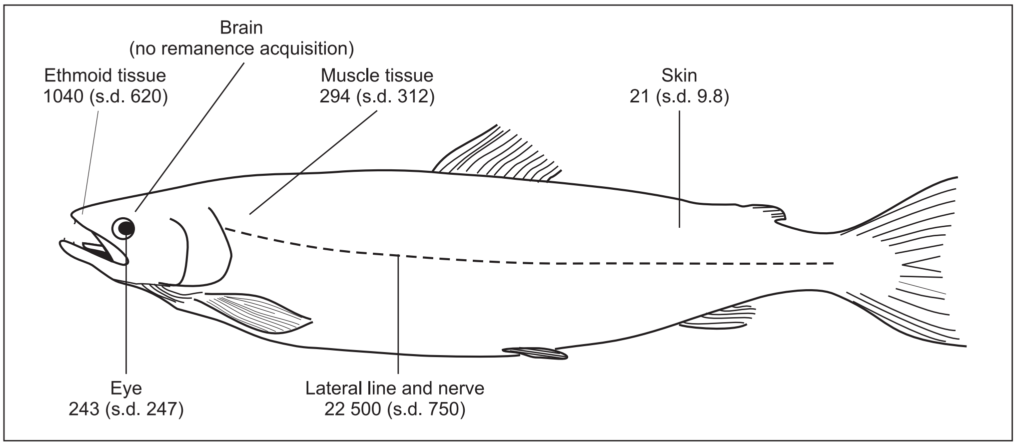

Figure 7.6 An Atlantic salmon showing measurements of 'magnetic remanence' in different tissues, indicating the possible distribution of biomagnetic ferric oxide particles that may play a role in navigation. Particle concentrations are denoted by SIRM values measured in pA m^2 g^{-1}

and appeared to be of biogenic origin. Calculations of the quantities of material present suggest that the particles would allow the salmon to follow a rough compass heading but would not permit them to orientate using a genetically derived map based upon contours in the earth's magnetic field. The lateral line and associated magnetic particles were suggested to have a role in allowing the salmon to orientate with respect to the geomagnetic field during the high-seas phase of their migration.

The results of the biomagnetic research generated widespread scientific interest and press reports. Further studies (**SF0208**) were planned to demonstrate how this sense may be used during migration, but the work could not be completed. A preliminary anatomical study demonstrated that the magnetic particles were located within the receptor cells of the lateral line organ. A further more detailed study on the innervation of the particles and receptor cells within the lateral line was partially completed by a student from the University of East Anglia along with a preliminary electrophysiological study of the feasibility of recording the responses to changes in magnetic field strength from the lateral line nerves. Similar magnetic particles were found in European eels but, unlike in salmon, the material was concentrated in the region of the mandibular canals of the eel's lateral line system.

7.7 Uptake of the results of salmonid migration studies

The results from these studies have been used in providing advice on a range of factors affecting emigrating smolts and returning adult salmonids. The timing and speed of movement of smolts through an estuary may be critical to their subsequent survival in the sea, and the research has produced some of the first detailed descriptions of the physiological and environmental cues controlling the migration of wild salmonid smolts in estuaries, as well as reliable indications of areas where smolts may be most vulnerable, for example to predation by fish, birds or seals.

Adult salmon movements back into freshwater are controlled mainly by river discharge, and the presence of holding areas will determine whether adult salmon remain within an estuary under unfavourable river discharge conditions. This can affect their vulnerability to fisheries, and such knowledge is routinely used in considering the effects of fisheries on stocks. These results were also used in the Salmon Advisory Committee's deliberations on effects of low flows on salmonid fisheries and factors affecting emigrating smolts and returning spawners.

Results from the study of fish movements around the Tawe Barrage showed the consequences for salmonids of a major estuarial obstruction placed across their migration routes and provided a basis for advice relating to the possible effects of other proposed barrage schemes (e.g. River Usk and Cardiff Bay) on salmonid stocks. Published reports from the project were also used in the Public Inquiry relating to the Usk barrage proposals. Advice has also been given on operating procedures to reduce the impact of existing barrages (e.g. Rivers Tawe and Tees) on migratory salmonids.

There are currently serious concerns about the decline in survival of salmon stocks during the marine phase of their life-cycle. Determining appropriate responses to these changes depends upon understanding the factors affecting the migratory behaviour and distribution of salmon in the sea. While many of the factors affecting salmon in the sea, such as environmental change, may be outside our immediate control, research has demonstrated that there are anthropogenic factors operating both in freshwater (e.g. use of pesticides) and in the sea (e.g. pelagic trawl fisheries) which may affect post-smolts and which could be more tightly regulated to reduce their impacts. Work is therefore continuing to investigate salmon in the sea both through practical tracking studies in coastal waters (**SF0230**) and by means of a new modelling study to investigate the effects of food availability and marine conditions (**SF0237**).

7.8 Publications and other outputs from migration projects

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8. SALMONID POPULATION GENETICS

The projects addressed in this section are:

SF0102 Genetic Identification of Atlantic Salmon Populations (CEFAS)

SF0103 Genetic Protein Variation in Atlantic Salmon in the British Isles (Queen's University, Belfast)

SF0210 Molecular Genetics for the Discrimination of Salmon Stocks CEFAS)

SF0223 Behavioural Genetics and Spawning Success of Spring-run Salmon (University of Stirling)

SF0224 Detection of Triploidy in Rainbow Trout and Brown Trout (University of Reading)

8.1 Background

Genetic diversity is an important feature of animal populations. A loss of diversity may affect the fitness of individuals and reduce the potential of populations to adapt to changing environments. The susceptibility of a fish species, such as salmon, to loss of genetic diversity through exploitation or other anthropogenic factors depends in part upon its population structure. Species with sub-populations that are strongly or completely reproductively isolated may be particularly prone to rapid loss of genetic diversity. The homing behaviour of Atlantic salmon to their natal river system has long been thought likely to produce a series of populations that are at least partially reproductively isolated from each other and adapted to their local environments. Atlantic salmon from a number of these putative populations may be exploited in coastal and oceanic fisheries along their migration routes, and there is therefore a potential for fisheries, or habitat loss, to selectively deplete individual populations and thus increase the rate of loss of genetic diversity.

Small populations are also liable to rapid genetic change through gene flow, acting through natural dispersal or stock transfers by man. The genetic adaptation of declining salmon sub-populations to their local conditions could therefore be affected by long-term consequences of supplemental stocking with fish from other rivers or by inter-breeding with escaped fish from salmon farms. Mating between native and non-native salmon has the potential to alter the constitution of the native gene pool and breakdown co-adapted gene complexes.

Genetic differences between river stocks may also provide a means for identifying salmon from different rivers or regions. Such information would be of great help in the management of distant water or coastal mixed stock fisheries, and an ability to discriminate between salmon stocks and identify largely non-interbreeding populations is therefore of considerable importance for stock conservation. Modern molecular techniques may also allow us to investigate relationships between individual fish and thus learn more about their behaviour which may assist the management of spawning populations.

A group of projects was therefore undertaken to provide information on geographical patterns of genetic variation taking advantage of the rapid advances in genetics techniques experienced during the past decade. Initial projects in this series examined historic data from allozyme studies; but the work then progressed to employ the developing molecular techniques and to study genetic variability within single stream populations.

8.2 Genetic identification of Atlantic salmon stocks in the British Isles

Various techniques have been developed for discriminating genetic differences between individuals or populations. One approach is the use of 'electrophoretic separation' to examine variation in genetically determined proteins. For some genes there are two or more variants (alleles) which will produce slightly different proteins (allozymes). Each individual receives one allele from each parent and these may be the same or different. Individuals are therefore characterised by the combinations in which the alleles are paired, and populations can be compared by the overall frequencies with which the alternative alleles occur. (Explanations of some terms are given in Annex 2).

Such electrophoretic studies can demonstrate genetic differences between fish populations, although these cannot generally be directly linked to biological characteristics. However, it is possible that these differences are indicative of variations throughout the whole genome which allow each population to be adapted for its particular environment.

Three studies were undertaken: a preliminary literature review at Queen's University, Belfast (**SF0103**) and two practical investigations at CEFAS (**SF0102, SF0210**).

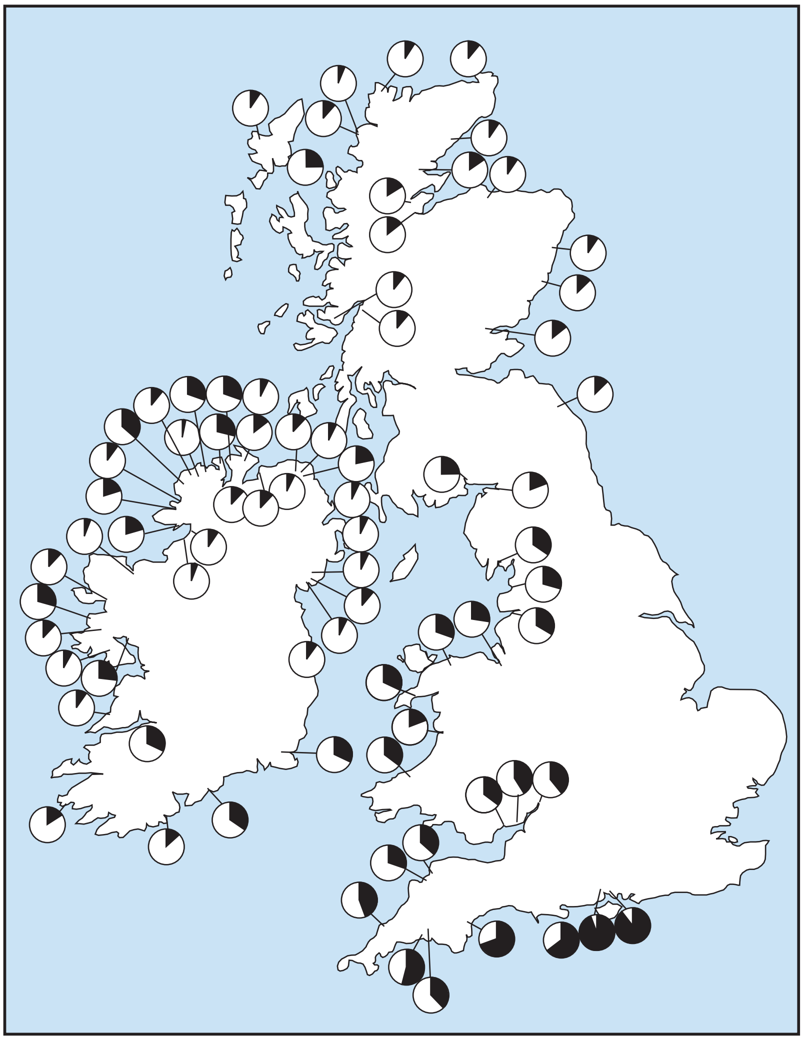

*Figure 8.1 The geographical pattern of genetic variation in Atlantic salmon between rivers in the British Isles. Population differences are revealed by variation in the amount of the allele AAT-4*50 present in fish (denoted by the proportion of black in the circles).*

