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Recently increased river discharge in Scotland: effects on flow hydrology and some implications for water management

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Abstract

A marked trend to increasing wetness over Scotland, amounting to around 40 per cent in terms of yearly mean flows during the 1970–89 period, is demonstrated by analysis of annual, seasonal and extreme monthly river flow in six key catchment areas. The absence of a reliable database precludes the direct investigation of any associated rise in flood emergencies and losses, but examples are provided of the effects of increased runoff on reservoir storage. Questionnaire responses showed that, whilst over two-thirds of the 28 senior water managers sampled were aware of this recent shift in hydroclimate, their organizations lacked any means of dealing with climatic uncertainty in future planning.

Hydrologists and water engineers alike have begun to recognize that the future stationarity of climate cannot be taken for granted and that water resource systems, which typically have a long life expectancy, may well have to cope with different rainfall and runoff regimes in coming decades (Riebsame 1988; Waggoner 1990; Cole *et al.* 1991; Smithers 1992). However, the existing general circulation models (GCMs) give widely varying predictions for future precipitation/evaporation relationships at the regional scale and offer no guidance at the level of the individual drainage basin, which is the most relevant spatial unit for determining hydrological and water resource impacts. Despite these uncertainties, there is some consensus about a future scenario of wetter winters and drier summers in the UK (Rowntree 1990; UK Climate Change Impacts Review Group 1991), with suggestions that overall increases in precipitation will be relatively greater in the north and west than the south and east (Hulme and Jones 1989; Santer *et al.* 1990). This suggests that areas like Scotland will become wetter overall.

Comparatively few studies have concentrated on the effects of increasing wetness on hydrology and water resources, especially in areas that are already relatively well endowed with water. In this situation, an improved knowledge of recently observed climatic fluctuations and their impact (if any) can be an important complement to scenarios of future climate change, despite the difficulty of matching short-term trends with longer-term change. This is partly because such studies shed light on how environmental systems, and their managers, respond to variations in the present-day climate. But major variations can also provide some indication of how far—and how quickly—the present climate has to change before water managers perceive the new regime and make adjustments to maintain the performance of the physical facilities for which they are responsible. For example, a recently observed trend from drier to wetter conditions over large parts of Illinois, USA, has led to increased soil erosion and has compromised the operation of some water reservoirs (Smith and Richman 1993).

This paper examines the extent to which a similar shift towards increasing wetness over Scotland during a recent 20-year period (1970–89) has influenced the flow hydrology of some rivers and explores the effects that this has had on water management, the performance of reservoirs, and the perceptions of water managers.

Background and approach

Over Britain as a whole, the 1980s were the wettest decade on record (Marsh and Monkhouse 1990). Arnell *et al.* (1990) indicated that the average annual runoff was generally higher during the 1980s than in the two previous decades across much of the country. This shift in the hydroclimate appears to have been most pronounced in northern Britain. Gregory *et al.* (1991), using a composite rainfall series for Great Britain, showed that Scotland was at least 5 per cent wetter in the 1980s than in any decade since the 1930s. In fact, the step up in that series from a mean areal rainfall of 1270 mm in the 1970s, which was a very dry decade, to a value of 1445 mm in the 1980s, amounts to an increase of almost 14 per cent and constitutes the largest inter-decadal switch in rainfall over Scotland in at least the last 60 years. This general increase in rainfall has been attributed to a changed pattern of regional airflows over the British Isles, characterized by a much greater frequency of westerly activity over Scotland since the mid-1970s (Mayes 1991). Under these synoptic conditions, the largest percentage increases in rainfall tend to occur in the western areas, which are subject to orographic enhancement of rainfall in westerly airstreams, compared to the more sheltered 'rain-shadow' districts in the east.

This shift to wetter conditions has already attracted some comment. For example, Rowling (1989) documented a rise in flood frequencies in central Scotland between 1971 and 1985 arising mainly from increases in autumn and winter rainfall. Curran and Poodle (1990) noted a trend to higher levels in Loch Lomond associated with increases in the mean annual flow of the contributing rivers. On the other hand, although conceding the occurrence of some notable flood events in the late 1980s and early 1990s, other workers (Mott Macdonald 1990; Sprott and McKenna 1992) have failed to detect any statistically significant trend to increased flood flows. Curran and Robertson (1991) claimed that the enhanced dilution from consistently higher flows has had a positive effect on observed improvements in biochemical oxygen demand within the Clyde basin.

