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Management of habitat for rehabilitation and enhancement of salmonid stocks

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Abstract

Most of the river systems in the British Isles have been subjected to anthropogenic influence to varying degrees over recent times, in many instances leading to deleterious impacts on salmonid habitat to the detriment of populations. This paper considers the range of management options that can be utilised to overcome habitat degradation. When examining salmonid habitat management three areas need to be taken into account: water quality, water quantity and the physical structure of the riverine environment. Although discussed separately, it should be remembered that these components of habitat are inter-related, and should be viewed as a continuum. Water quality problems include pollution from point and non-point source pollutants, although major improvements in the former have been achieved in recent years via the legislative framework and further benefits may be anticipated from the introduction of the Water Framework Directive. However, diffuse forms of pollutant, notably silt, still remain a significant threat to salmonid habitat and are yet to be tackled in any meaningful way. Changes to modern agricultural and land management practices are urgently required. Water quantity is impacted upon in a number of ways ranging from abstraction, which may reduce flows, through to land-use and flood defence that may alter the shape of the hydrograph changing velocities and influencing stream power. Society's conflicting demands are bound to increase these pressures, although imaginative and integrated planning of schemes can avoid many deleterious impacts and actually provide benefits to salmonid populations, provided the ecological requirements of the species are taken into account. Arguably a more flexible and targeted approach to river regulation and abstraction would be beneficial to salmonid populations. Degradation of physical stream habitat has been widespread caused primarily by insensitive land-use practices, agriculture and flood defence. A significant commitment to consider long-term investment of resources will be required to negate the widespread deterioration in habitat caused by such damaging management techniques. Although a wide range of physical habitat restoration techniques have been demonstrated both in-stream and within the riparian zone with significant success, it is suggested that some form of land-use regulation is required to prevent further damage. Treating the root cause of the problems of deterioration with respect to water quality, quantity and physical habitat, and not just the symptoms, should be a fundamental priority for salmonid management in the 21st century.

Keywords: Salmon; Trout; Habitat; Water quality; Water quantity; Flow; Physical structure; Management; Restoration

1. Introduction

Most of the river systems in the British Isles have been subject to anthropogenic influence to varying

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degrees over recent times. In some rivers man's influence has progressed to the point at which habitat deterioration has occurred resulting in a concomitant impact on salmonid stocks. This has led to an increasing need to understand habitat requirements of salmonids (Armstrong et al., 2003) so that the freshwater environment can be managed to rehabilitate and enhance fish stocks. The object of this paper is to review the range of management actions that can be applied to overcome habitat deterioration.

When considering salmonid habitat management three areas need to be taken into account: water quality, water quantity and the physical structure of the riverine environment. These three areas are discussed separately, but it should be remembered that in many ways they are inter-related, and should be viewed as a continuum. Management action to resolve problems in one area will be ineffective if deficiencies in either of the remaining two persist.

2. Water quality

The basic water quality requirements of salmonids can be summarised as follows:

- Well oxygenated water with natural nutrient content and temperature range, typically of upland or spring origin.
- Suitably buffered water to prevent sustained variations in pH outside of the normal range.
- Water devoid of significant chemical contaminants.
- A naturally low silt/fines content within the normal sediment matrix.

In the natural state these water quality parameters are determined by localised geochemistry within the catchment and, to a degree, can become modified by chemical processes and physical interactions as rivers flow from source to sea. For example in upland areas, naturally acidic water arising from granite rocks and peat soils can become more alkaline as geology changes to different strata, such as limestone. In spring-fed streams natural water plant growth can lead to diurnal fluctuations in oxygen and pH. Furthermore, physical interactions between fresh and saline water occurs in estuaries promoting stratification, which in naturally enriched estuaries can lead to depleted oxygen concentrations during warmer periods. However, it should be recognised that these are natural processes which drive variations in water quality that occur both spatially, within a catchment, and seasonally as a result of physical, chemical and biological interactions.

2.1. Reasons for deterioration—man's influence

Despite these natural variations in water quality, salmonid species in the UK and Ireland have evolved and adapted to localised variation. Man's activities however, which lead to a deterioration in water quality, often outside the range to which the pollution sensitive salmonids are adapted, invariably have a deleterious impact on the species. Depending on the extent of degradation, poor water quality can have a marked effect on salmonid stocks, but the impact can vary greatly in terms of scale and longevity. Nutrient increases, at a low level, can be tolerated but excessive enrichment can lead to a slow decline in salmonid populations. Isolated incidents such as accidental spillage of pollutants (e.g. agricultural silage liquor) can wipe out entire juvenile year classes in a stretch of river but recovery in future years can be rapid. However profound land-use change involving agriculture, urbanisation and industrialisation has historically resulted in widespread organic enrichment and toxic industrial discharges that ultimately can lead to the extinction of the species within a catchment (e.g. salmon in the River Mersey). There are two sources of pollution: 'point' and 'non-point', that result in critical "bottlenecks" for the various life history stages of salmonids on any specific river.

2.1.1. Point source pollution

Point source pollutants are discharges from a specific location (pipe, drainage ditch, etc.). These can be either regulated pollutants, such as sewage effluents from consented discharges (see below), or illegal unlicensed discharges, usually as a result of an accidental failure in storage or transport of a potentially polluting substance (Milne et al., 1992).

Industrial contaminants such as heavy metals and organic chemicals are often by-products from industrial processes. In recent years, the environmental effects of such by-products have been significantly reduced due to the introduction of new and more stringent pollution and water quality regulations (NRA, 1990). Similarly, the point discharges from sewage treatment works have come under more stringent control and received significant investment over the last 10 years. Future investment will continue and will be extended to contain the risks from expanding urbanisation via improved infrastructure and increased discharge standards.

Farm wastes have also become much more of an important issue over recent decades, as European policy has encouraged an intensification of agriculture (NRA, 1992). Intensification has been accompanied by attendant changes in practice resulting in accumulations of potentially damaging pollutants on farms such as livestock slurry and silage liquor. The problem is further compounded by storage and disposal procedures for the ever accumulating volume of farm wastes (MAFF, 1991).

However, one of the most worrying pollution impacts on salmonid streams in recent years is the effect of inadequate disposal of the comparatively new synthetic pyrethroid (SP) sheep dips on stream invertebrates. SP sheep dips are many times more toxic than the organophosphate (OP) products previously used. Recent evidence from the Environment Agency suggests that inadequate disposal has seriously affected several thousand kilometres of upland stream in England and Wales, sometimes wiping out invertebrate populations over several kilometres during each incident, leaving little or no food for juvenile salmonids (Millbrand (1997)). In Scotland, the Scottish Environment Protection Agency (SEPA) has said by 2010 the major threat to the freshwater environment north of the border will be agricultural pollution, and at present the greatest single threat is SP sheep dips. Many kilometres of river within the River Tay catchment have been severely damaged by SP dips during 1999 and 2000.

2.1.2. Non-point source pollution

Non-point source pollutants emanate from diffuse sources, such as run-off from agricultural land. One of the most widespread impacts is nutrient enrichment or eutrophication (Mason, 1998). Nutrients applied to arable land and pasture for agricultural purposes often find their way into watercourses. Both artificial chemical applications and organic manure, either as a result of over-fertilisation or inappropriate application, are equally culpable, particularly when applied in fields adjacent to rivers, streams and ditches or on steep slopes (Furness et al., 1991).

Nutrient enrichment has a number of deleterious effects, notably encouragement of excessive macroalgae and water based vegetative growth, and in deeper slow moving water-bodies, algal blooms. In rivers, excessive plant growth can lead to the choking of the channel bed with actively growing plant material. This not only alters the physical characteristics of the stream to which salmonids and their prey items are adapted, but also accelerates entrapment of silts resulting in permanent habitat alteration. This process can lead to a situation where typical middle reach and lowland river species including grayling, barbel, dace and other coarse fish may find these areas more suited to their habitat requirements.

In addition, excessive plant growth, whether from algae or aquatic macrophytes, can lead to alterations in water chemistry via photosynthesis (Alabaster and Lloyd, 1982). In extreme cases, oxygen depletion around dawn can occur as plant respiration reaches its peak, the resultant oxygen sag being sufficient to cause salmonid mortalities, particularly in eutrophic still-waters. Under these circumstances pH elevation can also occur, carbon dioxide levels being depleted during peak photosynthetic activity, usually in the early afternoon, resulting a shift in the carbonate balance which in turn causes the pH to increase. When pH is elevated above 9.0, even normally acceptable concentrations of ammonia will be converted to the un-ionised form (UIA). UIA is many times more toxic to fish, particularly to salmonids and can result in stress or in extreme events direct mortalities (Train, 1979).

Another diffuse source of pollution comes from power generation and fossil fuel combustion in industrial nations that result in releases of gaseous oxides of sulphur and nitrogen (Schofield, 1976; Schindler, 1988). Nitrous and sulphurous oxides act in various ways, both directly from the atmosphere (acid rain), catchment run-off (sulphate particulate transfer) and indirectly via internal catchment processes (soil acidification) to cause acidification (Mason, 1998). Increased acidity increases the mobility of toxic metals, particularly aluminium. Eggs and alevins are highly sensitive to acidification and cannot tolerate a pH of much less than 4.5. Older parr stages are also susceptible, even to short duration acid events (Mills, 1989).

Silt arising from bank erosion and poor land management practices, in particular agriculture and land drainage, is also a non-point source pollutant and arguably one of the most significant causes of deterioration in salmonid rivers seen today. Although not widely recognised as such, silt is probably one of the most significant causes of salmonid decline (MAFF and NAW, 2000). It affects salmonids either directly, via the siltation of redds, causing mortality at the egg stage, or indirectly by smothering the bed in juvenile rearing areas thereby reducing productivity.

The role of the European Common Agricultural Policy (CAP) in precipitating changes in agricultural practice that have led to increased silt inputs into streams and rivers is particularly important. Over recent decades the CAP has encouraged an intensification of agriculture particularly with respect to upland farms where increasing numbers of livestock are encouraged by subsidies paid on a 'headage' basis (MAFF and NAW, 2000). The consequence has been to maintain artificially high stock levels on ill-suited land resulting in overgrazing, increased stream run-off and power, with consequent erosion and a subsequent increase in silt levels. Changing practices such as over-wintering on the moors and little or no shepherding exacerbate the problem (APEM, 1998). In lowland rivers, subsidies such as the Arable Area Payments Scheme, encourage the cultivation of maize in the flood plain and have resulted in large areas of pasture adjacent to rivers being put under the plough. Over-winter the soil surface is afforded little protection, allowing huge quantities of silt to be washed into the river during flood events (Johns, 1997).