8.2.1 Genetic protein variation

An initial review was undertaken in the early 1990s to examine the results from allozyme studies on salmon taken from 76 rivers throughout the UK and Ireland (**SF0102**). The collected data represented one of the most comprehensive sets available on allozyme frequency variation in any species within a limited geographical area. Statistically significant differences in allele frequencies were found among population samples both within and between river systems. Figure 8.1 shows the geographical pattern of frequency variation between rivers in the AAT-4*50 allele. The survey results also suggest that within major river systems the salmon cannot be treated as single populations. However, the degree of population differentiation was low compared to the maximum possible, and to that observed in brown trout over the same geographic range. Most genetic variation did not show strong geographic patterns and there was no evidence for discrete celtic and boreal races of salmon in the British Isles, as had been suggested previously.

8.2.2 Mitochondrial DNA analysis

With the development of methods to analyse mitochondrial DNA (mtDNA), a study (**SF0210**) was initiated in the early 1990s to apply the approach to investigate genetic variability among wild populations of salmon and compare these with protein allozymes in tissue samples taken from salmon parr and smolts caught in 15 rivers throughout England and Wales. Collaborative research between CEFAS and the University of Buckingham showed differences in mtDNA between parr from the Rivers Itchen and Conwy. Major differences were also recorded between parr and smolts of the same year-classes sampled in the same part of the River Itchen, which suggested differential survival or emigration rates of different genetic groups. Parallel allozyme studies showed slight but significant allele frequency differences in most populations, notably between salmon from the Test and Itchen rivers and those from elsewhere.

8.3 Use of molecular genetics to discriminate salmon stocks

Further work was undertaken to investigate changes in the genetic composition of salmon in the River Test, Hampshire, where the fish had been found by an earlier study (**SF0102 above**) to be distinctly different, at the sAAT-4* locus, from salmon in other rivers (Figure 8.1). The Test had been stocked with hatchery-reared fish and these releases included fish derived from a Scottish stock which was thought to produce a high proportion of multi-sea-winter fish. There were concerns, however, that the introduction of non-native fish, may have a detrimental effect upon the overall 'fitness' of the native Test population. Tissue samples from many batches of stocked (released) fish, from wild parr and adults, and from brood-fish being stripped in the local hatchery, were examined therefore for genetic variation at the sAAT-4* allele locus.

This study indicated that the genetic make-up of the Test stock had already been significantly modified by introductions of salmon parr from other sources. The genetic compositions of the introduced Scottish juvenile fish were found to be clearly different from that of the indigenous Test fish. However, the study also revealed further confusion between the stocks, suggesting that inadvertent mixing of Test and Scottish fish had occurred in the release programme. Although, all further introductions of parr to the River Test after 1994 should have been derived from fish of Test origin, some subsequent releases also appeared to differ from the original Test stock.

Changes in the frequency of the sAAT-4* alleles indicated that the stocking had resulted in a significant introgression of the Scottish genotype, although there was no evidence that this had increased the multi-sea-winter component in the stock.

8.4 Behavioural genetics and spawning success of spring-run salmon

Effective salmon management frequently depends on the appropriate interpretation of routine spawning census data, such as counts of the number of ascending adults or of spawning redds. However, such data may be misleading if fish have variable spawning success or spawn more than once, and so information is also required about the mating behaviour of salmon and its consequences for genetic variability and differentiation within a river system. The development of highly variable minisatellite DNA markers for Atlantic salmon studies provided the practical means to identify close kinship in this species, and DNA profiling ('finger-printing') afforded the opportunity to study in detail salmon mating behaviour and its consequences in both experimental and natural populations.

A study (**SF0223**) was therefore undertaken in the Girnock Burn (Figure 8.2), a tributary of the River Dee in Aberdeenshire (Figure 1.2, Site 1), by the University of Stirling to establish the degree of genetic variation in a salmon population - in a single highland stream - and to relate this to observed patterns of spawning behaviour and success. Intensive DNA sampling of returning spawners, and fertilised eggs from resultant redds (Figure 8.3), was achieved over several years (1991-1995). The aim was to measure the spawning pattern and success of individual returning migrants, by assigning parentage to all identified redds, and to subsequent progeny within the redd.

Figure 8.2 Upper Girnock Burn, a tributary of the River Dee, Aberdeenshire (© D. Hay)

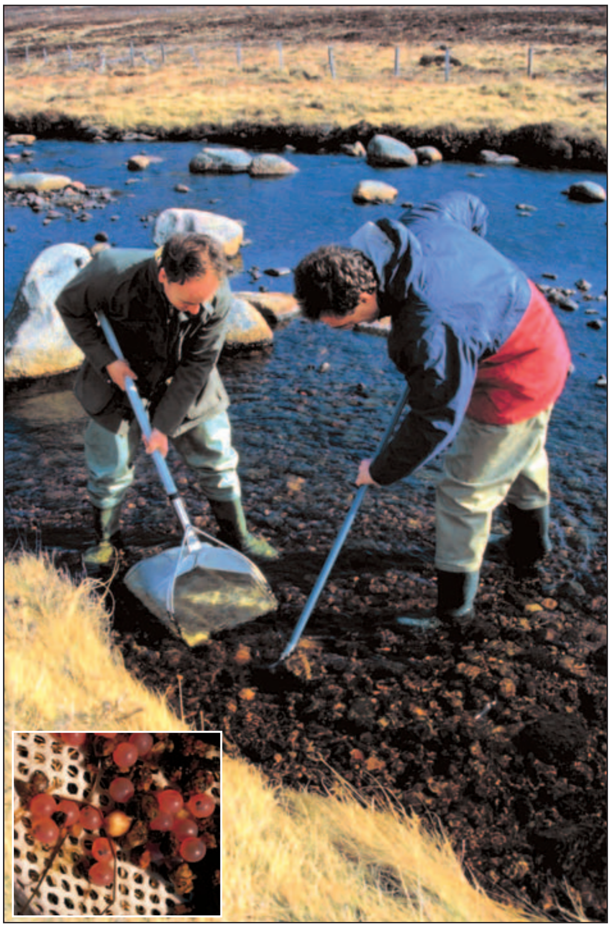

Figure 8.3 Redd-excavation sampling on Girnock Burn. Inset: salmon ova from redd (© D. Hay)

8.4.1 Spawning behaviour

The spawning behaviour of Atlantic salmon was found to be unexpectedly complex. Multiple spawning by individual adult fish was prevalent; more than half of detected adult spawners of both sexes contributed to more than one redd, with up to six redds for a single female and seven for a single male. The distance between redds involving the same parent varied in both sexes from a few metres to more than 5 km, and distances of more than 1 km were common. Adult salmon did not remain monogamous, but males and females mated with different partners at different sites. Mature parr achieved very high levels of mating success, (40-50% of total progeny being recorded), indicating that these are likely to contribute greatly to the effective population size. Overcutting (super-imposition) of redds was more common than expected (13-22%), though this behaviour was not correlated with the number of anadromous spawners present.

Thus, Girnock Burn progeny of any one year comprise a complex series of half-sibling families, whose genetic relatedness is further complicated by accurate homing, overlapping generations and co-existing male strategies of pre- (parr) and/or post-sea migratory sexual maturation. At an individual level the various mating tactics observed may be explained in terms of 'genetic risk spreading' within a heterogeneous environment. The net result at the population level is the maintenance of a high level of genetic variability within the tributary, which is unlikely to be significantly affected by short-term fluctuation in numbers of adult spawners. Differentiation between tributaries may be expected if mature parr do not migrate and levels of anadromous straying between rivers remain low.

Genetic variability within the Girnock (and nearby Baddoch) Burn was high, and at the upper limits of the range observed for a number of European salmon populations. Within-sample variation accounted for more than 99% of the genetic variability detected. There was no evidence that the grilse and multi-sea-winter components of the run were genetically distinct. These findings do not conflict with predictions based upon behavioural spawning data.

8.5 Detection of triploidy in cultivated trout

Fish farmers often use chemical techniques or pressure shock to induce triploidy in fertilised eggs. The commercial advantage of triploidy is that offspring hatching from treated eggs grow faster than fish hatched from normal diploid eggs, and male fish do not exhibit secondary sexual characteristics that affect their marketability. There is also felt to be a benefit for conserving natural biodiversity in that triploid fish are reproductively sterile and thus are unable to interbreed with and genetically contaminate wild stocks should they escape or be released. However, triploidy induction rates have often proved to be variable and unpredictable, and could be measured only by waiting until first signs of maturity appeared, or by sophisticated analysis (flow cytometry) of red blood cells from groups of fry. This short (3 month) project (**SF0224**), at the University of Reading in 1997, was commissioned to overcome this bottleneck in hatchery procedures, and thus promote the production of triploid fish by trout farmers.

The aim was to develop a simple, rapid and reliable assay to determine accurately the percentage of triploid eggs obtained after treatment in trout hatcheries. The intended method for assessing the success of triploid treatment was fluorescent *in situ* hybridisation.
In this, a labelled DNA probe is hybridised to complementary sequences in 'intact' cells and then viewed by fluorescent microscopy. The objectives of this exploratory project were to produce, by cloning, a sequence specific DNA probe using trout DNA, and to develop *in situ* hybridisation technology by setting up a tissue culture system.

