Hydrology and the ecological quality of Scottish river ecosystems

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Accepted 15 October 2001

Abstract

Hydrology is a primary control on the ecological quality of river systems, through its influence on flow, channel geomorphology, water quality and habitat availability. Scottish rivers are widely perceived to be of high ecological quality, with abundant flow volumes and high water quality. However, historical and current river flow regulations, and land use change have altered the physical and chemical characteristics of Scottish rivers, with adverse consequences for aquatic biota. Baseline hydrological, geomorphological and water quality conditions in Scottish rivers are thus summarised. The impacts of river regulation and land use change on the hydrology, geomorphology and water quality of Scottish rivers are then discussed. Consequences of these changes for aquatic habitat are examined, with particular reference to the economically significant salmonid species (Salmo salar and Salmo trutta). Policy and management issues relating to the future ecological quality of Scottish rivers are reviewed. These include the impacts of climate change on ecological quality, the calculation and implementation of ecologically acceptable flows, and river restoration and best management practices within integrated catchment planning. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Floods; Land use; Management; Policy; River habitat; River regulation; Salmonids; Scottish rivers

1. Introduction

Scotland has a moist temperate climate with an average (1961–1990) precipitation of 1431 mm per annum. As such, the country has over 6000 rivers and a total stream length of in excess of 100 000 km (Smith and Lyle, 1994; Mackay et al., 1998; SEPA, 1999). Flow per unit area varies from 0.019 m$^3$ s$^{-1}$ km$^2$ for the joint regions of Forth and Tweed to 0.062 m$^3$ s$^{-1}$ km$^2$ for the Highland region. Exploitable water resources are equivalent to 16 000 m$^3$ per person per annum in comparison with 2090 m$^3$ per person per annum for the UK as a whole (Scottish Office, 2000). The natural water quality of most Scottish rivers is high, with low concentrations of nutrients and a pH of between 5 and 6 (Soulsby et al., 2002). In 1997, 91% of the classified river length in Scotland was determined by the Scottish Environment Pro-
tection Agency (SEPA) to have excellent or good water quality. Scotland’s rivers are important for nature conservation, water supply, recreation and tourism, and hydroelectric power generation. In 1996, there were 14 million day-visits by Scottish adults to canals and rivers, during which a total of 90 million pounds was spent. Seventy per cent of all visits to canals and rivers were for walking and other outdoor sports (Scottish Office, 2000). There are a number of fish species that inhabit Scottish freshwaters, which are a major component of Scotland’s freshwater biodiversity and are also of economic importance. Salmon (Salmo salar), sea trout and brown trout, both forms of Salmo trutta, rely on a hydraulically intact, clean freshwater environment. Latest estimates suggest that salmon alone brings in 50–100 million pounds per annum to the Scottish economy from recreational fisheries (Scottish Office, 1997).

As a consequence of the perception that Scottish rivers contain plentiful water of a high quality, one might think that their ecological quality, defined as ‘the totality of features and characteristics of the water that bear upon its ability to support an appropriate natural flora and fauna’ (Pugh, 1996), is assured. However, declining Atlantic salmon stocks and other species dependent upon riverine environments, such as the water vole (Arvicola terrestris) suggest that the physical habitat and ecological functioning of Scottish rivers are impaired. Hydrology is a primary control on the ecological quality of rivers, through its influence on geomorphology, flow regime, water quality and thus, habitat availability. Fluvial processes are critical in creating a range of river and floodplain landforms and ages of substrate, which provide instream habitat for many forms of biota and at a number of life stages. These, in turn, create a mosaic of biotic communities via the occurrence of differing physical conditions for colonisation and stages of biotic succession. For example, river channel planform changes have been demonstrated to be critical in controlling vegetation patch dynamics, within riparian zones of wandering gravel bed rivers, at the confluence of the rivers Feshie and Spey (Gilvear et al., 2000). Fluvial disturbance is also a key component of undisturbed rivers and may have benefits to the ecology, for example through the cleansing of spawning gravels used by salmonids. The flow regime of a river, together with its influence on water quality and sediment movement, thus determine river biotopes and create a ‘habitat template’ for aquatic flora and fauna.

To illustrate the interdependence of hydrology, geomorphology, water quality and ecological quality in rivers, Fig. 1 summarises the effects of these and other abiotic factors on site selection by salmon parr. The relationship between salmon populations and hydrology is complex and varies over time. Late spawning salmon may move independently of discharge, unlike their earlier counterparts, who respond to discharge increases (Alabaster, 1970). Indeed, fish migration may not be controlled by discharge, but by variables, such as turbidity and water chemistry, that vary with discharge. Armstrong et al. (1998), under experimental conditions, demonstrated the reluctance of salmon to move from their home territory despite severe reductions in river discharge.

Human activities that directly and indirectly affect the hydrology of Scottish rivers will therefore influence their ecological quality. The two areas of human activity that currently cause the most widespread impairment of the ecological quality of Scottish rivers are river regulation and land use change. This paper aims to demonstrate how river regulation and land use change have altered the hydrology, geomorphology and water quality of Scottish rivers. The effects of these changes on ecological quality are assessed using salmonids as a case study, due to the economic and conservation significance of these species. The potential impacts of future changes in hydrology, arising from climate change, on ecological quality in Scottish rivers are discussed. Finally, the effects of developments in policy and management on the hydrology and ecological quality of Scottish rivers are evaluated.

2. Natural character of Scottish rivers

In order to evaluate the impacts of river regulation and land use change on hydrology, geomorphology, water quality and ecological quality, the
Fig. 1. The relationships between river flow and other abiotic factors that determine fish populations (diagram compiled by Paul Kemp).
natural or baseline character of Scottish rivers must be established.

2.1. Flow regime

Runoff regimes reflect, under natural conditions, climate and catchment characteristics. Runoff per unit area in Scotland is generally high, due to high rainfall totals and low evapotranspiration values, but there is a marked gradient across the country, with decreases in rainfall and runoff and increased evapotranspiration from west to east (Marsh and Anderson, 2002). In addition, generally steep slopes, together with thin podzolics soils, result in flashy regimes, due to the predominance of saturation overland flow and rapid movement of soil water through the upper soil horizons (Wade et al., 1999). There is evidence, however, that groundwater contributions to the runoff regimes of some upland streams are more significant than one might imagine, due to inputs from superficial fluvio-glacial aquifers, (e.g. Soulsby et al., 1998a).

Climatically, floods are normally caused by snowmelt, intense summer rainfall or prolonged periods of rain falling on an already highly saturated catchment (Black and Burns, 2002). The largest floods are generally a combination of snowmelt and rainfall. These hydrological characteristics are reflected in the fact that the River Tay has the highest runoff and accurately recorded peak flow of any UK river, despite its catchment area being less than 50% of that of the River Thames. The Tay’s long term average flow is 164 m$^3$ s$^{-1}$ and in January 1993, a flood with a peak discharge of 2269 m$^3$ s$^{-1}$ occurred. The other principal Scottish rivers, (e.g. Carron, Clyde, Don, Findhorn, Nith, Spey, Tweed) have a lower average (50–100 m$^3$ s$^{-1}$) and maximum (500–1000 m$^3$ s$^{-1}$) discharges, but still reflect a high specific discharge.