2.2. *Regulatory controls—the consent system and European Legislation*

The primary process by which point source pollutants are prevented from entering watercourses is via the consent system where potentially polluting substances are subject to concentration limits in discharges. These limits are defined based on the ability of receiving waters to dilute deleterious polluting impacts. In England and Wales they are based on Environmental Quality Standards for the parameters concerned, or in the future on River Quality Objectives set by the Environment Agency. The permissible concentrations of various parameters in receiving waters are defined primarily by European Legislation, including the Freshwater Fish Directive (EU, 1978) which sets out specific limits for designated salmonid waters for a range of determinants, together with directives concerning urban wastewater treatment (EU, 1991) and the control of dangerous substances discharged into aquatic environments (EU, 1976) and groundwaters (EU, 1979). The new Groundwater Regulations derived from this last directive, provide a powerful tool to tackle the problem of SP sheep dips, requiring all dischargers of dips to apply for specific authorisation for disposal.

By and large, the implementation of these regulatory controls has brought dramatic improvements in many of the worst affected rivers in the UK and Ireland which for years suffered from urban sewage and industrial pollution. Several river systems, devoid of migratory salmonids for generations, including the Rivers Thames and Clyde, now support salmonid populations, whilst the Tyne, which saw its rod catch decrease to zero in 1959 is now one of the most prolific salmonid rivers in England. However, considerable difficulties are still being experienced elsewhere. New European Legislation under the Water Framework Directive should be in place in the near future that requires dischargers to take account of the impact of the discharge on the ecology of receiving waters. The new directive is considered to be a potentially more powerful regulatory tool for pollution control than those available in the past and should bring a further level of water quality improvement to all waters affected by discharges.

Non-point source pollutants can also be controlled to an extent under existing legislation, e.g. designation as a 'Sensitive Area' or under the *aegis* of the Habitats Directive (EU, 1992). Other land-based habitat management schemes which may influence water quality and fish habitat indirectly include Environmentally Sensitive Areas (ESAs), the "Set-aside" scheme (whereby farmers are compensated for taking land out of agricultural production), the MAFF Habitat Scheme for Water Fringe Areas and many others. However, although designation of such areas can enforce fertiliser use reductions in agriculture, e.g., the extent of land covered is minor compared with the overall scale of the problem.

This area of regulation in agriculture is of fundamental importance to the issue of habitat management.

Many of the problems discussed in this paper are created by a combination of weaknesses in the current regulatory regime and actual incentives in the form of subsidy payments. In promoting the intensification of agriculture CAP subsidies encourage many problems, such as erosion, siltation and increasing run-off rates, which many rivers face today (Evans, 1990; Orr, 2000; APEM, 1998). The habitat damage that results will be reversed on a sufficiently wide-scale only by fundamental reform of both the regulatory system such that it applies more widely to agriculture and by fundamental reform of the CAP. Land-use controls which influence the use of floodplain land are essential together with a move towards area-based subsidy payments and a catchment-wide approach to agriculture-related conservation schemes.

With respect to acidification, internationally agreed emission limits on nitrogenous and sulphurous oxide production, by reducing burning of fossil fuel, is an example of agreed international regulation to reduce a recognised trans-border problem. However, closer to home, arguably much more effort is required to tackle the problem of within catchment non-point source pollution.

2.3. *Direct management of land and rivers*

2.3.1. *Catchment-based land management*

Whilst the consent system regulates point source discharges and wider European Legislation can influence non-point source impacts to a degree, there is a wider requirement to influence land-use to avoid cumulative damage from diffuse pollutants. Clearly it is not possible to separate salmonid fisheries and their habitats from the wider catchment environment and the detrimental activities which are pursued within it. Inevitably, external forces, such as the CAP or pure economic drivers encourage these activities. In this context it should be recognised that salmonids are sensitive indicators of environmental change and consideration of environmental impact and in river habitat needs must therefore be integrated into the process of government policy formation and accompanying regulation. Thus a holistic catchment-based approach embracing all facets of land-use management is essential for truly sustainable management of river habitats. Land-use controls are inevitable if this goal is to be achieved.

2.3.2. *Buffer strips and water quality*

Whilst integrated catchment management and land-use controls offer a long-term solution to fisheries habitat quality problems, non-point source pollution can be intercepted, at least in part by the use of buffer strips. The vegetation alongside a river has the potential to reduce the impact of non-point source pollution from a variety of origins (e.g. slurries from livestock, nitrates and phosphates from fertilisers, suspended solids from land erosion etc.). Large and Petts (1992) and Muscutt et al. (1993) provided detailed information on land management techniques and buffer strips for the prevention of diffuse pollution within catchments.

Pollutants present in water moving through the riparian zone can be immobilised and degraded by the physical and biological processes operating in this strip ecosystem. The recommended width is 10 m for upland streams and 100 m for lowland rivers (Large and Petts, 1992). Effective treatment is achieved by management of the riparian corridor so that environmental conditions, such as slow rates of underdrainage, favour these processes (Reddy and Debusk, 1987; Reddy and Smith, 1987).

Buffer plants such as *Phragmites communis* and *Typha latifola* can be used to create a riparian reedbed system which will act as an effective substrate–plant biofilter. These species are capable of high rates of growth associated with elevated levels of nutrient uptake and demand (particularly nitrogen and phosphorous). The presence of a wider land-based riparian plant community will also act as a physical barrier to pollutants, retarding their translocation from soil to water as well as having a role as a biofilter. As water passes through the rhizosphere, microbial activity results in the decomposition of organic matter and the denitrification of nitrogen sources. Depending on the rooting medium, much of the phosphorous component may become fixed within the soil itself (Brix, 1987).

To maximise the removal of nitrogen and phosphorous via direct uptake into the plant tissue, high growth rates and levels of standing biomass must be achieved. Hence frequent harvesting may be required to remove the accumulated nutrients, encourage new growth, and prevent any release of pollutants from senescent plant material (McEldowney et al., 1993).

However, riparian vegetation growing in buffer strips will also provide overhead cover, inputs of allocthanous material and from a water quality perspective, shade. This can be vitally important in shallow salmonid nursery areas, particularly during low flows when strong sunshine can cause peak summer water temperatures to rise to dangerously high levels for salmonids. The advent of climate change may result in greater importance for shade to maintain adequate water quality. Therefore frequent removal of riparian vegetation may need to be balanced against other requirements, and hence the time of year when pruning occurs could be critical.

2.3.3. *In-stream habitat structures and water quality*

In-stream habitat restoration techniques designed to enhance steam energy and increase velocities (Section 4) will also have a beneficial effect on water quality. Water turbulence generated when water flows over weirs into plunge pools, or merely surface agitation from flow constriction, will aid re-aeration elevating water oxygen levels. Lowland and chalk streams, particularly those subjected to organic enrichment, are particularly susceptible to the problem of reduced oxygen, which again may well be made worse by climate change.

The increased local turbulence and velocity created by in-stream structure has another important function, mobilisation of silt. A variety of structures (Table 1) can be used to create these effects, which in addition can be used to trap or retain gravels to create spawning areas. The hydraulic conditions created maintain a low fines content. Wesche (1985) for example refers to the use of deflectors (groynes) to reduce silt content of spawning areas and encourage accumulation of gravels.

Table 1
An inventory of salmonid riverine enhancement techniques being used in Ireland

Timber structures	Rock applications
Notched straight log weirs	Horseshoe stone weirs
V-notched log weirs	Vortex stone weirs
Paired timber deflectors	Rubble mats
Timber channel constrictors	Gravel beds
Crosslog revetments	Alternating deflectors
Plank/log deflectors	Rip-rap
Log/Xmas tree bank revetments	Individual random boulders
Log/rock bank revetments	Covers shelves on lateral scour pools
Plank/rock cover shelves on lateral scour	Rock breaking to reintroduce sinuosity
Pools	Create pools and step impassable falls
Conifer tree bank revetments	Gravel desilting
Half logs	
Bed logs	
Rootwads	
Shrub pruning and tree planting	

2.3.4. *Gravel cleaning*

Gravel cleaning is a popular restoration technique for reducing silt content. For Pacific species Wilson and Sheridan (1974) claim that the normal egg to fry survival rate of typically 10% can be increased to a level in excess of 40% in silt can be reduced or removed. A variety of techniques can be used to clean gravels (Gerke (1973)) perhaps the most simple being tractors with forks, rakes or blades to clean spawning gravels by stirring up the bed and causing the fines to be mobilised and carried away in suspension by the flow (Solomon and Templeton, 1976). Another popular technique is the high powered water jet using a simple water pump to wash fines out of gravel spawning areas (Finnigan et al., 1980). Considerable success has been achieved with Atlantic salmon spawning areas in the eastern USA (Semple, 1987) and the technique is being more widely applied in Britain and Ireland both in lowland chalk streams and high energy upland rivers.

Sediment accumulation is also a common problem downstream of impoundments. However, reservoirs offer the opportunity to provide flushing flows before the spawning season to rework the gravels and remove the silt deposits. Successful use of flushing flows has been reported for the River Shin in Sutherland, and a flow programme has been developed in the case of the Roadford Reservoir in Devon which allows for such releases (Sambrook and Gilkes, 1994). The velocities generated need to be sufficient to rework the upper layers of gravel beds, but not so high as to scour away the gravel. Appropriate velocities are likely to be generated by flows equivalent to $1.7\,m^3\,s^{-1}\,m^{-1}$ of channel width (Frederikson Kamine and Associates (1980)). Thus in a 15 m wide channel, a riffle in the target reach would require a flow of $25\,m^3/s$ to initiate silt removal. The time period required for effective cleaning will vary, depending on the degree of siltation, but is likely to be 1–3 days. Where an armour layer has formed, higher flows are likely to be needed, and some prior mechanical disruption of the gravel surface may be required (Nelson et al., 1987).

2.3.5. Acidification and lime addition

The widespread phenomenon of acidification of upland streams induced by atmospheric pollution can be neutralised to an extent by the addition of lime. Direct addition of lime (calcium carbonate) to acidic headwater streams, lakes and wetlands has met with various degrees of success (Mills, 1989). Powdered limestone has been used in Sweden in upland lakes to good effect (Andersson et al., 1984), whilst limestone slurry has proved more successful in riverine systems (Rosseland et al., 1986). Although in many cases a single application will last for several years, more frequent, possibly annual applications may be required in lakes with a low retention period. However, limestone addition to surrounding land and bogs has proved successful for long-term treatments, actually increasing calcium levels during periods of heavy rain (Howells (1986)).