Potentially, a wide range of discharge parameters can be used to test river flow records for stationarity over the relevant periods of time. In this case, emphasis is placed on monthly, seasonal and annual values, rather than extreme events, in order to demonstrate a sustained, climatically driven trend in flow. The longest reliable river flow record in Scotland is for the Dee at Woodend from 1929. This station is used as a baseline against which to assess recent experience, despite the fact that its response may not be typical of Scotland as a whole. A further five stations, gauging other large regionally representative basins, were then selected to examine the 1970–89 period in more detail. The location of the selected basins is shown in Fig. 1. With the exception of the Tay at Ballathie, where 43 per cent of the

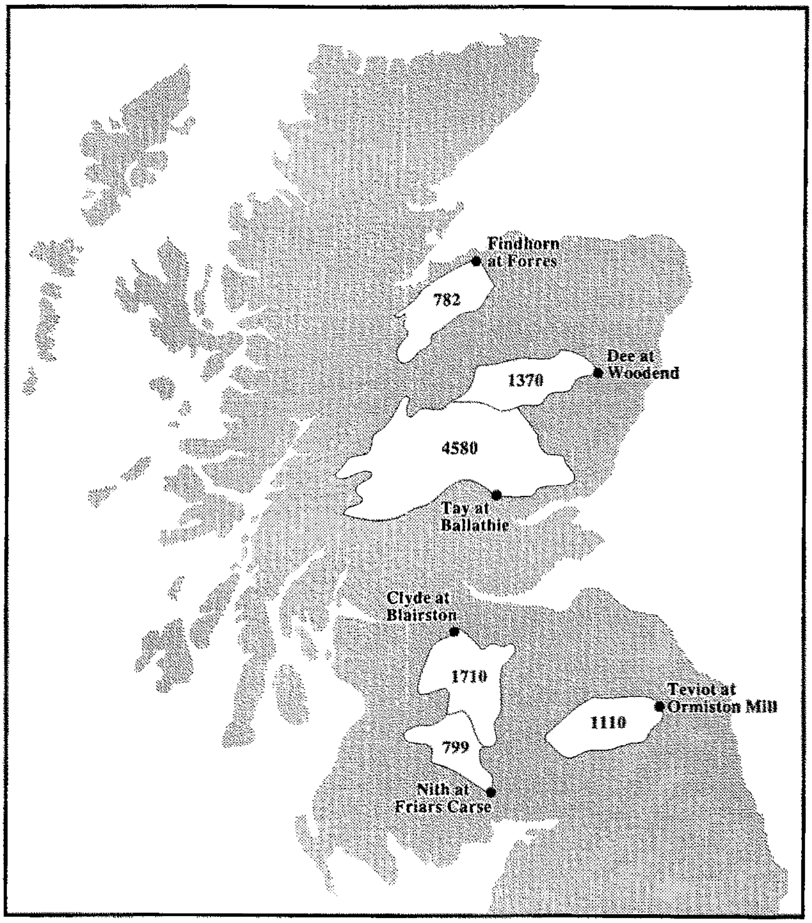

Figure 1. Location of the six selected drainage basins and gauging stations. Figures within the drainage basins indicate the area in km^2

catchment is involved in hydro storage but which was included as the best all-Scotland surrogate, all stations comply with the quality control criteria adopted by Arnell *et al.* (1990). It was not possible to find a suitable flow station covering the whole of the study period for either the north of Scotland, or the west coast, where the flow regime was not totally dominated by hydropower development.

Effects on flow hydrology

Figure 2 shows the mean daily flow of the River Dee at Woodend plotted as a four-year running average. It is evident that the lowest and highest flows occurred in the 1970s and 1980s respectively, a period when most of the flows were significantly different from the long-term mean. From 1970 until 1989 a marked upward trend is apparent, with an increase in mean flow from around 30 to 42 cumecs, a rise of 40 per cent. A Box Jenkins time-series analysis, performed on the