The natural hydrological regime of many Scottish rivers is difficult to determine, since flow-gauging stations have been established historically in a piecemeal fashion to provide data for specific purposes, such as flood warning, water supply or discharge consents. Furthermore, many stations have only arisen after change has occurred. There has been some progress in modelling the ‘natural’ hydrology of Scottish rivers, (e.g. Steel et al., 1999) and using the UK Institute of Hydrology computer package ‘Micro Low Flows’ (A. Black, personal communication). Hydrological data from the FRIEND database (Gustard et al., 1989) were analysed to quantify the nature of Scottish flow regimes. Some 76 stations, with catchment areas of 1.5–741 km$^2$, were selected, where river flows were not substantially affected by flow regulation or abstraction and thus, the data give an indication of natural runoff regimes. The mean daily runoff of these sites is 0.03 m$^3$ s$^{-1}$ km$^2$, with values ranging between 0.012 and 0.1 m$^3$ s$^{-1}$ km$^2$. The higher values are generally associated with smaller catchments. The mean annual flood is 0.84 m$^3$ s$^{-1}$ km$^2$, with values ranging from 0.06 to 2.1 m$^3$ s$^{-1}$ km$^2$. Floods have been a particular focus of hydrologists in Scotland. For example, the long-term and seasonal pattern of flood peaks and physical controls of floods in Scotland has been researched by Black (1995) and Black and Werrity (1997), but further research is still required to elucidate the precise flood generating mechanisms. The importance of high flows in Scottish rivers is emphasised by generally low Base Flow Indices (fraction of annual flow contributed as base flow), which vary between 0.17 and 0.67, with a mean value of 0.31. The $Q_{95}$, or 95%-ile, as a percentage of average daily flow, is also low, producing values of between 2.6 and 20.7%, with an average of 8.5%.

2.2. Geomorphology

Hydrology and geomorphology are intimately related and critical to the ecological quality of rivers (Soulsby and Boon, 2001). River channel cross-sectional geometry, planform, bed material size and levels of bed, and bank stability are all controlled by river flow regime, both in terms of overall water yield, and the frequency and magnitude of flood events. Rates of sediment transport and river channel change have not been routinely studied in Scottish rivers. An understanding of the morphology and sediment transport dynamics of Scottish rivers relies on a few detailed investigations of particular river reaches, most notably on the Rivers Feshie, Allt Dubhag, Tummel and Dee, (e.g. Werrity and Ferguson, 1980; MacEwan,
Table 1
River water quality classification results for mainland Scotland, 1997 (SEPA, 1999)

<table>
<thead>
<tr>
<th>River reach</th>
<th>Excellent</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
<th>Seriously polluted</th>
</tr>
</thead>
<tbody>
<tr>
<td>km</td>
<td>37 064.7</td>
<td>8552.9</td>
<td>3336.1</td>
<td>1158.6</td>
<td>141.7</td>
</tr>
<tr>
<td>%</td>
<td>73.8</td>
<td>17.0</td>
<td>6.6</td>
<td>2.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>
of 22 people per km², only approximately 10% of river length was classified as fair/poor/seriously polluted in 1996, compared with 20% in western Scotland (population density 118 people per km²) and 18% in eastern Scotland (106 people per km²) (SEP A, 1999) (Table 1).

2.4. Ecological quality—a case-study of salmonid fish

Salmonid populations are controlled for a large part by the abiotic factors of hydrology, geomorphology and water quality in Scottish rivers, and as such are an indicator of their ecological quality (Soulsby and Boon, 2001). Salmon spawn in self-excavated hollows made in gravels (known as redds) in rivers and streams in the autumn and winter, with eggs hatching in the spring. The newly hatched alevins emerge and begin their existence as parr and then, after 1–5 years, migrate seaward as smolts. Fish which return to freshwaters after 1 year are known as grilse, while those that return after two or more winters to spawn are known as salmon. A large amount of literature has been produced on salmonid populations in Scotland, but there still gaps in our understanding of their behaviour and cause of their current decline. A review of fish in Scotland more generally is that of Maitland (1994).

Although it is difficult to accurately establish trends in salmon numbers, there is a consensus that they are declining in Scottish rivers (Scottish Office, 1997). Section 15 of the Salmon and Freshwater Fisheries Protection (Scotland) Act 1951 provides for the collection of catch data from proprietors and occupiers of salmon fishings. These catch statistics show dramatic declines over the last 30 years, but they may not be an accurate indicator of changes in the overall population, since no account is taken of catching effort. Fish counter data are a more reliable means of estimating salmon populations. Data collected on certain rivers in recent years have shown a decline in salmon numbers and indicated that 1999 was the worst year on record. Data for the River Conon in northern Scotland show the marked fall in 1999, below the last 5-year average (Fig. 2). The above average count for 1998 can be partially explained

![Graph showing cumulative counts of fish moving on the River Conon](image-url)
by the considerable stocking work undertaken by
the local District Salmon Fishery Board. Over 350
of the fish that passed the fish counter on the Torr
Achilty hydropower dam on the Conon were
counted upstream at Luichart, where the fish stock-
ing is well established, suggesting that the majority
of fish returning were stocked fish seeking their
home waters and not the natural population. In
1999, there will have been salmon passing through
Torr Achilty, which were again the result of the
stocking programme. In 1990 the record annual
low this was not the case. Thus, in the absence of
stocking in the Conon, the values for 1999 will
probably have been considerably lower.

Establishing the cause of the observed decrease
in salmon populations and the relative importance
of the river and marine life stages to the decline
is complex. Programmes to improve at-sea survival
need to be complemented by appropriate river
management, especially regarding the maintenance
of in-stream hydrology (Richter et al., 1997). River
flow regulation and the attendant loss of riparian
habitat, gravel bed siltation and water quality
deterioration, may all be contributory factors. Riv-
er geomorphology and habitat availability are like-
ly to be more limiting for salmon in Scottish rivers
than water quality. A total river length of 36 658
km in Scotland is designated for salmonids under
the EC Fresh Water Fish Directive (87/659/EEC),
in which minimum water quality standards must
be met. In 1995, 99.26% of designated river
reaches in Scotland complied with the standards,
though the industrialised Clyde region which
includes Glasgow had the worse performance, with
94.78% compliance (Scottish Office, 2000). This
evidence that water quality is not currently a major
constraint on salmon populations in Scottish rivers
is supported by the work of the Carron and Avon
Initiative for Salmon (CARIS, 1994), which found
that, despite water quality clean-up in the rivers
Carron and Avon, salmon populations are still
restricted, due to the physical structure of the river
and paucity of good habitat. It has also been
reported, independently, that the main constraint
on the number of smolts that a river can produce
is the availability of suitable habitat for young
salmon (Scottish Office, 1997). To a large extent,
this reflects the regulation of Scottish rivers and
land use changes in their catchments, leading to
modified hydrological and geomorphological
regimes.

3. Impact of flow regulation on Scottish rivers

During the late 18th and early 19th centuries,
land drainage, construction of flood embankments,
dredging and channelisation significantly affected
the middle and lower courses of many Scottish
rivers (Gilvear et al., in prep). Towards the late
19th century, water supply schemes and early
hydropower power generation schemes also
resulted in significant changes to river flow (Gil-
vear, 1994). During much of the 20th century,
there was a continuation of some of the early
trends. River flow regulation and water abstraction
increased markedly as a result of the development
of large hydroelectric power and water supply
schemes (Gilvear, 1994). More recently, smaller
‘run-of the river’ hydropower schemes have been
developed under the Scottish Renewables Order.
The water authorities operate 287 abstractions from
lochs and reservoirs and 223 abstractions from
rivers for drinking water (SEPA, 1999). Surface
water is also abstracted by freshwater fish farms,
distilleries, paper mills and other industries, and
for potato irrigation in eastern Scotland. Catch-
ments with hydropower schemes cover 20% of the
area of mainland Scotland. Hydropower schemes
involve not only direct impoundment of the main
rivers, but also substantial cross-catchment trans-
fer, using an estimated 1000 off-takes to divert
discharge from smaller rivers. In addition, there
are over 400 groundwater abstraction boreholes of
more than 15 m depth and many more small
private abstractions, which may have indirect
effects on river discharge through the depletion of
baseflows (Robins, 1990).

These modifications have been to the benefit of
water supply for domestic, industrial and agricul-
tural use, and hydropower production. There is
little doubt that historical changes in Scottish rivers
were accompanied by changes in hydrology, geo-
morphology, water quality and ecological quality,
yet there are few data with which to quantify
change. One example of the scale of change is the
fact that in the 19th century there were 125 fish
species in the River Forth and its estuary, while today the value has fallen to 45; the fall represents a loss of one species roughly every other year (FDSSFB, 1994). In the last few decades, more consistent records of discharge, water quality and fish catches have enabled a better understanding of the effects of river regulation on hydrological regime, geomorphology and water quality, and direct and indirect impacts on the ecological quality of Scottish rivers.