An example from the River Towy in Wales shows what can be achieved in a system that was totally fishless in its upper reaches as a consequence of acidification in 1992. Powdered lime was added to Llyn Brianne, a reservoir formed by a dam on the main river, initially directly but subsequently via large hopper feeders to in-flowing streams. The results were quite spectacular, the upper reaches of the River Towy now supporting a class A/B juvenile salmon population (NRA, 1994). An alternative approach is the addition of limestone gravel to the stream bed, which has met with considerable success in several upland locations. Acidity problems in the upper tributaries of the Lancashire Wyre were dramatically improved by additions of limestone gravels, adult trout being observed actually spawning in the gravel (Dr. D. Evans, pers. commun.). Similar techniques have been successfully employed in Canada (Mills, 1989).

2.3.6. Reservoirs and water banks for quality improvement

Water resource and flood alleviation schemes can be used to great advantage in overcoming water quality problems commonly experienced during low flows in estuaries. For example, in the highly regulated Welsh Dee catchment, a water bank is available for specific fisheries purposes to allow quantities of water to be released to improve quality in the estuary by dilution. Even under naturally low summer flows, this somewhat artificial intervention can provide a much need refuge area for migratory salmonids trapped in otherwise poor water quality conditions in the estuary.

2.3.7. Aeration, oxygen injection and hydrogen peroxide

In extreme oxygen depletion situations aeration and oxygenation techniques can be employed. Artificial mixing/aeration techniques have been used for many years in still-water trout fisheries to overcome low summer oxygen levels (Bailey-Watts et al., 1987). However, in recent years, recovering industrial/urbanised rivers such as the Tyne and Thames have required direct oxygenation to maintain satisfactory oxygen concentrations. Oxygen injection has been used on both rivers, in either temporary installations (drop in venturi units) or purpose designed vessels. However, permanent installations are currently being implemented in a number of water-bodies including the Manchester Ship Canal, part of the Mersey catchment, salmon and sea trout recently having returned to the river (Wilson et al., 2000).

Hydrogen peroxide offers a rapid response solution in oxygen depleted waters. It is particularly effective for use in episodic events such as organic pollution incidents or oxygen sags caused by algal bloom die back, a problem sometimes encountered in the organically enriched lower reaches of migratory salmonid waters. Hydrogen peroxide added to receiving waters at a concentration between 35 and 50 ppm, in either aqueous or powdered form dissociates into water and oxygen. Roughly 5 t of peroxide are required for every tonne of oxygen delivered to the system (Litton and Hendry, 1998).

3. Water quantity

The basic water quantity requirements of salmonids can be summarised as follows:

- Adequate flows at appropriate times of year to encourage and permit migration of adults and smolts.
- Presence in nursery areas of appropriate water velocities, volumes and depths for spawning fish and juveniles, and in the case of non-migratory trout, for adults.

- Regular occurrence of "flushing" flows to ensure that spawning gravels are maintained in an unsilted condition.
- Adequate dilution of effluent inputs, from both point and diffuse sources, to ensure that water quality is satisfactory.

More detailed considerations of these requirements are given by Armstrong et al. (2003).

3.1. Reasons for deterioration—man's influence

The "fluvial hydrosystem" comprises the whole river corridor, the river channel, the riparian zone, the flood plain and the alluvial aquifer, and the natural flow regime in any river is influenced by factors such as climate, geology, topography and vegetation cover in the catchment. In the vast majority of rivers in England and Wales the balance of the various natural processes has been affected by human activity (NRA, 1996). The principal activities by which flow regimes can be modified include land-use changes such as drainage and agricultural/forestry practices, water abstraction and transfer between catchments, impoundment and flow regulation, and hydro-electric power generation. In terms of simple hydrology, the effects of these various activities can be to reduce flow, to increase flow, and to modify patterns of flow fluctuations.

The consequent physical effects of these flow changes on the various stages of the salmonid life cycle can be summarised as follows:

(a) A modified flow regime that results in both temporal and spatial changes to the availability of flows for salmonid migration.
(b) Modified water velocity, wetted area and water depth along affected river reaches, which will impact on the availability and distribution of the habitats preferred by different life stages of salmonids.
(c) Modified flows which directly affect channel morphology, with resulting habitat changes along the river.
(d) Modified sediment dynamics, including the processes affecting the amount of the sediment load and the distribution and deposition of the finer fraction in sensitive spawning and nursery areas.

The various environmental issues associated with the life cycle of salmonids in rivers and estuaries are often complex, with potentially a wide variety of interactions which can mask the exact mechanism controlling critical changes. However, in many instances, flow and its associated hydraulic characteristics can be pivotal to many of the processes (DeGraaf and Bain, 1986; Heggenes and Saltveit, 1990; Morantz et al., 1987) and hence are potential biological "bottlenecks" to optimum productivity of any salmonid system.

In addition, loss of depth in holding pools (Kennedy and Strange, 1986) and inadequate dilution of point and diffuse sources of pollution are also impacts to be considered which arise from artificially induced low flows. Exacerbation of other adverse physical influences such as high water temperatures and reduced habitat diversity following channel modification schemes can also occur. Where river regulation schemes or land management practices result in excessive flows, there can be increased scouring of river bed deposits with damage to spawning beds and juvenile habitat, and also increased bank erosion and sediment input to rivers.

With ever-increasing demands for water, future management of water resources should ideally be based on sound "hydro-ecological" principles with the objectives of achieving a balance between the needs of water users and the environment of the catchment, together with the resolution and prevention of actual impacts. Although the main theme of this section deals with management and manipulation of flows, it must be stressed that establishment of good land management practices can play a key role in restoration of a more natural flow regime in a river.

3.2. Management solutions to benefit flow and habitat

3.2.1. Land management practices and hydrology

Modern land management practices, such as high sheep densities and upland drainage have been implicated in influencing the hydraulics and hydrology of rivers, resulting in increases in peak flows and increased velocities (Johns, 1997; Robinson, 1986; Howe et al., 1967; Burt, 1995). Evans (1996) provides evidence that as sheep numbers increased in the north Derwent catchment, so too did the rate of run-off, an observation supported by a study in Shetland by Birnie and Hulme (1990). Furthermore, in a detailed review of the influence of drainage on river hydrology downstream, Burt (1995) concluded that the combined effect of agricultural under-drainage and channel improvements is to generate quicker, higher peak flows but not to alter flood volumes.

The influence of land management on hydrology has however, been the subject of much debate over the last century. In a detailed review of the subject Robinson (1990) concluded that a number of complex processes are involved and hence there are dangers in over-simplification of cause and effect; soil type, gradient, nature of drainage and scale all being important. However, the study supported the conclusion of Burt (1995) that drainage reduces peak flows from clay soils but increases them from permeable soils, a particularly important issue in relation to upland salmonid nursery streams which are often situated in porous peat based soils. Further it suggests that farming practices affecting soil compaction and tillage may have a significant effect on flows under local circumstances but questions whether this is likely to be significant at the catchment scale, particularly in larger systems. Importantly the study highlighted the need to consider the land management history of a catchment when assessing its flows; suggesting that even a comparatively 'stable' catchment with little change in land-use may show changes over time in the rainfall–run-off relationship.

Arguably, reversal of these practices, even on a local scale, should enable a return to more natural flow characteristics. The principles of river restoration are discussed in Section 4, but the overall aim must be to establish the basis of sustainable and environmentally acceptable land practices in the catchment to benefit, wherever possible, the natural flow regime.

In impacted catchments, reinstatement of a more natural fluvial hydrosystem may take a considerable time to achieve but the overall gain in habitat, biota and biodiversity will reflect a more balanced and less damaging flow regime resulting in slower run-off and reduced stream power. This in turn will help reduce erosion during storm events (Hendry et al., 1998). It should also be recognised that the adoption of improved land management practices will be required to buffer the extremes associated with changed weather patterns experienced in recent years, as well as the increased risks associated with the predicted changes resulting from climate change.

3.2.2. Establishment of flow requirements in individual rivers

In any individual situation the particular needs of fish in terms of flow are going to be specific. It is therefore essential that any management solutions adopted are tailored to the local needs, and a first priority must therefore be to ascertain these needs, as far as is possible.

3.2.2.1. Flows required for migration. Recent studies on migration of radio-tagged salmon in relation to flow in several rivers in south west England have resulted in the development of an analytical technique which can be used to determine threshold flows for upstream migration (Solomon et al., 1999). This technique is based on the cumulative frequency of available flows compared with the flows actually used by fish for migration, and allows the derivation of a migration index for each flow. An index less than 1.0 indicates that upstream migration is under-represented at that flow, but an index greater than 1.0 indicates that the flow is unlikely to be inhibiting migration. Thus the flow with an index of 1.0 can be regarded as the migration threshold. At the tidal limits of the rivers studied by Solomon et al. (1999) the migration threshold ranged from 101 to 284% of the Q95 (the flow exceeded for 95% of the time). Adoption of this technique where appropriate data are available, either from tracking studies, fish counters or fish traps, coupled with flow data, would allow determination of threshold flows for migration in different parts of the river and at different times of year.

Where appropriate data are not available, the approach developed by the former Lancashire River Authority (Stewart, 1973) might be considered. From studies on fish movement derived from counters it was concluded that upstream migration of salmon commenced when the flow reached $0.084\,m^3\,s^{-1}\,m^{-1}$ of channel width, peaking at a flow of $0.20\,m^3\,s^{-1}\,m^{-1}$ width. However, these relationships were derived from data from spate rivers in North West England, and should be used with caution as they may not be universally applicable. In addition there is also the approach proposed by Baxter (1961) based on the percentage of the Average Daily Flow to provide adequate discharge for fish migration at different times of year. However again, the approach was based on spate rivers, in this case in Scotland, and hence may not apply to all river types.

The migration flow requirements of sea trout are known to be less than those of salmon, so any flow management to protect salmon migration is also likely to be effective for sea trout.

3.2.2.2. Flows required by juvenile stages. The historical approach to this problem has been to take some arbitrary proportion of the naturally occurring flow, typically 10% of the average daily flow (ADF) or in more recent times the Q95, as a flow below which there should be no further reduction, except as a consequence of naturally occurring events. The Lancashire River Authority approach referred to above adopted a figure of $0.03\,m^3\,s^{-1}\,m^{-1}$ width as an "inactivity" or "survival" flow, but again, this was based only on spate rivers in North West England. This suggested survival flow was derived for adult salmonids in the lower reaches of rivers. In rivers experiencing naturally low flows and drought conditions then the likely survival flow for juvenile salmonids would be markedly less.