Unfortunately, attempts to produce a specific DNA probe were unsuccessful, in the short time available, because the molecular weight of primary trout DNA appeared to be too high for cloning. The researchers recommended that future attempts should proceed by the construction of an appropriate genomic library, based on carefully prepared genomic DNA originating from cultured trout cells. The basic feasibility of the hybridisation technology for trout cells was demonstrated using a ribosomal DNA (rDNA) model system. Some guidelines were derived upon which future work could be based, and a set of recommended protocols was produced. Two cloned trout rDNA plasmids, vitellogenic primers, and DNA from cultured trout cells were stored for future application.

8.6 Uptake of the results of salmonid genetics studies

The results from studies of genetic differences between stocks and populations have continued to be used to support policies for the conservation of salmon stocks and the management of fisheries. The findings indicate that a cautious policy in relation to restocking of salmon rivers is genetically sound, and have been used to advise on salmon stocking policies in England and Wales. The investigations with new molecular techniques have demonstrated that this is a powerful tool to study salmon population structures and behaviour.

The stream studies have indicated that salmon spawning behaviour is far more complex than previously thought. Future management plans may need to take account of the contribution of mature parr in maintaining genetic variability within, and differentiation between, individual river populations. The results also indicate that the redd counts and other purely observational spawning data provide only a superficial view of both the extent and pattern of spawning, and should be interpreted with caution. These studies may therefore have significant implications for the use of spawning targets in salmon management.

The brief exploration of applying a new genetic technique to assist trout farmers showed potential but needed further time to set up and optimise the technology. It may be appropriate for such initiatives to be explored further by the aquaculture industry.

8.7 Publications and other outputs

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Webb, J.H., Fryer, R.J., Taggart, J.B., Thompson, C.E. and Youngson, A.F., 2001. Dispersion of Atlantic salmon (*Salmo salar*) fry from competing families as revealed by DNA profiling. Can. J. Fish. Aquat. Sci, 58(12): 2386-2395.

9. ASSESSING SALMONID STOCKS

The projects addressed in this section are:

SF0207 The Status of Atlantic Salmon in the River Frome, Dorset (Centre for Ecology and Hydrology)

SF0226 The Development of Applications and Validation Methods for Hydroacoustic Salmonid Counters (EA, CEFAS, Fisheries Research Services (Scotland), and the Spey Research Trust)

9.1 Background

The research described in this Section is closely linked with the routine monitoring and assessment undertaken by the CEFAS and the EA to support the regulation of salmonid fisheries in England and Wales and to provide annual advice to ICES and NASCO for the management of the distant water salmon fisheries. CEFAS and the EA have been at the forefront of international efforts to advance salmon assessment methods, and their use of conservation limits in England and Wales has developed in line with the requirements of ICES and NASCO and the need to manage and conserve individual salmon stocks. The EA has developed methods for setting conservation limits, and provisional levels have been established for all principal salmon rivers and are being refined as Salmon Action Plans are prepared. CEFAS has led the development of methods to assess the national status of salmon stocks in the North East Atlantic.

These programmes have been supported by monitoring programmes on both juvenile and adult salmon. The sound management of fish stocks, as with any natural resource, depends upon by being able to obtain reliable measures of their abundance. In the absence of such data, the effects of exploitation will be more uncertain, and protection and conservation of stocks will be more difficult. An ability to estimate stock abundance is also an essential component of studies of the structure and abundance of populations and the effects of various natural and anthropogenic factors on them. Such studies provide the basis for setting biological reference levels, against which the status of stocks may be evaluated and management requirements determined.

Measuring the abundance of migratory salmonid stocks is greatly facilitated by the fact that all emigrating smolts and returning adults must pass through the lower reaches of a stream or river. Various counting systems have therefore been developed, and counts derived from such facilities on around a dozen rivers in England and Wales are routinely used to develop management advice and determine the effects of regulations upon stocks. However, the use of automatic counter systems may be constrained by a range of factors, in particular the size of rivers on which they can be installed.

The two projects described in this section address the analysis of a long time-series of data obtained from an existing counter and the development of new counting methods for use on large river systems.

9.2 Stock abundance methodology: development of new salmonid counters

Conventional systems for automatically counting migratory fish, such as resistivity counters, have to be installed on gauging weirs, or in fish passes or similar structures where migrating fish are confined to a narrow channel. This limits their application, particularly for large rivers where the cost of constructing or modifying a weir or pass for the installation of a counter can be prohibitive. Unfortunately it is the larger river systems that tend to support salmon stocks with high proportions of multi-sea-winter fish, and it is these stocks that have suffered the greatest declines in recent years and where there is therefore an urgent need to obtain more reliable data as a basis for management decisions. New advances in hydroacoustic techniques in the 1990s appeared to offer the opportunity for developing cost-effective counters that could be used on some of the larger salmon rivers in the UK without major engineering works. Defra therefore funded a study involving the EA, CEFAS, Fisheries Research Services (Scotland) and the Spey Research Trust, to investigate the operational value of hydroacoustic fish counters, and to encourage the uptake of the technique, by fully evaluating and testing the technology, from initial deployment through to validation methods, in different river types (**SF0226**). The core development work was carried out at three established fixed location hydroacoustic counter sites on the River Wye (England/Wales border), River Spey (north-east Scotland) and River Tavy (south-west England) and, later, at a new site on the River Teifi in west Wales (Figure 1.2).

The study evaluated the Hydroacoustic Technology Inc. (HTI) Model 243 split-beam 200 kHz or 420 kHz system, which has been widely used in North America to monitor salmonids passing dams on impounded rivers. The heart of the hydroacoustic system is the transducer (Figure 9.1), which is fixed in the river or fish pass and emits high frequency sound pulses and then 'listens' for any returning echoes. These echoes are transmitted by cable to the acoustic counting and data recording apparatus, housed nearby in a secure site (Figures 9.2), and analysed to identify passing fish. Continuous recording and analysis of fish movements was maintained over long periods at the four experimental sites.

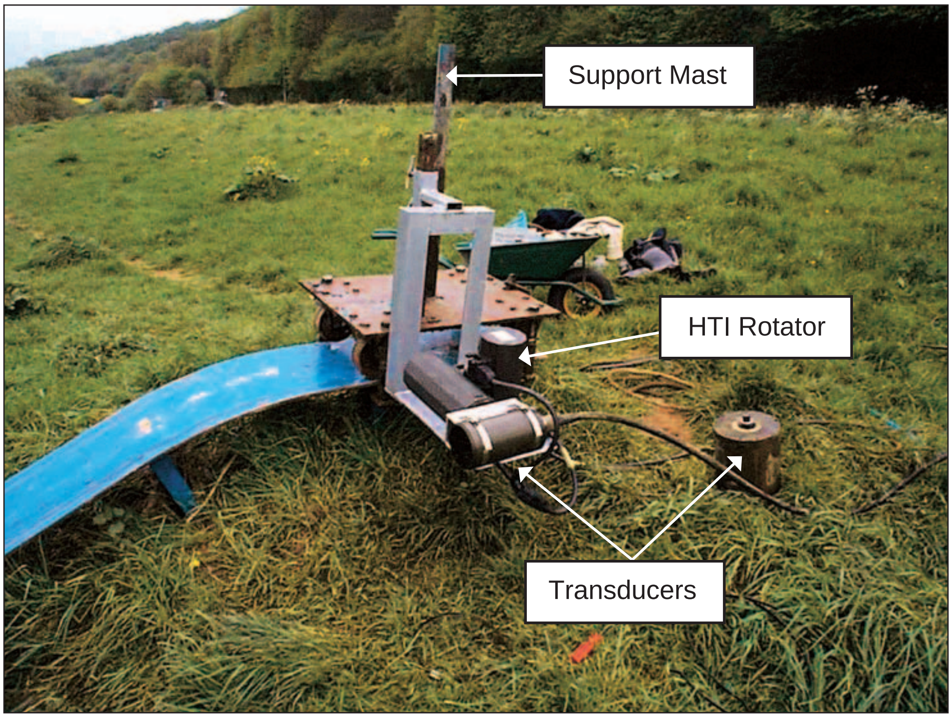

***Figure 9.1** Hydroacoustic counting of salmonids in rivers: transducer and rotator mounted on a metal trolley prior to deployment in the river (© Environment Agency)*

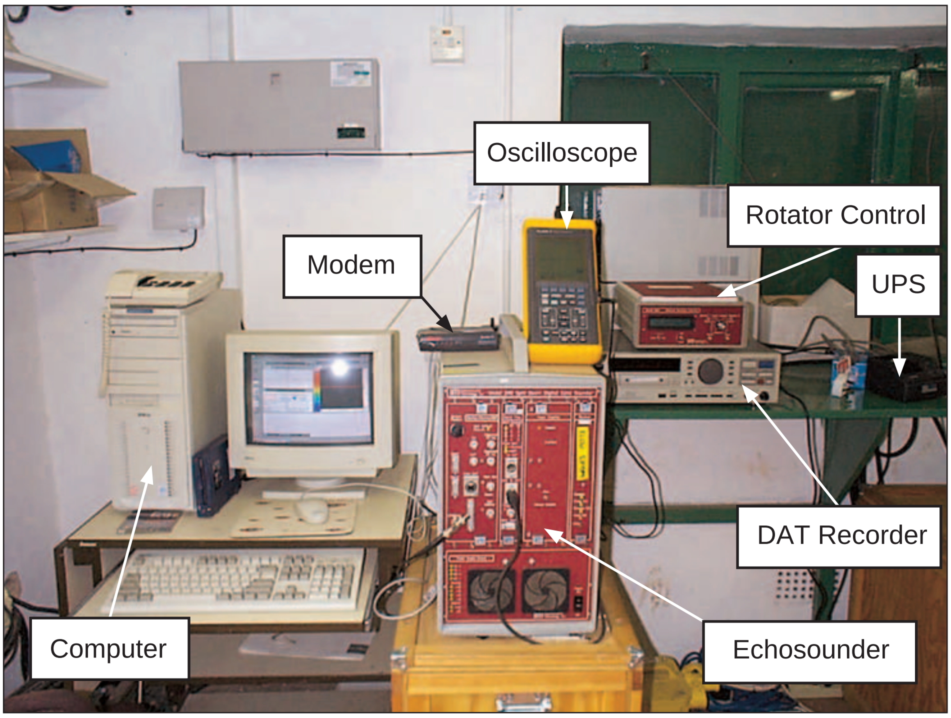

***Figure 9.2** Hydroacoustic counting of salmonids in rivers: HTI Model 243 acoustic counter and auxiliary equipment housed securely on river bank; UPS denotes the uninterruptible power supply unit (© Environment Agency)*

An essential step in commissioning any counter is to determine whether the counts actually represent the real numbers of each target species moving in the river. The fish detection rate (proportion detected and counted) and the incidence of spurious counts (false readings due to flotsam and non-target species, for example) therefore needs to be checked. Validation is the process by which such errors are identified and quantified under operational conditions, at different times and over a range of flow conditions. Checking the acoustic counts at each site required comparison with a fully independent visual method of measuring fish passage. In this case, an efficient computerised video system for image analysis was developed by the EA in order to automate the processing of large amounts of information collected from an array of video cameras.