3.1. Effects of flow regulation on hydrological regime

Hydropower and water supply schemes and abstraction for other purposes have affected the hydrological regime in many Scottish rivers (Gilvear, 1994; Johnson, 1994). Impacts include elevated and depressed low flows, diurnal fluctuations, reduced flood frequency and magnitude, unnaturally rapid rates of stage change (Fig. 3) and elimination of flow and floods all together (Gilvear, 1994). Large-scale and smaller ‘run-of-the-river’ hydropower schemes may divert all the water during low flow periods. The empty riverbed of the River Garry, Perthshire, below the Trinafour diversion dam, which feeds water into the Tummel valley hydroelectric scheme, is a well-known example.

Most major dams in Scotland must release a compensation flow to protect downstream users, but there are no consistent means of calculating these flows or of monitoring their implementation. Some compensation flows are identified in the Statutory Instrument or Acts of Parliament for specific water supply, or hydropower schemes. Alternatively, informal compensation agreements may be reached between the operator and downstream water users. In practice, compensation flows below hydropower dams in Scotland are set at between 3.4 and 38.7% of the ADF, with an average value of 13.7%. Higher flows, known as freshets, may also be released from dams at the request of Fisheries Boards and Trusts, to assist the upstream migration of salmonids. The magnitude of freshets released from hydropower dams in Scotland varies from 0.33 to 82.95% of the average daily flow (ADF) or 1.99–24.3 times the compensation flow (mean 7.78%) (Gilvear, 1994).

Gustard (1991) calculated the average $Q_{95}$ as 18.5% of average daily flow (ADF) on regulated rivers in Scotland, in comparison with 10.7% for unregulated catchments with no storage and 14.95% for those with lochs located on the stream network. This demonstrates that river regulation may be useful in eliminating very low flows on mainstem rivers. For example, it has been estimated that the lowest drought flow on the River Tay, at its junction with the River Almond, has increased from 10.5 to 31.6 m$^3$s$^{-1}$ as a result of river regulation (Central Scotland Water Development Board, 1991). In this case, the flow not only reflects reservoir storage, but also inter-basin transfer from the upper reaches of the River Spey. However, in many cases, the artificial elevation of low flows on one river is offset by reduced or nil flow on a number of ‘donor’ streams.

3.2. Effects of flow regulation on geomorphology

As a result of the intimate link between river regimes and channel morphology, alteration of river flows can modify channel size and shape, and induce a range of geomorphological problems. Increased flood peaks as a result of urban runoff have thus been shown to result in channel widening and deepening in a range of situations where channel boundaries are erodible, (e.g. Whitlow and Gregory, 1989). Conversely, reduction in the magnitude and frequency of flood events can also bring about changes in channel morphology and instability. Regulated rivers are therefore often characterised by reduced channel widths, sediment aggradation, large tributary confluence bars and siltation of channel substrates. Reports of such occurrences have been well documented in Scotland. For example, Petts (1980) showed that channel capacities on five impounded rivers in the Southern Uplands were reduced to between 0.16 and 0.54 of their pre-impoundment size. Similarly, peak flow reduction by the Spey Dam, completed in 1942, has resulted in marked channel narrowing and appreciable aggradation for over 10 km downstream (Gilvear, 2000; Gilvear, submitted). A channel width reduction of approximately 50% is reflected in the view shown in Fig. 4. The wooded
Fig. 3. Examples of altered river flows on Scottish rivers. (a) Comparison of the flow of the unregulated River Tilt with that of the downstream River Tummel below the Pitlochry Dam. (b) Rates of stage change on the River Tummel due to hydropower releases. (c) Fluctuations in river levels on the River Tay resulting from hydropower releases from Loch Faskally.
area to the right of the channel represents post-dam vegetation colonisation of once active channel.

Conversely, clearwater erosion in the vicinity of dams, resulting from the upstream entrapment of the bedload, has been shown to be a significant geomorphic phenomenon elsewhere, but in Scotland, bedrock control generally limits the rate of stream bed degradation (McEwen, 1997). However, a few incidents of bank erosion immediately below dams have been documented in Scotland, (e.g. below the Pitlochry Dam on the River Tummel during a flood in 1990). Also, the lack of gravel input, due to reservoir sedimentation, to the regulated river may deplete the extent of available salmonid spawning habitat.

A key issue with regard to the effect of any change in fluxes of sediment on channel morphology is the sensitivity of the river to change and timescales of response. Some changes may not be important or the effect may not be felt for a number of years. However, in other cases, threshold conditions may be surpassed, and unanticipated and unwanted changes may suddenly accrue. The prediction of how channels will respond to changes in hydrological processes is complex, but enough examples exist to predict directions of change. Advances in knowledge are increasingly being incorporated within improved techniques for minimising the impact of river regulation. For example, when relocation of the Evan Water near Moffat was required, in connection with a trunk road upgrade, the diverted channel sections were constructed with a near natural morphology and substrate (Gilvear and Bradley, 1997). After completion of the work, the invertebrate and fish populations in the diverted channel cannot be distinguished from those found in the rest of the river system, demonstrating the success of such an approach. Similar environmentally sound engineering approaches have also recently taken place on the rivers Nith, Allan water and Éye water.

3.3. Effects of flow regulation on water quality

Regulation of Scottish rivers has also altered their water quality. Increased baseflow as a result of regulation may improve river water quality through increased dilution of pollution, whilst depletion or complete removal of flow may cause the reverse. The majority of changes in water quality, which occur following river regulation,
arise from the impoundment of surface waters, as fluvial processes are replaced by limnic processes. Thermal stratification of impounded waters results in the formation of a warm, well-oxygenated surface layer, the epilimnion, and cooler anoxic bottomwaters, the hypolimnion. Elevated concentrations of iron and manganese typically occur in the hypolimnion as the result of reduction of oxides in basal sediments. Hence, one of the key controls on the effects of reservoirs on water quality is the draw-off level for water. Stratification of the water column is rare in Scottish impoundments, probably due to high windspeeds, but redox-driven transport of manganese at the sediment-water interface has been reported in a number of freshwater lochs (Bryant et al., 1997).

The retention time of water and water level fluctuations in the impoundment also influence the extent of chemical and biological modification. For example, for river impoundments in northern Finland, significant positive correlations were reported between total nitrogen and impoundment area and retention time, and also between total dissolved solids, total phosphorus and the area exposed by water level fluctuation in the impoundment (Vehanen and Riihimaki, 1999). Suspended sediment concentrations and turbidity are usually reduced in rivers downstream of impoundments. Fluctuations in ion concentrations at the outflow are usually reduced compared to the inflow. This will be particularly significant in terms of water temperature and dissolved oxygen content, but also releases of iron and manganese to the regulated river. Scour valve releases and other types of reservoir releases, (e.g. freshets) can be important in affecting river water quality downstream, due to differences in the chemical composition of the reservoir water and the mobilisation of in-channel chemical stores. Thus, Foulger (1986) monitored chemical changes during a 15 m³ s⁻¹ release on the River Garry draining to Loch Ness and found that, although chemical dilution was the principal water quality response, a small increase in the concentration calcium was observed on the rising limb of the flow increase.

3.4. Effects of flow regulation on ecology—a case-study of salmonids

Hydrological regimes are of fundamental importance to the well being of salmonid fish in Scottish
rivers. Hydrology determines, to a large extent, not only the physical habitat in which salmon live, but organisms on which the salmon and trout feed, who are also dependent on stream hydraulics. There are thus, direct and indirect relationships between river flow regime and salmonid populations. Low and medium flows control the amount of available habitat, spates trigger fish migration and floods can be advantageous in de-silting spawning gravels. Extreme flood events may also have detrimental consequences: For example, a large flash flood in the Ettrick a tributary to the River Tweed washed out salmon eggs laid in the gravels. As this tributary is of great importance to the spring salmon component of the Tweed stock, it has been shown that 5 years (the average life span of salmon on the River Ettrick from egg to spawning) since the wash out, the spring salmon catch has been depleted. Impoundments are also physical barriers to fish migration. A number of studies in Scotland have examined fish survival rates through hydroelectric turbines for instance, (e.g. Munro, 1965). Scottish and Southern Energy Group are conducting tests on the effectiveness of fish lifts and ladders, and the importance of creating suitable flow hydraulics for fish migration. One of the problems in determining the impact, if any, of flow regulation, is that fish counters were often only installed at the time of dam construction and thus, no reliable data prior to regulation is available for comparison. Rod catch statistics have been used to demonstrate that flow regulation has no apparent impact, for example on the River Awe (Johnson, 1994), but catching effort also needs to be taken in to account and maintenance of numbers does not necessarily mean that regulation is not having a significant control on the population.