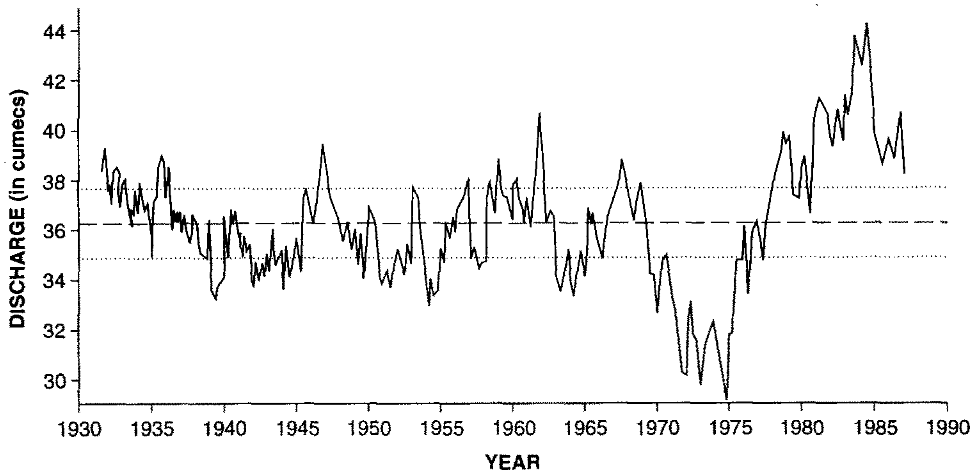

Figure 2. Four-year running mean of average daily flows for the River Dee at Woodend between 1929 and 1989 with confidence lines at ±2 SE

complete data set, confirmed that from 1929 to 1969 inclusive the flow record contained random fluctuations from year to year but displayed no significant trend, unlike the 1970–89 period.

Linear regression of annual runoff over the 1970–89 period, summarized in Fig. 3, shows that all six catchments have experienced an increase in mean annual flow, the relationship being statistically significant (reaching at least the 95 per cent level) for all catchments other than the Dee. It should be noted that the River Dee record understates the general situation, perhaps because of its more easterly location in the 'rain-shadow' area for westerly circulations, although other basins—such as that of the Findhorn—also lie on the east side of Scotland. Table 1 gives the

Table 1. Direction of seasonal flow trends (+ or −) and significance levels of correlations of flow with time (1970–1989) for actual flows and for seasonal flows expressed as a percentage of the annual total using Kendall's tau

Season	Dee	Findhorn	Tay	Clyde	Nith	Teviot
Winter	−	+	+95	+95	+	+
Spring	+90	+95	+98	+90	+95	+99
Summer	+	+	+99	+	+	+90
Autumn	+	+	+98	+	+	+90
Winter %	−95	−90	−	−	−	−90
Spring %	+	+	+	+	+	+
Summer %	−90	+	−	+	+	+
Autumn %	+	−	+	+	+	+
Mean max. monthly	+	+	+99	+95	+95	+95
Mean min. monthly	+	+	−	+	−	−