In rivers with mixed salmon and sea trout populations it is important also to be able to assess reliably the ratio of the two species in a river's total salmonid spawning stock. The acoustic signals (echoes) from salmon and sea trout proved to be too similar for reliable identification of individual fish, but the problem was resolved by using underwater video cameras, operated at intervals in conjunction with the acoustic counter, to identify the ratios of salmon to sea trout passing during specific sampling periods. A statistical model was then developed to estimate the total numbers of each species.

The hydroacoustic counters proved to be an effective method for estimating the stock abundance on the Rivers Wye, Tavy and Teifi. The estimated proportions of the immigrating fish that were detected and counted ranged from 51% in the Wye to 63% in the Teifi. However, the system was less successful on the River Spey where a range of factors including very variable flows, shallow depths and spring ice floes caused major problems. On the basis of their experience, the EA prepared detailed guidelines for the installation and use of hydroacoustic counters.

9.3 Status of Atlantic salmon in the River Frome, Dorset

The River Frome is one of a group of chalk streams in southern England, which have in the past been renowned for the quality of their salmonid stocks. As a result of the national concern about the perceived decline in runs of salmon in English and Welsh rivers during the 1980s, Defra funded a study (**SF0207**) by CEH in 1992 to analyse their 20-year data set from this river. The data were derived from the institute's resistivity counter located in the lower reaches of the Frome and, along with the net and rod fishery catches, were used to document and interpret changes in salmon numbers and levels of exploitation in this river.

At that time, the Frome fish counter records (Figure 9.3) showed that the annual run of salmon (1973-92) had been quite variable (1000 to 5000) with an average of about 2700 fish. The main salmon run occurred as grilse in the autumn while the spring run of multi-sea-winter salmon was very small. The proportions of the salmon run occurring in the spring and autumn were not related to the size of the total run.

Between 1973 and 1992, there had been no overall trend in numbers and, contrary to the situation in many other

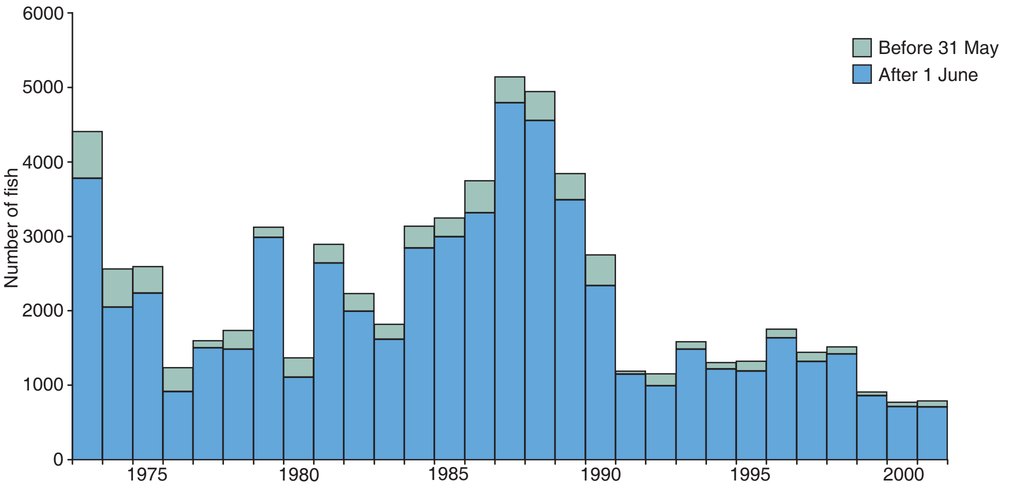

Figure 9.3 The annual run of salmon migrating through the fish counter on the River Frome, Dorset, during 1973-2001, showing the spring run (before 31 May) and the summer/autumn run (after 1 June) (Source: Centre for Ecology and Hydrology)

UK rivers, there was no evidence of a decline in the spring run during the period.

The downturn in numbers between 1988 and 1991 coincided with a marked reduction in the marine survival observed for many North Atlantic salmon stocks, suggesting that it was caused by a change in the marine environment affecting salmon survival rather than a natural population fluctuation or a result of deleterious changes in the river. Two earlier poor periods, observed in the 1970s, had been followed by good recruitment of parr, and subsequently adults, from the low spawning stocks. This had suggested that it was possible for stocks to recover quite quickly if riverine conditions were right for parr. However, data collected since 1992 show that the stock has remained in a depleted state (Figure 9.3).

9.4 Uptake of the results of salmon assessment studies

A wide range of factors may affect the operation of fisheries, and thus the proportion of the stock that they take, and so changes in catches may sometimes give a misleading impression of the status of the stock. The study on the Frome (**SF0207**) demonstrated the value of having reliable counter information for a salmon population, and such work emphasises the need to develop a reliable network of counters throughout England and Wales to support the management of salmonid stocks. There is also a need to formulate a strategy for operating the counters on a consistent basis and develop quality assurance procedures to ensure collection of comparable data.

The research on hydroacoustic counters (**SF0226**) demonstrated that the approach offered a viable, site adaptable and cost-effective tool for automated monitoring of the numbers of migrating salmonids in large rivers. Although the counting efficiency was not as good as that reported for some existing counter methods (e.g. resistivity), a major advantage of the acoustic technique is that it requires little civil engineering work to install and is completely unobtrusive to migratory salmonids. The systems installed in England and Wales are continuing to be used for monitoring and assessment purposes. A database and CD-ROM of counter data, including acoustic examples, was produced by the EA as a training aid, and the results have been disseminated and are available in the following formats: Operational Guidelines including a Field Manual; a database Package; Image Analysis Software Package; and an Event Library of Fixed Location and Acoustic Information.

As part of this study a method was developed for verifying the counts of fish passing through the acoustic beam using underwater cameras and computer image analysis. This method has the potential to be developed into a new counter system in its own right and further research has been proposed.

9.5 Publications and other outputs from stock assessment studies

Beaumont, W.R.C., Welton, J.S. and Ladle, M., 1991. Comparison of rod catch data with known numbers of Atlantic salmon (*Salmo salar*) recorded by a resistivity fish counter in a southern chalk stream. pp.49-60, *In:* (Cowx, I.G. (ed.)) Catch effort sampling strategies. Their application in freshwater fisheries management. Fishing News Books, Oxford.

Beaumont, W.R.C., Welton, J.S. and Ladle, M., 1992. The exploitation by rod and line of Atlantic salmon (*Salmo salar*) in a southern chalk stream. Joint Atlantic Salmon Trust/Royal Irish Academy Workshop on The measurement and evaluation of the exploitation of Atlantic salmon, Dublin, April 1991.

Gregory, J., Bray, J. and Gough, P., 2001. The Development of Applications and Validation Methods for Hydroacoustic Salmonid Counters. An R&D collaboration between the Environment Agency, CEFAS, FRS and the Spey Research Trust. Environment Agency R&D Technical Report W2/037/TR1, 51 pp.

Hilton, J., Welton, J.S., Clarke, R.T. and Ladle, M., 2001. An assessment of the potential for the application ot two simple models to Atlantic salmon, *Salmo salar*, stock management in chalk rivers. Fish. Mgmt. Ecol., 8(3): 189-205.

Nealson, P.A. and Gregory, J., 2000. Hydroacoustic differentiation of adult Atlantic salmon and aquatic macrophytes in the River Wye, Wales. Proceedings of Second International Conference on Shallow Water Fisheries Sonar, Seattle, USA. pp. 331-339, *In*: Aquatic Living Resources, vol. 13 (5). Elsevier, Paris.

Welton, J.S., Beaumont, W.R.C. and Ladle, M., 1993. The status of Atlantic salmon (*Salmo salar* L.) in the River Frome, Dorset. Institute of Freshwater Ecology Report to MAFF, RL/T 11053t5/2, 36pp.

Welton, J.S., Beaumont, W.R.C. and Ladle, M., 1999. Timing of migration and changes in age structure of Atlantic salmon, *Salmo salar* L., in the River Frome, a Dorset chalk stream, over a 24-year period. Fish. Mgmt. Ecol., 6(6): 437-458.

10. EELS AND COARSE FISH

The projects addressed in this section are:

SF0304 Long-term Changes in Windermere Perch and Pike Populations (Centre for Ecology and Hydrology)

SF0305 Eel Stock Assessment in the U.K. (Centre for Ecology and Hydrology)

SF0307 Eel and Elver Stocks in England and Wales - Status and Management Options (University of Westminster)

SF0236 Development and Implementation of Biological Reference Points for the Management of the European Eel (King's College, London)

SF0238 The Impact of Introduced Fish Species on Aquatic Ecosystems. (CEFAS)

Key features of the eel life cycle (Figure 10.1)

The European eel is another species that migrates between freshwater and the sea, but it adopts the opposing (catadromous) life strategy to salmonids, by breeding in a specific region of the North Atlantic (Sargasso Sea), from where the young eels (leptocephali) are transported back towards European coasts by prevailing currents. The leptocephali metamorphose into 'glass eels' as they arrive on the continental shelf, and subsequently become pigmented 'elvers'. Most elvers enter freshwater to grow (into 'yellow eels') and mature, although some individuals may remain in estuaries or coastal waters rather than moving upstream. Eels normally grow for 7 to 12 years before undergoing a further metamorphosis into 'silver eels' and beginning their spawning migration to their ocean spawning areas. European eels are generally thought to comprise a single reproductive population, although recent genetic studies suggest that there may be some regional differentiation between groups.