The relationship between salmon populations, fish behaviour and discharge is complex and thus, the effects of flow regulation difficult to unravel. Thus, fish migration may not be directly controlled by discharge, but by variables such as turbidity and water chemistry that vary with discharge. For example, data from the smolt run on the River Bladnoch in 1998 (West Galloway Fisheries Trust, 1999; Fig. 5) suggest that flow does not trigger the run but influences the numbers of smolts descending the river, in that the higher numbers tend to coincide with flood events. Several studies have found results contrary to what might be expected. The aforementioned work of Armstrong et al. (1998) demonstrated the reluctance of salmon to move from their home territory despite severe reductions in discharge, showing that the effects of site fidelity in fish may hinder their ability to respond to flow changes. Such findings have also been reported elsewhere; for example, Aass et al. (1989) found that the brown trout population of a Norwegian river showed no response to a 93% reduction in winter discharge. More significantly, Harris et al. (1991) showed that a 4-year period of a five-fold increase in the minimum flow did not alter the brown trout population in a small stream on the west coast of the USA. In relation to flow variability, Cowx and Gould (1989) reported a large decrease in the recruitment of Atlantic salmon and brown trout to a Welsh regulated river, with high fluctuations in summer discharge. This contrasts with the findings of Crisp et al. (1983), which indicated enhanced trout populations with similar regulation discharges on the River Tees, north-east England.

Although the relationships between salmonid populations and hydrology are not fully understood, adverse impacts on salmonids have been reported in regulated Scottish rivers. For example, the stranding of migratory salmonids has been reported in the River Leven, West Dumbartonshire, as the result of rapid flow fluctuations, caused by operation of the barrage controlling levels in Loch Lomond, Scotland’s largest public water source (SEPA, 1999). Adverse impacts on salmonids have been observed, even where compensation flows are released, because few have been based on ecologically sound science and, as a result, the proportion of average daily flow released varies widely between rivers. Increasingly, the importance of flow variability, including extreme events, is being seen as critical to the maintenance of river geomorphology and ecological quality. Disturbance, caused by flooding, is now regarded as an important component of river ecosystems, allowing pioneer species to be present and maintaining natural channel morphology (Gibbins et al., in press). Flow is also critical for sediment transport processes that maintain suitable substrate condi-
tions for a range of benthic organisms on which salmon feed. Maintaining facets of the natural flow regime in Scottish rivers is thus important for salmonid populations, not merely the release of stable compensation flows. For example, on the River Devon in Clackmannanshire, the release of stable compensation flows, from drinking water reservoirs in the headwaters, has been cited as the cause of silt and algae on the river bed and a deterioration in the condition of the fishery (SEPA, 1999). Similarly on the River Spey, as already mentioned, reduced flood magnitudes below the Spey Dam has resulted in channel narrowing and aggradation over the last 60 years and this has presumably decreased the areas of suitable fish habitat (Gilvear, 2000).

4. Impact of land use change on Scottish rivers

Land use in Scottish river catchments has changed markedly in the 20th century. The National Countryside Monitoring Scheme (NCMS) quantified changes in Scotland’s land cover from the 1940s to the 1980s, based on examination of air photography of 7.5% of the land area in 1947, 1973 and 1988 (Mackay et al., 1998). A summary of the net change in features is shown in Fig. 6. The changes in land cover with greatest impact for Scottish rivers and their ecological quality are: drainage of heather moorland and rough grassland for conversion to conifer plantation (Johnson and Thompson, 2002); arable expansion and agricultural intensification in lowland Scotland, with the loss of lowland mires, woodlands and riparian vegetation; and the encroachment of urban development onto lowland agricultural land. These changes in land cover have affected the baseline hydrology, geomorphology, water quality and salmonid populations in many Scottish rivers.

4.1. Effects of land use change on hydrology

Conifer afforestation, land drainage and urbanisation, by altering the pathways of water flow and
rates of water flux, have resulted in changes in runoff and river regimes on a number of Scottish rivers. For example, a decline in the output by 26% of the Tarsen hydroelectric power scheme in north-west Scotland between 1966/7 and 1984/5 was attributed to higher rates of evapotranspiration with the growth of coniferous forests in the catchment area (Johnson, 1994). Similarly, Greene and Taylor (1989) attributed a reduction of flow from 273 to 91 m³ per day of the Red Letter Springs, a local water supply source on the island of Arran, south-west Scotland, to Sitka spruce afforestation within the catchment. The most well known hydrological experiment in Scotland, which analysed the effect of conifer afforestation on water yield, is the Balquhidder experiment (see Johnson, 1991; Whitehead and Calder, 1993). The most significant result from the experiment was that conifer afforestation in this part of Scotland reduces the summer minimum low flows. The practice of land drainage is often used for ground preparation in commercial forestry, but also for improving agricultural land. In England and Wales, investigations have demonstrated that land drainage can both increase, (e.g. Reid and Parkinson, 1984) and decrease, (e.g. Newson and Robinson, 1983) flood magnitudes according to circumstances. However, upland land drainage, in most cases, is likely to increase runoff.

4.2. Effects of land use change on geomorphology

By altering catchment runoff and sediment loads, land use change can alter channel geomorphology. Increases in channel capacity downstream of urbanisation has thus been widely reported outside of Scotland and a channel with increases below streams draining coniferous forests, where canopy closure suppresses bankside vegetation, has also been observed. This mechanism of channel widening and the associated shallowing has been reported in the River Tweed catchment (Campbell and Maitland, 1996). Over-grazing of riverbanks will also have a similar effect. Sediment spoil from mining also has affected the physical and chemical properties of river channels (Rowan et al., 1999).

No other published scientific studies for Scotland are available, however, it is apparent that land use change will have modified the geomorphology of many channels in some way. More significant has been deliberate and inadvertent modification to man’s activities alongside rivers (Gilvear et al., in prep). The advent of the National River Habitat Survey (RHS) Methodology (Raven et al. 1998) has recently shed more light on the geomorphological status of Scottish rivers and will provide a benchmark against which change can be measured. The RHS assesses the whole physical structure of watercourses, including the recording of habitat features, artificial modifications, flow types, vegetation structure and land use. Habitat modification scores are calculated from the extent of direct, (e.g. reinforcement, dams, weirs, culverts) and large scale modifications, (e.g. flow control and channel realignment), and classified into six categories from predominantly unmodified to heavily modified. A survey of 779 sites in Scotland between 1995 and 1997 revealed that 48% of sites were classified as semi-natural, with 28% classified as either obviously, extensively or heavily modified (Table 2; SEPA, 1999). Some 40% of sites in Scotland had riverbanks reinforced to prevent bank erosion, resulting in the loss of riparian and gravel bar habitats. This is shown in Fig. 7, which contrasts the habitat in a heavily modified reach of the Ruthven Water with that of the semi-natural and wandering gravel-bed River Tummel. The geographical distribution of this

<table>
<thead>
<tr>
<th>Status/Sites</th>
<th>Predominantly modified</th>
<th>Obviously modified</th>
<th>Extensively modified</th>
<th>Heavily modified</th>
<th>Semi-natural</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of sites</td>
<td>182</td>
<td>113</td>
<td>92</td>
<td>10</td>
<td>382</td>
</tr>
<tr>
<td>% of sites</td>
<td>23</td>
<td>15</td>
<td>12</td>
<td>1</td>
<td>49</td>
</tr>
</tbody>
</table>

SEPA currently classifies 50 524 km of the estimated 100 000 km of rivers in mainland Scotland.