The critical point at which reduction in flow begins to have a damaging impact on production of juvenile salmonids in any particular situation is very difficult to define. Predictive habitat models such as PHABSIM (Bovee (1986)) and its derivatives have been used in such situations (Bode, 1996) but there are some concerns about their reliability. There is still insufficient information about the overall ecological impacts of the changes in habitat predicted by these models, and the reliability of the suitability curves for individual fish species and age components have not been confirmed (Holm et al., 2001). More detailed work on salmonid habitat requirements is therefore required together with dedicated refinement of these models to confirm their applicability to rivers in the British Isles.

Regarding the needs of juvenile salmonids, the flows required to promote downstream migration of smolts need to be considered. At present there is little reliable information available on the flow requirements of migrating juveniles, but generally the flow levels likely to promote upstream migration of adults will be adequate to encourage downstream movement of smolts.

3.2.3. Abstraction control measures

Once the flow requirements of different life stages have been determined, operating rules for abstractions can be applied. This section identifies the most common methods employed.

3.2.3.1. Prescribed flow (PF) and percentage take rules. A single prescribed flow PF below which abstraction must cease is the most usual operating rule, with the Q95 being a commonly adopted figure. However, the effectiveness of this figure in protecting salmon and trout migration is known to vary from river to river and within an individual river. A flexible approach with a higher PF at times and in locations where fish are migrating, and a relaxation at other times of year when no migration is likely to occur would be more effective, provided water quality or the requirements of juveniles was not compromised.

Some abstraction operating rules allow only a proportion, typically 50%, of the flow above the PF to be taken (Cragg-Hine, 1985). This rule preserves flow variability, and avoids a "plateau" of residual flow which can occur where an abstraction takes all the flow above the PF until the capacity of the pumps is exceeded. In reality, it may also have the effect of increasing the lowest flows from which abstraction takes place, as there is usually a minimum take associated with pump capacity. While a percentage take rule represents a precautionary approach and is potentially beneficial as far as salmon migration and general well being is concerned, it does reduce the time when the full take can be abstracted, and reduces the reliable yield of an abstraction scheme. A likely consequence of this is that to satisfy overall supply demands other sources of water will have to accessed, with resulting environmental impacts elsewhere. Adoption of a percentage take rule should therefore be targeted and used where it is perceived to offer significant advantages over a 100% take above the PF. Such situations might include: (a) schemes where there are insufficient data to evaluate likely impacts reliably; (b) schemes where the abstraction is large relative to the PF, when a 100% take could cause very long periods of "plateau" flows at times of environmental sensitivity; (c) situations where flow variability per se is considered important, e.g. for biota other than migratory salmonids.

Overall, the application of prescriptive and generic operating rules may be considered to represent a rather rigid and sometimes inefficient means of managing water resources, such that critical flows and time periods are not specifically targeted. Also, this results in the sterilisation of available abstraction from environmentally benign flows. Further, the efficient use of resources at times when no adverse impact is apparent, particularly in conjunctive use schemes, may offer the potential for reduced abstraction under more environmentally sensitive conditions. Again, experience suggests a more flexible approach will be required by the regulators and operators in response to climate change.

3.2.4. Protected flow range

Where the flows justifying protection are too high for an effective PF rule, and in some cases where a low PF already applies, there may be scope for adopting a protected flow window. For example on the Hampshire Avon, ceasing abstraction for a 7–14 days period when the residual flow first falls below 9 m^3/s on the falling summer hydrograph (May–July) would significantly reduce the effects of abstraction on the flows being used by salmon for migration (Solomon et al., 1999). Usually after 2 weeks natural flows have fallen further, so that continuing protection would be much less effective in terms of additional salmon entering the river.

The protected flow range approach may be particularly attractive for abstraction at sites located well upstream where salmon migration is typically associated with a higher flow band relative to the ADF. However, as is the case with percentage take rules, there could be impacts elsewhere if the shortfall had to be made up from sensitive alternative sources. It is also important to consider the impact of reduced residual flows downstream to the estuary where the relationship between salmon movement and flow will be different.

3.2.4.1. Protection of critical spates. In dry years, certain flow events of limited magnitude and duration can be associated with disproportionately large levels of salmon migration (Alabaster, 1970; Banks, 1969). Wherever possible, such flow events should be protected. There are various ways in which this might be achieved, such as closing down an abstraction for the duration of the minor spate event and bringing another source of supply on line. Where regulation releases are being used to support an abstraction, augmentation could be continued, even though the control flow at which augmentation would normally cease has been exceeded. Factors which need to be considered when developing such spate sparing include absolute flow levels, relative increases in flow level, occurrence of spates in the preceding period, spate thresholds and duration of sparing (Lawson et al., 1991).

3.2.4.2. Location of the abstraction point. The lowermost reaches of rivers are often the locations selected for major abstractions because they are likely to provide a more reliable yield during droughts than sites further upstream, because the supply demand/use tends to be concentrated in the lower reaches, and because of a perception that, overall, less environmental damage will be caused by an abstraction near the tidal limit. The results of the study reported by Solomon et al. (1999) support this perception as far as salmon migration is concerned. Threshold flows for summertime movement increase in an upstream direction. On the Avon, the increase over a 60 km reach was only modest reflecting the lowland nature and low gradient of the river. On other rivers, the threshold flow increases several fold (in terms of multiples of the appropriate Q95) over the length of river studied. Thus the impact of any water resource proposal is heavily dependent upon the location along the river, and can vary even over a short distance of a few kilometres. Extrapolation from river to river and from location to location should therefore be treated with caution and avoided if possible. Observations from fixed locations (counters and traps) cannot be simply interpreted for other locations even in the same river.

3.2.4.3. Diurnal and tidal modulation of abstraction. The pattern of salmon migration up to and past the tidal limit appears to be modulated to a considerable extent by the time of day and the state of the tide. Particularly at times of low freshwater flow, movement is greatest at night, with peaks after dark and around dawn. It is likely that salmon utilise the flood tide for much of their landward migration. This pattern offers a potential operating rule for abstraction points located near the tidal limit, based on reduction of abstraction to protect critical times when migration is likely to be at its greatest and allowing a commensurate increase in take at other times to maintain overall yield. However, for such modulated regimes a degree of off-river storage may be required.

3.2.4.4. General considerations for the management of abstractions. The various approaches outlined above provide a range of measures aimed at achieving a balance between minimising environmental impacts, maximising scheme yields, sustainability and cost effectiveness. The application of generic operating rules may be an ineffective and inefficient means of managing water resources, such that critical flows and time periods are not specifically targeted. Unnecessarily stringent operating rules, while apparently honouring the precautionary principle, may in fact have indirect adverse effects on other river systems where alternative supply sources have to be used. A general consideration applicable to all approaches is that there should be scope for operating rules to vary seasonally to maximise their effectiveness in protecting fisheries and to minimise disruption to scheme yields. The efficient use of resources at times when no adverse impact is apparent, particularly in conjunctive use schemes, may offer potential for reduced abstraction under more environmentally sensitive conditions.

3.3. Reservoir management and the control of regulated rivers

Flow regulation of rivers through environmentally and scientifically sound principles of reservoir management can present opportunities for fisheries and environmental benefits which are low risk and sustainable. These approaches are dependent on our knowledge of the life history and environmental requirements of salmonids as detailed in Armstrong et al. (2003), which form the basis of the criteria for the operating rules. Experience has shown that idealistic regimes are not always achievable due to real constraints imposed by engineering and operational conditions for each specific site. It is easier to design and implement the necessary features to enable environmental gain when dealing with any new scheme. Retrofitting modern concepts and standards to old engineering has its limitations. This generally results in making use of the best available solutions as defined by the real constraints.

3.3.1. Compensation flows

A general feature of on river reservoirs, whether they were constructed for direct supply, river regulation, hydropower generation or a combination of these uses, is that they release compensation water to the impounded river. The pattern of these releases varies, being either set at a fixed daily volume or with some seasonally based variation. The quantities also vary, historically often based on 1/8th ADF of the impounded stream, or more recently the Q95. In some cases the compensation flow provides a significant benefit over the natural flows experienced in dry and drought years, an example being the River Wolf downstream of Roadford Reservoir, where formerly under extreme conditions the stream would be reduced to inter-gravel flow, leaving extensive reaches of dry river bed (Dr. W.M. Duncan, pers. commun.).

Seasonal variations in compensation flows can be used for the benefit of fisheries. In particular, increases in the quantities released during the autumn and winter months can be used to provide optimum conditions for spawning of fish and to ensure that redds are not left high and dry during the incubation period. However, in the Scottish context there is a complication in that compensation flows and freshet release volumes were set in the past to prevent damage to fisheries. The fishery proprietors through the District Salmon Fisheries Boards have right to alter the flows as they see fit (within the overall yearly allocation of water). This has in many situations resulted in flows being utilised to help the fishing in the summer and not the upstream migration of fish to their spawning burns or the provision of adequate habitat in the winter (Stephen, 2001).

3.3.2. Management of releases to benefit fisheries

Reservoirs offer the potential to control the timing and volume of releases, and any adverse environmental impacts of a reservoir and its operation may in part be offset through innovative management of releases. For example, reservoirs provide a degree of flood and peak flow control, and can reduce the incidence of the damaging scouring flows which occur on unregulated rivers. This is particularly valuable in the early months of the year, around the time of fry emergence. In some cases, a “bank” of water may be held in storage which can be used specifically for fisheries purposes. Such water banks may consist simply of a total volume of water available in each year, or may be based on more complicated arrangements, with availability depending on the total volume being held in storage at any one time of year in relation to operating rule curves for the reservoir. As is the case with developing optimal patterns of release of compensation water, programmes for using special releases should be based on a knowledge of the in-stream requirements of salmonids. Typical reasons for making releases are to stimulate upstream migration of adult salmon and sea trout or downstream migration of smolts, to provide flushing flows to clean gravels prior to the spawning season, and to mitigate the effects of pollution incidents. There can also be situations where some release of stored water can be justified to ameliorate extreme drought conditions, as discussed earlier.

3.3.2.1. Releases to stimulate upstream migration. Various patterns and timings of releases of stored water have been adopted over the years in attempts to encourage upstream migration, particularly of salmon. Experience has shown that the releases most likely to succeed in this aim are ones made to coincide with naturally occurring increases in run-off from other parts of the catchment. Releases of stored water made at other times have in many instances failed to stimulate significant upstream movement. The magnitude and duration of releases needed to produce upstream migration will depend on local conditions. Evidence from tracking studies has shown that upstream migration occurs most freely during the recession of spates (Sambrook and Broad (1990)). Where information on the flows typically used for migration is available, e.g. from tracking studies or counters, releases could be used during the recession of a natural spate to hold the flow at an appropriate level for a longer period (Lawson et al., 1991; Sambrook and Gilkes, 1994). It has been suggested that this period should last for at least 48 h (Hendry and Cragg-Hine, 1997). This would be particularly useful in the case of small spates where naturally occurring migration flows might only last for a few hours.