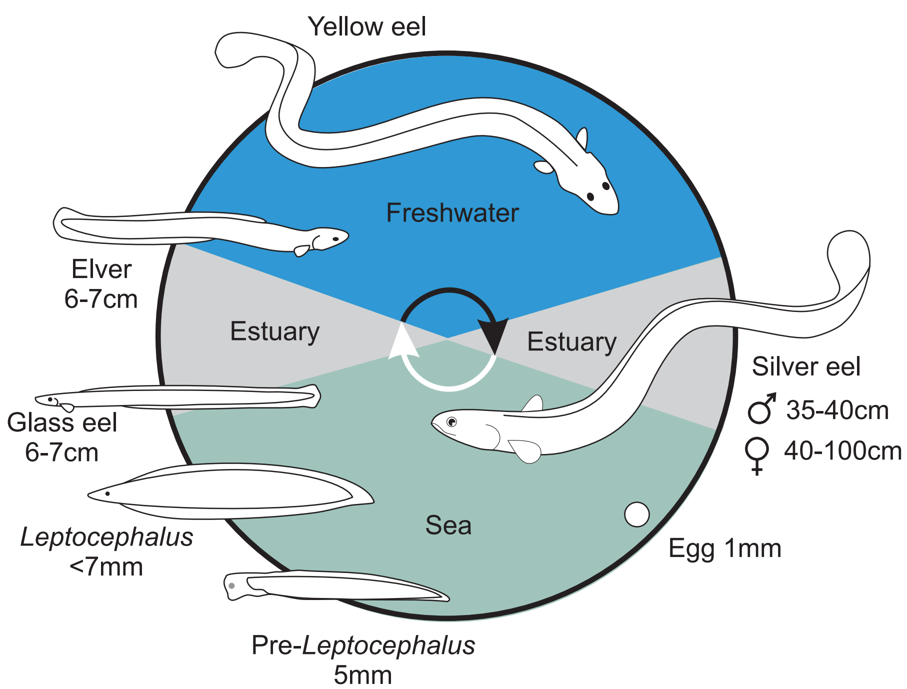

Figure 10.1 Life cycle of the European eel (redrawn from White and Knights, 1994)

10.1 Background

Although Defra's freshwater research programme has concentrated mainly upon salmonids, work has also been funded on the European eel (*Anguilla anguilla*) and coarse fish species. Eel stocks are important components of many freshwater ecosystems, and their commercial fisheries provide employment in a number of rural communities. However, the complex life-cycle of eels and paucity of data on their stocks means that conventional fishery management methods cannot easily be applied to this species. Research has therefore been required to clarify the status of eel stocks and determine appropriate management approaches.

Defra also has statutory responsibilities for issuing licences for the keeping or release of non-native fish species listed under the Import of Live Fish (England and Wales) Act 1980 (ILFA) and, under the Wildlife and Countryside Act 1981, for their release into the wild. Defra, therefore, needs to be in a position to balance the risks posed by the introduction of non-native species against any potential benefits. As a result Defra is funding the development by CEFAS of a Risk Assessment Framework for the introduction of non-native species.

10.2 Eel and elver stocks in England and Wales: status and management

During the 1980s and early 1990s, stocks of eels declined significantly over much of Europe. The catches of glass eels fell in various estuary fisheries, as did catches of elvers moving into rivers. By the mid-1990s, the low recruitment had lasted for a period equivalent to the average life-span of a mature eel in the northern part of its range, and there was widespread concern in Europe that the stocks could be on the verge of collapse.

Few accurate data on the status of UK eel stocks existed despite the widespread distribution of the species in UK freshwaters. Lack of appropriate information on the stocks of eels during their various developmental stages (elver, yellow or brown eel, silver eel) was rendering decisions on eel stock management difficult, most being based then on inadequate data and subjective assessments. Defra therefore initiated a programme of research on eel stocks to seek evidence of changes in eel stock abundance and to formulate new stock monitoring and management approaches.

10.2.1 Assessment of eel stock status in UK

In the early 1990s, a desk study **(SF0305)** was commissioned, from CEH, to determine the status of UK eel populations through a review of the scientific literature and available catch data from eel fisheries. This study concluded that, with the exception of studies in the Thames and Severn catchments, little was known about the fisheries and ecology of eel populations in England and Wales, and there were few accurate estimates of eel population densities in UK waters. Most were derived from general fish surveys in which eels were caught incidentally; population densities in most UK waters were below 5 eels per 100 square metres (500 per hectare). The study also highlighted the problems caused by obstructions; eels can pass upstream over small weirs, but large weirs and vertical barriers inhibit their migration.

This study was followed up by a more detailed investigation **(SF0307)** to seek evidence for changes in the status of river stocks of eels, to propose a methodology for future monitoring programmes, and to review management options for sustaining stocks and fisheries. The project was funded jointly by Defra and the EA, and undertaken by the University of Westminster and King's College, London. Historical fisheries and stock survey data-sets were collected from a range of sources and analysed to determine stock structures, population trends and habitat requirements.

Recruitment of glass eels in the UK, as elsewhere in Europe, declined, by ~55% between the 1970s and 1990s, whereas catches of yellow and silver eels peaked in the late-1980s and mid-1990s before declining markedly. Assessing changes in eel stocks was hampered by a lack of good quality data series, the best information coming from intensive re-surveys of those few rivers for which good previous population estimates had been made. For the River Severn (despite its estuarine glass eel fishery) and River Dee, no significant overall decline in stocks of yellow eels was evident over the previous 20-25 years. However, significant declines in eel numbers, but not biomass, were revealed in the Rivers Piddle and Frome (Dorset). Biomass appeared to have been maintained largely by a change in population structure, from domination by male eels (small) to domination by females (large). Low recruitment and the impacts of Poole Harbour as an alternative habitat ('sink') for immigrants were implicated, rather than fishing mortality. It was therefore suggested that the scattered and low intensity commercial fisheries in England and Wales have had little impact on stocks and spawner escapement. Recent glass and yellow/silver eel catches were estimated to be, respectively, less than 0.5% and less than 5.0% of natural yields.

Shorter rivers and lower reaches of large catchments generally appeared to receive sufficient recruitment to meet carrying capacities, and they had relatively high density populations dominated by small eels, the majority of which matured and emigrated as males. Density tended to decline with distance from tidal limits (but biomass to a lesser extent because of

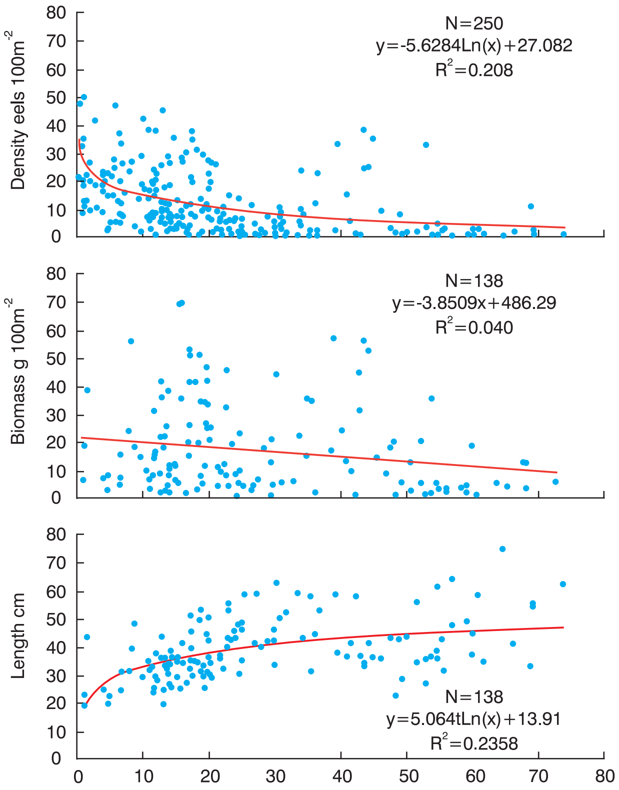

Figure 10.2 Relationships between the density, biomass and mean length of eels and their distance from the tidal limit in 11 rivers in south-west England, 1978-91. (from Knights et al., 2001)

increasing average individual size) due to density-dependent migration and habitat segregation (Figure 10.2). Larger females dominated in upper reaches although major declines in populations tended to occur at more than 50 km from tidal limits. Densities (but not necessarily biomass) were generally greater in west and south coast rivers compared to east coast rivers. This reflected distances from Atlantic migration pathways and differences in river lengths, channel slopes and productivity. Low initial recruitment together with migration barriers explained the apparently restricted distributions of eels in the upper reaches of large catchments such as the Thames, possibly exacerbated by the presence of estuarine and coastal habitat 'sinks' for immigrants.

Eel habitat preferences are very catholic, and no evidence was found that habitat changes had significantly affected stocks, spawner escapement or fisheries over the previous 20 - 25 years. Distance from tidal limits, altitude, natural and anthropogenic migration barriers, habitat productivity and, especially, availability of day-time refuges were found to be the main determinants of density, biomass and population structures in specific sites. Because of the adaptability of eels, enhancing stocks by eel-specific habitat improvements would not be cost-effective, but the adverse effects of poor water quality and physical migration barriers need to be minimised. Indices of habitat suitability and biomass were considered to be of limited use for monitoring and setting management reference points, and better models are required.

10.2.2 Management options and recommendations

The study concluded that eel fisheries should not be allowed to expand in effort or geographical range beyond the average status of the last five years. Instead, managers should adopt a 'precautionary approach' in order to reduce risks to stocks and their environment. This approach will need to define biological reference points, to promote escapement of spawners and other life stages, and to establish appropriate harvesting and monitoring strategies. Because of the problems of quantifying spawner escapement and glass eel recruitment, it was recommended that population indices (density, biomass and length class frequencies) would be the best surrogate measures of stock status and escapement.

A further project (**SF0236**) has been initiated to pursue the findings and proposals from the above study so as to provide practical advice on the sustainable management of our eel stocks and fisheries. This project is being undertaken by King's College, the University of Westminster and Imperial College, London.

10.3 Introductions of non-native species

'User groups' have for a long time been interested in trying to translocate species which they consider beneficial, and introductions of non-native species into the UK date back hundreds of years. While the transfer of some species has had benefits, at least in economic terms, there are numerous examples world-wide of adverse impacts resulting from the introduction and transfer of fish and shellfish. It is internationally recognised that the spread of non-native species can have far-reaching ecological consequences for both animal and plant communities, which are frequently impossible to reverse.