Table 2
River habitat survey results for Scotland, 1995/7 (SEPA, 1999)
physical degradation is primarily correlated with the pattern of agriculture and urban land use. Modification of water courses is likely to be much more widespread than identified by RHS, because historical alteration may not be evident. On the Moffat Water in the southern uplands, for example, a seemingly semi-natural section in fact represents an artificially straightened channel cut through
mine spoil (N. Chisholm, pers comm). The Channel subsequently widened due to the increase in stream power. Instream structures are now being used to promote channel narrowing and provide appropriate flow depths and velocities for salmon and trout.

4.3. Effects of land use change on water quality

Land use changes have affected water quality in Scotland through both point source, (e.g. industrial and sewage effluents) and diffuse pollution, (e.g. leaching of nutrients from agricultural land). The effects land use change on water quality varies across Scotland, depending on the nature and rate of change (Ferrier and Edwards, 2002).

Acidification of surface waters has occurred mainly in south-west Scotland, due to high rates of acidic deposition, the poor buffering capacity of the soils and the widespread presence of conifer plantations, which enhance the deposition of atmospheric acidity (Soulsby et al., 2002). Extensive studies of the mechanisms, impacts and solutions to surface water acidification have been conducted in the Dee and Fleet catchments in south-west Scotland (Howells and Dalziel, 1992; Welsh and Burns, 1987). Diffuse agricultural pollution occurs mainly in the productive arable areas of eastern Scotland and is well documented in the Ythan, (e.g. Balls et al., 1995) and Lunan catchments (Grieve and Gilvear, 1994). River pollution from sewage effluent and urban drainage is concentrated in central Scotland, where population densities are highest. In the River Almond, 43% of poor quality waters are caused by sewage effluent and 19% by urban drainage (River Almond Catchment Partnership, 1997). Pollution from highway runoff, outside of urban areas, has also caused significant deterioration in water quality, (e.g. McNeill and Olley, 1998) unless sustainable urban drainage practices are used. The impacts of mining activities on river water quality in Scotland are concentrated in central Scotland, where mineral and coal mining was formerly widespread (Chen et al., 1999; Robins, 2002) (Table 3).

<table>
<thead>
<tr>
<th>Cause of pollution</th>
<th>% of Fair, poor and seriously polluted river reaches affected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sewage</td>
<td>33.9</td>
</tr>
<tr>
<td>Agriculture—diffuse</td>
<td>26.2</td>
</tr>
<tr>
<td>Acidification</td>
<td>11.7</td>
</tr>
<tr>
<td>Urban drainage</td>
<td>11.4</td>
</tr>
<tr>
<td>Mine drainage</td>
<td>8.9</td>
</tr>
<tr>
<td>Agriculture—point sources</td>
<td>6.3</td>
</tr>
<tr>
<td>Industrial effluent</td>
<td>2.1</td>
</tr>
<tr>
<td>Contaminated land</td>
<td>1.0</td>
</tr>
<tr>
<td>Waste management</td>
<td>1.0</td>
</tr>
<tr>
<td>Forestry</td>
<td>0.4</td>
</tr>
<tr>
<td>Fish farming</td>
<td>0.3</td>
</tr>
</tbody>
</table>

4.4. Effects of land use change on ecology—a case-study of salmonids

Land use changes have adversely affected salmonid populations in some Scottish rivers, through alterations in flow regime, geomorphology and water quality. In addition to the impacts of alterations in flow regime on geomorphology and water quality discussed earlier, land use change is significant in terms of loss of bankside vegetation and has been particularly damaging to salmonid populations for a number of reasons. Bank instability and erosion may occur after the loss of bankside vegetation, resulting in channel widening and loss of pool-riffle sequences. Increased river water temperatures, which are stressful to salmonids, are also associated with decreased water depth, as channels become wider and loss of shading from bankside vegetation. The capacity of bankside vegetation to trap suspended solids and nutrient inputs in runoff from forestry and agricultural land uses, is also reduced when it is depleted. Reduced bankside vegetation also reduces the leaf litter and terrestrial insect inputs to river water, which are important food supplies for salmonids, particularly in upland rivers where autochthonous production is low. One Scottish study found that up to 75% of the invertebrates eaten by trout in a moorland stream were of terrestrial origin (Egglishaw, 1967). In Scotland, most research on the relationship between land use and salmonid populations has been undertaken in relation to the effects of for-
Scottish river flow regimes. Years have already led to noticeable changes in mate change. Climatic changes over the last 20 century, mediated by socio-economic responses to climatic change scenarios indicate that wetter winters with negative impacts on ecological quality, geomorphology, water quality and ecological quality of flow regimes, and indirectly through changes in runoff regime. In the acid sensitive catchments of Galloway, data relating salmonid populations to percentage of forestry suggests that where forestry comprises more than 60% of the catchment, there is a severe decline and where the cover reaches 80%, salmonids are devoid (Puhr et al., submitted). Another impact of land use change that may be disadvantageous to salmon population is siltation of salmon redds (Soulsby et al., 2001). Levels of fine sediment input to some Scottish rivers are increasing due to enhanced soil erosion, with the conversion to the growing of autumn sown cereals. Eutrophication, resulting from fertiliser runoff, is usually beneficial to fish populations, though it has been cited as the cause of disappearance of the Arctic Charr from Loch Leven (Maitland and Lyle, 1991) but not salmonid decline.

5. Impacts of climate change on Scottish rivers

It has been demonstrated that river regulation and land use changes have altered the hydrology, geomorphology and water quality of Scottish rivers, with negative impacts on ecological quality, as evidenced by salmonid populations. In the 21st century, it is anticipated that climate change will also affect the character of Scottish rivers (Werrity, 2002). This will occur directly through alteration of flow regimes, and indirectly through changes in geomorphology, water quality and ecological quality, mediated by socio-economic responses to climatic change. Climatic changes over the last 20 years have already led to noticeable changes in Scottish river flow regimes.

Increases in winter runoff (Smith and Bennett, 1991) and the frequency and magnitude of flooding (Black, 1996) have been observed. Climate change scenarios indicate that wetter winters with greater climatic extremes may be the trend in the 21st century (Beven, 1993). One possible scenario will be that winter temperatures in the UK may rise by up to 1.5 °C, with the largest increases in the north and a possible winter precipitation increase of 5%. There is palaeo-ecological evidence that when climate change occurs in Scotland, it may be fairly rapid. Anderson et al. (1998) thus reported evidence of a shift to wetter climatic conditions during the period of approximately 3900–3500 BP and suggest that the transition may have occurred over a decadal to century timescale. In many respects, this rapid change in climate occurred in the 15th century and led to what is termed the little ice age (Whittington, 1985). Prediction of how climate change will affect river flows is complex, but understanding the overall response of river ecosystems is even more problematic. This is particularly true where land use management and water resource use will also alter as a socio-economic response to climate change (Scottish Executive, 2000). For example, Gilvear and Black (1999) demonstrated that modest changes in flood flows on the Rivers Tay and Earn have a significant impact on agricultural flood embankment stability. This, in turn, could impact on riparian management, floodplain land use and water quality. Smith and Bennett (1991) showed how small changes in river flow in Scotland can have important implications for water resource management strategies and hence, river flows.

A number of studies have demonstrated a close association between the magnitude, frequency and seasonality of floods in Scottish rivers and patterns of climate change (Sargent and Ledger, 1995; Black, 1996; Black and Werrity, 1997; Steel et al., 1999). This knowledge will help with prediction of the effects of climate change on flow regimes in Scottish rivers, particularly where the occurrence of snow is already marginal, but snowmelt provides an important contribution to summer low flows and winter and spring flooding. Consequently, an increase in winter temperature could have a dramatic effect on the flow regime of rivers rising in the uplands. There is ongoing research by Dunn and Langan (1998) and Dunn et al. (2001) on snowmelt and flow hydrology in Scotland, which shows the sensitivity of snowmelt to climatological variables.
Fig. 8. The impact of climate change on stream water quality and salmonid populations.