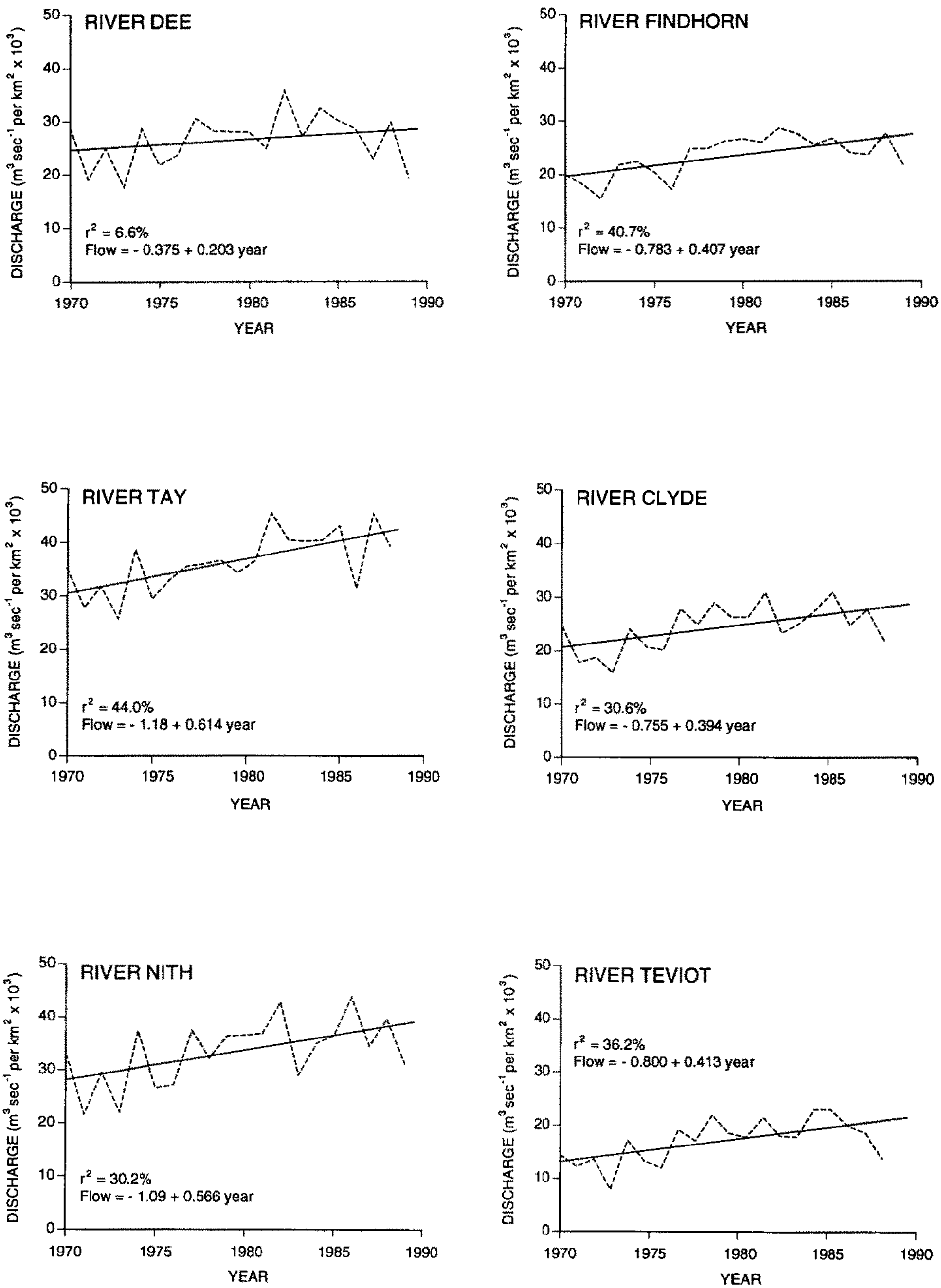

Figure 3. Relationships between annual flow per unit area and year for the six drainage basins with the linear regression lines

seasonal pattern of flow trends on both an absolute and a relative basis by showing the correlation through time of the flow volumes and the proportion of mean annual flow occurring in each season, using Kendall's non-parametric tau test (Kendall 1973). The increase has been fairly consistent throughout the year and all six basins show an absolute increase in flow during spring, summer and autumn. Exceptionally, the Dee exhibits a slight decrease in winter. The situation is more complex with regard to changing seasonal proportions of annual flow. However, all six basins show a proportionate drop during winter. For the Dee this relationship is significant at the 95 per cent level and it is at the 90 per cent level for the Findhorn and Teviot.

Extreme monthly flows are important indicators of sustained hydrological variability. All six basins show an increase in the mean maximum monthly runoff. The relationship is statistically significant for the Tay, Clyde, Nith and Teviot but is weak for the Dee and Findhorn. This again suggests some anomaly in northeast Scotland. For mean minimum monthly flows the pattern is less strong and more complex. Whilst the Dee, Findhorn and Clyde show an insignificant increase, the Tay, Nith and Teviot actually show a decrease. This suggests that water management may have become more difficult in the last three catchments since they have all experienced strong increases in maximum monthly flows but have also recorded some decrease in monthly minima.

Effects on water management

Climatic trends over decadal time scales have potential implications for many parameters relating to the management of both water quantity and water quality regimes, but increasing wetness is most likely to create problems for the control of sustained high flows.

Floods

It might be expected that an increase in flood hazard would be the most visible sign of increased wetness but this is difficult to demonstrate because the statutory responsibilities in Scotland are spread amongst various bodies. Primary responsibility for flood prevention, especially in rural areas, is allocated to individual riparian owners under the Land Drainage (Scotland) Act of 1958. The regional councils also have some powers under the Flood Prevention (Scotland) Act 1961, mainly in the urban areas, relating to non-agricultural land. Since the implementation in 1984 of the Local Government and Planning (Scotland) Act of 1982, the seven river purification boards (RPBs) have had discretionary powers to install flood warning schemes. The RPBs are normally required to pass any warnings on to the police, who then disseminate the information.