However aquatic ecosystems are complex and it is very difficult to predict how a non-native (alien) species will perform under novel conditions, where the 'normal' checks and balances that operate within its native range may not apply. There is thus considerable uncertainty regarding the impact that a new species may have on the receiving ecosystem and the potential benefits that might accrue from the introduction of such a species. Alien species theoretically can affect receiving ecosystems and resources in a number of ways. These include ecological impacts, (such as predation and competition), the introduction of new diseases and parasites, as well as genetic effects such as hybridisation. Introduced species may also have socio-economic impacts by changing fishing practices or other activity patterns among 'user groups'.

A precautionary approach is therefore considered to be appropriate in relation to the keeping and release of non-native fish species, and national and international guidelines on the introduction and transfer of non-native species generally reflect this. However, a complete ban on the importation and movement of non-native fish is not legally possible nor, arguably, desirable. Managers therefore need to be in a position to address both negative and beneficial aspects of species introductions and to have a consistent framework within which to operate. A new study (**SF0238**) has thus recently been initiated at CEFAS to develop methods for providing a risk assessment framework, in relation to the potential impact (invasiveness) of non-native species, on native species and ecosystems

10.4 Long-term changes in Windermere perch and pike populations

Windermere, in the English Lake District, is some 15 km^2 in surface area and is subdivided into north and south basins, the latter being subject to long-term habitat change and eutrophication. Its fish community is relatively simple, the predominant species being perch (*Perca fluviatilis*) and pike (*Esox lucius*), together with significant populations of Arctic charr (*Salvelinus alpinus*) and brown trout, while salmon pass through the lake. The fish fauna has been studied for more than 50 years by CEH and its predecessors, and most notably, a long-term study has been undertaken of pike (predator) and perch (prey) population dynamics, and their commercial and recreational fisheries. This has provided a unique predator-prey data-base which could be used to help construct multi-species models of similar interactions in other waters of England and Wales. Because of the potential value of these data, Defra funded a project **(SF0304)** to enable CEH to construct a computer data-base readily accessible to other users, and to update their previous population analyses of these two species

Perch were exploited intensively (as an emergency war-time food resource) during 1941-45 with a commercial trap fishery on the stock continuing until 1964. During the fishery period, the numbers of mature perch fell by about 90% (Figure 10.3), based on population reconstruction modelling. The residual stock of mature fish then recovered steadily until 1976 when it was nearly extinguished by an outbreak of perch disease. The perch population after 1976 then became limited virtually to just two age-classes (formerly six), and also subject to large variations in recruitment and adult mortality, both features suggesting the establishment of an endemic disease. The perch population had not recovered by 1994.

Detailed studies showed that the annual variations in perch recruitment were positively linked with zooplankton biomass but not with water temperature. The growth of the young (underyearling) perch, on the other hand, was found to be positively correlated with water temperature but not with either zooplankton biomass or the numbers of young.

The pike population, by contrast, increased slowly up to the early 1980s, then rose dramatically to a peak in the mid-1980s before the numbers of mature fish fell back (Figure 10.4). Catches in the gill-net fishery fluctuated markedly (100-400 fish per winter) but without trend

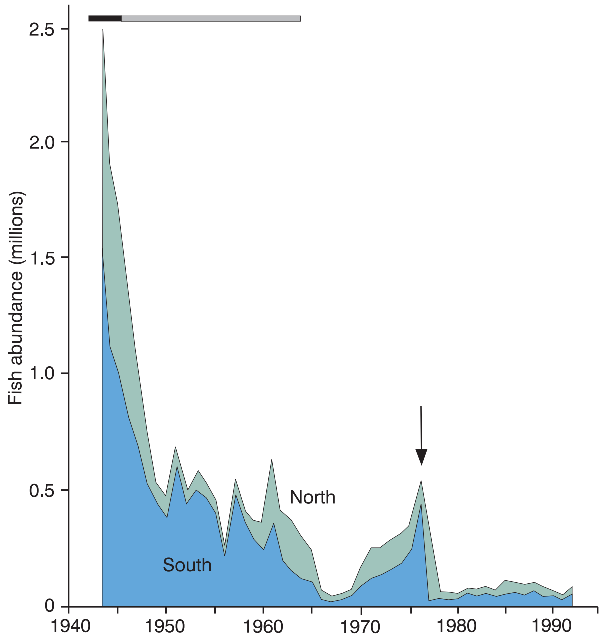

***Figure 10.3** Estimated numbers of 2-6 year old perch in Windermere north and south basins between 1943 and 1992. Horizontal bar denotes commercial fishery period (intensive during wartime); arrow marks disease outbreak (© CEH)*

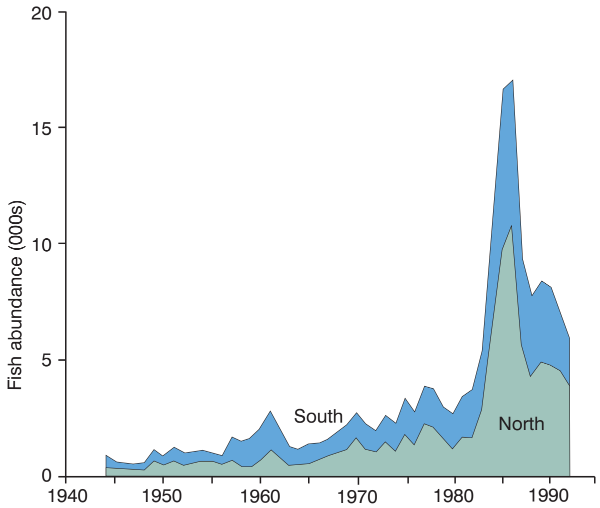

***Figure 10.4** Predicted abundance of 3-9 year old pike in Windermere north and south basins between 1944 and 1992 (copyright CEH)*

during 1944-75; then at a lower level in the 1980s. Modelling suggests that interactions between pike sex/year-classes and their prey (including cannibalism), other environmental variables and fishing together may have caused the observed marked annual variations in recruitment, growth and survival. Increased fishing mortalities for adult pike seem to have been compensated by decreased natural mortalities of newly-recruited fish, suggesting that cannibalism may be an important control for this pike population.

10.5 Uptake of the results of eel and coarse fish studies

Results from the studies of eel populations have been used to present information to ICES on the status of stocks in England and Wales as part of the international programme to prepare advice on the management of eel stocks and fisheries. The information was also used to prepare a submission on the management of eel stocks to the European Union in an effort to apply precautionary controls on fisheries and protect the spawning escapement of silver eels throughout Europe. It is anticipated that the outputs from the current study will play an important part in determining future management strategies for the European eel.

The risk assessment framework for introductions of non-native fish species will be used to inform policy with regard to controlling the keeping and release of non-native species and will be applied to assess, and where possible quantify, the risks associated with key species listed by DEFRA under the Import of Life Fish (England and Wales) Act 1980.

The largest data-base ever collected on perch and pike from a single lake was put into an accessible format, thereby greatly widening the scope for further research into these species and into predator prey relationships in fish populations. For example, a new age-structured population model was developed which allows an estimation of different vulnerabilities and natural mortality rates for males and females by year and age-group. The perch data-base also could be linked with the plankton data-base for analysis of historical variations in perch recruitment in relation to eutrophication and climate change.

10.6 Publications and other outputs

Des Clers, S., Fletcher, J.M., Winfield, J.M., Kirkwood, G.P., Cubby, P.R. and Beddington, J.R., 1994. Long-term changes in Windermere perch and pike populations at the basin level. Institute of Freshwater Ecology Report, 40 pp.

Des Clers, S., Winfield, I.J., Fletcher, J.M., Kirkwood, G.P., Cubby, P.R., and Beddington, J.R.., 1994. Further analysis of the long-term Windermere perch and pike data. Institute of Freshwater Ecology Report, 53 pp.

Knights, B., Bark, A., Ball, M., Williams, F., Winter, E. and Dunn, S., 2000. Eel and Elver Stocks in England and Wales – Status and Management Options. Environment Agency R&D Technical Report No. W248, 294 pp.

Copp, M.H., Fox, M.G., and Kovac, V., 2002. Growth, morphology and life history traits of a cool-water population of pumpkinseed *Lepomis gibbosus*. Arch. Hydrobiol., 155: 585-614.

Copp, G.H., Fox, M.G., And Kovac, V., 2002. Geographical patterns in Europe of life history traits of the introduced North American sunfish, pumpkinseed *Lepomis gibbosus*. Presentation to British Ecological Society Meeting, York, England, December 2002.

Mann, R.H.K., 1994. Eel Stock Assessment in the U.K. Institute of Freshwater Ecology, Report to MAFF, 46pp.

Moore, A. and Riley, W.D., 1996. Biomagnetism in the European eel (*Anguilla anguilla* L.). Working Paper, 7 pp. ICES/EIFAC Working Group on Eel, Ijmuiden, Netherlands, September 1996.

Paxton, G.C.M., Fletcher, J.M., Hewitt, D.P. and Winfield, I.J., 1999. Sex ratio changes in the long-term Windermere pike and perch sampling program. Ecol. Freshwtr. Fish, 8(2): 78-84.

Russell, I. C., and Potter, E.C.E. (in press). Implications of the precautionary approach for the management of the European eel. Fisheries management and Ecology.

Winfield, I.J., George, D.G., Fletcher, J.M. and Hewitt, D.P., 1998. Environmental factors influencing the recruitment and growth of underyearling perch (Perca fluviatilis) in Windermere North Basin, UK, from 1966 to 1990. NATO Advances Research Workshop on Management of Lakes and Reservoirs during Global Climate Change, Prague, November 1995. pp. 245-261, *In*: George, D.G., Jones, G., Puncochar, P., Reynolds, C.S. & Sutcliffe, W (eds). Management of Lakes and Reservoirs during Global Climate Change. Kluver Academic Publishers, Dordrecht, Netherlands.