The direction and extent of channel adjustment to climate change is likely to be primarily controlled by the ratio of sediment delivery increase from the catchment to river discharge. The extent of change is uncertain, given that the geomorphic sensitivity of Scottish river systems is not well characterised and also geomorphic thresholds exist whereby channel change can be pronounced if a critical flow threshold is exceeded. Higher flows during the winter months are anticipated in Scottish rivers, as a result of the predicted increase in winter rainfall. Such a change is likely to lead to increased levels of channel instability and may include more frequent shifts in channel position, higher rates of bank erosion, channel incision in some reaches and greater bedload transport rates. Werrity and Leys (2001) suggests that major changes in channel form, (e.g. from meandering to braided) will not occur, but this would not preclude significant changes in rates of bank erosion and bedload transport rates. Changes in river channel geomorphology will depend on socio-economic responses to the rate of channel modification, such as land ownership issues and the stability of engineering structures such as bridges, roads and railways.

Climate change is expected to adversely affect the water quality of Scottish rivers, both directly and indirectly (Fig. 8). As the climate becomes wetter, a greater magnitude and frequency of acidic episodes may occur in the north and west, and pollution from urban drainage and diffuse agricultural sources may become more extensive and severe in the east. The hydrological effects of climate change, which will have the greatest impact on water quality, are changes in rainfall...
and flow regimes. If rainfall and flow regimes become more variable, with drier summers and wetter winters, then there will be less flow to dilute pollution in the summer months. This may particularly affect rivers rising in the uplands, where a decrease in snowfall and snowmelt is expected to reduce spring and summer baseflow. Discharge consents for the control of point source water pollution are based on the current low flows but, if these decrease, the consents may require revision in order to prevent widespread water pollution. Water quality impacts of changes in river flow will also need to be considered in future abstraction licences. Water pollution from urban drainage is expected to increase if the climate becomes more extreme and pollutants are flushed from impermeable urban surfaces by intense rainstorms, after prolonged dry antecedent conditions. Increased hydrological extremes may also result in a rise of acidic episodes and DOC concentrations in rivers in upland catchments, due to the effects of climate change on soil moisture conditions and hydrological pathways. Research from Norway shows that stormier winters are associated with increased sea-salt induced acidification in coastal areas (Lydersen, 1995). Warmer soil temperatures and more intense wetting and drying cycles could promote the mineralisation of soil nitrogen and the formation of organic carbon to be leached into rivers (Soulsby et al., 2002). For example, modelling of water quality in the River Don, northeast Scotland, suggests that nitrogen inputs to rivers could increase as a result of enhanced nitrogen mineralisation in the soil, although demineralisation in the river channel may reduce this effect (Ferrier et al., 1993). In addition, increased water temperatures will reduce the dissolved oxygen levels.

Climate change is anticipated to have positive and negative effects on the ecological quality of Scottish rivers. Increases in channel instability, up to a certain level, often result in increased species diversity. Moderate levels of channel migration have thus been demonstrated to be conducive to floodplain habitat diversity and high levels of natural heritage value, (e.g. Gilvear et al., 2000; Parsons and Gilvear, in press). However, the predicted deterioration in water quality may adversely affect channel fauna and flora and alter competition between species. For example, coarse fish are expected to be favoured by higher temperatures and lower oxygen conditions in Scottish rivers. In addition, the greater magnitude and frequency of flood events could affect the reproductive success of salmonids in Scottish rivers. On the River Broom, in north-west Scotland, there is significant evidence of reduction in numbers of juvenile salmon in years following major redd wash out.

6. Improving the ecological quality of Scottish rivers

Maintaining and improving the current status of ecological quality in Scottish rivers poses a number of challenges for the 21st century. This section describes the research and policy initiatives in the areas of hydrology, geomorphology, water quality, ecological quality, and holistic river ecosystems, which are currently underway to improve the future ecological quality of Scottish rivers. Future hydrologically based research requirements are also outlined which will inform improvements in ecological quality.

6.1. River flow regulation

6.1.1. Ecologically acceptable river flows

One major contentious area associated with biology and hydrology is the relatively recent introduction of a number of predictive modelling methodologies, the most well known being PHABSIM. Soulsby et al. (1998b) undertook a combined hydrological–ecological modelling approach, using PHABSIM to assessing the impact of a proposed groundwater abstraction on Atlantic salmon spawning habitat on the Luther Water in East Grampian; in this case habitat loss due to the scheme was predicted to be less than 6%. However, on different rivers, or consideration of other life stages of fish or greater flow modification, the loss could be much higher. Increasingly, modelling of the effects of river flow on other aspects of the natural heritage of Scottish rivers is going to be needed to conserve their natural heritage status. However, there must be confidence in the modelling approaches being used both from a hydrolog-
ical and biological standpoint. The primary problems arise not from the hydrologist’s point of view, because it is relatively easy to measure the various physical parameters involved with the models, but from the biologist’s perspective. The models rely on species suitability curves to define the habitat requirements of particular species or life stages. Fish preference curves for juvenile Atlantic salmon from the River Almond obtained using flume experiments, have, however, been shown to be discharge and population density dependent (Holm and Armstrong, 2001). The work tends to suggest that methods of constructing preference curve are invalid and thus, the value of PHABSIM is seriously weakened. This highlights the major problem for hydroecologists and anyone wishing to manage river systems and the biota that inhabit them—there is insufficient knowledge, particularly in Scotland, to fully understand the way in which animals interact with their complex aquatic environment. The Scottish and Northern Ireland Forum for Environmental Research (SNIFFER) has commissioned a research project on the use of categorising river flow variability, based on previous work by Richter et al. (1997) in the USA, as an aid to determining ecologically acceptable flows. The major challenge for freshwater scientists is to narrow the knowledge gap sufficiently to enable ecologically acceptable flow management to occur.

The effects of future flow regulation and water abstraction schemes will increasingly be scrutinised in relation to whether they threaten the integrity of river ecosystems (Fox and Walker, 2002). The unacceptable ad hoc situation at present is described in a paper by Adeloye and Low (1996). SEPA thus welcomes the EU Water Framework Directive, which requires the introduction of abstraction and impoundment licensing, except where it can be demonstrated that an abstraction or impoundment has no significant impact upon the ecological status of water (SEPA, 1999). A key concern here is whether abstraction licences granted in the past and old compensation flow agreements will be able to be re-evaluated, in the light of greater knowledge about their environmental impacts. Moreover, a single constant flow cannot be expected to maintain the ecological integrity of stream systems where flow variability is a key issue (Webb et al., 2001; Gibbins et al., in press).

6.1.2. Channel maintenance flows

In recent years, the importance of periodic high flows in controlling river channel morphology and preventing sediment aggradation and siltation problems within impounded rivers has been realised. Thus, in some parts of the world, channel maintenance flows are periodically being released from reservoirs, to help maintain the stream ecosystem (Hill et al., 1991; O’Brien, 1987). Concomitant with this, sediment deposited in reservoirs and trapped behind river diversion dams or water of-takes is being excavated and introduced into the river downstream (a procedure known as substrate replenishment). Implementation of channel maintenance flows and substrate replenishment should thus be considered on Scotland’s regulated rivers; however, it should be emphasised that a combination of both approaches is needed to bring about long-term geomorphological or ecological benefit. Nevertheless, Scottish and Southern Energy have recently introduced substrate replenishment as a best management practice. Determining appropriate channel maintenance flows is also problematic, although a general ‘rule of thumb’ is that 80% of bankfull discharge, (e.g. Maddock and Petts, 1996) should bring about beneficial geomorphic changes. Such a release strategy, however, may not be able to restore the natural channel morphology through time, if vegetation has colonised and stabilised former sand and gravel bars, and channel margins following regulation (c.f. Fig. 7). In these cases, acceptance of the existing situation or a one-off disturbance of the riparian zone might be needed. These approaches if implemented, would be in tune with the ethos that humans should work with and not against natural fluvial processes.