As a result of this diffuse responsibility, systematic flood records have not been maintained in Scotland over a sufficiently long period to produce a reliable archive for matching with hydrological trends. For example, Strathclyde Region police retain flood emergency information on a computer database for only two years (McMaster 1991), whilst the Emergency Planning Officer for Strathclyde reported that flood incidents recorded on a manual log were only available from 1984 as an earlier log had been lost (Macnamee 1991). Contacts with other regional councils revealed a similar lack of useful records. Although the RPBs maintain records of flood warnings, the data are comparatively recent because most of the 26 flood warning schemes operating within mainland Scotland have only been installed within the last two decades (Anderson *et al.* 1992). There is, therefore, an urgent need for some agency to be given the task of coordinating the collection of more comprehensive flood emergency and loss data in Scotland.

Reservoir performance

Gleick (1990) has shown that the vulnerability of water resource systems to climatic fluctuations depends on the ratio of storage volume to the quantity of river supply as an indicator of ability to withstand prolonged drought or severe flooding. Because many reservoirs operated by the regional water supply authorities and by Scottish Hydro-Electric plc are comparatively small, it was expected that their performance would be sensitive to changed river flow regimes resulting from the increased wetness.

For example, in the extensive Loch Katrine system of storages operated by Strathclyde Regional Council, which supplies water to Glasgow, the reservoirs were either full or spilling water for an average of 4·2 weeks per year during the 1970s. This rate almost doubled to an average of 8·0 weeks during the 1980s. The increase in uncontrolled spillage of water is most serious for hydropower interests, for whom any spill represents a loss in potential revenue. At one relatively small storage in central Scotland (Loch Faskally), the total average annual volume of water spilled increased by almost 238 per cent between the 1970s and the 1980s, compared with a proportionate rise of less than 40 per cent for the much larger reservoir at Loch Eigheach.

Despite variations due to flow: storage ratios, the actual increases in spill volume can be directly linked to the trend to greater wetness. Figure 4 shows the three-year running mean spill volumes from Lochs Faskally and Eigheach, operated by Scottish Hydro-Electric plc, correlated with year over the 1970–89 period. In both cases the relationship between spill and year is statistically significant at the 99·5 per cent level.

Effects on water managers

In order to test the awareness of water managers in Scotland about the recent trend to increased wetness, and to assess their perceptions about the importance of climate change issues in general, a questionnaire on climate change and water resources was mailed to 32 named senior individuals in the water and sewerage divisions of the regional councils (directors), the river purification boards (directors and chief hydrologists), Scottish Hydro-Electric plc (group and production managers) and the Engineering, Water and Waste Directorate of the Scottish Office Environment Department (principal engineers). A response rate of 28 (87 per cent) was achieved.

The first part of the questionnaire explored the general sensitivity of Scottish water resources to weather and climate. Respondents were asked about the importance of climate/weather to their organization's activities in water resource management and asked to identify which aspects of climate/weather most affected their work. The most significant result was that climate was deemed to be very important by 85 per cent of all respondents. Excess rain and drought periods were mentioned in 88 per cent of the returns. The second part of the questionnaire was designed to measure managers' awareness of recent climatic fluctuations by asking whether they believed that the Scottish climate had changed during the past 20 years. If so, the respondents were asked about the change(s) they thought had

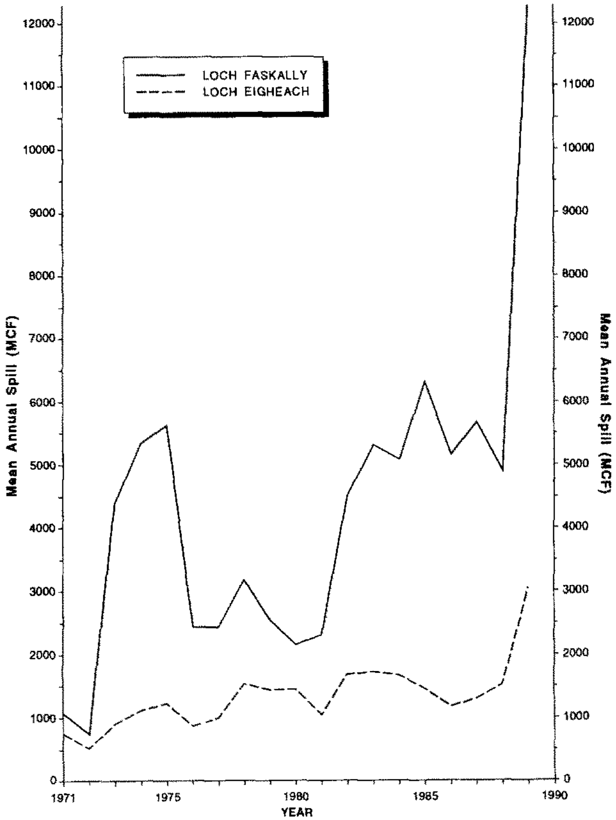

Figure 4. Three-year running mean of the annual spill of water from Lochs Faskally and Eigheach, 1970–89