ANNEX 1. Registry of salmonid and freshwater research projects funded by MAFF/Defra, 1990-2002

Code	Project Title	Contractor	Start	End	Total cost	Summary Objectives
SF0102	The genetic identification of Atlantic salmon populations	CEFAS - Lowestoft	Apr-90	Mar-93	£315,185	Assess the genetic variability among wild salmon populations and assess the likely survival and reproductive success of farm escapes and fish reintroduced for restocking.
SF0103	Collation and analysis of data on genetic variation in Atlantic salmon from the British Isles	Queen's University, Belfast	Dec-91	May-92	£24,242	Collate available data on genetic variation in salmon and analyse geographical patterns in gene frequencies and the possible link with physical and chemical environmental parameters (e.g. river size, flow, conductivity).
SF0104	The structure of trout populations : inventory of migratory types by pigment analysis	University of Aberdeen	Dec-93	Apr-94	£11,930	Establish whether natural variations in carotenoid pigmentation in brown trout can be used to determine migratory history for different stocks of brown trout.
SF0201	Physiology of Salmonid migratory mechanisms	CEFAS - Lowestoft	Apr-90	Mar-93	£240,114	Describe the role of olfactory and biomagnetic mechanisms in river and open sea navigation and assess the possible influence of human activities on these mechanisms.
SF0202	Migratory behaviour of adult salmonids in rivers.	CEFAS - Lowestoft	Apr-90	Mar-94	£480,399	Describe the behaviour of migratory salmonids in estuaries and rivers as affected by changing flow regimes and other significant environmental factors.
SF0203	Salmonid ecology and stock enhancement	CEFAS - Lowestoft	Apr-90	Mar-93	£213,688	Identify factors affecting smolt abundance including egg numbers and avian predation, and recommend optimal stock enhancement methods.
SF0204	Growth and survival of sea trout in the sea	CEFAS - Lowestoft	Apr-91	Mar-96	£173,762	Describe the growth and survival of sea trout during the first year in the sea and analyse recent trends in catches, particularly in East Anglia and the north east.
SF0205	The ecology of young stages of salmonid fish and the implications for practical river management	Centre for Ecology and Hydrology	Apr-90	Sep-94	£244,495	Conduct base-line studies on Welsh sea trout populations to establish how populations and water quality and quantity change during afforestation.
SF0206	The efficacy of manual gravel cleaning as a means of improving salmonid spawning grounds.	Centre for Ecology and Hydrology	Oct-91	Oct-94	£47,750	Measure the particle size distribution of the river bed gravels used by spawning salmon, before and after manual cleaning, and monitor the removal of fine particulate material.
SF0207	Investigation of the perceived decline in size of Atlantic salmon (Salmo salar) in the River Frome, Dorset	Centre for Ecology and Hydrology	Aug-91	Oct-92	£51,000	Analyse historical net and rod catch data and records of ascending salmon in order to ascertain reasons for the perceived decline in the River Frome salmon population.
SF0208	Biomagnetic navigation in salmon (SC0109)	CEFAS - Lowestoft	Apr-93	Mar-95	0 (Seedcorn)	Investigate the role geomagnetic cues play in controlling the oceanic migration of Atlantic salmon.
SF0209	Olfactory responses in salmonids	CEFAS - Lowestoft	Apr-93	Mar-96	£227,690	Describe the nature and extent of chemical recognition between sibling juvenile salmon and the effects of changes in water quality on olfactory-based behaviour and physiology of salmonids.
SF0210	Molecular genetics for discrimination in marine fish and salmonids (SC0107)	CEFAS - Lowestoft	Apr-93	Mar-95	0 (Seedcorn)	Investigate the efficacy of novel molecular genetic methods for the discrimination of stocks in fisheries management.
SF0211	Movements of salmonid smolts and adults around barrages	CEFAS - Lowestoft	Apr-93	Mar-96	£755,536	Provide a better understanding of behaviour of adult salmonids and smolts when they encounter natural or man-made obstructions in rivers or estuaries, and consider methods of improving the passage of fish past these obstructions.
SF0212	Improving natural production of juvenile salmonids	CEFAS - Lowestoft	Apr-93	Mar-96	£262,843	Evaluate the use of habitat improvement and stock enhancement techniques to overcome bottle-necks in the production of juvenile salmonids caused by habitat degradation through siltation and flow rate changes, in certain rivers.

ANNEX 1. continued

Code	Project Title	Contractor	Start	End	Total cost	Summary Objectives
SF0213	Pheromone reception in salmon and trout	Centre for Ecology and Hydrology	Apr-93	Mar-95	£26,500	Investigate the structure, function and communication role of phermone receptors in olfactory salmonids and the disruptive effects pollutants may have particularly during reproduction.
SF0214	Pheromonal control of the behaviour and physiology of the Atlantic salmon (Salmo salar)	University of East Anglia	Jun-94	May-97	£106,510	Study the structure, function and release of phermones in salmonids, and investigate how waterborne pollutants disrupt their detection and response in salmon.
SF0215	Studies on sea trout and brown trout in a stream in mid-Wales.	Centre for Ecology and Hydrology	Apr-94	Mar-99	£128,000	Investigate how variations in the hydrological regime (water quality and flow) of an upland stream may impact on sea trout and brown trout recruitment, through reduced entry of spawners, and high mortality in the early life stages.
SF0216	A climatological study of sea surface temperature and salmon habitat	Atlantic Salmon Trust	Feb-94	Feb-95	£12,500	Investigate long-term variations in the size of suitable marine habitat for Atlantic salmon based on historical satellite data on sea surface temperatures, and relate this variation to observed changes in population size.
SF0217	The role of the major histocompatability complex in kin recognition in Atlantic salmon (Salmo salar L.)	Institute of Zoology	Dec-95	Mar-98	£179,683	Characterise the genetic variability of the Major Histocompatability Complex (MHC), which may be used by salmon in kin odour recognition, and determine its usefulness as a genetic marker.
SF0218	Ecotoxicological factors affecting salmonids	CEFAS - Lowestoft	Apr-96	Mar-99	£234,220	Describe the nature and extent of the sub-lethal effects of low levels of persistent aquatic contaminants, e.g. agricultural pesticides and ammonium, on reproduction and migration in salmonids.
SF0219	Movement and distribution of emigrating salmonid smolts and adult salmon at sea	CEFAS - Lowestoft	Apr-96	Mar-99	£590,076	Develop radio tags and other equipment and use this to study the movement of salmonid smolts and adults in riverine, coastal and sea areas and investigate environmental and physiological cues controlling migration.
SF0220	Restoration of degraded salmonid habitat	CEFAS - Lowestoft	Apr-96	Mar-99	£267,263	Describe the extent of gravel siltation in salmon spawning streams based on gravel core studies, assess common causative factors and investigate corrective measures, including buffer zones.
SF0221	Diet of Sea Trout in the sea	CEFAS - Lowestoft	Apr-96	Mar-99	£191,187	Assess the potential impact of industrial fisheries on the food of sea trout in England and Wales through baseline studies of the diet of sea trout throughout the marine phase of their life cycle, and assess levels of sea lice infestation in wild sea trout.
SF0223	Behavioural Genetics and spawning success of spring run Atlantic salmon in the Girnock Burn, Aberdeenshire	University of Stirling	Sep-96	Aug-98	£81,848	Using molecular techniques establish the degree of genetic variation in a population of salmon, and relate this to observed differences in spawning behaviour and success.
SF0224	Detection of triploidy in Rainbow Trout (Oncorhynchus mykiss) and Brown Trout (Salmo Trutta) by fluorescence in situ hybridisation (fish)	University of Reading	Jan-97	Mar-97	£18,000	Develop a simple, rapid and reliable assay to accurately determine a percentage of triploidy at the egg stage.
SF0225	Equilibrium sediment loads in salmonid spawning gravels	University of Southampton	Sep-99	Mar-03	£233,732	Establish a UK database relating salmonid fisheries productivity and environmental parameters, to provide a detailed assessment of the historical changes in salmonid fisheries. Also, to develop a predictive model that can be used to relate changes in salmonid productivity.

ANNEX 1. continued

Code	Project Title	Contractor	Start	End	Total cost	Summary Objectives
SF0226	The development of applications and validation of hydroacoustic salmonid counters - phase III	Environment Agency	Nov-97	Mar-01	£627,122	Evaluate and test the application of hydroacoustic technology for counting adult salmonids migrating in UK rivers.
SF0227	Sediment dynamics in river catchments - a review	CEFAS - Lowestoft	Apr-98	Mar-99	£17,000	Undertake a review of existing knowledge and current R&D on sediment dynamics including; the origins of sediments within river catchments; their routes of transport into rivers; their effects on river ecology (with particular reference to spawning gravels).
SF0228	Impacts of agricultural and aquaculture contaminants on wild salmonids	CEFAS - Lowestoft	Apr-99	Mar-04	£418,359	Describe the nature and extent of the impact of aquatic contaminants derived from agriculture (e.g. pesticides) on migration and marine survival of salmonid smolts and post-smolts.
SF0229	Habitat utilisation and population dynamics in wild salmonids	CEFAS - Lowestoft	Apr-99	Mar-04	£455,289	Describe the seasonal utilisation of freshwater habitats by wild juvenile salmonids, and determine the impact of salmon enhancement and stocking programmes on wild salmonid populations.
SF0230	Salmonid migration and climate change	CEFAS - Lowestoft	Apr-99	Mar-04	£726,364	Describe and model the environmental factors affecting the migration of salmonids and predict the effects of climate change on salmonid migration and survival in the sea.
SF0231	Habitat selection and the distribution of migratory salmonids in river systems	CEFAS - Lowestoft	Apr-99	Mar-04	£410,551	Determine and describe the environmental habitat preferences of adult migratory salmonids and factors affecting growth, and selection of spawning areas.
SF0232	Spring Salmon: Impact of catch and release and identifcation of spawning areas in the River Eden.	Environment Agency	Jan-00	Jun-01	£62,500	Through radio tagging programme, assess the impact of catch and release on the survival of spring salmon, following release through to the time of spawning. Identify spawning areas in the Eden catchment to assist with the future management of stocks
SF0236	The development and implementation of biological reference points for the management of the European Eel (*Anguilla anguilla* L.)	Kings' College, London	Aug-02	Jul-06	£238,381	Develop and test approaches and models for establishing biological reference points (limits and targets) to inform sustainable management of eel stocks and fisheries.
SF0237	Modelling the Bioenergetics of Salmon Migration	Centre for Ecology and Hydrology	Aug-02	Jul-06	£162,324	Develop a model for predicting changes in growth and survival of migrating Atlantic Salmon that may occur as a result of annual changes in oceanographic conditions, including sea temperature and ocean circulation.
SF0238	Impact of introduced species.	CEFAS - Lowestoft	Apr-02	Apr-07	£518,631	Review and develop methods for providing risk assessments for the impacts of non-native fish species on indigenous stocks and aquatic ecosystems
SF0241	Impacts of intensive in-river aquaculture on wild salmonids	CEFAS - Lowestoft	Nov-01	Oct-06	£324,259	Describe the nature and extent of the impact of aquatic contaminants (effluents, pesticides, antibiotics, and hormones) arising from intensive aquaculture on the reproduction, migration and survival of wild salmonids.
SF0242	Summary of MAFF funded R&D on salmonid and freshwater fisheries 1990-200	CEFAS - Lowestoft	Dec-01	May-02	£27,711	Provide a summary of the scientific findings of MAFF funded R&D on salmon and freshwater fisheries, between 1990 and 2000, in a form that is easily accessible to the lay reader, and provides references to other scientific publications.
SF0303	Oestrogenic consequences of trace organics	CEFAS - Burnham-on-Crouch	Apr-92	Mar-96	£380,139	Establish a clearer understanding of the freshwater links between the observed oestrogenic effects in fish and the sewage effluents, contraceptive pill and other organic contaminants, and the significance of this for fish population structure.
SF0304	Further analysis of the long-term Windermere data	Centre for Ecology and Hydrology	Apr-91	Mar-93	£74,900	Complete the data entry and analysis for the Windermere pike and perch populations on to the IFE database.
SF0305	Eel stock assessment in the U.K.	Centre for Ecology and Hydrology	Apr-93	Apr-94	£36,400	Determine the status of eel populations through a review of scientific publications and available catch data on eel fisheries in the UK.
SF0307	Sustainable management of eel stocks in England and Wales	University of Westminster	Apr-98	Dec-00	£63,202	Assess current status of eel stock & fisheries in England & Wales, establish a methodology for future monitoring programmes and suggest a national management strategy.