Restrictions on rates of stage change in regulated rivers should also be considered. On the relatively new Roadford Reservoir in Devon, England, for example, the hydropower release strategy incorporated ‘saw-tooth’ hydropower generation reservoir releases, with rates of rise and fall approximately mimicking natural flood hydrograph
conditions. Petts (1996) suggested that one needs to identify a range of benchmark flows for maintaining stream morphology and biota. An interesting relationship between river flow, fish behaviour and fish management, in the context of this paper is the use of freshets to stimulate fish migration. These have not always met with success, due to incomplete knowledge of the factors that trigger fish migration. Moreover, in Scotland, some District Salmon Fishery Boards have arranged freshet releases more as an aid to catching fish than allowing them to reach their spawning grounds.

On the River Cassley, the success of a new freshet regime was monitored using a counter on a Borland lift. Freshets were made when there were natural spates occurring. However, at the Borland Lift, movement upstream only occurred once the distracting flow created by the freshet ceased (Fig. 9). This type of arrangement, mirroring natural runoff, is a model that Scottish and Southern Energy are trying to introduce elsewhere, but are encountering reluctance to change from fishery interests.

With reference to Scottish rivers, there is considerable scope for hydrological research in these areas. Further consideration of instream flow requirements, in connection with maintaining a natural channel geomorphology and biota, are given below, in the hydrology and geomorphology, and hydrology and biota sections. Given hydrological change at the decadal scale has been a feature of the Scottish climate in recent years and future hydroclimatic uncertainty, water resource organisations would benefit from undertaking 10-year reviews of their use of water and operational procedures in relation to current flow regimes. Scottish and Southern Energy have such a policy. In particular, the possibility of identifying surplus flow that can be used for maintaining stream ecosystem health via appropriate releases, rather than extra financial profit should be considered.

6.2. River engineering, river restoration and hydrology

Typically, river engineering has been used to produce river channels that are hydraulically more efficient and to stabilise channel morphology. Such approaches have been seen to cause adverse environmental and hydrological consequences, (e.g. increased flooding downstream) and occasionally to fail, whereby the relationship between river flow and sediment transport in natural channels was not accounted for. Such a situation has recently been highlighted by the World Wide Fund for Nature (WWF Scotland) on the Water of Ruchill in Perthshire. Dredging, to try and alleviate flooding resulted in headward erosion, and a suite of unwanted hydraulic and geomorphic effects, which now need to be fixed using instream structure such as submerged vanes. The target for future river engineering and rivers restoration will be to design and construct river channels, and undertake bank stabilisation where really necessary, which are environmentally sensitive, hydrologically sound and sustainable solutions, (e.g. Hey, 1996). Such an approach will be reliant upon a sound understanding of river hydrology, flow hydraulics and possible future changes in channel regime.

6.3. Land use

6.3.1. Land use change

Given that it is well accepted that land use changes, such as urbanisation, land drainage and forestry can influence runoff and flow variability, greater consideration needs to be given to the signficance of land use changes on river flows. This is particularly the case where low flows already result in adverse environmental effects. For example, reforesting Scotland with species similar to its original forest cover (such as Pine and Birch) is a welcome nature conservation initiative. The hydrological effect of such a catchment land use, however, has not been fully considered and warrants research (however, see Wade et al., 2001). The authors anticipate, however, that the hydrological impact will not be great; certainly the scientific literature does not consider deciduous forest to result in the same level of increase in interception losses and evapotranspiration, and hence, depletion of runoff and low flows as coniferous forests. The Calder–Newson formula, for example for coniferous forests, suggested runoff reductions of approximately 20% in the UK, for a 100% forest cover (Pyatt, 1984). Moreover,
Fig. 9. Patterns of freshet release and fish movement past the counter on the River Cassally at Duchally between 1st June and 31st August 1997.
increased deciduous woodland alongside rivers and in the wider catchment are likely to bring many ecological benefits, including increased organic input, coarse woody debris accumulations and more shade to Scotland’s river systems (Gurnell and Linstead, 1998; Keller and Swanson, 1979). In the respect of commercial forestry, the Forest and Water Guidelines (Forest Authority, 1993) were a major step in reconciling this land use and river conservation. An issue to be resolved in Scotland, however, is the planting up of whole catchments in that it can exacerbate low flow problems.

The key issue with respect to the hydrological effects of land use is that it considered within an integrated catchment management framework (Werrity, 1995). In this way, the hydrological effects of land use change on river flow and water quality will be addressed, and result in sustainable water management. The setting up of the Loch Leven Catchment Management project in Fife, in 1995, provided a useful example in this context. The Loch, which is a lowland lake and a Site of Special Scientific Interest, has suffered from eutrophication from sewage and diffuse agricultural inputs (Ferrier and Edwards, 2002). An integrated, catchment approach was therefore required to restore water quality. Other catchment management plans or studies in Scotland include those for the Ythan, Eden, Water of Leith, Tweed, Loch Leven and West Galloway catchments. Here, the pioneering work of the Tweed Foundation, which has taken a fairly holistic, catchment-wide approach to safeguarding and enhancing the salmonid population of the river Tweed is particularly significant (Campbell and Maitland, 1996). This initiative involves a grass-roots response to catchment management, and involves both regulatory and a range of other stakeholder groups all working towards sustainable catchment management.

Tackling diffuse pollution is considerably more complex than controlling point source pollution, as an understanding of the complexities of river ecosystems is required (Ferrier and Edwards, 2002). As we have already shown, in river ecosystems, the relationships between hydrology, water quality and biota may not be linear or reversible, and critical thresholds may exist. It is also difficult to define the objectives of controlling diffuse pollution in terms of the natural heritage of river ecosystems and evaluate when these objectives have been met, because change often only happens over long timescales (decades), and changes may be difficult to measure due to the inherent variability of the system. Furthermore, climate change may influence the effectiveness of measures to control diffuse pollution. Application of MAGIC (Model of Acidification of Groundwater in Catchments) to the Monachyle catchment at Balquhidder showed that, even if diffuse atmospheric deposition of acidic oxides decreased, climate change may hinder the recovery of acidified waters (Ferrier et al., 1993).

6.3.2. Best management practices

Given concern over dealing with problems of diffuse pollution, Best Management Practices (BMPs) can be encouraged to control diffuse agricultural pollution and urban drainage (D’Arcy and Frost, 2001). BMPs are already being promoted and adopted in Scotland—a recent survey found 79 examples of urban drainage BMP structures (McKissock et al., 1999)—but they need to be developed on a sound scientific basis. For example, buffer zones may not always improve the chemistry of agricultural runoff, where groundwater or field drains bypass the buffer zones (Haycock and Muscutt, 1995; Petry et al., 2002), though river ecology may benefit from wooded buffer zones. BMPs for water quality improvement should therefore be targeted at variable source areas, where most catchment runoff originates. Incentives are also often required for BMPs to be adopted, since benefits may be long-term and not immediately tangible. Demonstration projects at carefully selected sites, where benefits are rapidly apparent, are probably vital for gaining community support and adoption of BMPs. A Scottish example is the Greens Burn buffer strips project in Fife, which forms an inflow to Loch Leven, with the buffer strips intended to minimise pollutant inputs.

6.3.3. Living with channel instability

The traditional response to bank erosion and channel bed aggradation has been bank protection and dredging, respectively. Both of these activities
can potentially be damaging to stream ecosystems and can be banned if the river has high nature conservation status. On many river reaches, sediment loss will be balanced naturally by gain elsewhere or vice versa. Acceptance of this situation is difficult for riparian owners, who see the river from the perspective of their specific needs. Where the sediment budget is in a state of quasi-equilibrium, the situation should ideally be accepted, but there are cases where upstream activities have created the problem and often a management solution is less clear cut. For example, Fergus (1998) demonstrated that an upstream impoundment on the River Fortune in Norway reduced peak flows, but because of massive in-channel aggradation and channel narrowing, channel capacity was reduced by more than the flood peak, resulting in elevated flooding of the valley floor. Geomorphic adjustment to natural and human-induced changes are thus complex. Such issues need to be tackled, based on good scientific enquiry as to the cause, and with appropriate consultation and dialogue with riparian owners.