taken place, whether they had firm evidence of such changes, and whether these changes had been sufficient to affect and/or change water management operations. A clear majority of 69 per cent expressed the belief that the climate had changed within the last 20 years, with most respondents who held this view specifying more variable, warmer and wetter conditions, including an increased frequency of storm rainfall. No less than 46 per cent of all respondents claimed to have firm evidence in support of these changes, including different rainfall distributions, more flood events, increased reservoir spills and drainage problems. Despite this, however, only about one-third of respondents (31 per cent) felt that the changes had been sufficient to affect their water management operations. Specific concerns mentioned included water supplies in dry summer spells (greater extension of public supplies into rural areas served by small local sources), pollution control problems resulting from reduced effluent dilution in dry weather, changed use of water sources, including more groundwater abstractions, and closer monitoring of reservoir storage levels for both water supply and flood prevention purposes.

The final part of the questionnaire looked forward to possible future changes of climate by asking questions about the vulnerability of water management in Scotland to climatic change, the likelihood and nature of any expected changes over the next 20 years and the planning arrangements available to cope with any such changes. The majority of the respondents (85 per cent) claimed that water resource management in Scotland is potentially vulnerable to future climate change, citing a wide variety of possible impacts, including drought planning, meeting peak demands for purposes such as irrigation, flood control, silting of water supply intakes, sewage treatment and water quality problems such as algal blooms and the maintenance of fisheries. Given this high level of concern, it is interesting that 65 per cent of managers also thought that the climate would change during the following 20 years (as opposed to 15 per cent who did not anticipate any change and some 19 per cent who did not know). There was also a wide range of views on the likely nature of such changes amongst those who expect a change, with the most frequent responses being towards warmer (53 per cent), more variable (35 per cent) and wetter (29 per cent) conditions. Despite the fact that the majority of water managers anticipate changes in climate over the following two decades, over two-thirds (69 per cent) admitted that their own organization lacked any methods or review procedures for incorporating climatic uncertainties into strategic planning. Of the 23 per cent who claimed to have procedures available, several replies indicated preliminary actions only, such as current investigations under way, general awareness and the increasing adoption of more flexible management attitudes.

Conclusion

This work has demonstrated that, during the two decades from 1970 to 1989, several large drainage basins representative of Scottish rivers showed a statistically significant trend to increased flows. These increases have been driven by the greatest shift in inter-decadal rainfall for at least 60 years which, in turn, has been dependent on a regional trend to more frequent westerly airstreams over Scotland. For some rivers the flows also appear to have become more variable, although the patterns are not consistent between individual basins and suggest the presence of more local factors that require further investigation. One influence is likely to be an east–west contrast due to more pronounced 'rain-shadow' effects. These results emphasize the importance of scale in studies of the impacts of climate change and the need for more areally specific outcomes when considering scenarios of future climate change.

There has been an associated increase in the annual spill of water from reservoirs in Scotland but it has proved impossible to link the shift in hydrological conditions directly to increased flood events or flood losses. Part of the problem lies in the difficulty of finding a definition of a flood that satisfies all interests. It would seem important, therefore, that some central initiative is taken for the systematic collection of information on flood emergency events and economic loss data in Scotland in order to provide a more reliable archive in the future.

Finally, the questionnaire survey indicated a high level of awareness of existing climatic impacts amongst senior water managers in Scotland, coupled with concern for future conditions. If, as a result of climate change, there is to be a longer-term trend towards wetter conditions over Scotland, a more detailed study of the two recent decades could provide an analogue for future water management strategies. But it must be stressed that, in the present state of knowledge, the recent fluctuations cannot be regarded either as unusual in the context of very long-term records or as a fingerprint of future climatic change. This is because what appears as a trend in the short run may be only part of a longer-term oscillation. On the other hand, the ongoing variability in climate from one decade to another will continue to influence hydrological conditions and raise operational issues which require a response from water managers.

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