ANNEX 2. Glossary of terms and acronyms used in the Review

acoustic tag	an electronic transmitter which emits pulses of high frequency sound and is attached to a fish to enable its position to be determined
alevin	young salmonids, from hatching to end of dependence on yolk sac as primary source of nutrition, during which stage they remain within the gravel
allele	one of a number of alternative forms of a gene that can occupy a given genetic locus (position) on a chromosome
allozyme	one of a number of forms of the same enzyme having different electrophoretic mobilities
anadromous fish	fish, born in freshwater, that migrates to sea, to grow and mature, and then returns to fresh water as adult to spawn (e.g. salmon)
androgens	a group of steroid hormones produced by males that promote development of male sexual organs and male secondary sexual characteristics
anthropogenic	produced or caused by man
atrazine	(2-chloro-4-ethylamino-6-isopropylamino-s-triazine)
biological reference point	a stock level (e.g. number of spawners) calculated from the life history characteristics and population dynamics of a stock and used to assess stock status or inform management decisions
biomass	the total weight of a particular species or of a collection of animal and/or plant species in a given area
brown trout	form of the trout, *Salmo trutta*, that remains in freshwater throughout its life
by-catch	capture of non-targeted fish
carbofuran	(2,3-dihydro-2, 2-dimethyl-7-benzofuranyl methyl carbamate)
carrying capacity	size to which a fish population in a river or stream is limited by natural factors, such as space and food
catadromous fish	fish, born in the sea, that migrate to fresh water to grow and mature, and then returns to sea to spawn (e.g. eels)
CEH	Centre for Ecology and Hydrology, into which the Institute of Freshwater Ecology (IFE) was incorporated in 1999
CEFAS	Centre for Environment, Fisheries and Aquaculture Science, an executive agency of Defra (formerly DFR, Directorate of Fisheries Research within MAFF)
coarse fish	freshwater fish other than 'game' fish
conservation limits	threshold levels below which a spawning stock should not be permitted to fall
cypermethrin	[(R,S)-a-cyano-3-phenoxybenzyl (1 R,S)-cis, trans-3-(2,2-dichlorovinyl)- 2,2-dimethylcyclopropane carboxylate]
Defra	Department for Environment, Food and Rural Affairs; which was created in June 2001 incorporating the Ministry of Agriculture, Fisheries and Food, (MAFF)
demographic	relating to the numbers of organisms in a population and their variation over time

density-dependent	factors limiting the growth of a population which are dependent on the existing population density
diadromous	migrating between fresh and salt water; subdivided into anadromous and catadromous types (q.v.)
diazinon	(O.O-diethyl O-2-isopropyl-6-methylpyrimidin-4-yl phosphorothiate: IUPAC)
DNA	deoxyribonucleic acid, a very large and complex chain molecule composed of carbon, oxygen, hydrogen, nitrogen and phosphorus, found in all living cells, and the physical carrier of genetic information
drift net	type of gill net released from or attached to a boat and free to drift with the wind or tide
EA	Environment Agency (formerly NRA, the National Rivers Authority)
ecosystem	a community of different but interdependent plant and animal species together with their non-living environment, which is relatively self-contained in terms of energy flow, and is distinct from neighbouring comunities
EIFAC	European Inland Fisheries Advisory Committee
electrophysiology	study of nervous conduction and other electrical phenomena associated with living organisms
environmental levels	concentrations of contaminants that have been observed in the environment
EQS	Environmental Quality Standard, being the maximum permissible concentration of a substance in the aquatic environment
escapement	salmon or sea trout that survive to spawn
exploitation	removal of fish from a stock by fishing
fry	young salmonids at stages from independence on yolk sac as primary source of nutrition up to dispersal from spawning
game fish	a term sometimes used for salmon and all kinds of trout
genome	all of the genes carried by a living organism or single cell; sometimes used for the total DNA content of a nucleus
genomic library	a large DNA collection of fragments of chromosome DNA of a given species
grilse	an adult salmon that has matured, or is about to mature, after just one winter at sea
hormone	a substance that is produced by ductless glands and then transported in the blood to another tissue where it induces a specific physical response
ICES	International Council for the Exploration of the Sea
IFE	the former Institute of Freshwater Ecology, now incorporated into the Centre for Ecology and Hydrology (CEH)
introduction (species)	the intentional (or accidental) transportation and release by man of species or races into an environment outside their natural geographic range (see also reintroduction below)
invertebrates	animals lacking a vertebral column or backbone, such as insects and worms
kelt	a salmon that has spawned up until the time when it returns to the sea

MAFF	the former Ministry of Agriculture, Fisheries and Food; was incorporated in June 2001 into Defra (q.v)
magnetic remanence	the strength of the magnetic field that remains in the magnetic particle after it is exposed to a strong, external magnetic field and the external field is then removed (see also 'SIRM')
minisatellite DNA marker	region of DNA composed of a short DNA sequence, which is very variable within a population, and can be used in DNA fingerprinting to identify individuals and family relationships etc.
mitochondrial DNA	genetic code material that is maternally inherited, being passed on mainly through the egg cell to the embryo; used to reveal evolutionary differences between closely related species
multi-seawinter-salmon	a salmon that has spent two or more winters at sea before returning to fresh water to spawn
NASCO	North Atlantic Salmon Conservation Organisation
oestrogens	a group of steroid hormones, the principal female sex hormones, synthesised chiefly by the ovary, and responsible for the growth and function of female reproductive organs, and development and maintenance of female secondary sexual characteristics
olfactory rosette	functional part of the "nose" of a fish
parr	young salmonid, in the stage from dispersal from the redd until its migration as a smolt or for non-migratory forms until if becomes an adult
pheromone	a chemical released, usually in minute amounts, by an animal and which is detected by, and acts as a signal to, another member of the same species
phytoplankton	very small freshwater and marine plants, including single -celled algae, that drift with the surrounding water
pH	chemical value, on a scale of 0-14, that gives a measure of the acidity or alkalinity of a medium such as water; a pH value of 7 denotes neutrality, a value below 7 denotes acidity, and a value above 7 denotes alkalinity
plasmid	an autonomous self-replicating genetic particle usually of circular double-stranded DNA
post-smolt	young salmon, at the stage from leaving the river until the end of its first winter in the sea
production (of species or ecosystem)	the assimilation of nutrients into biomass; used an indicator of population growth (usually over a given period)
productivity (of species/habitat)	the amount of organic matter fixed by a species or ecosystem per unit time (usually in a year)
radio tag	an electronic transmitter which emits radio frequencies and is attached to a fish to enable its position to be determined
redd	the depression made in the gravel on the river bed by a female salmonid and in which her eggs are laid
reintroduction	the deliberate release of fish by man into a geographic area in which the species formerly was indigenous but became extinct
run-timing	the time of year in which salmon or sea trout first return to fresh water and move up river
salmonid (fish)	a fish belonging to the family *Salmonidae*, which includes the Atlantic salmon (*Salmo salar*), trout (*Salmo trutta*), charr (*Salvelinus alpinus*) and rainbow trout (*Oncorhynchus mykiss*)

sea-age	the number of winters that a salmon has spent at sea
sea trout	diadromous form of the trout (*Salmo trutta*) after the post-smolt stage
simazine	(2-chloro-4,6-bis(ethylamino)-s-triazine)
SIRM	Saturation Isothermal Remanent Magnetisation is the highest amount of magnetic remanence that can be produced in a sample by applying a large magnetic field
stocking	the intentional release of fish into an ecosystem
smolt	fully silvered juvenile salmon or trout migrating within a river system river or about to enter the sea
spring salmon	multi-sea-winter salmon which return to rivers early in the year, usually before the end of May
swim-up fry	the first free-feeding stage newly emerged from the gravel
testosterone	male steroid hormone (produced chiefly by the testes) which stimulates development of sexual organs and secondary sexual characters, and maintains sexual function in the adult male
triploid fish	fish derived from eggs that have been physically treated to prevent sexual maturation
vitellogenesis	yolk formation
WAG	Welsh Assembly Government

The Centre for Environment, Fisheries & Aquaculture Science
Lowestoft Laboratory, Pakefield Road
Lowestoft , Suffolk NR33 OHT UK
Tel: +44 (0) 1502 562244
Fax: +44 (0) 1502 513865
www.cefas.co.uk

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ISSN 0308 - 5589