In the absence of empirical local information on migration flows, the method developed by the Lancashire River Authority might be adopted for spate rivers, using the predicted peak migration flow figure of $0.2\,m^3\,s^{-1}\,m^{-1}$ of channel width as a target flow. An alternative approach would be to use releases to hold the flow at some multiple of the baseline flow. An addition of 20 million gallons per day ($1.05\,m^3/s$) to the prevailing baseline flow of 8 million gallons per day ($0.42\,m^3/s$), a multiple of 2.5, for a period of 3 days has been found to be successful in moving salmon through to the upper reaches of the River Cassley when released on the back of natural run-off (Stephen, 2001).

Purely artificial freshets to encourage migration are more likely to be successful during the autumn, or in attracting fish into freshwater from the tideway, than in other situations. Flat-topped freshets of a relatively small magnitude but of long duration are generally unsuccessful in stimulating migration, especially in the upper parts of a river system (W. Purvis, unpublished data). The same total volume of release in a shorter duration event which mirrors a natural freshet is more likely to succeed in such areas. In the case of the Welsh Dee it was proposed that releases from Llyn Tegid during the autumn months aimed at promoting movement of salmon into the upper reaches should be made over a 4 days period, generating flows two, four, three and two times the baseline flow (Dr. D. Cragg-Hine, pers. commun.).

A similar stepped approach is being adopted by Scottish and Southern Energy, with typically flows being built up over a 6 h period, followed by 12 h at peak flow, then with a 24 h recession. To attract fish into freshwater from the tidal reaches of the Welsh Dee after prolonged periods at baseline flows, a 4 days period with the residual flow raised from the normal 4.2–13 m^3/s was recommended (i.e. a multiplier of 3), on the basis of observations on movement of radio-tagged fish into the freshwater river (APEM (1998b)).

3.3.2.2. Releases to benefit juvenile stages. Reservoir release can be used in some circumstances to benefit juvenile life stages. The advantages of enhanced flows during winter low flows to benefit egg incubation have been mentioned. This can be particularly important during hard frosts when low flow situations similar to summer discharges can be encountered, especially in upland streams. For fry and parr stages, enhanced flows in regulated rivers can also be beneficial. The Enhanced Flow Programme adopted on the River Wolf in Devon as part of the Roadford Reservoir scheme has produced encouraging results with this technique. Using data from two 5-year periods before and after impoundment (late 1980s and late 1990s respectively) marked improvements in both juvenile salmon and trout were observed in the lower reaches of the River Wolf following implementation of the Enhanced Flow Programme (Sambrook and Gilkes, 1994). Salmon fry and parr increased by 130 and 43%, respectively, whilst trout fry and parr increased by 670 and 57%, respectively. In the case of salmon and trout fry these increases elevated densities from grade 'E' to grade 'C' according to the Environment Agency National Fishery Classification Scheme (NRA, 1994). In comparison the control sites on the River Lyd displayed mainly modest declines in salmonid density over the same time periods.

3.3.2.3. Control of releases in river regulation and hydro-electric power schemes. Truncated patterns of release, with rapid rising and recession limbs should be avoided where possible because of the hydraulic stress this can impose on the regulated river channel. There is also the possibility that sudden and large increases in flow might put human life at risk, and that sudden reductions in flow might put fish at risk through stranding. However, it needs to be recognised that in many locations where HEP schemes operate they do so to satisfy peak demand and a gradual stepped increase in production is not an option, being incompatible with the effective production of energy when it is required. Fortunately, most of the major stations that are regularly brought up to full load very quickly discharge into lochs or reservoirs rather than into a riverine situation, largely buffering the effects of changes in flow and water height.

Nevertheless, as far as possible the pattern of release should simulate a natural spate hydrograph for the river, although the extent to which this will be achievable will be dependant on the technical limitations of the machinery used to manage the release. Ideally the releases will involve small stepped changes which are smoothed by short time intervals. In the case of Roadford Reservoir, the increase to a maximum discharge of 320 Ml per day (3.7 m^3/s) from the base flow of 9 Ml per day (0.104 m^3/s) takes place over 3.5 h and reduction of releases back to 9 Ml per day takes 40 h. However, where fixed gate opening intervals are involved, larger stepped changes may have to be accepted (H.T. Sambrook, pers. commun.).

3.4. Channel manipulations

3.4.1. Channel modification to mitigate impacts of unfavourable flow conditions

Following reservoir construction on a river, the reduced flow often means that the original channel is oversize for some distance downstream of the dam relative to the regulated flow regime which it will receive. To reinstate favourable velocity and depth conditions, physical narrowing of the channel by application of appropriate river engineering techniques may be necessary. However, such a channel may still have to cope with occasional high flows, e.g., when dam overspill occurs, or when large quantities of augmentation water are being released. In such circumstances a two-stage channel may be required, with a low flow channel designed to carry compensation flows and normal regulation releases, and a higher level channel over shallow side berms to carry high flows. Alternatively some form of relief-channel or creation of refuges and in-stream cover may be appropriate. Various designs for achieving these various channel modifications are given by Hendry and Cragg-Hine (1997) and in the New Rivers and Wildlife Handbook (RSPB/NRA/RSNC, 1994).

3.4.2. Replenishment of spawning gravels

Although appropriate management of releases from reservoirs can reduce the incidence and severity of damaging peak flow events, these can still occur when dams overspill. One consequence of these events is a scouring of the river bed below the dam and removal of the small material used by spawning salmonids. The presence of the dam prevents replacement of this material from further upstream, leaving areas devoid of spawning gravel (APEM (1995)). Scottish and Southern Energy have developed a policy of placing gravel which has been dug out of intakes and small dams back into the river downstream of the dam, so that the normal process of replenishment can continue (Dr. A. Stephen, pers. commun.).

4. Physical habitat

The physical habitat requirements of salmonids can be described as follows:

- Adequate quantities of spawning gravel of the appropriate size range (16–150 mm) and with a low fines content.
- In close proximity to spawning grounds, extensive nursery areas for fry and under-yearlings, with water depth around 20–40 cm and velocities of the

order of 20–75 cm/s. In-stream cover should be provided by small cobble (up to 64 mm) and bankside vegetation should provide a degree of overhead cover and shade.

- Adjacent to the fry habitat large areas of deeper faster water (up to 46 cm) with velocities up to 100 cm/s for yearling and older parr. The substrate should be coarse, predominately cobble and boulder in size, ranging from 64 to 256 mm to provide in-stream cover.
- For adults free access to the spawning areas is essential, and with adequate secure holding areas (1–2 m deep) for adults adjacent to the spawning riffles. Obstacles should not exceed a vertical height of 3 m.

In a physically undisturbed river channel the conditions outlined above, would normally be present with rubble strewn riffle/pool sequences in high gradient areas, and riffle/glide/pool sequences in low gradient reaches.

4.1. Reasons for deterioration

Freshwater riverine habitats may be modified as a result of natural changes in river channel and climate but by far the largest impact is human use of the river and the surrounding land. In the UK and Ireland adverse effects are predominately related to agriculture, land drainage, water supply, hydropower, flood control and historically industrial use associated with the construction of weirs (Hendry and Cragg-Hine, 1997). Hydropower and water supply dams, together with industrial weirs have all played their part in providing obstacles to upstream migrating salmonids, helping to eradicate salmon and migratory trout populations from many tributaries and even whole river systems. However, smaller obstacles, such as bridge culverts and engineered fords, can also be widespread within catchments, severely restricting upstream migration in some cases. For example on the River Tweed, several hundred man-made obstacles of this type were recently identified (Dr. R. Campbell, pers. commun.).

However, agriculture and associated land drainage schemes are considered the greatest single cause of habitat decline today (Hendry et al., 1998). Poor agricultural management practices include activities such as overgrazing as a consequence of unsustainably high stock densities, changes in sheparding practices resulting in over-wintering on vulnerable hillsides and planting of crops such as maize in floodplain areas previously suitable only for pasture. Large scale land drainage to increase the area available for cultivation, such as the arterial drainage schemes in Ireland in the 1960s and 1970s, have also had a profound impact on the ability of watercourses to support salmonids (O'Grady, 1991). The consequences of these practices for rivers and streams include:

(1) higher run-off speeds with concomitantly greater stream power;
(2) increased erosion resulting in bank collapse, stream widening and instability;
(3) greater in-stream sediment loads with resulting siltation and compaction of critically important spawning areas.

Poorly managed or neglected forestry and woodland sites can also have deleterious consequences for salmonids. Dense shading caused by un-managed overgrown streamside vegetation, limits primary productivity and consequently the abundance of stream invertebrates on which salmonids depend for food (O'Grady, 1993).

Although these practices arguably impact rivers on a local scale, the driving force behind them is the CAP. Farmers are encouraged by the prevailing subsidy regime to farm in a manner that causes widespread damage to riverine environments. The CAP combined with the current lack of any effective land-use control legislation to specifically police and control these detrimental effects of agriculture and forestry, is arguably the biggest single threat to the survival of many salmonid populations throughout the British Isles.

4.2. Identifying habitat deterioration

When considering habitat improvement it is essential to understand the nature of the deterioration, its extent, and, an issue of crucial importance, identifying which of the salmonid life history stages it impacts upon. Once identified, the critical factors leading to deterioration, known as "bottlenecks" or "pinch points", can be overcome by specific habitat improvements aimed at alleviating the bottleneck to salmonid production (Garcia de Jalon, 1995). However, the process of identifying the critical factors leading to deterioration requires detailed information on a spatial scale.

Therefore a dedicated baseline survey, carried out on a catchment-wide basis, is a critical pre-requisite to designing and implementing major habitat enhancement/rehabilitation programmes. The catchment-wide basis of such an exercise is critical. Many such surveys have indicated that different sub-catchments and discrete reaches of the "main stem" can have very different functions in salmonid terms (O'Grady, 1995). It is only with an overview of an entire catchment that the various imbalances leading to bottlenecks can be recognised and subsequently prioritised for enhancement/rehabilitation purposes (O'Grady, 1991).

Essentially a baseline survey, from a salmonid fishery management viewpoint, is an attempt to divide a catchment into a series of discrete zones each of which has a different function in salmonid terms within the context of an overall catchment. There are four primary factors involved in defining a zone (assuming good water quality and adequate quantity); mean summer discharge value; channel gradient or slope; channel bed type, and the nature of the riparian zone. Once one or more of these primary factors changes significantly then the capacity of a channel to support, or produce, salmonids will be altered (O'Grady (1994)).