Changes to valley floor land use compatible with flooding, such as floodplain forests and abandonment of flood embankments are also being advocated by organisations such as WWF (Scotland). The Royal Society for the Protection of Birds (RSPB), in their management plan for the Insh Marshes in Speyside, also advocate a non-interventionist approach to hydrological management—involving absence of water control structures and a policy of letting 18th century flood embankments fall in to a state of disrepair. Such moves are welcomed in terms of reductions in flood damage and improving the nature conservation value of floodplains. In terms of their hydrological impact, flood wave attenuation is likely, but the exact magnitude of the effect is a research area that could be pursued.

6.4. Other actions need to improve the ecological quality of Scottish rivers

6.4.1. Biodiversity action plans

Salmonid fish are economically important and are the focus of much management action (Table 4). Protection of other, less economically significant, but ecologically important, riverine species is being pursued via Local Biodiversity Action Plans (LBAPs), which are being produced by Local Authorities as a consequence of the Biodiversity Convention signed at the Earth Summit in 1992. The LBAP initiatives are going to be potentially significant in prioritising local action to maintain and enhance various habitats and species, as they have been initiated by local government, and are supported by a wide range of NGOs and industry, along with SNH, SEPA and the Water Authorities.

One of the most important species in the LBAP process from a freshwater perspective is the Freshwater Pearl Mussel (*Margaritifera margaritifera*) and the hydrology of rivers in which these molluscs live can be of great importance. The presence of the juvenile forms of the trout and salmon are also critical in the Pearl Mussel’s life cycle, as the young mussels use the juvenile salmonid gills to disperse and colonise new sites. Without healthy salmonid populations, the mussels will not survive.

6.4.2. Monitoring of ecological quality

The classification scheme for river water quality used by SEPA was revised in 1996, to include biological quality, nutrients and litter, as well as standard chemical measurements. Water quality monitoring is thus pretty efficient. Since water quality in Scottish rivers is particularly affected by storm events there is also, however, a need for detailed water quality sampling at selected sites during storm events.

From a fisheries perspective, the key data required as prerequisites for any prospective management are information on the fish stocks themselves and an accurate picture of the aquatic habitat in which the fish are living. The latter habitat information extends to relevant terrestrial data of the immediate bank side. The link between habitat and fish population data can be explored using HABSCORE (Milner et al., 1985). Over the past decade, a number of different methodologies have been developed in an attempt to quantify the instream and bankside habitat for a wide range of purposes. General conservation-orientated data collection protocols have been developed, such as the System for the Evaluation of Rivers for CONser-
Table 4
River management and restoration strategies that would assist in protecting and maintaining salmonid populations in Scotland

<table>
<thead>
<tr>
<th>Water quantity</th>
<th>Water quality</th>
<th>Adult habitat</th>
<th>Spawning habitat</th>
<th>Juvenile habitat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low flows</td>
<td>Flow regulation</td>
<td>Flow regime</td>
<td>Gravel cleaning</td>
<td>Provide shade</td>
</tr>
<tr>
<td>Flow augmentation</td>
<td>Banned substances</td>
<td>Natural obstruction (access/removal)</td>
<td>Flushing flows (regulation)</td>
<td>Depth increases via channel restrictions</td>
</tr>
<tr>
<td>Channel narrowing</td>
<td>Operational restrictions (sheep dip)</td>
<td>Create correct upstream stimulus in areas where flows are controlled</td>
<td>Gravel addition</td>
<td>Riparian fencing and planting</td>
</tr>
<tr>
<td>Flow regulation</td>
<td>Dilution via flow augmentation</td>
<td>Create and enlarge Holding Pools</td>
<td>Gravel collection (in-stream interception)</td>
<td></td>
</tr>
<tr>
<td>Relief channels</td>
<td>Buffer strips</td>
<td>Man-made obstruction (fish pass)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refuge areas</td>
<td>Set-aside (agri-environment schemes)</td>
<td>Create correct upstream stimulus in areas where flows are controlled</td>
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<tr>
<td>Abstraction controls</td>
<td>pH adjustment</td>
<td>Consent limits</td>
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<td>Catchment liming</td>
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</table>

vation (SERCON), which attempt to be all encompassing, but, by their very nature, are somewhat subjective (Boon, 1995). Other methodologies, such as River Habitat Survey, are being widely used by the Environment Agency in England and Wales, and SEPA in Scotland. Again, this methodology is somewhat of a broadbrush approach and the fisheries interests in Scotland have developed a separate protocol for assessing the habitat from a fisheries perspective. This has been achieved by the Scottish Fisheries Co-ordination Centre (SFCC), set up in 1997, and supported in partnership by Scottish and Southern Energy (formerly Scottish HydroElectric), the Scottish Executive, SEPA and SNH. The initiative now covers two-thirds of Scotland and it is hoped the remaining areas will be incorporated early in the next century. The main aim of the SFCC, the need for which was foreseen by the Scottish Salmon Strategy Task Force (Scottish Office, 1997), is to serve the organisations in the partnership in three areas:

i. creating and maintaining high quality databases on fish and associated aquatic resources;

ii. providing direct assistance with local fishery management initiatives, in particular through the provision of appropriate IT; and

iii. providing a high quality research facility based on an integrated catchment approach.
Since establishment of the SFCC, its partners have developed common juvenile fish sampling and habitat survey protocols to ensure that data are collected to the highest possible standards. Unlike other fish and habitat survey methods, those used by the SFCC were developed specifically for fishery management applications. It is also the first time juvenile fish and habitat data collection is comparable nationally across Scotland. Customised databases and Geographic Information Systems (GIS) have been developed to store, retrieve and analyse the information collected more efficiently. Without baseline data from which to work, the SFCC partners have recognised it is impossible to quantify changes to the physical habitats, which are so important to the fisheries. It is also impossible to produce cost effective remedial work without these data.

### 6.4.3. Further scientific research

Environmentally-sound river management of Scottish rivers should be based on best available science. There are still many areas where lack of understanding hampers sound management of riverine ecosystems. Within the context of the scope of this paper, key research areas are: modes of flood generation; the temporal and spatial variability in patterns of flooding and low flows; the mechanisms of release and uptake of agriculturally and urban derived pollutants; the significance of the initiatives to restore Scotland’s native woodland; and the impacts of climate change on water quality. In each case, the way in which salmonids and other biota living in Scottish rivers respond to changes in habitat variables is poorly understood.

### 7. Conclusions

Considerable improvements in many aspects of the natural heritage status of Scottish rivers have taken place over the last few decades. At the same time, degradation of many river reaches has been witnessed due to variety of causes, including increased water abstraction, diffuse pollution, unsympathetic river engineering and the over-grazing of riverbanks. This paper has demonstrated that hydrology and its control on water chemistry, channel geomorphology and biota is of central importance to tackling such issues, and in conserving and enhancing the natural heritage of Scotland’s rivers. However, there are still gaps in our knowledge, and inadequate understanding with regard to the link between hydrological processes and the ecological quality of Scotland’s rivers and streams. These inadequacies should be addressed by scientists, but in the meantime, river managers need to move forward, based on the best available knowledge, which in some cases may well be sufficient for their needs. Hydrological understanding alone is not enough, however. There needs to be the will, policy framework and legislation for implementation of river management techniques, and schemes aimed at maintaining and enhancing the natural heritage of Scottish river ecosystems. Fortunately, during the last decade of the 20th century, there has been a shift in attitude towards rivers in Scotland, and a realisation that change is necessary if the natural heritage status of Scotland’s rivers is going to be maintained and improved. Such a change in attitude has many drivers, but notable ones include grass-roots initiatives such as WWF’s Wild Rivers programme and the Tweed Foundation, and statutory changes such as the establishment of SEPA and Scottish Natural Heritage. Moreover, the new EU Water Framework Directive will also have a major role in emphasising the importance of a holistic approach to safeguarding the natural heritage of Scottish rivers.

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