A knowledge of man's activities in a specific catchment, both historically and currently, is also invaluable in designing a specific survey programme that will be of practical value to the fishery manager in understanding a particular catchment and its problems. For example, historical problems from heavy industry and arterial drainage in the past, serious overgrazing and bankside erosion problems, excessive shading from deciduous and/or coniferous plantations and siltation of channels from agricultural practices are typical issues which may be encountered.

Various baseline survey methodologies have evolved overtime in different countries (O'Grady and Duff, 2000; Hendry and Cragg-Hine, 1997; Summers et al., 1996). A fishery manager challenged with the task of surveying an individual catchment should take cognisance of the various methodologies already developed, compile as much background information on the particular catchment as possible and then "tailor" a survey programme specifically to take account of any special characteristics (problems both historical and current) in a particular watershed.

4.3. Physical habitat restoration

When considering physical habitat restoration it is essential to realise the importance of river type. Hendry and Cragg-Hine (1997) identified the range of river types in which salmonids are found in the British Isles. These range from comparatively low energy chalk streams of southern England, to low Moorland rivers of moderate energy in Ireland to the high energy spate rivers of the Scottish highlands. Techniques that may be applicable in one type of river may be hopelessly inadequate in others. An understanding of channel types as defined by Rosgen (1996) combined with geomorphological and hydrological expertise is essential in physical habitat restoration.

4.3.1. Removal of obstacles

A baseline survey of the Tweed Catchment illustrated the presence of 861 natural and man-made obstacles (Dr. R. Campbell, pers. commun.). The Tweed Foundation have since removed or made passable many of the man-made obstacles, in the process re-opening up improving access to 640 km of spawning and nursery water. If the level of obstructions located on the Tweed is a reflection of general developmental trends on British rivers then clearly there is a need for "walk-over" surveys and subsequent electro-fishing programmes to clarify the extent of this problem in all major salmonid catchments in Britain. The removal or easement of passage over such barriers clearly represents the single most cost effective rehabilitation proposal one could undertake.

On a larger scale, for obstructions such as weirs and dams, there is a wealth of information on fish passage obstructions and means of overcoming obstacles using fish passes, fish ladders etc. (e.g. Beach, 1984; Reeves et al., 1991). There are two basic types of fish pass which are commonly used in England and Wales including the pool and traverse passes and the "roughened channel" passes (e.g. the Denil Pass and its variants, such as the Alaskan Steep Pass and the Larinier Pass). Where access past high dams is required, a fish lift or fish lock, such as the Borland Lock, may be necessary. Borland Locks have been installed in some hydro-electric dams in Scotland and Ireland.

The issue of temporary obstructions caused by large woody debris has been subject to considerable investigation in North America. Woody debris is perceived to have a positive important impact on spawning and juvenile habitat for Pacific salmonids (Chapman and Knudson, 1980; House and Boehne, 1985). The loss of large woody debris is regarded as a long lasting phenomenon that transforms streams into considerably less productive environments (House and Boehne, 1985). Consequently, the issue of trash dam removal to facilitate either fish passage and/or land drainage is heavily criticised. Obviously this is at odds with removal of large woody debris that is considered to be an impediment to fish migration, hence a balanced approach needs to be adopted.

4.3.2. Control of tunnel vegetation

Poorly managed riparian vegetation, from a fishery perspective, can be easily "re-balanced" by selective thinning and pruning. On the River Arrigle in Ireland, a continuously heavily shaded reach some 800 m in length was selected for study in 1990. Scrub trees, briars and woody shrubbery were removed along the banks from the lower 400 m length, leaving mature bankside trees uncropped, whilst no pruning was undertaken in the upper 400 m reach. A statistically significant 6-fold increase in 1+ year old salmon and a doubling in the 1+ year old trout numbers were evident in the pruned section 2 years post-works, whilst no increase was observed within tunnelled zone (O'Grady, 1993).

These data illustrate that the management of the riparian zone to prevent overshading is critical in order to optimise the standing crop of salmonids but it is also necessary to understand that a suitably vegetated riparian zone has other functions also essential to salmonid production.

4.3.3. Fencing and the protection of riparian vegetation

Well vegetated banks are essential in order to prevent unnaturally high erosion levels, to provide cover for fish, reduce critically high summer water temperatures and reduce the run-off of silt from adjacent land. Fencing to exclude livestock and prevent grazing of riparian vegetation is now commonplace and a central theme of salmonid restoration strategy. The direct benefits include promoting channel stability, controlling erosion, diversification of habitat by providing overhead vegetative cover, and increased in-stream productivity (Hynes, 1970; Anderson and Ohmart, 1985).

Where the riparian zone is inadequate to provide cover for fish and prevent excessive erosion but channel physical form has not yet deteriorated significantly, it is crucial that banks are fenced-off from stock and planted. This is often an essential preventative measure that, of itself, will address excessive erosion problems before they arise thereby maintaining the channels physical form. In the long-term this strategy is likely to lead to increased salmonid standing crops as the riparian zone regenerates and has been used very successfully both in Ireland and Scotland, notably on the River Tweed (Dr. R. Campbell, pers. commun.).

Given the potential conflict between unchecked riparian vegetation and a need to prevent denudement from grazing clearly a balanced approach is needed. This should comprise a long-term management programme of fencing, planting and pruning to maintain and where possible maximise salmonid productivity.

4.3.4. Channel modification using riparian structures

In low energy river systems, such as chalk streams, "soft engineering" techniques can be employed (RSPB/NRA/RSNC, 1994) harnessing geomorphological processes to accomplish aims such as channel narrowing and deepening. The natural process of fluvial erosion can be harnessed and manipulated by incorporating structures such as live trees, dead trunks and brushwood into the riparian zone. Woody materials will create a colonisable natural habitat, compared to the sterile homogenous environment occurring where "hard" structures are used.

Large tree trunks, half submerged alongside the riverbank, can help to halt erosion by directly absorbing energy from the water. Bundles of live willow withies can then be placed behind the trunks where they will develop roots and shoots, binding bank material together and trapping silts which act as a growth medium for colonising emergent macrophytes (Hemphill and Bramley, 1989).

Spiling is an useful technique in low energy streams where live willow withies are weaved around freshly cut winter willow stakes. The stakes are placed into the bankside material and will protect over-steep/vertical banks or scour holes as the stakes root and produce living and long lasting protection (Hemphill and Bramley, 1989). In more energetic systems, live willow stakes planted into a revetment structure (e.g. log structures, rip-rap or gabion baskets) will root and consequently bind the fill material together thus increasing its longevity and improving habitat diversity (Dr. M. O'Grady, pers. commun.).

Hazel hurdles (constructed from coppiced materials) will not root but will protect a regarded bank from wash and scour. The natural riparian community will grow through the weave and, after approximately 10 years, the wood will rot away. Another successful technique used in low energy chalk stream rivers involves the use of faggots (brushwood bundles) placed in the bankside material. They trap silt and sediment and hence consolidate the bank through accretion. Subsequent scour is prevented by emergent shoots (if willow is used) and the woody branches buried in the silt (Lewis and Williams, 1984).

4.3.5. Channel modification using in-stream structures

In-channel modifications can be used to great effect to improve in-stream habitat for all life stages of salmonids. Techniques range from gravel addition and retaining structures, to weirs and deflectors designed to increase stream turbulence and direct flow to promote habitat diversity. Other techniques include a range of bank protection measures from boulder armouring or rip-rap to log and christmas tree revetments. A full description of the range of techniques can be seen in Hendry and Cragg-Hine (1997) and Summers et al. (1996).

The most extensive programme of in-stream salmonid habitat enhancement/restoration schemes undertaken in the British Isles has been implemented in Eire (O'Grady, 1995). A wide variety of techniques have been employed to varying degrees and in different combinations to solve individual problems (Table 1). Techniques used are similar to those employed in North America since the 1930s (Duff et al., 1995). Natural materials (rock and timber) were largely used with the exception of iron pins used to secure logs and sheets of terram (fibreglass cloth) laid beneath the bed upstream of log weirs (after Hunt, 1993) to prevent "wash out".

Three examples illustrating the success of in-stream habitat restoration works from Ireland are presented in Table 2.

The data indicate that enhancement in both lowland streams and rivers and upland channels has proved successful, the data being statistically significant at the 95% confidence level. In Ireland over the past 10 years, quantitative data on fish stocks have been compiled for over 200 paired sites (developed and control areas), in a wide variety of channels (0.5–25 m in width) in many different catchments (Kelly, 1997; O'Grady, 1991; O'Grady and Duff, 2000 and O'Neill, 1998). The results presented for the Borroe, Grange and Deel channels are fairly typical of this entire data set.

In Britain, with a few exceptions, habitat restoration and monitoring of its effectiveness has been limited to date (Hendry and Cragg-Hine, 1997), although habitat restoration programmes carried out by the Tweed Foundation on tributaries of the Tweed using some of the techniques already described for Irish channels have also proved successful (D.I. Glen, pers.

Table 2
Observed changes in salmonid stocks in two lowland, and one upland channel in Ireland 2 years after enhancement works

Channel	Base width (m)	Gradient (%)	Problems and solutions	Results (2 years post-works)
Borroe stream	3.5	0.75	Drained in 1950s. Good riparian recovery since pool areas rebuilt with stone and timber structures over 1 km length of channel	2.5-fold and 2-fold increase in 1+ salmon and trout nos., respectively
Grange River	5.0	0.1	Drainage and subsequent bank trampling eliminated natural channel form. Banks rebuilt in stone. Riffle pool glide sequence rebuilt. Spawning gravel placement. Fencing and planting willows. An 4.39 km length was developed	2-fold increase in 1+ salmon nos. 6-fold increase in 1+ and older trout stocks
Deel River	5.0	2.8	Overgrazing by sheep led to severe bank erosion on meander bends. Log/Xmas tree revetments used to stabilise banks. Willows planted. Banks fenced-off. An 4.0 km length of channel was repaired	2.4-fold increase in 1+ salmon nos. No significant change in trout stocks

commun.). Giles and Summers (1996) also report positive results in relation to in-stream habitat enhancement on the River Piddle in Dorset.

4.3.6. Costs and returns

The benefits from salmonid riverine rehabilitation/enhancement proposals can be very positive when compared to other strategies such as stocking (Bilsby et al., 1996). The unit costs of producing additional fish from habitat enhancement will obviously be variable, dependant as it is on both the level of works required to protect, restore or enhance channel form and the riparian zone in tandem with the natural capacity of a particular channel to produce fish.

The Irish experience over the period 1995–1999 indicates that there are probably many circumstances where additional salmon pre-smolts and/or 1+ year old trout can be produced for between 20 and 40p per fish assuming the capital costs are written off over the lifetime of the works, typically 25–30 years. This is probably an over-estimate of the cost per fish because the restored channel form is likely to remain in place for longer than 30 years. For example, many timber weirs built in American streams in the 1930s are still in place and functional (D. Duff, pers. commun.). The principal long-term maintenance costs will be in relation to fence maintenance and, in smaller rivers and streams, a pruning of the riparian canopy at intervals.

5. Conclusions

Salmonid habitat is a complex and interactive mixture of water quality, quantity and physical structure. If any one component is degraded or inadequate, then salmonid productivity will decline. Historically, many of man's activities have severely impacted on all of these components and have contributed to a decline in salmonid populations, in some cases leading to their total eradication from whole river catchments.

In these more enlightened days we have made significant progress with regard to water quality deterioration, and as a society have demanded the wide-scale removal of pollutants from our rivers necessitating better treatment of effluents and more effective regulation. This is largely being achieved with unprecedented levels of industrial investment after generations of neglect. However, diffuse forms of pollutants, notably silt, which impact on water quality arising from poor land management are yet to be tackled in any meaningful way.

With respect to water quantity, arguably our approach is not yet as advanced as that which applies to water quality. Proposals for a more effective and sustainable regulatory regime are currently under consideration but water quantity must be recognised as an equally delicate and finite resource and one that must be sensibly managed. This is not merely an issue of abstraction for the water supply industry but is of much wider significance relating equally to land management, flood defence and the active management of water resources for environmental benefit. In the case of water regulation and supply, society's demands for increasing quantities of water and better flood defences will undoubtedly increase. However, with imagination and integrated planning many environmental benefits advantageous to salmonid populations can be built into schemes without the need for detrimental impacts. It should also be realised that many of the benefits that may accrue from environmentally sensitive flow management programmes cost little or nothing to implement.

Effective physical habitat restoration has been demonstrated in a wide range of river types and in particular on an extensive scale in Ireland. Suitably monitored pilot schemes are an integral part in developing the discipline of physical habitat restoration, and are essential to developing these restorative and enhancement techniques as a major tool for fisheries management. The implementation of in river and bankside rehabilitation programmes designed to benefit fish stocks, can clearly be successful. However, the benefits extend way beyond the increases in fish numbers. Once the natural physical form of a channel has been restored and the banks protected, then the natural ecology of the whole river corridor starts to recover bringing benefits to a wide diversity of flora and fauna.

However, we are currently merely scratching the surface, attempting to reverse damage and neglect inflicted and often unwittingly funded by misguided policies over many years. In England and Wales alone, the Environment Agency estimates that for the foreseeable future a rolling programme of expenditure in excess of £10 million a year will be required to reverse historic damage (MAFF and NAW, 2000). However, in contrast to water quality and quantity deterioration, the damage is continuing largely unchecked due to current agricultural policies and a lack of land-use regulation.

In comparison to the water quality and quantity components of salmonid habitats, physical riverine structure is largely neglected when it comes to regulatory protection. There is no effective regulatory control to prevent habitat deterioration and the deleterious aspects of land management that contribute so much to the decline of our salmonid populations. The CAP continues to encourage damaging land practice and a lack of regulatory control effectively rules out any effective land management strategy.

Clearly, we must tackle the cause of the problem and not just treat the symptoms. Therefore fundamental reform of the CAP is essential, coupled with meaningful regulatory controls for land-use which impact upon river catchments to the detriment of all aspects of salmonid biology. Ultimately tackling these fundamental issues will benefit the environment as a whole and not just fisheries, leading to truly sustainable management of our natural resources.

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References

Alabaster, J.S., 1970. River flow and upstream movement and catch of migratory salmonids. J. Fish Biol. 2 (1), 1–14.

Alabaster, J.S., Lloyd, R., 1982. Water Quality Criteria for Freshwater Fish, 2nd ed. Butterworths, London, p. 361.

Anderson, B.W., Ohmart, W., 1985. Riparian revegetation as a mitigating process in stream and river restoration. In: Gore, J.A. (Ed.), The Restoration of Rivers and Streams. Butterworths, London.

Andersson, B.I., Alenas, I., Hultberg, H., 1984. Liming of a small acidified river (River Anrasean) in southwestern Sweden, promoting successful reproduction of sea trout (*Salmo trutta* L.). Rep. Inst. Freshwater Res. Drottingholm 61, 16.

APEM, 1995. River Wyre: Salmon and Sea Trout Spawning Habitat Restoration/Creation. NRA NW Region Internal Report, p. 82.

APEM, 1998. The impact of grazing and upland management on erosion and runoff. R&D Technical Report P123. Environment Agency, Bristol, p. 42.

APEM, 1998b. An investigation into the impact of flow regulation on fisheries of the River Dee. Environment Agency, Welsh Region, p. 95.

Armstrong, J.D., Kemp, P.S., Kennedy, G.J.A., Ladle, M., Milner, J., 2003. Habitat requirements of Atlantic salmon and brown trout in rivers and streams. Fish. Res. 62, 143–170.

Bailey-Watts, A.E., Wise, E.J., Kirika, A., 1987. An experiment in phytoplankton ecology and applied fishery management: effects of artificial aeration on troublesome algal blooms in a small eutrophic loch. Aquat. Fish. Manage. 18, 259–275.

Banks, J.W., 1969. A review of the literature on the upstream migration of adult salmonids. J. Fish Biol. 1 (2), 85–136.

Baxter, G., 1961. River utilisation and the preservation of migratory fish life. Proc. Inst. Civ. Eng. 18, 225–244.

Beach, M.H., 1984. Fish pass design-criteria for the design and approval of fish passes and other structures to facilitate the passage of migratory fish in rivers. Fisheries Research Technical Report, 78, MAFF, Doctorate of Fisheries Research, Lowestoft.

Bilsby, M.A., Cragg-Hine, D., Hendry, K., 1996. Cost benefit analysis its use in recreational fisheries development and management. In: Proceedings of the EIFAC Symposium on Social, Economic and Management Aspects of Recreation Fisheries, Dublin, June 1996.

Birnie, R.V., Hulme, P.D., 1990. Overgrazing of peatland vegetation in Shetland. Scottish Geogr. Mag. 106.

Bode, K.I.D., 1996. Perspectives on two-dimensional river habitat models: the PHABSIM experience. In: Leclerc, M. (Ed.), Proceedings of the Second IAHR Symposium on Habitats Hydraulics, Quebec, IRNS, Ecohydraulics, 2000, B149–B162.

Bovee, K.D., 1986. Development and evaluation of habitat suitability criteria for use in the instream flow incremental methodology. Instream Flow Information Paper 21. US Department of the Interior, Washington.

Brix, H., 1987. Treatment of wastewater in the rhizosphere of wetland plants—the root—zone method. Water Sci. Technol. 19 (10), 107–118.

Burt, T.P., 1995. The role of wetlands in runoff generation from headwater catchments. In: Hughes, J., Heathwaite, L. (Eds.), Hydrology and Hydrochemistry of British Wetlands. Wiley, Chichester, pp. 21–38.

Chapman, D.W., Knudson, E., 1980. Channelization and livestock impacts on salmonid habitat and biomass in W. Washington. Trans. Am. Fish. Soc. 109 (4), 357–363.

Cragg-Hine, D., 1985. The assessment of the flow requirements for upstream migration of salmonids in some rivers of North-West England. In: Alabaster, J.S. (Ed.), Habitat Modification and Freshwater Fisheries. Butterworths, London, pp. 209–215.

DeGraaf, D.A., Bain, L.H., 1986. Habitat use by and preferences of juvenile Atlantic salmon in two Newfoundland rivers. Trans. Am. Fish. Soc. 115, 671–681.

Duff, D., Willstein, L.H., Nackowski, M., Wilkins, M., Hreha, A., Gurrin, J., 1995. Indexed bibliography on stream habitat improvement. USDA Forest Service/Trout Unlimited, Utah.

European Union (EU), 1976. Council Directive 76/464/EEC of 4 May 1976 on pollution caused by certain dangerous substances discharged into the aquatic environment of the Community.

European Union (EU), 1978. Council Directive 78/659/EEC of 18 July 1978 on the quality of fresh waters needing protection or improvement in order to support fish life.

European Union (EU), 1979. Council Directive 80/68/EEC of 17 December 1979 on the protection of groundwater against pollution caused by certain dangerous substances.

European Union (EU), 1991. Council Directive 91/271/EEC of 21 May 1991 concerning urban waste water treatment.

European Union (EU), 1992. Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora.

Evans, R., 1990. Water erosion in British farmer's fields—some causes, impacts, predictions. Prog. Phys. Geogr. 14, 199–219.

Evans, R., 1996. Soil erosion and its impacts in England and Wales. Friends of the Earth Trust.

Finnigan, R.J., Marshall, D.E., Mundie, J.H., Slanery, D.A., Taylor, G.D., 1980. Stream Enhancement Guide. Vancouver, Department of Fisheries and Oceans.

Frederikson, Kamine and Associates, 1980. Proposed Trinity River Basin Fish and Wildlife Management Programme. US Bureau of Reclamation, Sacramento, CA.

Furness, G.W., Webb, S.W., Colman, D.R., Hendry, K., 1991. The status of waste handling facilities on livestock farms in Great Britain 1990/91. Joint Ministry of Agriculture Fisheries and Food, Welsh Office Agriculture Department and Scottish Office Agriculture and Fisheries Department Publication, p. 227.

Garcia de Jalon, D., 1995. Management of physical habitat for fish stocks. In: Harper, D.D., Ferguson, A.J.D. (Eds.), The Ecological Basis for River Management. Wiley, Chichester, pp. 363–373.

Gerke, R.J., 1973. Salmon Spawning Habitat Improvement Study. State of Washington Department of Fisheries and National Marine Service, Project No. AFC-S9-2.

Giles, N., Summers, D., 1996. Helping fish in lowland streams. Game Conservancy Ltd., Hampshire, p. 36.

Heggenes, J., Saltveit, S.J., 1990. Seasonal and spatial microhabitat selection and segregation in young Atlantic salmon, *Salmo salar* L., and brown trout, *Salmo trutta* L., in a Norwegian river. J. Fish Biol. 36, 707–720.

Hemphill, R.W., Bramley, M.E., 1989. Protection of river and canal banks. CIRIA/Butterworths, London.

Hendry, K., Cragg-Hine, D., 1997. Restoration of riverine salmon habitats. Fisheries Technical Manual 4. Environment Agency, Bristol.

Hendry, K., Johns, M., Fisher, E., 1998. Upland management: the implications for fisheries. In: Proceedings of the IFM 29th Annual Study Coarse, Cambridge, September 22–24, 1998, pp. 80–84.

Holm, C.F., Armstrong, J.D., Gilvear, D.J., 2001. Investigating a major assumption of predictive instream flow models: is water velocity preference of juvenile Atlantic salmon independent of discharge. J. Fish Biol. 59 (6), 1653–1656.

House, R.A., Boehne, P.L., 1985. Evaluation of instream structures for salmonid spawning and rearing in a Coastal Oregon stream. North Am. J. Fish. Manage. 5, 283–295.

Howe, G.M., Slaymaker, H.O., Harding, D.M., 1967. Some aspects of the flood hydrology of the upper catchments of the Severn and Wye. Trans. Inst. British Geogr. 41, 33–58.

Howells, G., 1986. A report of the pre-intervention phase 1984–1986. Loch Fleet Report. Central Electricity Generating Board, Southern Scotland Electricity Board, and British Coal.

Hunt, R.L., 1993. Trout Stream Therapy, The University of Wisconsin Press, p. 70.

Hynes, H.B.N., 1970. The Ecology of Running Waters. Liverpool University Press, Liverpool.

Johns, M., 1997. A potential link between sheep overgrazing, erosion and flooding. In: Proceedings of the Sixth National Hydrology Symposium, British Hydrological Society, Salford, September 1997, pp. 1.39–1.46.

Kelly, F., 1997. Fisheries enhancement of the Rye water, a tributary of the River Liffey. Ph.D. Thesis, National University of Ireland.

Kennedy, G.J.A., Strange, C.D., 1986. The effects of intra- and interspecific competition on the distribution of stocked juvenile Atlantic salmon, *Salmo salar* L., in relation to depth and gradient in an upland trout, *Salmo trutta* L., stream. J. Fish Biol. 29, 199–214.

Large, A.R.G., Petts, G.E., 1992. Rehabilitation of river margins. In: Calow, P., Petts, G.E. (Eds.), The Rivers Handbook, vol. 2. Blackwell Scientific Publications, Oxford, pp. 401–418.

Lawson, J.D., Sambrook, H.T., Solomon, D.J., Weilding, G., 1991. The Roadford scheme: minimising environmental impact on affected catchments. J. Inst. Wat. Environ. Manage. 5, 671–681.

Lewis, G., Williams, G., 1984. The Rivers and Wildlife Handbook. The Royal Society for the Protection of Birds and The Royal Society for Nature Conservation.

Litton, G., Hendry, K., 1998. Development of operational and policy guidance on the use of hydrogen peroxide. Environment Agency R&D Technical Report P191, p. 19.

MAFF, 1991. Code of Good Agricultural Practice for the Protection of Water. Ministry of Agriculture, Fisheries and Food Publications, London, p. 80.

MAFF, NAW, 2000. Salmon and Freshwater Fisheries Review. Ministry of Agriculture Fisheries and Food and the National Assembly for Wales, p. 199.

Mason, C.F., 1998. Biology of Freshwater Pollution. Addison-Wesley/Longman, Harlow.

McEldowney, S., Hardman, D.J., Waite, S., 1993. Pollution: Ecology and Biotreatment. Longman, UK.

Millbrand, H., 1997. An investigation to the Afon Twrch. Technical Memorandum EAN/97/TM13, May 1997, p. 9.

Mills, D.H., 1989. Ecology and Management of Atlantic Salmon. Chapman & Hall, London, p. 351.

Milne, I., Mallet, M.J., Clarke, S.J., Flower, T.G., Holmes, D., Chambers, R.G., 1992. Intermittent pollution. Combined sewage overflows, ecotoxicology and water quality standards. National Rivers Authority R&D Note 123, Bristol, p. 193.

Morantz, D.L., Sweeney, C.S., Shirvell, C.S., Longard, D.A., 1987. Selection of microhabitats in summer by juvenile Atlantic salmon (*Salmo salar*). Can. J. Fish. Aquat. Sci. 44, 120–129.

Muscutt, A.D., Harris, G.L., Bailey, S.W., Davies, D.B., 1993. Buffer zones to improve water quality: a review of their potential use in UK agriculture. Agric. Ecosyst. Environ. 45, 59–77.

Nelson, R.W., Dwyer, J.R., Greenberg, W.E., 1987. Regulated flushing in a gravel bed river for channel habitat maintenance: a Trinity River case study. J. Environ. Manage. 11, 479–495.

National Rivers Authority (NRA), 1990. Discharge consent and compliance policy: a blueprint for the future. Water Quality Series No. 1, p. 69.

National Rivers Authority (NRA), 1992. The influence of agriculture on the quality of natural waters in England and Wales. Water Quality Series No. 6, p. 156.

National Rivers Authority (NRA), 1994. The national fisheries classification scheme. R&D Note 206, Bristol, p. 102.

National Rivers Authority (NRA), 1996. River habitats in England and Wales—a national overview. Report No. 1, March 1996, National Rivers Authority, Bristol.

O'Grady, M.F., 1991. Rehabilitation of salmonid habitats in a drained Irish river system. In: Steer, M. (Ed.), Biology and Management of Irish Rivers. Royal Irish Academy, Dublin, Ireland, pp. 187–204.

O'Grady, M.F., 1993. Initial observations on the effects of various levels of deciduous bankside vegetation on salmonid stocks in Irish waters. Aquaculture Fish. Manage. 24 (4), 563–573.

O'Grady, M.F., 1994. Salmonid habitat enhancement in Ireland—current practice, observed gains and future plans. In: Proceedings of the Ninth International Trout Stream Improvement Workshop, Calgary AB, Trout Unlimited, Canada, September 6–9.

O'Grady, M.F., 1995. The enhancement of salmonid rivers in the Republic of Ireland. Water Environ. Manage. 9 (2), 164–172.

O'Grady, M.F., Duff, D., 2000. Rehabilitation ecology of rivers and lakes. Verh. Int. Verein. Limnol. 27, 97–106.

O'Neill, J., 1998. Productivity studies on selected tributaries of the River Bandon, Co. Cork including a detailed stream enhancement project. Ph.D. Thesis. National University of Ireland.

Orr, H., 2000. The impact of recent changes in land use and climate in the River Lune—implications for catchment management. Ph.D. Thesis. University of Lancaster.

Reddy, K.R., Debusk, T.A., 1987. State-of-the-art utilization of aquatic plants in water pollution control. Water Sci. Technol. 19 (10), 107–118.

Reddy, K.R., Smith, W.H., 1987. Aquatic Plants for Water Treatment and Resource Recovery. Magnolia Publication Inc., Orlando, FL.

Reeves, G.H., Paul, J.D., Roelofs, T.D., Hickman, T.L., Baker, C.O., 1991. Rehabilitating and modifying stream habitats. In: Meecham, W.R. (Ed.), Influences of Forest and Rangeland Management on Salmonid Fishes and their Habitats. American Fisheries Society, Bethesda, MD, USA, pp. 519–557.

Robinson, M., 1986. Changes in catchment runoff following drainage and afforestation. J. Hydrol. 86, 71–84.

Robinson, M., 1990. Impact of improved land drainage on river flows. Institute of Hydrology, Report No. 113, Wallingford, p. 226.

Rosgen, D., 1996. Applied River Morphology. Wildland Hydrology, Colorado.

Rosseland, B.O., Skogheim, O.K., Abrahamsen, H., Matzow, D., 1986. Limestone slurry reduces physiological stress and increases survival of Atlantic salmon (*Salmo salar*) in an acidic Norwegian river. Can. J. Fish. Aquat. Sci. 43, 1888–1893.

Royal Society for the Protection of Birds (RSPB), National Rivers Authority (NRA), Royal Society for Nature Conservation (RSNC), 1994. In: Ward, D., Holmes, N., José, P. (Eds.), The New Rivers and Wildlife Handbook. Royal Society for Protection of Birds, Sandy, Bedfordshire, p. 426.

Sambrook, H., Broad, K., 1990. Roadford water resources scheme: migration of Atlantic salmon in the River Tamar. In: Atlantic Salmon Trust and Wessex Water: Workshop Proceedings on Fish Movement in Relation to Freshwater Flow and Quality, Bristol University, April 1989.

Sambrook, H.T., Gilkes, P., 1994. Roadford Reservoir—Enhanced Flows, Fisheries and Hydroelectric Power Generation. Reservoir Safety and Environment, Thomas Telford, London, pp. 119–133.

Schindler, D.W., 1988. Effects of acid rain on freshwater ecosystems. Science 239, 149–157.

Schofield, C., 1976. Acid precipitation: effects on fish. Ambio 5, 228–230.

Semple, J.R., 1987. A simple and effective method of cleaning the gravel of Atlantic salmon spawning habitat. Canadian Manuscript Report of Fisheries and Aquatic Sciences, 1933, p. 13.

Solomon, D.J., Templeton, R.G., 1976. Movements of brown trout in a Chalk Stream. J. Fish Biol. 9, 411–423.

Solomon, D.J., Sambrook, H.T., Broad, K.J., 1999. Salmon Migration and River Flow. Environment Agency and South West Water: Environment Agency R&D Publication, No. 4.

Stephen, A., 2001. Scottish and Southern Energy Hydro-generation and Fisheries Review 1997–2001. Scottish and Southern Energy Report, p. 47.

Stewart, L., 1973. Environmental Engineering and Monitoring in Relation to Salmon Management. International Atlantic Salmon Foundation, Special Publication Series 4, vol. 1, pp. 297–316.

Summers, D.W., Giles, N., Willis, D.J., 1996. Restoration of riverine trout habitats—a guidance manual. Fisheries Technical Manual 1. Environment Agency, Bristol.

Train, R.E., 1979. Quality Criteria for Water. Castle House Publications Ltd., p. 256.

Wesche, T.A., 1985. Stream channel modification and reclamation structures to enhance fish habitats. In: Gore, J.A. (Ed.), The Restoration of Rivers and Streams, Theories and Experience. Butterworths, London, pp. 103–163.

Wilson, C., Sheridan, W.L., 1974. Potential Benefit/Cost Ratio for Gravel Cleaning. US Forest Service Memorandum, Juneau, Alaska, US Forest Service, Region 10.

Wilson, J., Hendry, K., Rebbeck, J., 2000. Oxygenation project on the Manchester ship canal in the North West of England. In: Proceedings of the Water and Environmental Federation 73rd Annual Conference and Exposition, WEFTEC 2000, Anaheim, CA, USA.